Energy Systems Integration Facility:

Hazard Analysis Review

David Post, Charles Visser, Robert Richardella, Margaret Martin, and Carolyn Elam
National Renewable Energy Laboratory

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NREL/TP-5B00-61699
August 2015

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Energy Systems Integration Facility

Hazard Analysis Review

Approved by David J. Post **Date** 4/29/2015

David Post, ESIF Director

Approved by Maureen Ray **Date** 7/29/2015

Maureen Ray, Environmental Health and Safety

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Preface

The National Renewable Energy Laboratory (NREL) has performed a hazard analysis review (HAR) for the Energy Systems Integration Facility (ESIF). The objective of the HAR is to ensure the continued safety of workers, the community, and the environment. The NREL HAR process applies a systematic risk assessment that incorporates a graded approach to determine: 1) the environment, health and safety (EHS) hazards presented by a facility or operation, 2) the level of risk presented by those hazards, and 3) the controls necessary to maintain the risk to an acceptable level.

The NREL HAR process began at the ESIF conceptual design stage, paralleled the design process through construction and facility fit-out, and will continue to be updated throughout the lifetime of the facility. The ESIF HAR will be reviewed annually to ensure its accuracy, to identify improvement opportunities, and to implement robust change management.

The ESIF houses the laboratories necessary to enable complex systems research and development that will fully integrate the most advanced engineering, analysis, and simulation techniques intended to transform the nation's energy infrastructure. The 182,500-gross-square-foot facility includes approximately 200 office spaces, 15 high-bay laboratories and collaboration areas, a High Performance Computing Data Center, and an outdoor test area. The ESIF was designed and constructed to meet the U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED) Platinum standards.

The ESIF incorporates many advanced engineered safety features (ESFs) as well as NREL administrative controls that have been derived and refined during operations in existing NREL facilities. The combination of a specifically designed and constructed facility with proven administrative controls provides confidence that the facility can be safely operated within a defined safety envelope. Based on the evaluations discussed in this HAR, the overall facility risk for the ESIF is determined to be Low, which is the acceptable level of risk established in NREL policy.

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List of Acronyms

AAMA	American Architectural Manufacturers Association
AASHTO	American Association of State Highway and Transportation Officials
AATCC	American Association of Textile Chemists and Colorists
AC	alternating current
ACGIH	American Conference of Governmental Industrial Hygienists
ACI	American Concrete Institute International
ACRB	Alternating Current Research Bus
ADAAG	Americans with Disabilities Act Accessibility Guidelines for Buildings and Facilities; Final Guidelines and Amendment to Final Guidelines
AHU	air handling unit
AMCA	Air Movement and Control Association, Inc.
ANSI	American National Standards Institute
ASCE	American Society of Civil Engineers
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASME	American Society of Mechanical Engineers
ASTM	ASTM International
BAE	Building Area Engineer
BAS	Building Automation System
BHMA	Builders Hardware Manufacturers Association
Br	bromide
CCPS	Center for Chemical Process Safety
CCR	Code of Colorado Regulations
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act of 1980
CFR	Code of Federal Regulations
CGA	Compressed Gas Association
CM	configuration management
CM	corrective maintenance
CMMS	computerized maintenance management system
CO	carbon monoxide
CO_2	carbon dioxide
CR	change request
cRIO	compact real-time embedded industrial
CRS	Colorado Revised Statute
CSE	Cognizant System Engineer
C-stop	controlled stop
DAQ	data acquisition

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DBA	design basis accident
DC	direct current
DOE	[U.S.] Department of Energy
DOT	[U.S.] Department of Transportation
DUT	device under test
EBA	evaluation basis accident
EERE	[DOE] Office of Energy Efficiency and Renewable Energy
EHS	Environment, Health, and Safety
EO	Executive Order
EPA	U.S. Environmental Protection Agency
EPO	emergency power off
ERW	energy recovery water
ESF	engineered safety feature
ESIF	Energy Systems Integration Facility
EUT	equipment under test
FDD	facility design description
FE	fixed equipment
Fe	iron
FESB	fixed equipment switch board
FTIR	Fourier-transform infrared spectroscopy
GSE	grid simulator equipment
H_2	hydrogen
H_2S	hydrogen sulfide
H_2SO_4	sulfuric acid
$HClO_4$	perchloric acid
HAR	Hazard Analysis Review
HEPA	high-efficiency particulate air
HMI	human-machine interface
HPC/DC	High Performance Computing/Data Center
HVAC	heating, ventilation, and air conditioning
HX	heat exchanger
IBC	International Building Code
ICBO	International Conference of Building Officials
ICC	International Code Council, Inc.
IEC	International Electrical Code
IECC	International Energy Conservation Code
IESNA	Illuminating Engineering Society of North America
IFC	International Fire Code
IHA	Integrated Hazard Analysis
IMC	International Mechanical Code

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IO	input/output
IPC	International Plumbing Code
IR	infrared
IROFS	item relied on for safety
ISMS	Integrated Safety Management System
LBE	load bank equipment
LEED	Leadership in Energy and Environmental Design
LEL	lower explosive limit
LEV	local exhaust ventilation
LFL	lower flammability limit
LLP	Laboratory-level Procedure
LOTO	lockout/tagout
LT	low temperature
LVPS	low-voltage power switch
MAQ	maximum allowable quantity
MAU	make up air unit
MAWP	maximum allowable working pressure
MCCB	molded case circuit breaker
MCS	molded case switch
MDSB	Main Distribution Switch Board
MEL	Master Equipment List
MM	maintenance management
MSDS	Material Safety Data Sheet
NAAMM	National Association of Architectural Metal Manufacturers
NASA	National Aeronautics and Space Administration
NCR	Non-conformance Report
NCS	National Codes and Standards
NEC	National Electric Code
NFPA	National Fire Protection Association
NH_3	ammonia
NIH	National Institutes of Health
NIOSH	National Institute for Occupational Safety and Health
NO_2	nitrogen dioxide
NP	not permitted
NREL	National Renewable Energy Laboratory
O_2	oxygen
OSHA	Occupational Safety and Health Administration
PCW	Primary Cooling Water
PdM	predictive maintenance

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PHA	process hazard analysis
PHW	Primary Heating Water
PLC	programmable logic controller
PM	preventive maintenance
PMEC	[NREL SITE Operations] Project Management/Engineering/Construction
PMT	post-modification or post-maintenance testing
POC	point of contact
PPE	personal protective equipment
PrHA	process hazard analysis [PHA is also used for Process Hazard Analysis or Preliminary Hazard Analysis]
PSM	Process Safety Management
PV	pressure vessel
PV/S	pressure vessel and pressure system
PVE	photovoltaic equipment
QM	quality management
R2A2	roles, responsibilities, authorities, and accountabilities
RCD	REDB control device
REDB	Research Electrical Distribution Bus
SAC	specific administrative control
SAO	Safety Assurance Officer
SCADA	supervisory control and data acquisition
SDD	system design description
SEPO	software emergency power off
SFPE	Society of Fire Protection Engineers
SIL	Safety Integrity Level
SITE [Operations]	Sustainability, Infrastructure Transformation, and Engineering
SME	superconducting magnetic energy storage system
SMP	Safety Management Program
SOP	Safe Operating Procedure
SSC	structure, system, and/or component
STM	South Table Mesa
SWP	Safe Work Permit
team	ESIF Design/Build team
TNT	trinitrotoluene
UC	utility connection
UF	user facility

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UFAS	Uniform Federal Accessibility Standards; April 1, 1988
UPS	uninterruptable power system
USC	United States Code
UV	ultraviolet
V	vanadium
VESDA	very early warning aspirated smoke detection
Zn	zinc

Laboratories and Test Areas

ECCL	Electrochemical Characterization Laboratory
ECL	Electrical Characterization Laboratory
ESFL	Energy Systems Fabrication Laboratory
ESIF	Energy Systems Integration Facility
ESIL	Energy Systems Integration Laboratory
ESL	Energy Storage Laboratory
ESOTA	Energy Storage Outdoor Test Area
ESSL	Energy Systems Sensor Laboratory
FCDTL	Fuel Cell Development and Test Laboratory
LVOTA	Low Voltage Outdoor Test Area
MCL	Materials Characterization Laboratory
ML	Manufacturing Laboratory
MVOTA	Medium Voltage Outdoor Test Area
OCL	Optical Characterization Laboratory
PSIL	Power Systems Integration Laboratory
RTA	Rooftop Testing Area
SPL	Smart Power Laboratory
TSML	Thermal Storage Materials Laboratory
TSPL	Thermal Storage Process and Components Laboratory

Units

°C	degrees Celsius
°F	degrees Fahrenheit
A	ampere
cfm	cubic feet per minute
ft	foot
hr	hour
Hz	hertz
kg	kilogram
kJ	kilojoule
kPa	kilopascal
kVA	kilovolt-ampere
kW	kilowatt

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L	liter
lb	pound
m	meter
mg	milligram
min	minute
mJ	millijoule
MJ	megajoule
mL	milliliter
mm	millimeter
MPa	megapascal
ms	millisecond
MW	megawatt
Pa	pascal
ppm	parts per million
psi	pounds per square inch
psig	pounds per square inch gauge
s	second
scf	standard cubic feet
V_{dc}	volts direct current
V_{rms}	root mean square voltage

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Executive Summary

The National Renewable Energy Laboratory (NREL) is the nation's premier laboratory for renewable energy and energy efficiency research and development. NREL's mission and strategy are focused on advancing the U.S. Department of Energy's (DOE's) and our nation's energy goals. The laboratory's scientists and researchers support critical market objectives to accelerate research from scientific innovations to market-viable alternative energy solutions. NREL develops renewable energy and energy efficiency technologies and practices, advances related science and engineering, and transfers knowledge and innovations to address the nation's energy and environmental goals. Emphasis is placed on a comprehensive energy approach that encompasses the relationship among key systems, including fuel production, transportation, the built environment, and electricity generation and delivery.

The Energy Systems Integration Facility (ESIF) is the nation's premier facility for research, development, and demonstration of the components and strategies needed to optimize our entire energy system. It was established in 2013 by the DOE's Office of Energy Efficiency and Renewable Energy (EERE) on the NREL campus and is a designated a U.S. Department of Energy user facility (UF). The ESIF was strategically designed to meet crucial research objectives for integrating clean energy technologies into the grid in a way that is safe, efficient, cost-effective, and respectful to the surrounding environment. The ESIF also has unique capabilities to support the integration of energy carriers such as electricity, thermal, fuels, and water with infrastructure such as transportation and communications.

To ensure the continued safety of workers, the community, and the environment, NREL has performed a hazard analysis review (HAR) for the ESIF. The NREL HAR process applies a systematic risk assessment that incorporates a graded approach to determine: 1) the environment, health, and safety (EHS) hazards presented by a facility or operation; 2) the level of risk presented by those hazards; and 3) the controls necessary to maintain the risk to an acceptable level.

The ESIF HAR is an ongoing process that began at the conceptual design stage, paralleled the design process through construction and facility fit-out, and will continue to be updated throughout the lifetime of the facility. Because the HAR is necessarily dynamic, it will be reviewed annually to ensure accuracy and robust change management and to uncover opportunities to improve.

The ESIF is a facility of 182,500 gross square feet that houses the laboratories necessary to enable complex systems research and development that will fully integrate the most advanced engineering, analysis, and simulation techniques intended to transform the nation's energy infrastructure. The ESIF includes approximately 200 office spaces, 15 high-bay laboratories and collaboration areas, a High Performance Computing Data Center, and 22,000 gross square feet of outdoor test area. The ESIF was designed and constructed to meet the U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED) Platinum standards.

The ESIF incorporates many advanced engineered safety features (ESFs). In addition to ESFs, NREL develops and applies administrative controls that have been derived and refined during operations in existing NREL facilities. The combination of a specifically designed and

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constructed facility with proven administrative controls provides confidence that the facility can be safely operated within a specifically defined safety envelope. Based on the evaluations discussed in this HAR, the overall facility risk for the ESIF is determined to be Low, which is the acceptable level of risk established in NREL policy.

The ESIF HAR provides the following information in one integrated document:

- Codes of record, records of decisions, and the basis of design
- Risk profile and operational safety envelope for the facility
- Specific methodology for implementing NREL's Integrated Safety Management System (ISMS) and Hazard Identification and Control programs now and in the future.

Facility Background

The ESIF provides laboratory and office space for approximately 200 NREL researchers and support staff. The 182,500-square-foot building houses research to overcome challenges related to the interconnection of distributed energy systems and the integration of renewable energy technologies into the electricity grid.

The ESIF houses a broad array of capabilities and laboratories focused on energy integration research. Its unique capabilities include:

- Hardware-in-the-Loop at Megawatt-Scale Power

  Megawatt-scale power-in-the-loop allows researchers and manufacturers to conduct integration tests at full power and actual load levels in real-time simulations and evaluate component and system performance before going to market.

- High-Performance Computing Data Center (HPC/DC)

  Peta-scale computing at the HPC/DC enables unprecedented large-scale modeling and simulation of material properties, processes, and fully integrated systems that would otherwise be too expensive, too dangerous, or even impossible to study by direct experimentation.

- Uniquely Connected

  Each laboratory in the ESIF has its own niche with different kinds of equipment and functionality fostering research on all aspects of energy integration. The Research Electrical Distribution Bus (REDB), the ultimate power integration circuit, is made up of two alternating current (AC) and two direct current (DC) ring buses that connect multiple sources of energy and interconnect "plug-and-play" testing components in all the laboratories.

- Supervisory Control and Data Acquisition System (SCADA)

  Integrated throughout the ESIF, a SCADA system monitors and controls the REDB operations and safety and gathers real-time, high-resolution data for collaboration and visualization.

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- Data Analysis and Visualization

  Analysis and visualization capabilities at the ESIF go beyond what is found in a typical utility operations center. Fully integrated with hardware-in-the-loop at megawatt-scale power capabilities, an electrical distribution bus, a SCADA system, and peta-scale computing, the ESIF allows researchers and NREL partners to visualize complex systems and operations in a completely virtual environment.

Facility Mission

The ESIF provides the laboratories necessary to enable complex systems research and development that will fully integrate the most advanced engineering, analysis, and simulation techniques intended to transform the nation's energy infrastructure. The facility is built to test integrated renewable systems concepts (energy system technology and system design, testing, and performance optimization in the context of the larger energy supply, delivery, and end use systems for deployment) that will form the center of DOE's energy efficiency and renewable energy capability. Research conducted in the facility will enable DOE and its industrial partners to assess the potential of new generation and end-use technology options for buildings, transportation, community, and utility utilization and develop engineering-scale collection and analysis of performance data for the most promising technologies and integrated energy systems. The ESIF provides the laboratories necessary to perform laboratory-scale testing quickly and at far less cost than commercial-scale demonstrations.

The ESIF includes a state-of-the-art HPC/DC. The Data Center supports simulations and emulations of new infrastructure scenarios that could hasten insight on a variety of new and advanced component and system combinations, facilitating industry decisions for commercialization.

The design of the ESIF is aligned with the following strategic mission goals:

- Renewable Resource Characterization

  Characterize renewable resource locations and temporal power delivery profiles to support development of accurate performance models for further deployment of renewable generating systems.

- Renewable Systems Operations and Analysis Support

  Coordinate with renewable energy manufacturers to acquire information on fielded system performance characteristics and work with them and their vendors to assist in designing and modeling of advanced systems.

- Integrated Testing and Field Validation of Components

  Demonstrate photovoltaic modules, batteries, electrolyzers, fuel cells, power conditioning equipment, inverters, controllers, small micro-turbines, combined heat and power units, etc., as parts of optimized systems to reduce perceived high risks of power disruption, instability, variability, and safety concerns in the adoption of renewable generation systems and associated equipment. Fully incorporate technical, economic, and financial analyses with technology validation efforts.

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- Simulation and Development of System Controls

  Develop and evaluate simulation tools to model then analyze the systems interactions, responses, and behavior of renewable energy installations in residential communities, commercial office/retail parks, and electric distribution systems to load changes and system balancing.

- Analyzing Storage Systems
  - Model the needs and impacts of storage technologies on renewable systems integration by analyzing combined system performance, reliability, and costs.
  - Develop new storage technology requirements for distributed renewable energy generators to ensure reliable power delivery to customers.
  - Enable the development and demonstration of remote monitoring and dispatch control capabilities for building operators.
  - Use flexible testing platforms to combine and compare various electrical generation and storage technologies.

- Advanced Energy Computing Capability
  - Eliminate the need for multiple costly prototypes by utilizing high-speed computing, robust data management and analysis capabilities, and data visualization to quickly model and validate hypotheses and cost prior to experimental testing.
  - Working with DOE's Office of Science, provide high-speed computing capability that meets modeling and simulation needs, and 1 petabyte of data storage to meet scientific data management, data capture, analytics, and distribution needs critical for managing growing scientific needs.

- Renewable Electricity Production and Hydrogen Synergies

  Test and evaluate hydrogen as an energy delivery and storage medium in a variety of energy system configurations to optimize renewable resources and build upon the synergism between hydrogen and electricity as energy carriers.

- Market and Integration Analysis

  Conduct analysis of business cases, market needs, and integration opportunities with fuel and electricity energy systems.

- Economic Validation

  Provide a dedicated, compelling demonstration facility for a range of renewable generating and energy delivery technologies within the context of electricity and fuel infrastructure elements to showcase the technical capabilities and to educate investors, policymakers, technology developers, and the public.

- Codes and Standards

  Explore generation issues for interconnection of advanced and existing technologies into the electricity delivery infrastructure, and in distributed energy applications, through

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testing and certification as well as in conformance with uniform standards. Update electrical and building codes for new technologies.

- Combined Heat and Power

  Create technical solutions for component and equipment needs, simulation software and design tools, and improved practices for integrating renewable energy technologies with innovative building methods to optimize building performance in addressing heating and electrical loads.

Facility Hazard Categorization

There is no DOE directive that requires a facility hazard categorization be performed for non-nuclear facilities However, NREL's Laboratory-level Procedure (LLP) 6-6.2, *Hazard Identification and Control,* uses hazard levels to determine whether a HAR is required and to determine risk levels to determine the level of review and approval. In the current revision of LLP 6-6.2 (01/07/2014), the EHS point of contact (POC) determines whether a HAR is required. The determination is performed during the hazard analysis. The criteria used to make the determination are:

- Substantial equipment loss or damage
- Programmatic interruption that could affect critical milestones
- Other unplanned events that could present severe risk to life, health, property, or the environment
- Environmental impact
- Offsite consequences, including routine generation of non-hazardous noise and odors.

The consequences listed above are the "unmitigated" consequences. The LLP does not make a direct correlation between these unmitigated consequences and the risk classification levels of Routine, Low, Medium, or High. However, it is apparent that most of the criteria would equate to catastrophic and/or critical unmitigated consequences and, depending on the likelihood of the event, could result in an initial risk level of High.

The ESIF process hazard analysis (PrHA) contains a large number of high initial risk scenarios for the laboratory areas, but none for the HPC/DC. (The PrHA scenarios for the HPC/DC include electric shock/arc flash and small fires where the initial risk is Moderate for equipment and facilities.) However, the HPC/DC would meet the criteria in the hazard analysis for substantial equipment loss or damage and programmatic interruption. Therefore, the ESIF requires a HAR under the current version of LLP 6-6.2 for both the laboratory areas and the HPC/DC.

NREL's planned revision to the LLP will have a different process for determining whether a facility requires a HAR. The new process uses the facility's use and occupancy classification as defined in the International Building Code (IBC). Because the ESIF contains High Hazard Group H operations, a HAR would be required. The HPC/DC has occupancy classes of S1, B, and A3. In the new schema, none of these alone would lead to the requirement for a HAR, but the decision logic includes a caveat similar to the criteria in the hazard analysis, so again, the HPC/DC would require a HAR. Figure 1 shows the HAR decision logic as it will appear in the next revision of LLP 6-6.2.

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The process for determining the level of review and approval of the HAR is tied to the mitigated or controlled risk level. Per NREL policy, all hazardous activities need to have sufficient controls in place to reduce the residual risk to Routine or Low. In that case, the approval authority is the line organization and EHS. It is conceivable that for some activities, it might not be possible to drive the residual risk to such levels. In those cases, in addition to the line organization and EHS, the Laboratory Director and DOE's Golden Office must approve Moderate residual risk operations. High residual risk operations also require the DOE EERE Assistant Secretary's approval. For example, the PrHA for the ESIF shows that all of the residual risks have been mitigated down to the Low or Routine levels. Therefore, the ESIF is in the Low risk level for approval. Only the ESIF Facility Manager and EHS Director are required to approve the ESIF HAR.

Safety Analysis Overview

The principal hazards at the ESIF are associated with the generation, compression, storage, distribution, and use of hydrogen and the bi-directional, distributive AC and DC systems testing and integration on a megawatt scale. Other hazards at the ESIF are easily categorized as typical to wet chemical laboratory operations, which include the use of various compressed gases and concentrated acids and bases. Loss prevention checklist evaluations helped guide a greater focus (and, subsequent facility design modifications) on the use of nanomaterials and perchloric acid, which are somewhat atypical and therefore are addressed in this HAR.

In this HAR, qualitative and semi-quantitative risk analyses are presented because of the scale of the research and development activities and because of the dynamic nature of the programs. The primary accidents or event transients examined were identified based on past experiences and knowledge and the published literature. Hazard assessment techniques included checklists, hazards and operability evaluations, and scenario development.

To develop estimates of event probabilities for these "what-if" accidents, LLP 6-6.2, NREL's experience, industry experience, and failure rate data were used. For hydrogen systems, the HAR uses component reliability information adapted to hydrogen systems that were used to support National Fire Protection Administration (NFPA) 2 code development.

Event probabilities are divided into six different classes: Improbable, Extremely Remote, Remote, Occasional, Reasonably Probable, and Frequent. In these assignments, it is recognized that failure of individual components in isolation may not result in the accidental release of a hazardous material or energy. Often a release may occur only after a series of components fail. Therefore, the probability estimates provided are conservative; that is, they likely overestimate the occurrence of the identified accident.

In a similar way, hazard consequences are divided into four different classes: Negligible, Marginal, Critical, and Catastrophic. Estimates of potential consequences were based on past experiences, published literature, and more detailed numerical calculations. In these calculations, it has generally been assumed that the defined event transient occurs in the absence of other passive or active hazard management control systems. In reality, multiple active and passive controls exist. As a result, the consequence estimates will almost always be conservative; that is, they will overestimate the potential hazard.

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Accident event probabilities and consequences are combined in a risk matrix to develop a semi-quantitative measure of risk. These are then divided into four final classes: Routine Risk, Low Risk, Moderate Risk, and High Risk. Events classified as Routine Risk are no different from those experienced by any individual in his or her daily life. Low Risk events are those that may have an impact within a facility and little or no impact to adjacent facilities or to health or the environment. Moderate Risk events are those that present considerable potential impacts within the facility or to people or the environment, but at most only have minor impacts off site. High Risk events are those with the potential for onsite and offsite impacts to a large number of people or for major impacts to the environment.

Integrated Hazard Analysis Summary

The foundation for the integrated hazard analysis (IHA) is a PrHA that systematically identifies and evaluates facility hazards. The PrHA specifically addresses defense in depth and protection of workers, protection of the facility and equipment, and protection of the environment. Basic industrial methods for a PrHA have been described in references such as the American Institute of Chemical Engineers' *Guidelines for Hazard Evaluation Procedures* (1992). This reference describes largely qualitative, not quantitative, methodologies for comprehensively defining the accident spectrum for workers and the public. The PrHA is focused on systematically assessing what can go wrong in a facility as opposed to deriving mathematical expressions of risk.

The PrHA provides an initial basis for the required safety programs, such as hazardous chemical protection. The hazard analysis goes beyond basic hazard identification to qualitatively estimate the expected likelihood and consequences of accidents. The HAR identifies preventive and mitigative structures, systems, and components (SSCs); specific administrative controls (SACs); and programmatic controls, such as Safety Management Programs (SMPs) and management measures. The most significant preventive and mitigative controls are subject to added rigor in their implementation. Other items noted are encompassed by the details of SMPs (e.g., procedures, training, maintenance, quality assurance.)

The analysis required by the IHA is geared to the facility hazards and needs. Analysis is generally simple, resource efficient, and qualitative; however, some bounding accident events are of sufficient complexity to require more detailed, quantitative analysis using selected evaluation basis accidents (EBAs) to understand the basis for safety assurance. Other postulated accidents, such as design basis accidents (DBAs), were analyzed as needed to thoroughly establish the safety basis.

Bounding Events and Controls

The complete spectrum of hazards, initiating events, and accident types is examined in the PrHA. The scenarios are classified by accident type and initiating event. A representative scenario is selected from each class, usually based upon the unmitigated risk. The classified scenarios are also evaluated to determine which ones contain dependent failures (either common cause or cascading failures). A set of *bounding events* is selected from the representative or the dependent event scenarios. The preventive and mitigative controls associated with the bounding events define the safety basis for the operations. While all the controls will be implemented, only a portion will be elevated to SACs or safety SSC status. These elevated controls are described fully in the HAR whereas the other controls are incorporated in the SMPs.

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Accident Scenarios and Items Relied on for Safety

The ESIF PrHA identified a limited subset of accidents to be carried forward to accident analysis. These accident scenarios constitute a complete set of bounding conditions to define the envelope of accident conditions to which the operation could be subjected. Accident analysis uses established methods to quantitatively or semi-quantitatively assess frequency and consequences of selected accident scenarios. The accident scenarios selected for further evaluation are those that present a significant unmitigated risk and therefore must have a sufficient set of preventive and mitigative controls.

The HAR identifies the items relied on for safety (IROFS) for the ESIF. IROFS are those administrative and physical controls that are credited with either a preventive or mitigative safety function. Preventive controls reduce the likelihood of accident events and are evaluated in the frequency analysis. Mitigative controls reduce consequences and are evaluated in the consequence analysis. Administrative IROFS that are deemed significant contributors to risk reduction are classified as SACs. Physical IROFS that are deemed significant contributors to risk reduction are classified as ESFs. All other IROFS are implemented through SMPs.

Operational Approach

The operational approach for the ESIF is consistent with the operational approach followed by all NREL facilities. NREL facilities are operated by establishing a *safety envelope* and by managing the facility within its safety envelope, maintaining adequate margins as the uses and configurations of the facility change over time.

Safety Envelope Concept

DOE G 450.4-1C, *Integrated Safety Management System Guide*, states:

> **"Core Function 3, Develop and Implement Hazard Controls**
>
> Applicable safety standards and requirements are identified and agreed-upon, controls to prevent/mitigate hazards are identified, ***the safety envelope is established***, and controls are implemented." (emphasis added)

The safety envelope is "a set of conditions that when met provide reasonable assurance[1] that the occurrence of any high consequence (catastrophic or critical) event is highly unlikely (improbable or extremely remote) and the occurrence of any intermediate consequence (marginal) event is unlikely (remote)." The degree of assurance should be commensurate with the potential consequences. To provide reasonable assurance that a particular accident sequence will not occur, not only must the hazard controls be identified and implemented, but the management measures (i.e., configuration management [CM]) and specific features of the SMPs (i.e., training, quality assurance, maintenance, calibrations, surveillance, etc.) that ensure the availability and reliability of those controls must also be demonstrated. The HAR describes the hazards and controls, accident frequencies and consequences, management measures, and the application of SMPs.

[1] The standard to be met is that of "reasonable assurance." The definition of reasonable assurance is: "Acknowledgment that it is not possible to assert absolutely and certainly that an event will (or will not) occur. Reasonable assurance is a high level of confidence but not absolute."

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The safety envelope is an abstract concept. While some elements of the safety envelope are material and/or measurable, other elements are intangible. For example, the maximum allowable working pressure (MAWP) for a pressure vessel is determined by the vessel design, and the rating of the pressure relief device can be validated through testing. However, the benefit gained by having personnel trained and qualified to a particular procedure is not tangible. One can check to see that the training has been delivered and that the recipient demonstrates proficiency, but the reduction in risk resulting from the training cannot be measured, only assumed to drive risk in the proper direction.

Inherent in the definition of the safety envelope is the concept of "margin." The prime objective of facility management is to demonstrate that the facility is operated and maintained within its approved safety envelope. Adequate margins make the task of determining if a new or significant change to an activity/system is within the facility envelope easier and straight forward. Margins should also be established within the Safe Work Permit (SWP)/Safe Operating Procedure (SOP) by specifying parameters as ranges rather than point values, consider frequent transients or anomalies such as "double batching," and provide for likely changes in research materials and conditions. The facility safety margin is derived from conservative assumptions used in design and certain assumptions pertaining to initial conditions (such as the amount of material at risk). This information is found in the system design descriptions (SDDs) and is summarized in the HAR. These critical assumptions are protected by SACs (e.g., control of combustibles) from being violated or becoming invalid.

The safety envelope is established at the activity/system, facility, and institutional levels (Figure ES-1). The facility-level safety envelope encompasses and integrates all of the activity/system level hazards and their associated controls. All work is performed in accordance with NREL policies, procedures, and programs.

Figure ES-1. The safety envelope is established at the system/activity, facility, and institutional levels.

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The safety envelope at the activity/system level is defined by the SWP or SOP for the activity/system. The hazards and controls are derived from the PrHA. The facility safety envelope is described in the HAR. Various implementing procedures and programs needed to establish and maintain the safety envelope are contained in the ESIF *Operations Manual*.

While the HAR describes the safety envelope, it cannot include all of the foundational material, such as process safety information and the complete design basis. Therefore, safety basis interpretations and determinations of whether proposed new or significant changes to activities and systems are included in the safety envelope should be made by people knowledgeable in all aspects of the facility. The Facility Manager is responsible for ensuring that programs are in place to ensure that the facility is operated within its safety envelope.

User Facility Model

The ESIF is currently the only facility at NREL that is classified as a UF. The UF designation enables the research community and industrial sector to develop and evaluate their technologies in safe and controlled environments. For UFs, the HAR must fully account for the UF's hazard profile and safety envelope.

A UF is a federally sponsored research facility available for use to advance scientific or technical knowledge under the following conditions:

- The facility is open to all interested potential users without regard to nationality or institutional affiliation.
- Allocation of facility resources is determined by merit review of the proposed work.
- User fees are not charged for non-proprietary work if the user intends to publish the research results in the open literature. Cost recovery is required for proprietary work.
- The facility provides resources sufficient for users to conduct work safely and efficiently.
- The facility supports a formal user organization to represent the users and facilitate sharing of information, forming collaborations, and organizing research efforts among users.
- The facility capability does not compete with any available private sector capability.

All UF projects are assessed for hazards and approved as appropriate, not only for the UF's operating envelope, but for the specific facility space in which the proposed work will take place.

The ESIF's UF classification can create special challenges in managing the safety envelope. UF users come from a variety of safety cultures, and they may be using the ESIF for short-term projects. The flux of research projects in user facilities require frequent changes in facility configuration that must be selected and managed within the approved safety envelope.

The HAR addresses the impacts on the facility safety basis of the UF stemming from the wide range of users, including:

- Users without prior experience in NREL and/or DOE facilities

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- Users from different safety cultures
- Users who have acquired rapid access to a UF for projects of limited scope and duration
- Proprietary users with lower review and scrutiny requirements.

ESIF Process Hazard Analysis

A PrHA was conducted for representative laboratories, systems, and processes within the ESIF. A preliminary PrHA conducted for the ESIF during the design and construction phase was updated for the final design in 2014. The PrHA process began with the generation of an extensive list of "what if" hazard/accident scenarios by the ESIF Design/Build team based on input from NREL subject matter experts familiar with the expected ESIF facility hazards. This PrHA formed the basis of the preventive and mitigative controls incorporated into the ESIF design. The Design/Build team postulated the nature of accidents and failure modes that could result from ESIF hazards, initiated by such triggers as human error, equipment malfunction, and external events, resulting in deviations from normal safe conditions and potentially producing a loss event and resulting impacts such as injury, exposure, or environmental damage. When construction was complete, the PrHA scenarios were reviewed for consistency with the final design and updated as appropriate. This PrHA formed the basis for the preliminary HAR published prior to the operational start of ESIF in 2013.

Since publication of the preliminary HAR, the PrHA has been further updated through application of a standardized methodology that was established for assessing ESIF hazards. Using this methodology, a PrHA form was completed for each scenario that captured the nature of the hazard, a potential accident scenario associated with the hazard, classification of the scenario (such as "fire") and the initiating event type, the ESIF controls that are in place to prevent or mitigate a loss from the accident scenario, and quantitative estimates of the likelihood and severity of the accident scenario with and without preventive and mitigative controls.

The events were classified into accident type categories and by the type of initiating event, either common cause events (where an initiating event such as human error leads to one or more deviations and loss events) or cascading events (where a loss event becomes another initiating event, resulting in another loss event, etc.).

A subset of events was classified in multiple accident categories or multiple initiating event types. Dependent analysis of these compound scenarios was conducted by the PrHA team to derive the primary accident category, the primary type of initiating event, and whether the events involved a dependent failure such as a common cause or cascade failure.

A representative scenario was selected for each accident classification, typically the scenario with the highest risk and/or loss. Each of the representative scenarios was examined to determine whether it rises to the stature of a bounding event, that is, an event of such significant risk, impact, and loss that it defines an outer boundary of the ESIF safety envelope. Together, the bounding events define the ESIF safety envelope and the minimum specifications of the ESIF preventive and mitigative controls required to keep the ESIF within the envelope.

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A set of eight bounding events was identified from the representative scenarios. A subsequent crosscheck review by the 2014 ESIF HAR Team identified four additional bounding events to address possible high impact accidents that were not covered in the representative scenarios.

The PrHA and bounding event exercise yielded a set of IROFS, defined as those administrative and physical controls that are credited with either a preventive or mitigative safety function. Preventive controls reduce likelihood and are evaluated in the frequency analysis. Mitigative controls reduce consequences and are evaluated in the consequence analysis. Administrative IROFS that are deemed significant contributors to risk reduction will be classified as SACs. Physical IROFS that are deemed significant contributors to risk reduction will be classified as ESFs.

Accident Analysis

The ESIF accident analysis began with the selection of events (i.e., EBAs) from the bounding events and other postulated accidents that were deemed by the team of subject matter experts to best define the safety envelope of the ESIF. While the PrHA was qualitative in nature, relying heavily on the analyst's experience, the ESIF accident analysis used quantitative or semi-quantitative techniques to develop more refined estimates of likelihood and consequences of accidents. The types and quantities of hazards present in the ESIF (and NREL generally) do not warrant a probabilistic risk analysis; a deterministic approach with carefully crafted assumptions and detailed initial conditions was deemed sufficient by the safety analysts.

As in the PrHA, the objective of the accident analysis was to identify the controls necessary to prevent or mitigate the hazards to an acceptable level, and to evaluate the effectiveness of those controls in reducing or eliminating the hazard risk. The controls having the most impact were deemed by the 2014 ESIF HAR Team to be IROFS and include both engineered and administrative controls. Not all IROFS, however, need to be implemented with the same amount of rigor. The Facility Manager and EHS POC are responsible for determining which controls will be implemented with added rigor, and these controls are so stipulated in the ESIF HAR. The other IROFS will be implemented through the NREL SMPs, and this commitment is stipulated in the HAR as well.

The ESIF accident analysis included a comprehensive risk analysis for each event, estimating the event probability and consequence. The risk assessment matrix, found in LLP 6-6.2, *Hazard Identification and Control*, and included in Appendix E, was used to combine the probability and consequence into a semi-quantitative measure of risk. NREL selected this approach because of the dynamic nature of the laboratory programs. If the analysis identifies an event to be moderate or high risk, then controls are identified that reduce the risk to a Low or Routine designation. All assumptions made in the accident analysis (i.e., defining points in scenario progression) are validated as part of the accident analysis activity.

Safety Management Programs

NREL has developed and implemented an ISMS, which fulfills applicable requirements in a manner that adequately protects workers, the public, and the environment from hazards associated with the operation of the ESIF. The ISMS is defined in LLP 6-1.5, *Integrated Safety Management and Environmental Management Systems.* Subsidiary documents implement the requirements of the NREL ISMS. These subsidiary documents include procedures that define the

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SMPs. The SMPs are developed and implemented for functional safety areas, inform workers of recognized hazards in the workplace, describe the potential adverse effects of these hazards, and specify the required protective measures.

The ESIF management team takes credit for controls established in the SMPs to assure worker safety and to protect the public and the environment.

Management Measures

Management measures are activities performed by the ESIF management team on a continuous basis to provide reasonable assurance that items relied on for safety will perform their intended safety function. IROFS include ESFs and administrative controls as defined in this HAR. The ESIF management team takes credit for controls established in the management measures to assure worker safety and to protect the public and the environment.

The ESIF management team used information provided in NUREG-1520, *Standard Review Plan for the Review of a License Application for a Fuel Cycle Facility,* as a guide to determine the management measures that should be developed and incorporated to provide reasonable assurance. The management measures are:

- Configuration management (CM)
- Maintenance management (MM)
- Quality management (QM).

The ESIF management team has developed facility-specific programs for each of these management measures. These programs are integrated and coordinated with each other and with other ESIF and NREL-wide policies and procedures.

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1 Hazard Analysis Review Summary

This Hazard Analysis Review (HAR) summary is an overview of the National Renewable Energy Laboratory's (NREL's) Energy Systems Integration Facility (ESIF) safety basis and presents information sufficient to provide a basic understanding of the ESIF, its operations, and the results of the integrated hazard analysis (IHA). The summary of the facility safety basis is documented in detail in this HAR. The summary includes:

- The ESIF description, location, background, and mission
- The ESIF hazard categorization
- The results of the ESIF IHA, including the operational hazards analyzed, the evaluation basis accidents (EBAs) selected for analysis, and significant prevention and mitigation attributes.

1.1 Introduction

NREL is the nation's premier laboratory for renewable energy and energy efficiency research and development. NREL's mission and strategy are focused on advancing the U.S. Department of Energy's (DOE's) and our nation's energy goals. The laboratory's scientists and researchers support critical market objectives to accelerate research from scientific innovations to market-viable alternative energy solutions. NREL develops renewable energy and energy efficiency technologies and practices, advances related science and engineering, and transfers knowledge and innovations to address the nation's energy and environmental goals. Emphasis is placed on a comprehensive energy approach that encompasses the relationship among key systems, including fuel production, transportation, the built environment, and electricity generation and delivery.

The purpose of the ESIF is to provide the capability to meet one of the DOE's most significant energy goals: to develop an integrated energy systems approach to facilitate large-scale adoption of clean energy technologies. With the ESIF, the DOE seeks to leverage the Department's technology programs, and also improve the market impact of clean technologies. The ESIF builds on NREL's hazard controls for similar emerging energy research activities that are now being performed in several of NREL's existing facilities, and incorporates the evolution of knowledge and lessons learned from two decades of operating experience in this field. The ESIF expands the scope and breadth of these activities and also promotes synergy among the research staff by collocating these research activities into one integrated facility. Necessarily, the ESIF HAR process is significantly expanded to include hazards and accident sequences resulting from collocated activities.

The HAR is based on design and construction documents prepared by the ESIF design-builder and the as-built conditions of the facility. The development of the ESIF HAR continues to be an ongoing process that began at the conceptual design stage and paralleled the design process through construction and facility fit-out.

The ESIF HAR provides the following information in one integrated document:

- Codes of record, records of decisions, and the basis of design
- Risk profile and operational safety envelope for the facility

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- Specific methodology for implementing NREL's Integrated Safety Management System (ISMS) and Hazard Identification and Control programs now and in the future.

1.2 Objectives

To ensure the continued safety of workers, the community, and the environment, NREL has performed a HAR for the ESIF. The NREL HAR process applies a systematic risk assessment that incorporates a graded approach to determine: 1) the environmental, health, and safety hazards presented by a facility or operation; 2) the level of risk presented by those hazards; and 3) the controls necessary to maintain the risk to an acceptable level.

1.3 Facility Background and Mission

This section presents information on the background and research mission of the ESIF and information relevant to the IHA, including facility life cycle, anticipated future change in the facility's mission, and approved DOE exemptions.

1.3.1 Facility Background

The ESIF provides laboratory and office space for approximately 200 researchers and support staff. The 182,500-square-foot (sq. ft.) building houses research to overcome challenges related to the interconnection of distributed energy systems and the integration of clean energy technologies into the electricity grid.

The ESIF houses a broad array of capabilities and laboratories focused on energy integration research. Its unique capabilities include:

- Hardware-in-the-Loop at Megawatt-Scale Power

  Megawatt (MW)-scale power allows researchers and manufacturers to conduct integration tests at full power and actual load levels in real-time simulations and evaluate component and system performance before going to market.

- High-Performance Computing Data Center (HPC/DC)

  Peta-scale computing at the HPC/DC enables unprecedented large-scale modeling and simulation of material properties, processes, and fully integrated systems that would otherwise be too expensive, too dangerous, or even impossible to study by direct experimentation.

- Uniquely Connected

  Each laboratory in the ESIF has its own niche with different kinds of equipment and functionality fostering research on all aspects of energy integration. The Research Electrical Distribution Bus (REDB), the ultimate power integration circuit, is made up of two alternating current (AC) and two direct current (DC) ring buses that connect multiple sources of energy and interconnect "plug-and-play" testing components in all the laboratories.

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- Supervisory Control and Data Acquisition System (SCADA)

  Integrated throughout the ESIF, a SCADA system monitors and controls the REDB operations and safety and gathers real-time, high-resolution data for collaboration and visualization.

- Data Analysis and Visualization

  Analysis and visualization capabilities at the ESIF go beyond what is found in a typical utility operations center. Fully integrated with hardware-in-the-loop at power capabilities, an electrical distribution bus, a SCADA system, and peta-scale computing, the ESIF allows researchers and NREL partners to visualize complex systems and operations in a completely virtual environment.

1.3.2 Facility Mission

The ESIF provides the laboratories necessary to enable complex systems research and development that will fully integrate the most advanced engineering, analysis, and simulation techniques intended to transform the nation's energy infrastructure. The facility is built to test integrated clean energy systems concepts (energy system technology and system design, testing, and performance optimization in the context of the larger energy supply, delivery, and end use systems for deployment) that will form the center of DOE's energy efficiency and renewable energy capability.

The ESIF was designed to align with the following strategic mission goals:

- Renewable Resource Characterization

  Characterize renewable resource locations and temporal power delivery profiles to support development of accurate performance models for further deployment of renewable generating systems.

- Renewable Systems Operations and Analysis Support

  Coordinate with renewable energy manufacturers to acquire information on fielded system performance characteristics and work with them and their vendors to assist in designing and modeling of advanced systems.

- Integrated Testing and Field Validation of Components

  Test and validate components such as photovoltaic modules, batteries, electrolyzers, fuel cells, power conditioning equipment, inverters, controllers, small micro-turbines, and combined heat and power units. Testing and validation will reduce risks of power disruption, instability, variability, and safety concerns in the adoption of renewable generation systems and associated equipment. Research in the ESIF will fully incorporate technical, economic, and financial analyses with technology validation efforts.

- Simulation and Development of System Controls

  Develop and evaluate simulation tools to model and analyze the systems interactions, responses, and behavior of renewable energy installations in residential communities, commercial office/retail parks, and electric distribution systems and to analyze load changes and system balancing.

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- Analyzing Storage Systems
    - Model the needs and impacts of storage technologies on renewable systems integration by analyzing combined system performance, reliability, and costs.
    - Develop new storage technology requirements for distributed renewable energy generators to ensure reliable power delivery to customers.
    - Enable the development and demonstration of remote monitoring and dispatch control capabilities for building operators.
    - Use flexible testing platforms to combine and compare various electrical generation and storage technologies.
- Advanced Energy Computing Capability
    - Eliminate the need for multiple costly prototypes by utilizing high-speed computing, robust data management and analysis capabilities, and data visualization to quickly model and validate hypotheses and cost prior to experimental testing.
    - Working with DOE's Office of Science, provide high-speed computing capability that meets modeling and simulation needs, and 1 petabyte of data storage to meet scientific data management, data capture, analytics, and distribution needs critical for managing growing scientific needs.
- Renewable Electricity Production and Hydrogen Synergies

  Test and evaluate hydrogen as an energy delivery and storage medium in a variety of energy system configurations to optimize renewable resources and build upon the synergism between hydrogen and electricity as energy carriers.
- Market and Integration Analysis

  Conduct analysis of business cases, market needs, and integration opportunities with fuel and electricity energy systems.
- Economic Validation

  Provide a dedicated, compelling demonstration facility for a range of renewable generating and energy delivery technologies within the context of electricity and fuel infrastructure elements, to showcase the technical capabilities and to educate investors, policymakers, technology developers, and the public.
- Codes and Standards
    - Explore generation issues for interconnection of advanced and existing technologies into the electricity delivery infrastructure, and in distributed energy applications, through testing and certification as well as in conformance with uniform standards.
    - Update electrical and building codes for new technologies.

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- Combined Heat and Power

  Create technical solutions for component and equipment needs, simulation software and design tools, and improved practices for integrating renewable energy technologies with innovative building methods to optimize building performance in addressing heating and electrical loads.

1.4 Facility Hazard Categorization

There is no DOE directive that requires a facility hazard categorization be performed for non-nuclear facilities. However, NREL's Laboratory-level Procedure (LLP) 6-6.2, *Hazard Identification and Control,* uses hazard levels to determine whether a HAR is required and to determine risk levels to determine the level of review and approval. In the current revision of LLP 6-6.2 (01/07/2014), the Environment, Health, and Safety (EHS) point of contact (POC) determines whether a HAR is required. The determination is performed during the hazard analysis. The criteria used to make the determination are:

- Substantial equipment loss or damage
- Programmatic interruption that could affect critical milestones
- Other unplanned events that could present severe risk to life, health, property, or the environment
- Environmental impact beyond that identified in the site environmental assessment and/or applicable permits
- Offsite consequences, including routine generation of non-hazardous noise and odors.

The consequences listed above are the "unmitigated" consequences. The LLP does not make a direct correlation between these unmitigated consequences and the risk classification levels of Routine, Low, Medium, or High. However, it is apparent that most of the criteria would equate to catastrophic and/or critical unmitigated consequences and, depending on the likelihood of the event, could result in an initial risk level of High.

The ESIF process hazard analysis (PrHA) contains a large number of high initial risk scenarios for the laboratory areas, but none for the HPC/DC. (The PrHA scenarios for the HPC/DC include electric shock/arc flash and small fires where the initial risk is Moderate for equipment and facilities.) However, the HPC/DC would meet the criteria in the hazard analysis for substantial equipment loss or damage and programmatic interruption. Therefore, the ESIF requires a HAR under the current version of LLP 6-6.2 for both the laboratory areas and the HPC/DC.

NREL's planned revision to the LLP will have a different process for determining whether a facility requires a HAR. The new process uses the facility's use and occupancy classification as defined in the International Building Code (IBC). Because the ESIF contains High Hazard Group H operations, a HAR would be required. The HPC/DC has occupancy classes of S1, B, and A3. In the new schema, none of these alone would lead to the requirement for a HAR, but the decision logic includes a caveat similar to the criteria in the hazard analysis, so again, the HPC/DC would require a HAR. Figure 1 shows the HAR decision logic as it will appear in the next revision of LLP 6-6.2.

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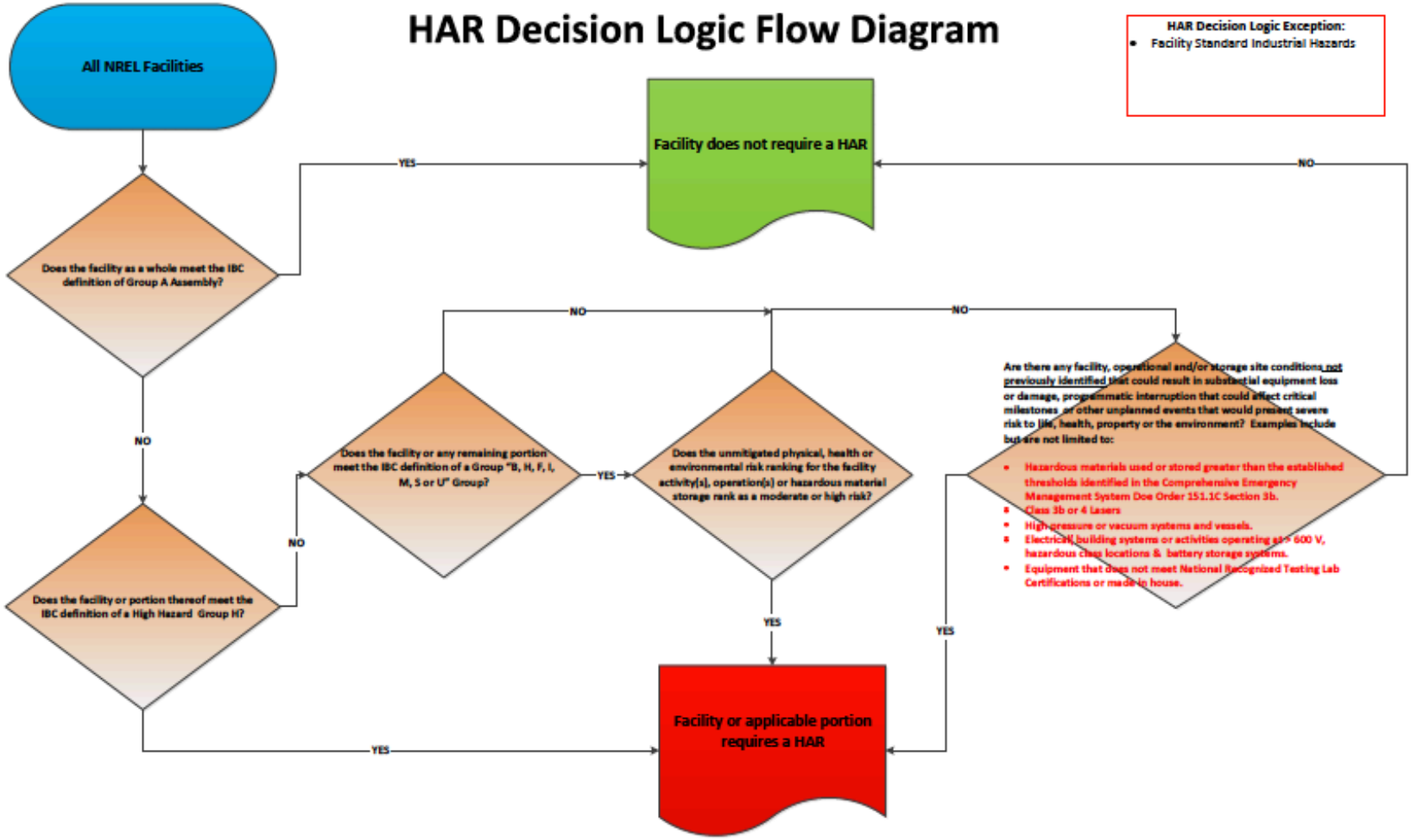

Figure 1. HAR decision logic flow diagram

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The process for determining the level of review and approval of the HAR is tied to the mitigated or controlled risk level. Per NREL policy, all hazardous activities need to have sufficient controls in place to reduce the residual risk to Routine or Low. In that case, the approval authority is the line organization and EHS. It is conceivable that for some activities, it might not be possible to drive the residual risk to such levels. In those cases, in addition to the line organization and EHS, the Laboratory Director and DOE's Golden Office must approve Moderate residual risk operations. High residual risk operations also require the Office of Energy Efficiency and Renewable Energy (EERE) Deputy Assistant Secretary's approval. For example, the PrHA for the ESIF shows that all of the residual risks have been mitigated down to the Low or Routine levels. Therefore, the ESIF is in the Low risk level for approval. Only the ESIF Facility Manager and EHS Director are required to approve the ESIF HAR.

Hazard Analysis Review (HAR) Decision Logic

1. Does the facility as a whole meet the IBC definition of Group A, Assembly?
    - 1.1 If yes, then a HAR is not required for the facility.
    - 1.2 If no, then:
2. Does the facility or portion thereof meet the IBC definition of a Group H?
    - 2.1 If yes, then a HAR is required for the applicable portion of the facility.
3. Does the facility or any remaining portion meet the IBC definition of a Group B, H, F, I, M, S or U?
    - 3.1 If yes, then is the unmitigated physical, health, or environmental risk ranking for the facility activity(s), operation(s), or hazardous material storage rank as a moderate or high risk?
    - 3.2 If yes, then a HAR is required for the facility or applicable portion.

      3.2.1 If no, then:
    - 3.3 Are there facility, operational, and/or storage conditions not previously identified that could result in substantial equipment loss or damage, programmatic interruption that could affect critical milestones or other unplanned events that would present severe risk to life, health, property or the environment? Examples include, but are not limited to:
        - Hazardous materials used or stored greater than the established thresholds identified in the Comprehensive Emergency Management System, DOE Order 151.1C Section 3b
        - Class 3b or 4 lasers
        - High-pressure or vacuum systems and vessels
        - Electrical (building systems or activities operating at > 600 volts (V), hazardous class locations and battery storage systems)
        - Equipment that does not meet nationally recognized testing laboratory certification or that was made in-house.

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3.3.1 If yes, then a HAR is required for the facility or applicable portion.

3.3.2 If no, then a HAR is not required for the facility and/or operations.

HAR Decision Logic Exception

- **Facility Standard Industrial Hazards:** These include hazards resulting from normal facility/building systems and/or infrastructure that do not directly support research activities. Examples of these would include standard building electrical systems; heating, ventilation, and air conditioning (HVAC); plumbing; gas and auxiliary power systems to include diesel generators, uninterruptable power supply (UPS), and photovoltaic systems. This would also include facility means of ingress/egress.

1.5 Hazard Analysis Review Overview

This section summarizes the significant hazards associated with facility processes and the main preventive and mitigative features relied upon in the facility safety basis.

1.5.1 Safety Analysis Overview

The principal hazards at the ESIF are associated with the generation, compression, storage, distribution, and use of hydrogen and the bi-directional, distributive AC and DC systems testing and integration on a megawatt scale. Other hazards at the ESIF are easily categorized as typical to wet chemical laboratory operations, which include the use of various compressed gases and concentrated acids and bases. Atypical hazards such as the use of perchloric acid and nanomaterials were identified using a checklist approach. This resulted in greater focus and subsequent facility design modifications for the use of these materials.

In this HAR, qualitative and semi-quantitative risk analyses are presented because of the scale of the research and development activities and because of the dynamic nature of the programs. The primary accidents or event transients examined were identified based on past experiences and knowledge and the published literature. Hazard assessment techniques included checklists, hazards and operability evaluations, and scenario development.

Estimates of event probabilities for these "what-if" accidents reflect NREL's experience, industry experience, and failure rate data. For hydrogen systems, the HAR uses component reliability information adapted to hydrogen systems that were used to support National Fire Protection Association (NFPA) 2 code development.

Event probabilities are divided into six different classes: Improbable, Extremely Remote, Remote, Occasional, Reasonably Probable, and Frequent. In assigning probability classes, it is recognized that failure of individual components in isolation may not result in the accidental release of a hazardous material or energy. Often a release may occur only after a series of components fail. Therefore, the probability estimates provided here are conservative; that is, they likely overestimate the occurrence of the identified accident.

In a similar way, hazard consequences are divided into four different classes: Negligible, Marginal, Critical, and Catastrophic. Estimates of potential consequences were based on past experience, published literature, and numeric calculations. In these calculations, it has generally been assumed that the defined event transient occurs in the absence of passive or active hazard

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management control systems. In reality, multiple active and passive controls exist. As a result, the consequence estimates will almost always be conservative; that is, they will overestimate the potential hazard.

Accident event probabilities and consequences are combined in a risk matrix to develop a semi-quantitative measure of risk. These are then divided into four final classes: Routine Risk, Low Risk, Moderate Risk, and High Risk. Events classified as Routine Risk are no different from those experienced by any individual in his or her daily life. Low Risk events are those that may have an impact within a facility and little or no impact to adjacent facilities or to health or the environment. Moderate Risk events are those that present considerable potential impacts within the facility or to people or the environment, but at most only have minor impacts off site. High Risk events are those with the potential for onsite and offsite impacts to large numbers of persons or for major impacts to the environment.

Table 1 summarizes the PrHA conducted during the conceptual design for the ESIF. (Note: this set of initial ESIF programming risks was updated from conceptual design to "as built" for the PrHA reviewed in Section 4.2) The probabilities and consequences reflect the full suite of engineering and administrative safety controls being implemented. Note that the probability and consequences are uniquely coupled for a given event. For instance, the corrosive spill event provided in Table 1 contemplates a relatively major spill event (or set of like events) that causes a serious injury; the Remote characterization for the frequency of this event does not represent the frequency characteristic of *all* chemical spills, only the frequency of that spill, which results in that particular consequence. This specific event tabulation below bounds the risk for all posited corrosive spill scenarios even though it does not reflect a singular risk assessment for each individual spill scenario (e.g., minor spills that are more frequent, but produce negligible consequences). For simplicity, several event scenarios may be combined into one event transient. Where probability, consequences, and risk categories vary within a single transient group, the worst-case risk profile is presented and therefore bounds all other events in that category.

Table 1. Summary of Initial Programming Risks at the ESIF

Reference	Event Transient	Probability						Consequences				Risk			
		I	ER	R	O	RP	F	N	M	C	CA	R	L	M	H
ESOTA-1, ESOTA-8, HPTF-4, 6.3.1.2	Hydrogen cylinder explosion	•								•			•		
ESIL-6, ESOTA-3, ESOTA-4 ESOTA-5, ESOTA-6, ESOTA-7, ESOTA-9, AL-2	Hydrogen gas deflagration outside		•							•			•		

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Reference	Event Transient	Probability						Consequences				Risk			
		I	ER	R	O	RP	F	N	M	C	CA	R	L	M	H
PSIL-1, PSIL-2, ESIL-7, ML-1, ESF-1, ESF-2, EChEM-5 EChEM-6	Solvent fire in laboratory			●					●				●		
PSIL-3 ESL-7, ESL-10, ESF-3	Corrosive spill			●						●			●		
PSIL-4 ESL-3	Natural gas fire/ Explosion			●				●				●			
PSIL-9, ESL-1	Harmful exposure to internal combustion engine exhaust	●							●			●			
PSIL-5, ESL-2, ESL-8, OTB-1	Diesel spill fire			●				●				●			
ESL-5, ESIL-1, FCL-1	Minor hydrogen gas release in laboratory area, deflagration				●				●				●		
HPC-2, PSIL-7, ESL-9, SPLPE-1, SPLPE-4, LVOTA-1, TP-3	Low voltage shock			●					●				●		
SPLPE-5	High-frequency noise						●	●				●			

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Reference	Event Transient	Probability						Consequences				Risk			
		I	ER	R	O	RP	F	N	M	C	CA	R	L	M	H
ESIL-2, ESIL-3, ESIL-4	Electrolyzer over-pressure		●							●			●		
ESIL-5, ESOTA-2, HPTF-1, HPTF-3	Compressor failure fire/shrapnel		¤	●					●	¤			●		
6.3.1.4	High-pressure hydrogen backflow in ESIL		●								●		●		
TS-1, TP-1, ESF-5, 6.3.1.5	Nanomaterial spill/potential harmful exposure		●							●			●		
TP-2	Thermal fluids spill/burn			●				●				●			
ML-2	Harmful exposure to x-rays		●					●				●			
AL-1, ECL-4, SL-1, HPTF-2	Major release of hydrogen into laboratory area		¤	●						●	¤		●		
ESF-4	Incompatible chemical reaction			●					●				●		
FCL-2	Fuel cell malfunction/ fire/ explosion		●					●				●			
MCL-1, FCL-3, EChEM-1, EChEM-2	Compressed gas leak toxic gas exposure			●				●				●			
ECL-3, MVOTA-1	Medium voltage arc flash/blast		●								●		●		

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Reference	Event Transient	Probability						Consequences				Risk			
		I	ER	R	O	RP	F	N	M	C	CA	R	L	M	H
NPH-1	Seismic activity/fire		●						●			●			
NPH-2	Volcanic tephra damage to systems	●								●		●			
ECL-2	Research fuel line damage/fire (excluding hydrogen)			●					●				●		
MS-2, EChEM-3, EChEM-4, 6.3.1.3	Compressed gas cylinder incident including fire		●							●			●		

AL =
ECCL = Electrochemical Characterization Laboratory
EChEM =
ECL = Electrical Characterization Laboratory
ESF = Energy Systems Fabrication
ESFL = Energy Systems Fabrication Laboratory
ESIF = Energy Systems Integration Facility
ESIL = Energy Systems Integration Laboratory
ESL = Energy Storage Laboratory
ESOTA = Energy Storage Outdoor Test Area
ESSL = Energy System Sensor Laboratory
FCDTL = Fuel Cell Development and Test Laboratory
FCL =
HPC = High Performance Computing
HPTF = High Pressure Test Facility
LVOTA = Low Voltage Outdoor Test Area
MCL = Materials Characterization Laboratory
ML = Manufacturing Laboratory
MVOTA = Medium Voltage Outdoor Test Area
NPH =
OCL = Optical Characterization Laboratory
OTB =
PSIL = Power Systems Integration Laboratory
RTA = Rooftop Testing Area
SL =
SPL = Smart Power Laboratory
SPLPE =
TP = Test Pad
TS = Thermal Storage
TSML = Thermal Storage Materials Laboratory
TSPL = Thermal Storage Process and Components Laboratory

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The most significant hazards at the ESIF are associated with the generation, compression, storage, and use of hydrogen, and with electrical power system testing up to 1 MW. These two areas are summarized below.

1.5.1.1 Hydrogen Production, Compression, Storage, and Distribution Systems

Hydrogen is generated by electrolysis using both commercially available and prototype electrolyzers with various integral detection and process shut-down systems. The output pressures from the electrolyzers typically range from 200 to 400 pounds per square inch (psi), although the laboratory housing these electrolyzers has been designed to manage catastrophic releases of up to 2,000 psi hydrogen at worst-case flow rates. The laboratory is equipped with ultraviolet (UV)/infrared (IR) cameras to detect jet fires near the electrolyzers and an aspirated area hydrogen gas detection system that initiates alarm notifications, process shutdown, and enhanced ventilation. The portion of the laboratory used for hydrogen generation is electrically classified as a Class I, Division II area.

The hydrogen gas is compressed using a combination of diaphragm and small capacity, air-driven positive displacement gas boosters, all with 316 stainless steel construction. Check valves, pressure transducers, automated negative feedback control systems on valves, and pressure relief valves provide control of hydrogen in the compression module.

The ESIF was also designed to accommodate component testing up to 15,000 psi. The basis of design was to provide compression to these pressures outside the facility and distribute the hydrogen to components within calorimeters in one of the two high-pressure test cells.

After initial compression to 3,000 psi, the hydrogen is piped outdoors and stored in a purpose designed (American Society of Mechanical Engineers [ASME] rated) cylinder with an operating pressure of 8,000 psi. From there, hydrogen is further compressed to 6,000 psi and stored. A final compression stage pressurizes the gas to 12,500 pounds per square inch gauge (psig) for vehicle refueling and to support hydrogen infrastructure testing such as the refueling hose reliability project. Software control, pressure switches, pressure relief devices, and vent masts are designed to prevent and mitigate pressure excursions at the compression stages. Hydrogen storage cylinders are outdoors and purposely located at a distance to mitigate catastrophic event transients. Air-operated isolation valves located at storage vessels and compressors automatically close (spring return, fail-safe position) in the event of an emergency or detection of an out-of-normal process condition.

The tubing used throughout the hydrogen distribution system is 316L stainless steel and all welded construction, except for key fittings, which are variable compression ratio, National Pipe Thread, and, in some cases, cone and thread for higher-pressure systems. The bulk of the distribution system is located in exterior areas to prevent confinement of hydrogen gas, and therefore prevent and mitigate fire and explosion potentials. Other components on the distribution system are specifically designed for hydrogen use and resist hydrogen embrittlement. The pressure regulation station and double block and bleed systems are located on the roof within a 15-foot “ignition-free zone.” House hydrogen radiates out on the ESIF rooftop with individual drops into each laboratory. This design greatly reduces the amount of tubing within the confines of the building. Lightning protection is provided for the distribution system.

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Within the laboratories, the house hydrogen is provided to individual stations at less than 300 psi and in quantities that effectively reduce the risk of an adverse event. Laboratories that use hydrogen are also equipped with gas detection systems that initiate the alarm and shutdown of the block and bleed valves on the roof.

All hydrogen installations comply with or exceed the requirements in NREL LLP 6-1.47, *Compressed Gas Safety*.

1.5.1.2 Electrical System Testing Using the Research Electrical Distribution Bus (REDB)

There are four research electrical buses present: two 250-amp (A) buses and two 1,600-A buses (in both cases, one bus is AC, the other DC). The facility design allows for the addition of two more 250-A buses (one AC and on DC) and two more 2,500-A buses (one AC and one DC). The AC buses and switchgear are rated to operate over a wide frequency regime (16-2/3 hertz [Hz] to 400 Hz) and can make/break under their rated load profile. The DC switchgear is not rated to make/break under load. Connections to the bus can be effected in several ways: through bus plugs, tap boxes, fixed equipment switch boards (FESBs) and data acquisition (DAQ) carts, some of which will be using diesel locomotive cables for connections. The main switchgear for the buses is located within dedicated concrete REDB rooms, with the AC, DC, and facility electrical gear residing in their respective rooms for isolation to improve safety. Access to these rooms is restricted by card key access and safety interlocks on the doors that prevent entry unless the areas meet certain safe criteria for entrance (as described in more detail in section 3.3.2).

The FESBs and DAQ carts are generally classified as REDB control devices (RCDs) and are monitored by programmable logic controllers (PLCs) and a supervisory control system that actively manages the system to avoid event transients and system configurations that exceed the ratings of the respective buses. The control systems also monitor bus status and are an important feature in the "dead" bus switching criteria to avoid arc flash, blast, or electric shock. The buses can be locked out using electro-mechanical safety key interlocks and interlocking systems.

The REDB control system has a Safety Integrity Level (SIL) rating of 2.[2] The PLC system maintains a periodic "heartbeat" to all system components to ensure connectivity and proper functionality. If the heartbeat drops off or other variances are detected beyond operational control parameters, the control system defaults the REDB to a safe state. Multiple levels of access authority within the control system exist to prevent tampering with fundamental safety control functions. The addition of more buses (2,500 A) or sections to existing buses require detailed regression testing to ensure robust control system stability and reliability.

1.5.2 Items Relied On For Safety

Items relied on for safety (IROFS) are those administrative and physical controls that are credited with either a preventive or mitigative safety function. Preventive controls reduce the likelihood of accidents and are evaluated in the frequency analysis. Mitigative controls reduce the consequences of accidents and are evaluated in the consequence analysis. Administrative IROFS that are deemed significant contributors to risk reduction are classified as specific

[2] A SIL is a measure of safety system performance in terms of probability of failure on demand. A SIL rating of 2 indicates an availability of 99% to 99.9%.

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administrative controls (SACs). Physical IROFS that are deemed significant contributors to risk reduction are classified as engineered safety features (ESFs).

Table 2 summarizes the IROFS for the ESIF identified from the bounding event analysis.

Table 3 summarizes the additional set of IROFS identified from the accident analysis.

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Table 2. Summary of ESIF Items Relied On For Safety from Bounding Event Analysis

Accident Type	Scenario	Items Relied on for Safety
Electric shock or arc flash	Flood from inadvertent sprinkler head operation	Design Feature: The REDB system components are located in standard National Electric Code (NEC)-rated electrical enclosures. Design Feature: All REDB systems source connections have standard overcurrent protection that will remove the energy in the event of a ground fault. Design Feature: Fire suppression flow switch generates a high bay fire alarm. A high bay fire alarm results in an emergency power-off (EPO) for the entire C Wing and a REDB EPO action that will disconnect all sources from the REDB system.
Electric shock or arc flash	Shock, arc flash, resulting from ground faults, short circuits	Work Control Documents for the REDB System require dead bus switching unless a recloser or other device designed for live switching is used. Work Control Documents require use of a dedicated industry-standard breaker for any device under test (DUT) to provide overcurrent protection. Design Feature: Dedicated industry-standard breakers are provided for DUTs. Design Feature: The REDB System was designed and installed in accordance with NEC requirements. The Preventative Maintenance (PM) program requirements for the REDB System include resistance (ohm) measurement and thermal imaging. (The intent of these PM requirements is to specify routine inspection and testing of the system that will identify weak spots prior to a failure.) Work Control Documents for the REDB system include Electrical Safety Program requirements for the use of proper personal protective equipment (PPE) and clothing by workers completing dead bus confirmation and changing switch positions. Work Control Documents for the REDB system require an operable SCADA system or define compensatory measures if the SCADA system is not operable. (The SCADA system provides remote indication and operation of critical components associated with the REDB System. The SCADA system is only credited as an administrative control as design does not include any provisions beyond component status and remote operation requests.) Design Feature: Protective reclosers are installed in the REDB system. (These reclosers were specified in accordance with normal standards for medium voltage distribution and have industry standard monitoring and programming that interrupt the source during a fault condition to limit the energy.) Work Control Documents for the REDB System include Electrical Safety Program requirements for proper bus labeling and lockout/tagout (LOTO).

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Accident Type	Scenario	Items Relied on for Safety
Fire – Small local fire in work area	Improper handling of flammable liquids leading to small fire	Flammable liquids are stored in cabinets per the requirements of the Chemical Safety Program. Work Control Documents include the requirements defined in the Chemical Safety Program to perform activities handling flammable liquids inside fume hoods whenever possible, and to limit the quantities of flammable liquids used in fume hoods. Design Feature: Smoke detectors are provided in the laboratories to notify facility personnel to evacuate prior to exposure to toxic smoke. Design Feature: The facility sprinkler system activates to extinguish fires that occur from improper handling of flammable liquids.
Release with exposure	Release of nanomaterials to room (drop of container or spill)	Work control documents require that nanomaterials are transported in containers with sealed or taped lids. Work control documents for nanomaterials include requirements for PPE to protect facility workers from exposure to nanomaterials during normal work or due to a dropped or spilled container. Design Feature: Nanomaterials are handled in enclosures with high efficiency particulate air (HEPA) filtration on the exhaust system. If the use of an enclosure is not possible, local exhaust with HEPA filtration is used. LLP 6-1.46, *Chemical Safety*, complies with DOE/ National Institute for Occupational Safety and Health (NIOSH) guidelines for safe handling of nanomaterials. Work Control Documents associated with nanomaterials will incorporate requirements in accordance with this LLP.

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Accident Type	Scenario	Items Relied on for Safety
Equipment damage with injuries	Catastrophic rupture of high-pressure hydrogen storage vessel, caused by overpressure from compressor, back flow, temperature swings	Design Feature: The house hydrogen system is designed per the requirements of LLP 6-1.62, *Pressure Safety*, including ASME Pressure Vessel Code requirements. Work Control Documents for the house hydrogen system define the required preventive maintenance requirements including monitoring the tanks for UV damage. Work Control Documents for the house hydrogen system define the requirements for filling the hydrogen storage tank to the desired pressure based on the outside temperature. Design Feature: Bollards or other approved means of protection are installed according to code around the hydrogen storage tanks to protect the tanks from normal vehicle traffic. Design Feature: The house hydrogen system is designed and installed per the International Code Council (ICC) and NFPA code requirements. Design Feature: Pressure relief devices are provided at appropriate points in the system, e.g., on storage vessels, piping, and other equipment, to protect against over-pressurization. Design Feature: The vent pipes from the pressure relief devices are raised vertically to release any hydrogen above people/property. Work Control Documents for the house hydrogen system require isolation valves to pressure relief devices to be in the open position. Work Control Documents for the house hydrogen system specify pressure relief device calibration frequencies and these requirements are incorporated in the preventive maintenance requirements for the system. Work Control Documents for the house hydrogen system require restricted access to hydrogen tanks through a locked gate. Design Feature: Check valves are installed on the house hydrogen system to provide reverse flow protection. Design Feature: The high-pressure hydrogen storage tanks are installed at the required separation from other facilities.

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Accident Type	Scenario	Items Relied on for Safety
Explosion – blast over-pressure	Backflow of hydrogen from storage (outside the building) to the Energy Systems Integration Laboratory (ESIL) (where hydrogen is generated/ compressed) causing over pressure of piping or equipment with release.	Design Feature: The hydrogen storage vessels are designed to meet the ASME Pressure Vessel Code. Design Feature: The hydrogen compressors are designed and installed according to ICC and NFPA code requirements. Design Feature: Pressure relief devices are provided on the house hydrogen system to protect against over-pressurization. Design Feature: The vent pipes from the house hydrogen system pressure relief devices are raised vertically to release any hydrogen above people / property. Work Control Documents for the house hydrogen system require isolation valves to the pressure relief devices to be in the open position. Work Control Documents for the house hydrogen system specify pressure relief device calibration frequencies and these requirements are incorporated in the preventive maintenance requirements for the system. Design Feature: Check valves are installed on the house hydrogen system to provide reverse flow protection.
Fire	Hydrogen fire during vehicle filling because connection is not leak-tight	Specific Administrative Control: Requirements for the control of ignition sources in accordance with classification of the hydrogen station (C1D2 Group B) are defined in the house hydrogen system work control documents. Design Feature: U.S. Environmental Protection Agency/NFPA safety standards for hydrogen refilling stations are incorporated into the hydrogen filling station design. Design Feature: The hydrogen filling station is designed according to NFPA guidelines, including the installation of pressure relief devices. Work Control Documents for the house hydrogen system specify pressure relief device calibration frequencies and these requirements are incorporated in the preventive maintenance requirements for the system. Design Feature: The hydrogen filling station is located outside to allow ventilation and dispersion of any released hydrogen. Design feature: A UV/IR camera is provided that covers the hydrogen dispensing area and will activate a shut-off valve if a hydrogen fire is detected. Work Control Documents for the house hydrogen system specify preventive maintenance requirements for the UV/IR camera and shut off valve.

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Accident Type	Scenario	Items Relied on for Safety
Fire	Grass fire heats hydrogen storage vessels, compressor, components, causing pressure relief valve to vent H_2 gas	Specific Administrative Control: Requirements for the control of combustible materials around the vessel storage area are defined in house hydrogen system work control documents. Design Feature: The hydrogen storage pad design is concrete to prevent a fire directly under a tank. Design Feature: Pressure relief devices are provided at the appropriate point in the system, e.g., on storage vessels, piping, and other equipment, to prevent over-pressurization. Work Control Documents for the house hydrogen system specify pressure relief device calibration frequencies and these requirements are incorporated in the preventive maintenance requirements for the system. Design Feature: The vent pipes from the house hydrogen system pressure relief devices are raised vertically to release any hydrogen above people / property.
Equipment damage	Pressure or flow required by compressor is not provided resulting in compressor damage and/or release of hydrogen (closed valves, obstruction, failed pressure transmitter, etc.).	Design Feature: The hydrogen control system has feedback on automated valves to alert the system of a failure (i.e., valve failing to open). Work Control Documents for the house hydrogen system specify preventive maintenance requirements for the automated valves, and these requirements are incorporated in the preventive maintenance requirements for the system. Design feature: The house hydrogen system includes pressure transmitters that monitor and shutoff the hydrogen compressor. Work Control Documents for the house hydrogen system specify pressure transmitter calibration frequencies and these requirements are incorporated in the preventive maintenance requirements for the system. Design Feature: The hydrogen compressor's supply pressure switch low cut off is interlocked with the compressor.
Explosion – fire	Accidentally connect air or O_2 cylinder to H_2 system	Design Feature: The standard design for gas bottles requires fittings for oxygen bottles and air bottles that are incompatible with hydrogen system connections. Work Control Documents for the house hydrogen system define the requirements and procedure for attaching gas bottles to the house hydrogen system if on-site generated hydrogen is not used.

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Accident Type	Scenario	Items Relied on for Safety
Release	Spill, leak or open liquid nitrogen dewar	Design Feature: The oxygen detectors will alarm prior to achieving an oxygen deficient atmosphere. Work Control Documents include PPE requirements in accordance with the Chemical Safety Program to protect workers from exposure due to spills or leaks. Work Control Documents include requirements and procedures for correct handling to prevent spills, and procedures for cleaning up spills. Design Feature: The lab ventilation supply and exhaust systems provide adequate air change rate to remove released inert gas. Design Feature: The size of the laboratories creates a large volume that will not be easily replaced with inert nitrogen in the event of a bottle spill. Design Feature: Dewars are designed so that they will not tip over, causing a spill. The material of construction for dewars prevents leaks.

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Accident Type	Scenario	Items Relied on for Safety
Equipment damage with injuries	Rupture of component in High Pressure Test Cell; media can be water, oil, helium, hydrogen or nitrogen gas	Design Feature: The high pressure test bays are constructed with blowout panels to relieve pressure in the bays caused by an overpressure event or explosion. Design Feature: Areas in front of the panels are fenced for restricted access. The panels are located at an elevation to prevent introducing additional hazards to personnel in the area. The panels are tethered to prevent them from blowing past the restricted area boundary. Design Feature: Shutoff valves and control components are located outside the high pressure test bays (to prevent damage to these components during an event and to assure that hazards can be removed at the end of a test). Design Feature: Duct work inside of the high pressure test bays is designed to handle expected pressures generated by a release. (Additional exhaust duct work provides an additional means of venting to relieve pressure.) Design Feature: Ignition sources inside the high pressure test bays are controlled (designed, installed, and maintained) in accordance with the hazard classification of the test bays. Design Feature: Hydrogen gas detection is provided inside the high pressure test bays. Work Control Documents address the following test design requirements: Experiments that require continuous hydrogen supply gas require design and installation of an automated valve that will shutoff of hydrogen supply to the test bays if hydrogen is detected. Work Control Documents for the gas detection system in the high pressure test bays require an operable SCADA system or define compensatory measures if the SCADA system is not operable. (The high pressure test bays have oxygen detection reported via the SCADA so that personnel can confirm that the space has returned to acceptable conditions prior to entering the space. The SCADA system is only credited as an administrative control as design does not include any provisions beyond monitoring and remote operation requests.) Design Feature: The walls of the high pressure test bays are designed to contain the pressure from the expansive gas and shrapnel from a failed component. Work Control Documents for the high pressure test bays include requirements for inspection after a rupture event to assure that the strength of the walls has not been compromised.

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Accident Type	Scenario	Items Relied on for Safety
Equipment damage with injuries (continued)	Rupture of component in High Pressure Test Cell; media can be water, oil, helium, hydrogen or nitrogen gas (continued)	Design Feature: The primary containment enclosure in the high pressure test bays is designed to absorb most of the energy from a rupture event. Design Feature: Fencing and signage restrict access to authorized personnel only. Work Control Documents for the high pressure test bays include setting limits for the testing media volume at 3.5L at 15,000 psi. Design Feature: The laboratory ventilation and exhaust systems provide an adequate air change rate to remove released gases.
Fire	Failure of power electronics board could causes fire and/or damage to laboratory fuel supply lines resulting in a sustainable fire	Design Feature: Code-compliant low resistance grounding of the test article reduces the heat generated during an event. Work Control Documents define the process to shield the lines from damage during testing. Design Feature: Fuel shut-off valves are located outside laboratories that contain fuel lines. Work Control Documents address the following test design requirement: Power electronics must be in a robust enclosure when being surge tested. Work Control Documents prohibit the coincident use of fuels and surge testing of articles that have the potential to produce shrapnel. Work Control Documents require that articles being tested, that have the potential to produce shrapnel, have a restricted access zone around them. Work Control Documents address the following test design requirement: Articles being tested, that have the potential to produce shrapnel, are required to have physical barriers to protect piping from shrapnel.
Spill	Spill of fuel collects in below-grade trenches	Work Control Documents require inspection of fuel tanks and fueled equipment before use. Work Control Documents define the spill prevention measures required when refueling equipment. Work Control Documents address the following test design requirement: Only U.S. Department of Transportation (DOT)-approved fuel tanks, 50-gallon maximum capacity, are to be supplied with equipment.

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Accident Type	Scenario	Items Relied on for Safety
Release with exposure	Exposure to toxic gas resulting from indoor use of combustion engines	Design Feature: The laboratory supply and exhaust ventilation systems provide an adequate air exchange rate to remove toxic gases. Design Feature: Toxic gas monitoring (CO) equipment is provided in laboratories used to test combustion engines. The equipment will alarm to alert personnel of a potential release. Design Feature: The laboratory exhaust ventilation system provides the capability to connect to vehicle/DUT exhaust. The Work Control Documents for operating vehicles or DUT indoors define the requirements for making the connection. Design Feature: The design of laboratories provides a large space relative to the exhaust rate. (This reduces the likelihood that toxic gas levels can be reached due to a leak, failure of vent system, or failure to connect the vent to the exhaust.)
Exposure to high temperature	Burns from exposure to release of heat transfer fluid and small local fire	Work Control Documents address the following test design requirement: Heat transfer fluid boilers must be supplied with a pressure relief device and an enclosure (i.e., spray shield) that would minimize the spray of the heated fluid from failed components. Work Control Documents address the following test design requirement: Noncorrosive construction materials must be used for thermal testing equipment containing corrosive materials. Work Control Documents define periodic inspection and maintenance of thermal testing equipment. Work Control Documents define the PPE requirements when working with thermal testing equipment. Design Feature: The fire detection system will detect a significant release and alarm, alerting personnel to evacuate. Design Feature: Hot vapors or fire will activate the fire suppression system and alarm, alerting personnel to evacuate.

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Accident Type	Scenario	Items Relied on for Safety
Electric shock or arc flash	AC ground faults (phase to ground or phase to phase) due to insulation breakdown, mis-wiring, physical damage or equipment failure in the REDB system	Design Feature: REDB system breakers provide industry standard overcurrent protection. Design Feature: Design and installation of the REDB system is per the NEC. The PM program requirements for the REDB system include resistance (ohm) measurement and thermal imaging. (The intent of these PMs is to specify routine inspection and testing of the system that will identify weak spots prior to a failure.) Design Feature: SCADA provides remote indication and operation of critical components. (SCADA is only credited as an administrative control for this area as design does not include any provisions beyond component status and remote operation requests.)

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Table 3. Summary of ESIF Items Relied On For Safety from Accident Analysis

Accident Name	Scenario	Items Relied on for Safety
Compressor Failure	A compressor with an internal volume of 1 liter operating at 15,000 psi fails catastrophically generating a pressure pulse equivalent to 22 grams of trinitrotoluene (TNT). The greatest hazard would be from the shrapnel produced.	Design Feature: Barriers prevent damage to nearby equipment. Work Control Documents require that only authorized personnel are inside the fenced area during compressor operations.
Hydrogen Storage Vessel Rupture	The ESOTA includes a FIBA vessel rated for 15,000 psig with a maximum operating pressure of 13,500 psig. The rupture will be assumed to occur at 15,000 psig due to corrosion, defect, cyclical failure, or impact.	Design Feature: The vessel is rated at 15,000 psig and constructed in accordance with ASME BPVC Section XIII, Division 3 and/or Section X, Class III standards and tested to at least 125% maximum allowable working pressure (MAWP). Design Feature: Compressor pressure controls, pressure relief valves, and pressure reducing stations prevent over-pressurization of the vessel. Installation is in accordance with NFPA 2 for risk-based separation distances. Design Feature: Electrical systems are classified Class I, Division 2, and ignition sources have been eliminated. Design Feature: Interlocked UV/IR sensors detect hydrogen fires with in the ESOTA and initiate alarms and shutdown sequences.
Leakage of Hydrogen into a Confined Space	The failure of a hydrogen supply line in the ESIL results in the contents of the 3,000-psig storage vessel (a maximum of 10.3 kilograms hydrogen) being released into the laboratory. The lower flammability limit (LFL) will be exceeded.	Design Feature: The ESIL is continually monitored by a hydrogen detection system. At 10% of LFL, the system causes the basic ventilation system to double its exhaust flow rate from 7,000 cubic feet per minute (cfm) to 14,000 cfm. At 25% LFL, the system generates an EPO that halts hydrogen production and transfer. Design Feature: The ESIL ceiling T-beams create 13 2-foot deep channels that have hydrogen detection system sample ports and forced (push/pull) ventilation. Design Feature: A check valve prevents backflow from the hydrogen storage vessel. Design Feature: The ESIL was constructed with Class 1, Division 2 electrical systems. Non-classified test articles are only allowed below 15 feet above floor level.

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Accident Name	Scenario	Items Relied on for Safety
Misconfiguration of REDB Racetrack and Laterals from REDB Control System Human-Machine Interface (HMI)	The wrong REDB laboratory lateral is inadvertently energized after an electrical source is connected to a misconfigured REDB system line-up due to human error.	Work Control Documents require that a second REDB control room engineer verify the configuration entered before energizing the experiment is allowed.
Improper Operating Limits are Entered into the REDB Control System HMI	A current overload on a portion of the REDB resulting from human error	Work Control Documents require that a second REDB control room engineer verify that the intended limits were properly entered. The safety PLC limits are under configuration management.
Corrupt or Compromised Control Logic is Introduced into the REDB Control System	Normal software-controlled safety functions performed by the REDB control system fail due to human error, malicious human intervention, or controller corruption	Work Control Documents require that the safety PLC system is under configuration management.
Release of Large Volume of Corrosive Liquid	A large-scale electrolyte leakage from a flow battery due to rupture of the containment vessel due to mechanical impact, over-pressurization, or a material defect or corrosion.	Design Feature: The flow battery has on-board leak detection and containment features. The leak detector interlock shuts off electrolyte transfer pumps. Design Feature: The room is equipped with a containment berm sized to contain the entire contents of the flow battery.

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Accident Name	Scenario	Items Relied on for Safety
Toxic Spill Inside	A container of strong acid is dropped during transportation, causing rupture of the container and subsequent release.	Work Control documents require that containers be limited to a maximum size of 1 gallon. Design Feature: Laboratories where acids are handled have a ventilation flow rate of at least one cfm per square foot.
Hazardous Material Spill Outside	Diesel, biodiesel, or gasoline-driven equipment can experience a spill during fueling or transfer, or a failure of a storage tank or on-board fuel tank.	Work Control documents require that only DOT-approved tanks or drums are used. Work Control documents require that all fueling and transfers are attended operations. Transfers are by hand pump only.
Toxic Gas Leak	The contents of a 170-pound hydrogen sulfide (H_2S) cylinder leak into the Fuel Cell Development and Test Laboratory (FCDTL) as the result of impact/mechanical damage of the process tubing.	Design Feature: Hydrogen sulfide cylinders and all connections are made within a vented and purged gas cabinet or hood, located in the service corridor. Design Feature: Stainless steel tubing transporting H_2S between the gas cabinet, fume hoods, and any enclosures has fully-welded construction and is doubly contained within a carrier pipe. Design Feature: The FCDTL has an occupied air change rate of at least one cfm per square foot, resulting in a minimum exhaust flow rate of 1,967 standard cfm. Work Control documents require that the process tubing and carrier pipe are pressure tested annually and between usage campaigns before introducing the H_2S. Work Control documents require that gas cabinets and fume hoods are inspected regularly and tested annually to ensure proper operation. Design Feature: FCDTL (C323) is equipped with an aspirating air sampler equipped with an Xtralis H_2S detector. At 5 parts per million (ppm), the system generates a yellow light on the light tree and a SCADA alarm on the HMI. At 10 ppm, the system automatically alarms (horn and blue light on the light tree), initiates an EPO (red light on the light tree), maximizes the laboratory exhaust flow rate, and closes the gas manifold valve.

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Accident Name	Scenario	Items Relied on for Safety
Toxic Fumes from Combustion of Power Electronics or Solvents	Research activities in a number of laboratories have the potential to create small fires that are not self-sustaining. These fires are created from the overheating of power electronics or the spill of solvents contacting an ignition source. Smoke from these fires can contain toxic substances as well as the products of combustion.	Work Control Documents require solvents are limited to a maximum container size of 1 gallon and are stored in flammable storage cabinets when not being used. Work Control Documents require laboratories to be kept clean and free of combustible debris such as cardboard boxes. Design Feature: Fire extinguishers are located throughout the facility allowing users to quickly extinguish a small fire. Design Feature: Construction of the laboratories uses low-flammable materials to prevent the spread of any small fires (epoxy-coated concrete floors, open steel structure, concrete ceilings, drywall walls, etc.) Design Feature: Ventilation is designed to keep any release in the associated lab and exhaust the smoke to the roof stacks. Design Feature: Ventilation removes any smoke (toxins) from the facility and provides safe egress routes and time for personnel to exit the facility, limiting the exposure to toxins. Design Feature: The fire alarm system with smoke detectors will sense and alarm, leading to evacuation of the facility. A high bay fire alarm results in an EPO for the entire C Wing.

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1.6 Integrated Hazard Analysis Summary

This section summarizes the IHA conducted on the ESIF. The foundation for the IHA is a PrHA that systematically identifies and evaluates facility hazards. The PrHA specifically addresses defense in depth and protection of workers, protection of the facility and equipment, and protection of the environment. Basic industrial methods for PrHA have been described in references such as the American Institute of Chemical Engineers' *Guidelines for Hazard Evaluation Procedures* (1992). This reference describes largely qualitative, not quantitative, methodologies for comprehensively defining the accident spectrum for workers and the public. The PrHA is focused on systematically assessing what can go wrong in a facility as opposed to deriving mathematical expressions of risk.

The PrHA provides an initial basis for the required safety programs, such as hazardous chemical protection. The hazard analysis goes beyond basic hazard identification to qualitatively estimate the expected likelihood and consequences of accidents. The HAR identifies preventive and mitigative structures, systems, and components (SSCs); SACs; and programmatic controls, such as Safety Management Programs (SMPs) and management measures. The most significant preventive and mitigative controls are subject to added rigor in their implementation. Other items noted are encompassed by the details of SMPs (e.g., procedures, training, maintenance, quality assurance.)

The analysis required by the IHA is geared to the facility hazards and needs. Analysis is generally simple, resource efficient, and qualitative; however some bounding accident events are of sufficient complexity to require more detailed, quantitative analysis using selected EBAs to understand the basis for safety assurance. Other postulated accidents, such as design basis accidents (DBA), were analyzed as needed to thoroughly establish the safety basis. The method used to perform the IHA is shown in Figure 2.

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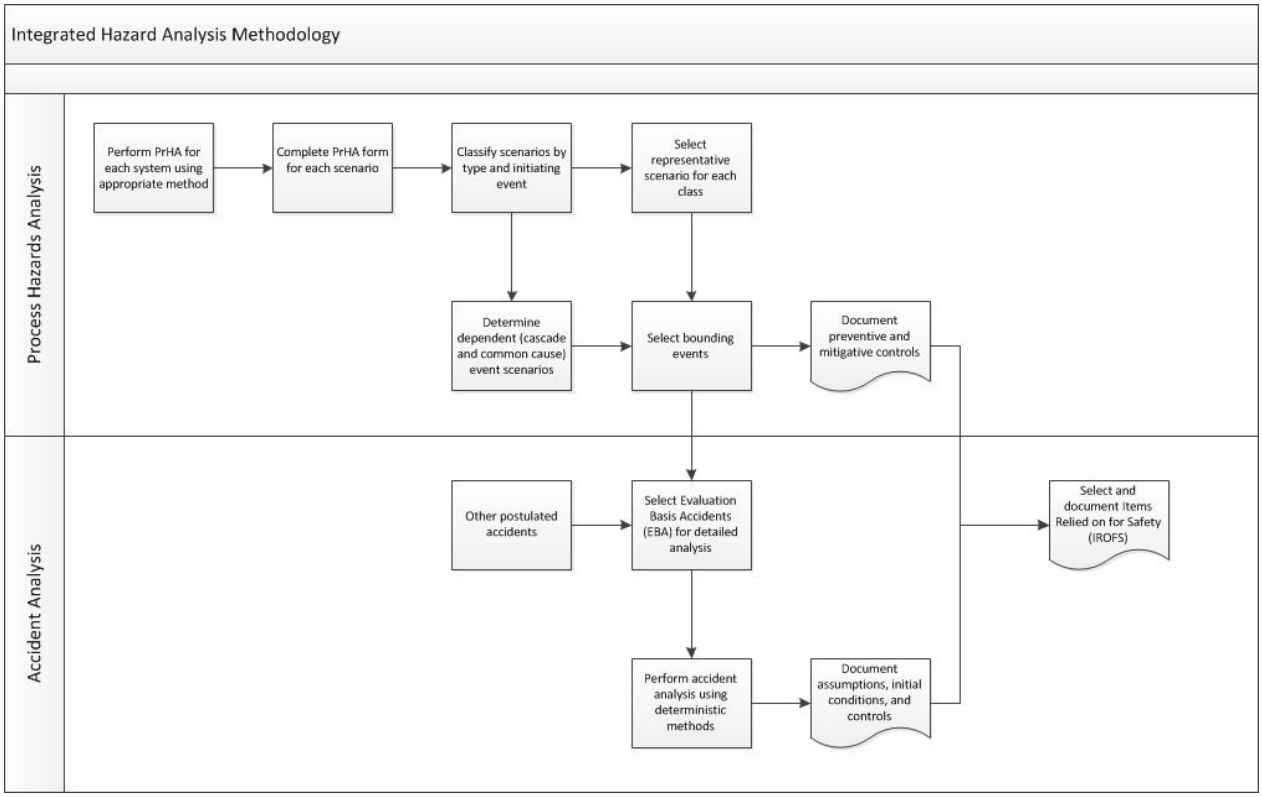

Figure 2. Hazard analysis block diagram

1.6.1 Bounding Events and IROFS

The complete spectrum of hazards, initiating events, and accident types is examined in the PrHA. The scenarios are classified by accident type and initiating event. A representative scenario is selected from each class, usually based upon the unmitigated risk. The classified scenarios are also evaluated to determine which ones contain dependent failures (either common cause or cascading failures). A set of *bounding events* is selected from the representative or the dependent event scenarios. The preventive and mitigative controls associated with the bounding events define the safety basis for the operations. While all the controls will be implemented, only a portion will be elevated to SACs or safety SSC status. These elevated controls will be described fully in the HAR whereas the other controls will be incorporated in the SMPs. IROFs identified through the bounding event analysis are presented in Table 2.

1.6.2 Accident Scenarios and Items Relied on for Safety

The ESIF PrHA identified a limited subset of accidents to be carried forward to accident analysis. These accident scenarios constitute a complete set of bounding conditions to define the envelope of accident conditions to which the operation could be subjected. Accident analysis uses established methods to quantitatively or semi-quantitatively assess frequency and consequences of selected accident scenarios. The accident scenarios selected for further evaluation are those that present a significant unmitigated risk and therefore must have a sufficient set of preventive and mitigative controls. IROFS identified through the accident analysis were presented in Table 3.

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2 Operational Approach

This chapter of the HAR explains the operational approach for the ESIF, which is consistent with the operational approach followed by all NREL facilities. NREL facilities are operated by establishing a "safety envelope" and by managing the facility within its safety envelope, maintaining adequate margins as the uses and configurations of the facility change over time. Section 2.1 describes the safety envelope concept.

2.1 Safety Envelope Concept

DOE G 450.4-1C, *Integrated Safety Management System Guide*, states:

> **"Core Function 3, Develop and Implement Hazard Controls**
>
> Applicable safety standards and requirements are identified and agreed-upon, controls to prevent/mitigate hazards are identified, ***the safety envelope is established***, and controls are implemented." (emphasis added)

The safety envelope is "a set of conditions that, when met, provide reasonable assurance[3] that the occurrence of any high consequence (catastrophic or critical) event is highly unlikely (improbable or extremely remote) and the occurrence of any intermediate consequence (marginal) event is unlikely (remote)." The degree of assurance should be commensurate with the potential consequences. To provide reasonable assurance that a particular accident sequence will not occur, not only must the hazard controls be identified and implemented, but the management measures (i.e., configuration management [CM]) and specific features of the SMPs (i.e., training, quality assurance, maintenance, calibrations, surveillance, etc.) that ensure the availability and reliability of those controls must also be demonstrated. The HAR describes the hazards and controls, accident frequencies and consequences, management measures, and the application of SMPs.

The safety envelope is an abstract concept. While some elements of the safety envelope are material and/or measurable, other elements are intangible. For example, the maximum allowable working pressure (MAWP) for a pressure vessel is determined by the vessel design, and the rating of the pressure relief device can be validated through testing. However, the benefit gained by having personnel trained and qualified to a particular procedure is not tangible. One can check to see that the training has been delivered and that the recipient demonstrates proficiency, but the reduction in risk resulting from the training cannot be measured, only assumed to drive risk in the proper direction.

Inherent in the definition of the safety envelope is the concept of margin. The prime objective of facility management is to demonstrate that the facility is operated and maintained within its approved safety envelope. Adequate margins make the task of determining if a new or significant change to an activity/system is within the facility envelope easier and straightforward. Researchers should also establish margins within their Safe Work Permit (SWP)/Safe Operating Procedure (SOP) by specifying parameters as ranges rather than point values, consider frequent

[3] The standard to be met is that of "reasonable assurance." The definition of reasonable assurance is: "Acknowledgment that it is not possible to assert absolutely and certainly that an event will (or will not) occur. Reasonable assurance is a high level of confidence but not absolute."

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transients or anomalies such as "double batching," and provide for likely changes in research materials and conditions. (This information should be documented in the process safety information developed to support the PrHA and will not be detailed in the HAR). The facility safety margin is derived from conservative assumptions used in design and certain assumptions pertaining to initial conditions (such as the amount of material at risk). This information is found in the system design descriptions (SDDs) and summarized in the HAR. These critical assumptions are protected by SACs (e.g., control of combustibles) from being violated or becoming invalid.

The safety envelope is established at both the activity/system level and at the facility level (Figure 3). The facility-level safety envelope encompasses and integrates all of the activity/ system level hazards and their associated controls. All work is performed in accordance with NREL policies, procedures, and programs.

Figure 3. The safety envelope is established at the system/activity, facility, and institutional levels.

The safety envelope at the activity/system level is defined by the SWP or SOP for the activity/ system. The hazards and controls are derived from the PrHA. The facility safety envelope is described in the HAR. Various implementing procedures and programs needed to establish and maintain the safety envelope are contained in the ESIF Desk Procedures or LLPs.

While the HAR describes the safety envelope, it cannot include all of the foundational material, such as process safety information and the complete design basis. Therefore, safety basis interpretations and determinations of whether proposed new or significant changes to activities and systems are included in the safety envelope should be made by people knowledgeable in all aspects of the facility. The Facility Manager is responsible for ensuring that programs are in place to ensure that the facility is operated within its safety envelope.

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2.2 User Facility Model

The ESIF is designated by DOE as a User Facility (UF), making available its capabilities to the entire research community and industrial sector to develop and evaluate their technologies in safe and controlled environments. For UFs, the HAR must fully account for the UF's hazard profile and safety envelope.

A UF is a federally sponsored research facility available for use to advance scientific or technical knowledge under the following conditions:

- The facility is open to all interested potential users without regard to nationality or institutional affiliation.
- Allocation of facility resources is determined by merit review of the proposed work.
- User fees are not charged for non-proprietary work if the user intends to publish the research results in the open literature. Cost recovery is required for proprietary work.
- The facility provides resources sufficient for users to conduct work safely and efficiently.
- The facility supports a formal user organization to represent the users and facilitate sharing of information, forming collaborations, and organizing research efforts among users.
- The facility capability does not compete with an available private sector capability.

2.2.1 User Categories

The customers for the ESIF include utilities, equipment manufacturers, renewable systems integrators, universities, other national laboratories, and related industries. Because funding for the ESIF's operation is provided by DOE's EERE, a majority of the space is made available for research to advance EERE's mission. Space will also be made available to non-EERE–sponsored research and development that is in line with the ESIF's core mission. The following categories of users may conduct work at the ESIF UF:

- **DOE-Funded Work at NREL:** This user group represents NREL staff and NREL partners executing work funded through DOE Annual Operating Plans, including activities at NREL funded through competitive Funding Opportunity Announcements. This also includes work executed under NREL cooperative research and development agreements in which DOE funds are being utilized.
- **Non–DOE-Funded Work at NREL:** This user group represents NREL staff and NREL partners executing work funded by other government agencies or public and private institutions through NREL cooperative research and development agreements in which no DOE funds are utilized, work for others agreements, or agreements to commercialize technology.
- **DOE-Funded Work at Other Institutions:** This user group represents all DOE-funded work other than work funded at NREL. User organizations include other DOE federally funded research and development centers, universities, private industry, non-profits, and state and local governments.

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- **All Others:** This user group represents non-NREL researchers who do not fall into one of the above categories. User organizations include federally funded research and development centers, universities, private industry, non-profits, and state and local governments. Included in this category would be non-NREL users who receive funding from DOE offices other than EERE or other government agencies or through their own institution.

2.2.2 User Facilities: Implications for Hazard Analysis Review

The ESIF's UF classification can create special challenges in managing the safety envelope. UF users come from a variety of safety cultures and they may be using the ESIF for short-term projects. The flux of research projects in user facilities require frequent changes in facility configuration that must be selected and managed within the approved safety envelope.

All UF projects are assessed for hazards and approved as appropriate, not only for the UF's operating envelope, but for the specific facility space in which the proposed work will take place.

The HAR addresses the impacts on the facility safety basis of the UF stemming from the wide range of users, including:

- Users without prior experience in NREL and/or DOE facilities
- Users from different safety cultures
- Users who have acquired rapid access to a UF for projects of limited scope and duration
- Proprietary users with lower review and scrutiny requirements.

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3 General Information

3.1 Site Description

This section describes the characteristics of the ESIF site and its environs that are critical to the ESIF safety basis. Information is provided to support and clarify assumptions used in the IHA to identify and analyze potential external and natural event accident initiators and accident consequences external to the facility. This section includes:

- Description of the location of the NREL site, location of the ESIF facility within the site, and its proximity to other NREL facilities and to the public
- Specification of population sheltering, population location and density, and other aspects of the area surrounding the site that relate to assessment of the protection of the health and safety of the public
- Determination of the historical basis for site characteristics in meteorology, hydrology, geology, seismology, volcanology, and other natural events to the extent needed for hazard and accident analyses
- Identification of evaluation basis natural events
- Identification of sources of external accidents, such as nearby airports, railroads, or utilities such as natural gas lines
- Identification of nearby NREL facilities impacting, or impacted by, the ESIF
- Validation of site characteristic assumptions common to integrated hazard analyses that were used in prior environmental analyses and impact statements, or of the need to revise and update such assumptions used in facility environmental impact statements.

The ESIF is part of NREL's South Table Mesa (STM) campus. The STM campus is generally located at the base of a mesa and is bordered by residential subdivisions on the west, east, and south, and open space easements with public hiking trails to the north. Figure 4 shows the location of the ESIF on the STM site.

The ESIF is located at the east end of the NREL STM site, northwest of the Education Center. The ESIF is bordered on the north by a conservation easement, to the west by the Science and Technology Center (which primarily supports photovoltaic research), to the southwest by the Research Support Facility (general NREL administrative offices), to the south by the visitor parking garage, and to the east by a natural drainage feature and meadow. The ESIF follows the geographic contours of the site, with elevation increasing from south to north.

3.2 Facility Description

This section provides descriptions of the facility and processes to support assumptions used in the IHA. These descriptions focus on all major facility features necessary to understand the IHA.

3.2.1 Facility Overview

The ESIF is approximately 182,500 gross sq. ft. in area and is fully integrated in the STM campus, with full utility access and fire infrastructure support. The ESIF is essentially three structures connected together with short segments, sometimes referred to as "knuckles." The

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southernmost structure houses the administrative offices, the middle structure is the HPC/DC, and the northernmost structure constitutes the laboratories. This layout was adopted to further enhance safety through basic occupancy separation. The offices have three levels and provide workspaces for approximately 200 personnel. The laboratory segment is connected to the offices via the main lobby "knuckle," which houses the HPC/DC, which occupies the topmost of the three levels in this segment (other levels are occupied by mechanical services and conference rooms). The HPC/DC was designed to provide 2 MW on Day One, with expansion capability up to 10 MW. These power levels are enough to accommodate a high-performance computational capability of at least 1 petaflop with a planned expansion capability estimated at 20 petaflops.[4] The laboratory segment is divided into two sections, the Level 2 laboratories and the Level 3 laboratories. The laboratories are single-story high-bay areas on local grade, with the title representing their relative elevation to the building overall as it tracks the geography up the mesa. The laboratory area has four outside test areas (OTAs), two on the west side, one on the north side, and provisions for a future test platform on the roof. The ESIF was designed to achieve a "platinum" rating in accordance with U.S. Green Buildings Council LEED-NC [Leadership in Energy and Environmental Design – New Construction] Green Building Rating System.

The Level 3 laboratories occupy the northernmost portion of the laboratory facility and are designed for bench-top chemistry, including thermal materials and hydrogen fuel cell stack research. The Level 2 laboratories occupy the southernmost portion of the laboratory facility and are generally designed for electrical grid research.

Outdoor test laboratories flank the western laboratory areas and generally consist of electrical infrastructure gear and pads for devices under test (DUTs) that relate to electrical grid research. Bulk hydrogen gas is stored outside the facility on the far northernmost part of the facility site with the storage cylinders situated against the mesa and separated from the laboratory.

3.2.1.1 Construction/Floor Plan

With respect to the IBC (2009), the building is divided into two areas: Type II-B (non-combustible construction) for the office and HPC/DC modules and adjoining knuckles and Type I-A (fire-resistive construction) for the laboratory areas. The laboratories are separated from the knuckle leading to the HPC/DC by a 4-hour firewall. The office and HPC/DC modules and knuckles are designed and designated for Business occupancy. Some conference rooms within these areas are designated as Assembly occupancies.

The Level 2 laboratories are mainly "dry" laboratories that primarily consist of electrical research activities. The Level 3 laboratories primarily house activities that conduct research on hydrogen generation and storage systems, fuel cell technologies, thermal materials research, and associated materials characterizations. The areas in Level 3 can be further subdivided into two areas by occupancy classification: the laboratories on the northernmost portion of the ESIF, which include the Energy Systems Integration Laboratory (ESIL) and the Electrical Characterization Laboratory (ECL), are within an area designed for hazardous H-2 occupancy. Additionally, the REDB room, which lies at the transition between the Level 2 and Level 3

[4] A petaflop is a measure of a computer's processing speed and can be expressed as a thousand trillion floating point operations per second.

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laboratories and is entirely constructed of pre-cast concrete, houses extensive electrical switchgear. The rest of the laboratory areas are designed for Industrial and Business occupancy. Currently, there are four control areas in the laboratory, excluding the H-2 area. The H-2 laboratories (ESIL and ECL) are classified electrical areas (Class I, Division 2), while the adjoining preparatory and storage rooms are unclassified.

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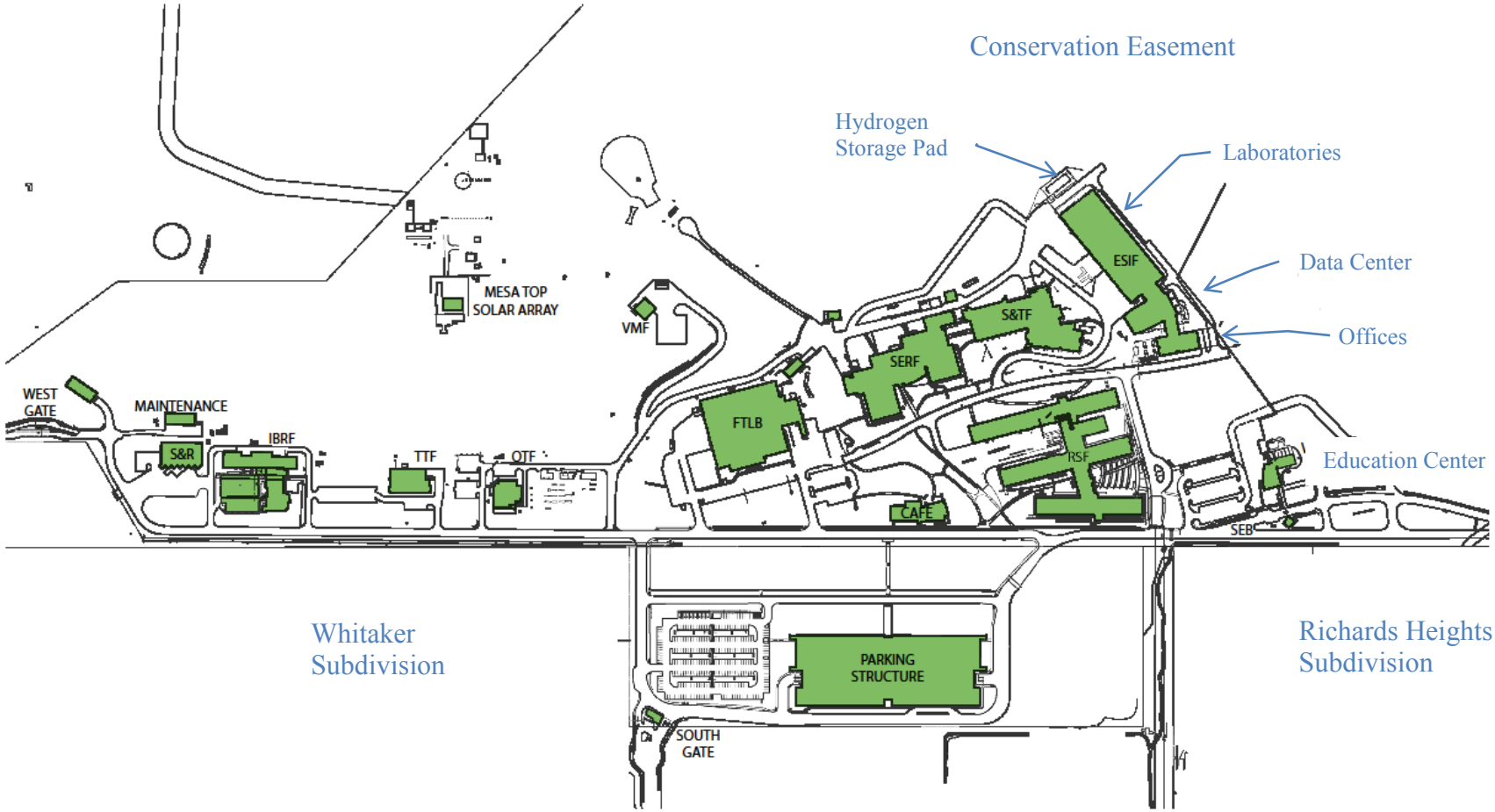

Figure 4. January 2013 STM site map showing ESIF location

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Laboratories and utility rooms are enclosed within 1-hour fire-rated assemblies; H-2 occupancy laboratories are segregated from the rest of the laboratory by a 2-hour fire rated assembly.

Within the ESIL, there are two high-pressure test cells that are intended to test small vessels to hydrostatic failure and small gas distribution components to failure at high gas pressures (including hydrogen). Commensurate with the hazards posed by this testing, the test cells are 12-inch poured concrete with reinforcement (on both faces and directions) and are capable of routinely resisting 1-psi overpressures and a maximum overpressure of 4.75 psi. While robust, the construction of the test cells is designed to function as a secondary containment/enclosure system only; for small component testing at high pressures using hydrogen, the basis of design conceptualized the test articles residing in a primary enclosure system, such as a calorimeter, situated within the high-pressure test cell. Both the high-pressure test cells and ECL are equipped with tethered blow-out panels for overpressure relief for catastrophic system failures and possible overpressure events. Standoff distances are provided outside these areas to reduce exposure to blast effects in the extremely unlikely event an explosion occurs in either of these laboratories.

Along the west side of the building there are two outdoor test areas—the low voltage (LVOTA) and medium voltage outdoor test areas (MVOTA). These areas contain test pads, load banks, transformers, reclosers, switches, generators, etc., and are enclosed by fencing. On the north side of the facility is the Energy Storage Outdoor Test Area (ESOTA), where hydrogen will be compressed and stored at 400 and 750 bar.

Table 4 lists the ESIF facility systems that enable research functions and ensure a healthy and safe environment, as well as the NREL personnel responsible for these systems.

Table 4. ESIF Facility Systems and Responsible Personnel

System	Document	Class	Function Summary	System Engineer
Fire detection	SDD	Safety	Fire detection and notification	ESIF Building Area Engineer
Fire suppression	SDD	Safety	Fire suppression system	ESIF Building Area Engineer
Very early warning aspirated smoke detection (VESDA) smoke detection – HPC/DC fire suppression	SDD	Safety	Fire detection and notification for HPC/DC	ESIF Building Area Engineer
Gas detection	SDD	Safety	Hazardous & toxic gas detection and notification (VESDA & Dregger)	ESIF Operations Manager
Laboratory gas supply (gas cabinets)	SDD	Safety	Storage and distribution of bottled gases to laboratories	ESIF Operations Manager

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System	Document	Class	Function Summary	System Engineer
Laboratory exhaust ventilation	SDD	Safety	Air exhaust for laboratories, hoods, canopies, and gas cabinets. Includes engine (Carmon) exhaust systems	ESIF Building Area Engineer
Laboratory supply ventilation	SDD	Safety	Air supply to laboratories	ESIF Building Area Engineer
Perchloric hood washdown	SDD	Safety	Wash out exhaust duct and perchloric acid hood	ESIF Operations Manager
Laboratory safety and alarm	SDD	Safety	PLC and associated alarm functions for each laboratory	ESIF Operations Manager/ESIF SCADA Engineer
House hydrogen	SDD	Critical to research	Distribution of hydrogen gas to laboratories and test pads, includes hydrogen and oxygen vent systems	ESIF Engineering Group Manager
AC REDB	SDD	Critical to research	AC research bus	ESIF Lead REDB Engineer
DC REDB	SDD	Critical to research	DC research bus	ESIF Lead REDB Engineer
SCADA	SDD	Critical to research	REDB control, monitoring, and data acquisition. Also provides laboratory safety & alarm info.	ESIF SCADA Engineer/ESIF Data, Communications & Visualization Systems
Compressed air	FDD		Distribution of compressed air to laboratory areas. (Also used to actuate valves)	ESIF Building Area Engineer
Nitrogen (house)	FDD		Distribution of gaseous nitrogen to laboratory areas. (Also used to actuate some hydrogen system valves)	ESIF Building Area Engineer
Vacuum	FDD		Localized vacuum for certain laboratories	ESIF Building Area Engineer
Laboratory fuel supply	SDD	Safety	Distribution of natural gas and diesel fuel to laboratory areas	ESIF Building Area Engineer
Laboratory de-ionized water	FDD		Generation and distribution of de-ionized water to laboratories	ESIF Building Area Engineer
Research chiller	SDD	Critical to research	Provides chilled water for specific laboratory heat loads	ESIF Building Area Engineer
Research boiler	SDD	Critical to research	Provides very hot water for specific laboratory uses	ESIF Building Area Engineer

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System	Document	Class	Function Summary	System Engineer
Large environmental chamber	SDD		Room C328 environmental chamber and associated support systems	ESIF Engineering Group Manager
Overhead cranes	FDD		Currently only rail supports installed	ESIF Building Area Engineer
Emergency electrical power	SDD	Safety support	Egen electrical power supply for emergency power loads. Could be combined with normal electrical power.	ESIF Building Area Engineer
Normal electrical power	FDD		Site electrical power supply for normal power loads	ESIF Building Area Engineer
Lightning protection	FDD	Safety support	Lightning protection for facility	ESIF Building Area Engineer
Transient voltage surge suppression	FDD		Electrical gear surge protection	ESIF Building Area Engineer
Uninterrupted power supplies (UPSs)	FDD	Safety support	Local UPSs in certain areas	ESIF Data, Communications & Visualization Systems
Office and support space air distribution	FDD		Supply and return air to offices/support area including natural ventilation systems	ESIF Building Area Engineer
HPC/DC air distribution system	FDD		Data center air supply and return is unique enough to be addressed separately	ESIF Building Area Engineer/HPC Engineer
Lighting controls	FDD		Lighting system inside and outside the facility	ESIF Building Area Engineer
Building automation	SDD	Safety support	This can be standalone or incorporated into HVAC	ESIF Building Area Engineer
Elevators	FDD		Passenger and freight elevators	ESIF Building Area Engineer
Low temperature heating water and radiant beam system	FDD		Heating water for office radiant beams and Insight Center/Lobby coils	ESIF Building Area Engineer
Primary cooling water	FDD		Cooling water to coils for ambient temperature control	ESIF Building Area Engineer
Primary heating water	FDD		Heating water to coils for ambient temperature control	ESIF Building Area Engineer
Energy recovery water	FDD		Recovers heat from HPC and returns cooling water	ESIF Building Area Engineer
Tower water	FDD		Tower cooling system	ESIF Building Area Engineer

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System	Document	Class	Function Summary	System Engineer
Process cooling water	FDD		Cooling water for specific laboratory heat loads	ESIF Building Area Engineer
Tempered water	FDD		Provides temperature-controlled water to eye wash/safety showers	ESIF Building Area Engineer
Campus heating and cooling water	FDD		Connection to campus hot and cold water supplies	ESIF Building Area Engineer
Domestic water	FDD		Provides hot and cold water for occupant use	ESIF Building Area Engineer
Laboratory vent	SDD	Safety	Passive vent system to roof and blowout panels in HPTB and ECL	ESIF Building Area Engineer
Sanitary sewer	FDD		Sewer system for occupant use	ESIF Building Area Engineer
Storm sewer	FDD		Site drainage system	ESIF Building Area Engineer
Laboratory waste drains	FDD		Drains from laboratories into sewer system—has a separate inspection manhole	ESIF Building Area Engineer
Roof drains	FDD		Primary draining system from roof to storm sewer, backup are the scuppers	ESIF Building Area Engineer
Perimeter drains	FDD		Passive draining around building foundation	ESIF Building Area Engineer
Snow melt	FDD		Hot water system under courtyard pavers	ESIF Building Area Engineer

FDD = facility design description
HPTB = High Pressure Test Bay
VESDA = very early warning aspirated smoke detection

3.2.2 Principal Hazards Summary

The following assessment of principal hazards was performed during the ESIF design phase based on initial programming. The final PrHA and accident analysis (Section 4) are based on current programming of the facility research functions and activities.

The principal hazards associated with operations in the ESIF arise from generation, handling, and use of flammable process gases in pilot-scale process equipment and DUT articles, and with the electrical shock and arc flash hazards associated with power system testing at the 1-MW scale. In the case of flammable gases, in some cases, the process gases, primarily hydrogen, will be generated, compressed, stored, and used in high-pressure systems. Because of the wide flammability range of hydrogen in air, there is potential for developing flammable concentrations within enclosed spaces that pose a deflagration or detonation risk. The basic hazards posed by industrial use of hydrogen gas are known, and the associated hazard controls afford routine, safe use of hydrogen in many industry and research facilities. Prior to construction of the ESIF,

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NREL had many years of experience in safely performing many of the activities and operations that are now integrated into the ESIF; hence, there is both general industrial and specific institutional knowledge and experience in the control of these hazards. Moreover, NREL researchers are actively studying hydrogen safety to support code improvements, and some of the leading experts in hydrogen safety and code development are located at NREL and were actively involved in the development of this HAR.

In the case of electrical hazards, the REDB, which is a research electrical system consisting of AC and DC buswork, interconnects experiments across multiple laboratory spaces up to the 1-MW scale. From a system standpoint, balancing the inputs and outputs from disparate systems and effecting safe control of the system pose challenges and require a robust safety control system to manage the balance and prevent errors. Prior to construction of the ESIF, NREL had many years of experience in operating a smaller version of the REDB so there was institutional knowledge on the design, implementation, and safety controls needed for such an installation.

The ESIF specifications, facility research equipment, and current and planned activities present a set of design and operating challenges through their integration. While similar to some of NREL's activities across the STM site, these challenges are nonetheless intensified because of their co-residence within one facility and the scale of the activities.

The ESIF's location on the northeast portion of NREL's STM site also necessitated careful engineering consideration to successfully integrate the facility into the NREL campus. The Science and Technology Facility, the Research Support Facility, and an eastern drainage border the ESIF. A perimeter around the entire building provides for fire protection to ensure successful firefighting and rescue capabilities, as well as multiple access points for attacking a fire. The perimeter also provides for accident containment to minimize the chance that an incident in one area does not affect or spread to other operations within the building or the OTAs or to other nearby facilities or installations. Ventilation control prevents entrainment of upstream exhaust from other facilities. Traffic flow is provided to ensure deliveries do not interfere with other activities, cause system damage or an accident, or result in traffic congestion that will affect emergency response to the ESIF or adjacent facilities.

Finally, the ubiquitous and necessary presence of various electrical systems and corrosive electrolyte chemistries pose worker safety issues, although these hazards are not unique and will be managed through established procedures and standard design practices.

3.2.3 Laboratory Summary

The following basic summary of the activities in each laboratory within the ESIF identifies some of the most prominent hazards that were considered as part of the design. The discussion also notes design considerations and other requirements that are unique to a given laboratory.

In the discussion below, the notation "routine laboratory hazards" is used to capture basic hazards working within a general laboratory environment (e.g., working with basic chemistry, electrical equipment and low energy circuitry, sharp objects, hot plates, chemical fume hoods, etc.). Similarly, the term "routine office hazards" is used for basic office hazards, such as trip and fall exposures from cords, workstation ergonomic exposures, etc. Figure 5 shows the Level 2 and Level 3 laboratories in the ESIF.

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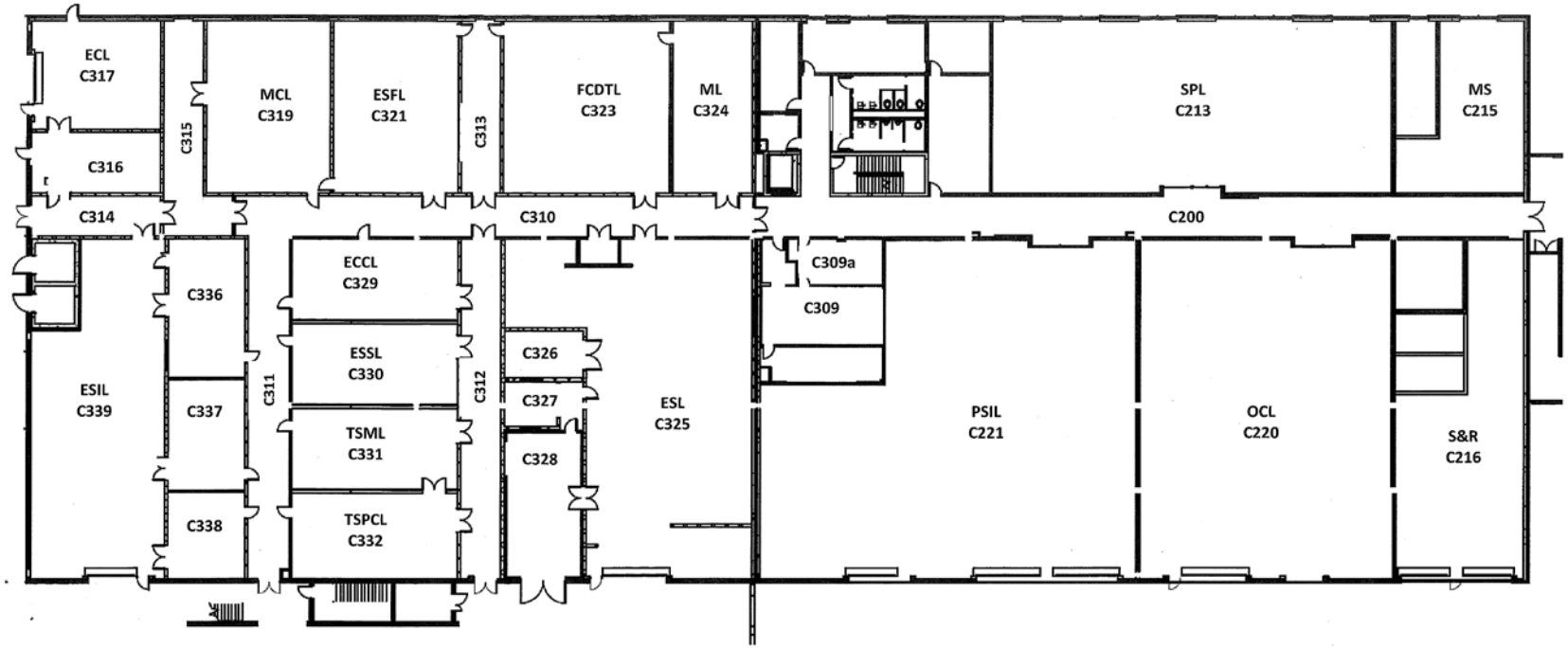

Figure 5. Map of ESIF laboratories

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3.2.3.1 Level 3 Laboratories

3.2.3.1.1 Energy Systems Integration Laboratory (C339)

The ESIL is designed to accommodate higher flammable gas concentrations, specifically those associated with hydrogen system testing, hydrogen gas production equipment, hydrogen gas handling systems, hydrogen gas compression, and hydrogen fuel cell equipment. Two high-pressure testing cells, which are accessible from the exterior of the facility, occupy a corner of this laboratory and can accommodate testing of high-pressure handling equipment and devices up to 10,000 psi. The main laboratory area is a Class 1, Division 2 rated space. Adjacent to the ESIL are a control room for computing, monitoring, and control equipment; an electrical power room that accommodates connections to the REDB; and a storage area.

Various safety systems are present in the ESIL to maintain a safe working environment in the presence of pressurized hydrogen gas, high-power electrical equipment, and certain chemicals that may be present. A hydrogen gas safety system is installed that utilizes both sensing and venting provisions to sense the presence of gaseous hydrogen. Alarms and interlocks will activate if hydrogen is sensed at a concentration at or above 25% of the lower flammability limit (LFL), or 1% concentration of hydrogen gas in air. The ventilation system includes two Class A spark-proof exhaust fans. Each fan is capable of meeting 100% design capacity, with one fan on backup power. The general scheme of the ventilation is to provide supply air low in the laboratory and exhaust higher in the room, increasing turbulence and mixing.

Adequately rated high-pressure hydrogen gas handling tubing, valves, and actuation devices are installed per manufacturer specifications in the ESIL. A safety controller dedicated to the ESIL controls valving, venting, routing, and actuation devices. This controller continually monitors conditions inside the laboratory and takes appropriate safety actions in the case of an emergency situation. An array of indicating lights is located outside the ESIL entrances that indicates the sensing status and condition of the laboratory interior.

Principal Hazards:

Both ESIL and High-Pressure Test Bays (HPTBs)

- Fire and Explosion: Release and subsequent confinement of flammable gases can result in deflagration or detonation. Hydrogen gas has a wide flammability range in air, 4% to 75%, and low ignition energy (as low as 0.02 millijoule [mJ]).
- Chemical: Exposure to corrosive electrolyte from spills (e.g., concentrated potassium hydroxide). Asphyxiation from inert gases.
- Electrical: Electrical shock hazards and arcing from electrical systems.
- Physical: Hoisting large, heavy objects. Noise from equipment. Exposure to hot surfaces or hot liquid coolants.

HPTBs

- Physical: Failure/bursting, shrapnel.

Other Requirements: The ESIL is a Class 1, Division 2 space. CM of the ESIL must consider the introduction of any non-electrically classified articles of equipment the space. The CM

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process will address the duration that this equipment will be allowed to operate, any required physical controls, laboratory access limitations, any restricted activities and signage and notification requirements.

3.2.3.1.2 Electrical Characterization Laboratory (C317)

Activities: Like the ESIL, the ECL is designed for the generation and use of flammable gases, specifically hydrogen. The ECL also has design considerations that support higher voltage work, such as surge testing (simulating lightning strikes) and high current, short circuit testing on equipment. It is also well suited for testing the initial operability testing and evaluation of supplied DUTs. This space has connections to the REDB, as well as an adjacent control room for monitoring and controlling experiments. Reinforced walls that are able to withstand blasts and explosions enclose the ECL testing space. The area is designed so that it can be rated as a Class 1, Division 2 space.

Principal Hazards:

- Fire and Explosion: DUTs may leak hydrogen. Flammable materials include hydrogen and natural gas.
- Chemical: Smoke emissions from deteriorating power electronic components.
- Electrical: High voltage in test chamber. Arc flash. Shock hazard in rest of laboratory. Potential energizing process lines and other utilities.
- Physical: Small electronic projectile ejection from surge testing activities. High frequency noise.

Other Requirements: The area has been designed to allow it to be rated as a Class 1, Division 2 space. CM of the ECL must consider the introduction of any non-electrically classified articles of equipment into the space. The CM process will address the duration that this equipment will be allowed to operate, any required physical controls, laboratory access limitations, any restricted activities, and signage and notification requirements.

3.2.3.1.3 Materials Characterization Laboratory (C319)

The Materials Characterization Laboratory (MCL) is designed as an analytical laboratory to support characterization of a variety of solids, liquids, gases, and reaction products. Some of the equipment that the MCL can support includes X-ray diffraction, Brunauer-Emmett-Teller for surface area measurements, evolved gas analysis from material decomposition, and a scanning electron microscope.

Principal Hazards:

- Chemical: Standard wet chemistry hazards; health effects from highly toxic, toxic, and corrosive materials; evolution of small amounts of potentially hazardous product gases; asphyxiation from inert gas; unknown effects from inhalation of unbound nanomaterials
- Fire: Ignition of flammable gases and materials
- Thermal: Tissue freezing and cryogenic burns from liquid nitrogen and liquid argon; burns from high temperature surfaces

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- Radiation: Ionizing x-ray radiation
- Electrical: Electrical shock
- Physical: Shrapnel from rupture of a vessel or high-pressure gas line; eye damage from class IIIb lasers; eye damage from radio frequency

3.2.3.1.4 Energy Systems Fabrication Laboratory (C321)

The Energy Systems Fabrication Laboratory (ESFL) is designed to serve as a standard chemistry laboratory.

NREL's Laboratory Chemical Safety Program describes the general laboratory practices to be followed for safe chemical handling and chemical storage.

Principal Hazards:

- Chemical: Standard wet chemistry hazards; health effects from highly toxic, toxic, and corrosive materials; evolution of small amounts of potentially hazardous product gases; asphyxiation from inert gas; unknown effects from inhalation of unbound nanomaterials.
- Fire: Small quantities of hydrogen gas in compressed gas cylinders. Small quantities of flammable solutions (e.g., Nafion).
- Electrical: Shock, arc, and fire are common risks to any piece of equipment connected to 110-V AC current.

3.2.3.1.5 Fuel Cell Development and Test Laboratory (C323)

The Fuel Cell Development and Test Laboratory (FCDTL) was designed as a standard chemistry laboratory with infrastructure support for electrochemical testing and characterization of membrane electrode assembly and fuel cell components, including fuel cell catalysts. Infrastructure includes manifolds for gas distribution to multiple test apparatuses.

- Hydrogen Supply: The hydrogen supply includes an excess flow valve at the hydrogen source. However, for additional safety, an excess flow valve with a lower flow threshold is installed on the hydrogen supply piping in the laboratory, located with the isolation valve and pressure regulator, and before the manifolding for hydrogen supply to the test stands. All hydrogen tubing up to individual shut-off valves is orbitally welded and uses variable compression ratio fittings. All other hydrogen tubing up to each test unit is 316 stainless steel standard or stainless steel flexible tubing assembled with 1-psi check valves and the minimum number of required fittings.

- Hydrogen Exhaust: The amount of hydrogen present in the laboratory is monitored using a hydrogen sensor system. Hydrogen sensors are placed in the laboratory, in enclosures, and in the service corridor. A low level alarm will be triggered when 10% of the lower explosive limit for hydrogen is breached; a high level alarm will be triggered when 20% of the lower explosive limit for hydrogen is breached. Hydrogen detection is tied to the Building Automation System (BAS) system and exhaust ventilation is increased when an alarm is triggered.

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Principal Hazards:

- Fire: Flammable materials include hydrogen and natural gas. Over-temperature from fuel cells (hydrogen crossover) or malfunction of fuel cell testing station equipment (electrical fault, hydrogen venting). Electrical component shorting.
- Chemical: Small quantities and dilute concentrations of perchloric acid may be used. Small quantities of sulfuric acid. Gases may include dilutions of carbon monoxide, ammonia, methane, hydrogen sulfide, and inerts or hydrogen.
- Electrical: Low voltage, high currents generated from fuel cells.
- Radiation: X-ray fluorescence use.

3.2.3.1.6 Manufacturing Laboratory (C324)

The Manufacturing Laboratory (ML) was designed as a general purpose laboratory space with an open floor plan to support installation and operation of manufacturing equipment, such as a roll-to-roll web line. The ML also has workspaces to support bench-scale testing of diagnostic equipment. The ML is serviced by the house hydrogen system.

Principal Hazards:

- Electrical: Typically 480V motors
- Physical: Material handling; rotating equipment, in-running nip points.
- Radiation: X-ray fluorescence from diagnostic tool
- Fire: Flammable materials include hydrogen.

3.2.3.1.7 Electrochemical Characterization Laboratory (C329)

The Electrochemical Characterization Laboratory (ECCL) was designed as a standard wet-chemical laboratory. The ECCL also has infrastructure to support operation of multiple bench-top ventilated enclosures that can support the generation and use of hydrogen. The ECCL is also intended to support the use of perchloric acid and includes a specially designed perchloric acid hood that is equipped with a wash-down system to prevent the accumulation of explosive quantities of perchloric salts in the duct work.

Principal Hazards:

- Fire: Flammable materials include hydrogen and natural gas. Over-temperature from fuel cells (hydrogen crossover) or malfunction of fuel cell testing station equipment (electrical fault, hydrogen venting). Electrical component shorting.
- Chemical: Small quantities and dilute concentrations of perchloric acid may be used. Small quantities of sulfuric acid. Gases may include dilutions of carbon monoxide, ammonia, methane, hydrogen sulfide, and inerts or hydrogen.
- Explosives: Accumulation of perchloric salts in duct work.

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3.2.3.1.8 Energy Systems Sensor Laboratory (C330)

The Energy Systems Sensor Laboratory (ESSL) was designed as a general purpose laboratory. It is supplied by a house hydrogen system. It is also fitted with a large ventilated walk-in canopy hood for housing large pieces of equipment, such as vapor deposition systems.

Principal Hazards:

- Fire: Flammable materials include hydrogen.
- Electrical: Electric shock and arc flash from electrical systems.
- Chemical: Dilute hydrogen sulfide (H_2S), ammonia (NH_3), carbon monoxide (CO), and nitrogen dioxide (NO_2). Asphyxiation from inert gases such as nitrogen.
- Physical: Extensive use of compressed gases. Process testing may require pure hydrogen and greater than ambient pressures.

3.2.3.1.9 Thermal Storage Materials Laboratory (C331)

The Thermal Storage Materials Laboratory (TSML) was designed as a standard chemistry laboratory with consideration for analytical equipment for high-temperature measurements of viscosity, heat capacity, heat of fusion, thermal stability, etc.

Principal Hazards:

- Chemical: Wet chemistry laboratory hazards (e.g., small quantities of hazardous chemicals, corrosive liquids). Small quantities of nanomaterials
- Physical: High temperature liquids (>500°C).

3.2.3.1.10 Thermal Storage Process Laboratory (C332)

The Thermal Storage Process Laboratory (TSPL) was designed as a general purpose laboratory with consideration given to the use of high temperature materials (e.g., molten salts) for energy storage applications. It is fitted with a large ventilated walk-in canopy hood for housing large pieces of equipment, such as vapor deposition systems.

Principal Hazards:

- Fire: High temperature liquids and test equipment. High electrical and thermal loads. Electric heaters. Flammable compressed gas (CO).
- Chemical: Small quantities of nanomaterials. Small quantities of hazardous chemicals. Hazardous compressed gases (nitrogen oxide [NO_x], CO).
- Physical: Potential handling of heavy equipment (1,000–3,000 lbs). Compressed gas cylinder handling and use.

3.2.3.1.11 Energy Storage Laboratory (C225)

The Energy Storage Laboratory (ESL) is a development and testing space for technologies associated with the storage and use of electrical energy. Energy storage media in the laboratory may range from purely electrical (such as supercapacitors or superconducting magnetics) to electro-chemical (batteries) to thermal (ice or phase-change materials), to liquid fuels. While the

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storage media may vary, the operations in the laboratory focus on the conversion of energy to and from electricity and the interaction and interconnection of this electricity with other electrical systems.

Because of the wide range of materials (and associated hazards) in the ESL, robust safety measures and provisions are required. As an example, a ventilated and secure location along the outer wall of the laboratory provides a safe place to store chemicals, batteries, or other articles that may exhume chemical fumes or dangerous gases. Further, containment is provided in this area for articles that have the potential to leak hazardous fluids.

The ESL includes provisions for handling combustion processes inside the laboratory. A combination of overhead, extendable vent snorkels and in-floor exhaust ventilation ports provides a means of controlling and containing combustion by-products, smoke, or other fumes.

The ESL is laid out to provide several sectionalized test bays of varying size. Each test bay is provided easy access to REDB connections, standard grid connections, water services, and gas services. Further, there is supporting infrastructure in the test bays to accommodate various sizes of environmental chambers for experimental purposes.

A large, drive-in environmental chamber resides in the ESL. This environmental chamber is designed to be able to accommodate up to a standard 20-foot shipping container as well as a medium-sized commercial truck. The large environmental chamber has pass-throughs for various experimental services, including REDB connections, standard grid connections, gases, and fluids.

Finally, a sub-room located in the ESL is home to a large dynamometer test stand. This drive stand exists for wind-turbine drivetrain simulation for emulation of wind turbine generator output electricity. Connections to the REDB are also available for the dynamometer test room.

Principal Hazards:

- Fire/Explosion: Release of hydrogen from batteries, multiple ignition sources. Flammable electrolyte in ultracapacitors. Vehicle storage and operation indoors with various energy generation systems.
- Chemical: Corrosive battery electrolytes (e.g., sulfuric acid). Combustion exhaust emissions and particulates.
- Electrical: Electric shock and arc from high voltages and currents. Potential high strength magnetic fields and very high current superconducting magnetic energy storage systems (SMEs).
- Physical: Fork truck handling of large test components. Flywheel destruction. Noise. Potential exposure to cold surfaces related to super-cooled SMEs. Asphyxiation hazard from potential SME quenching.

3.2.3.2 Level 2 Laboratories

Figure 5 shows the Level 2 laboratories in the ESIF.

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3.2.3.2.1 Power Systems Integration Laboratory (C221)

The Power Systems Integration Laboratory (PSIL) is a development and testing space for advanced electric power systems technologies. Typical test apparatus includes power inverters and converters, battery or storage systems, co-generation or turbine-based generators, combustion-based generators, control apparatus, power supplies, and experimental switchgear.

The PSIL's footprint is designed to be able to accept several large standard shipping containers. As a maximum, two 40-foot containers and one 20-foot container may fit into the laboratory space, while leaving room for various support equipment and connections. Handling such large and heavy equipment presents significant mechanical hazards. Infrastructure for an overhead crane is installed over the south bay of the laboratory, which is intended to bring large equipment into and out of this space. Further, special container-handling dollies or jacks and forklifts may be used to move large equipment into position within the laboratory.

The PSIL includes provisions for handling combustion processes inside the laboratory. A combination of overhead, extendable vent snorkels and in-floor exhaust ventilation ports provides a means of controlling and containing combustion by-products, smoke, or other fumes.

The PSIL includes three test bays along the north wall of the laboratory space. Each test bay has easy access to REDB connections, standard grid connections, water services, and gas services.

Principal Hazards:

- Fire/Explosion: Release of hydrogen from batteries, multiple ignition sources. Flammable electrolyte in ultracapacitors. Vehicle storage and operation indoors with various energy generation systems.
- Chemical: Corrosive battery electrolytes (e.g., sulfuric acid). Combustion exhaust emissions and particulates.
- Electrical: Electric shock and arc from high voltages and currents. Potential high strength magnetic fields and very high current.
- Physical: Fork truck handling of large test components. Flywheel destruction. Noise. Potential exposure to cold surfaces related to super-cooled SMEs. Asphyxiation hazard from potential SME quenching. Rotating parts, such as cooling fans for power electronics.

3.2.3.2.2 Smart Power Laboratory (C213)

The Smart Power Laboratory (SPL) is designed to support two primary areas of research: 1) integration of various distributed and renewable energy resources through power electronics, and 2) residential smart energy management and household-scale smart grid technologies and integration. The laboratory is designed to be highly flexible and configurable, essential for a large variety of smart power applications that range from developing advanced inverters to testing residential and commercial scale meters and control technologies.

The power electronics test area in the SPL was designed with consideration for research, development, and testing of power electronic components and circuits used in renewable energy and smart grid applications. Due to the noise abatement features of the test bays, they can be

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used for long duration test articles with high-frequency noise. One of the test bays also features a large ventilated walk-in canopy hood designed to exhaust emissions that can result from destructive testing of power electronics.

The SPL is also fitted with three residential-scale test areas with connections for 120/240-V electric service, water, and natural gas. The test areas are supported by multiple chambers that can emulate interior and exterior environmental conditions for test articles, such as thermostats and air conditioning units.

Principal Hazards:

- Electrical: Electrocution, shock, arc flash from both AC and DC systems
- Fire: Inadvertent ignition of natural gas; fire from failed power electronics
- Thermal: Burns from hot electrical components and mechanical devices
- Mechanical: Physical injury from rotating parts, such as cooling fans
- Chemical: Toxic fumes from electrical component failure; fumes and particulates from soldering
- Noise: High frequency noise emanating from switching power converters, supplies, or sinks.

3.2.3.2.3 Optical Characterization Laboratory (C220)

The Optical Characterization Laboratory (OCL) was designed as a large-area high-bay testing space with consideration for characterizing large optical devices (e.g., heliostats and parabolic troughs) and for commercial/industrial systems. Infrastructure for an overhead crane is installed over the north bay of the laboratory, which is intended to bring large equipment into and out of this space. Further, special container-handling dollies or jacks and forklifts may be used to move large equipment into position within the laboratory. The OCL houses a large walk-in environmental chamber that enables device testing over a wide range of temperature and humidity. The OCL is also fitted with pass-throughs to the roof allow installation of supply and return ducts for commercial HVAC systems. There is also a small pass-through in the west wall for electrical connection to exterior devices. The west wall also includes a multi-panel section that can be removed.

Principal Hazards:

- Physical: Struck-by and material handling injuries associated with hoisting and rigging structures, rotation of mirrors, etc. Fall exposures from temporary elevated work platforms and level surfaces due to low ambient lighting.
- Laser: Ocular damage from use of lasers for optical device characterization.
- Thermal: Low- and high-temperature exposure to environmental chamber surfaces and test articles.
- Electrical: Shock and arc hazards associated with commercial and industrial HVAC systems, environmental chambers, and test articles.

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3.2.3.3 Outdoor Laboratory Testing Areas

3.2.3.3.1 Rooftop Testing Area (RTA)

The Rooftop Testing Area (RTA) is designed for testing experimental equipment under test (EUT) that requires unshaded solar access. The RTA is designed for a metal test platform with connection to the REDB, as well as connections to house power. Examples of such EUT include photovoltaic arrays, concentrating solar power systems, solar hot water systems, and HVAC units.

Principal Hazards:

- Physical: Electrical shock and arcing. Falls from elevation. Slip/fall on level surface.

3.2.3.3.2 Low Voltage Outdoor Test Area

The LVOTA is designed for testing outdoor rated low voltage (up to 480 kilowatt [kW]) equipment, such as diesel and natural gas generators, gas microturbines, flywheel energy storage systems, and load banks.

Principal Hazards:

- Fire/Explosion: Flammable fuels including natural gas and diesel. Flammable electrolyte in ultracapacitors.
- Chemical: Corrosive battery electrolytes (e.g., sulfuric acid). Combustion exhaust emissions and particulates. Liquid fuels, such as diesel.
- Electrical: Electric shock and arc from high voltages and currents. Potential high strength magnetic fields and very high current.
- Physical: Fork truck handling of large test components. Flywheel destruction. Noise. Rotating parts.

3.2.3.3.3 Medium Voltage Outdoor Test Area

The MVOTA is designed to facilitate testing and interconnection of medium voltage (13.2 kilovolt [kV]) equipment. It also includes 1,000-kVA 13.2 kV to 480 V Y-Y transformers for connection of EUT in the MVOTA to the REDB, three 2.5-MVA 13.2 kV to 480 V for connection of the REDB and MVOTA to the utility grid, and one 200-A switch cabinet. The MVOTA was designed to accommodate a wide variety of equipment, including 1,000-kVA network protectors, utility reclosers, additional 200-A switch cabinets, additional transformers, load banks, and line impedance simulators. The MVOTA contains two 20-foot × 40-foot and three 10-foot × 10-foot test pads that facilitate easy configuration and connection of the EUT to the REDB at either 13.2 kV or 480 V.

Principal Hazards:

- Fire/Explosion: Flammable electrolyte in ultracapacitors.
- Chemical: Corrosive battery electrolytes (e.g., sulfuric acid).
- Electrical: Electric shock and arc from high voltages and currents. Potential high strength magnetic fields and very high current.

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- Physical: Fork truck handling of large test components. Noise. Rotating parts.

3.2.3.3.4 Energy Storage Outdoor Test Area

Activities: The ESOTA is designed to accommodate large-scale energy storage systems, especially hydrogen compression, storage, and delivery. This area includes a 700-bar hydrogen dispensing station. Trenching to handle electrical conduit and gas tubing has been coordinated for underground connectivity of the area back to the ESIL area.

Principal Hazards:

- Fire/Explosion: Compressor failure and overpressure/explosion of line components.
- Physical: High pressure gases.

3.2.3.4 Laboratory Support Areas Hazard Summary

3.2.3.4.1 Hazardous Waste Room (C333)

This room serves as a temporary staging of hazardous wastes. Basic laboratory packing of hazardous waste including strong acids/bases, alcohols, heavy metal solutions, and oil wastes without combination is anticipated.

Principal Hazards:

- Fire/Explosion: Flammable materials
- Chemical: Corrosives, toxics
- Physical: Material handling.

3.2.3.4.2 Loading/Receiving Room (C216)

The room serves as the central receiving area for the entire ESIF with the exception of chemical deliveries, which will be delivered directly to the Level 3 laboratories.

Principal Hazards:

- Physical: Material handling hazards. Falls from heights depending on rack configuration.
- Routine dock hazards.

3.2.3.4.3 Machine Shop (C215)

The machine shop is a standard light-duty machine shop and includes lathes, drill presses, saws, welding gear, etc.

Principal Hazards*:*

- Fire: Ignition sources, welding/cutting equipment. Combustible shavings, oils.
- Chemical: Metal and metal oxide fumes. Oils, solvents.
- Physical: Machine hazards, material handling.

3.2.3.4.4 General Building Electrical and Telecommunications Rooms

The general building electrical and telecommunications rooms house standard building systems.

Principal Hazards*:* Standard hazards.

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3.3 Special Systems Hazard Summary

3.3.1 House Hydrogen Supply

Generation and distribution of pure hydrogen to all Level 3 laboratories are provided, with the exception of the Thermal Materials laboratories and the ESL. Hydrogen is generated using one or more onsite electrolyzers located in the ESIL. Oxygen produced during electrolysis is directly vented. The distribution lines are ¼-inch to a ½-inch manifold for storage. The hydrogen will be stored at 450 psig (electrolyzer operating pressure), regulated down, and provided for general use (200 psi). Fuel lines to the compressors are ¼ inch. The outdoor test pad is designed to house compression and storage equipment to 400 bar and 750 bar for supplying the vehicle dispensing pad and high pressure test cells. General distribution to laboratories is through ¼-inch supply lines. The design includes double block and bleed valves, pressure relief devices, multiple stage regulation, excess flow valves, hydrogen detection and automatic valves, emergency power off (EPO) shut-down systems, and 316 stainless steel tubing.

Principal Hazards:

- Fire/Explosion. Release of gaseous hydrogen and confinement pose deflagration and detonation hazards.

3.3.2 Research Electrical Distribution Bus

3.3.2.1 Overview

The REDB is the heart of the ESIF electrical system testing capability, facilitating power flow between fixed equipment, as well as DUTs located throughout the high bay testing laboratories. The REDB includes AC and DC buses and related switchgear, and has been designed to maximize flexibility while minimizing the associated risks. Each REDB consists of a centralized ring-bus, called the Racetrack, to which are connected feeders, called laterals, to each of the individual laboratories. Electrically operated switches are used to control connection of each lateral to the Racetrack, as well as to isolate portions of the Racetrack, thus allowing multiple experiments to be performed simultaneously on the same bus. There may also be additional non-automated devices such as circuit breakers, disconnect switches, and fuses located where the laterals terminate in each of the individual laboratories.

3.3.2.2 Specifications

The system is designed for four AC and four DC buses. Table 5 summarizes the current and planned capabilities. The AC buses are four-wire and rated 600 V between any two poles and at 16-2/3 – 400 Hz. The buses, or isolated portions thereof, may be operated with any of the four poles grounded. Two of the buses are rated at 250 A, one at 1,600 A, and one at 2,500 A. In addition to the actual switchgear bussing, the AC REDB systems also include cabling, busway, molded case switches, and low-voltage power switches (LVPSs) as core components with additional components that may include circuit breakers, disconnect switches, and fuses located where the laterals terminate in each of the individual laboratories. The components may be subject to de-rating at operation with continuous loads (3 hours or greater) and at operation at other than 50/60 Hz. The overall system rating under these conditions will be dictated by the component with the largest de-rate. Table 5 shows the overall de-rating that must be applied to the Day One-supplied AC REDB System. This table is provides the overall rating of the REDB core components only. The devices located at the lateral terminations are typically not rated to the full bus ampacity.

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The DC buses are three-wire and rated at 500 V between the positive or negative pole and common and 1,000 V between the positive and negative poles. However, the DC REDB switchgear, as installed, is not rated for make/break operation (i.e., closing in the presence of applied voltage, or opening while carrying current) at voltages greater than 250 V. Therefore, the switches must only be opened or closed under dead bus conditions.

The DC buses, or isolated portions thereof, may be operated with any of the three poles grounded. In addition, although the poles are labeled as positive, negative, and common and all measurements assume this as the positive reference polarity, the DC buses and related switchgear are not polarity sensitive—i.e., it is possible to apply a voltage that is negative with respect to assigned reference polarity. Regardless, the potential difference between any two poles may not exceed the above-mentioned specifications. Two of the DC buses are rated at 250 A, one at 1,600 A, and one at 2,500 A. In addition to the actual switchgear bussing, the DC REDB systems also include cabling, busway, molded case switches, and LVPSs as core components with additional components that may include fuses located where the laterals terminate in each of the individual laboratories. The components may be subject to de-rating at operation with continuous loads (3 hours or greater). The overall system rating under these conditions will be dictated by the component with the largest de-rate. Table 5 shows the overall de-rating that must be applied to the Day One-supplied DC REDB System. This table provides the overall rating of the REDB core components only. The devices located at the lateral terminations are typically not rated to the full bus ampacity.

Table 5. REDB Current Ratings

REDB	Bus	Voltage	Frequency [Hz]	Current rating for non-continuous loads (< 3 hours)				Current rating for continuous loads (≥3 hours)			
				DC rating [A]	50/60 Hz rating [A]	$16^2/_3$ Hz rating [A]	400 Hz rating [A]	DC rating [A]	50/60 Hz rating [A]	$16^2/_3$ Hz rating [A]	400 Hz rating [A]
AC	250-A	600 V_{rms}	$16^2/_3$ – 400	NA	250	250	200	NA	200	200	160
	1600 A	600 V_{rms}	$16^2/_3$ – 400		1,600	1,600	1,000		1,600	1,600	1,000
	2500 A	600 V_{rms}	$16^2/_3$ – 400		2,500	2,500	1,600		2,500	2,500	1,600
DC	250-A	1,000 V_{dc}	NA	250	NA			200	NA		
	1,600 A	1,000 V_{dc}		1,600				1,600			
	2,500 A	1,000 V_{dc}		2,500				2,500			

V_{rms} = root mean square voltage

3.3.2.3 Architecture

The Racetrack and related switchgear are almost entirely housed inside switchboard enclosures in the AC and DC REDB Research Electrical Equipment Rooms and are physically divided into

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switchboard sections for each physical laboratory or OTA, as well as sections for the grid simulator equipment (GSE), load bank equipment (LBE), and future photovoltaic equipment (PVE). The GSE, LBE, and PVE, although not physical laboratories, are treated as unique laboratories from an electrical architecture point of view. Each laboratory has two laterals connecting to the Racetrack. Each switchboard laboratory section consists of five electrically operated switches, two located on the ring-bus proper, used to isolate experiments, and three located in a "ladder rung" attached to the ring-bus, used to connect the individual laterals to the Racetrack and to lock out individual laterals from the Racetrack. The utility connection (UC) to the AC REDB is also treated like a unique laboratory from an electrical architecture point of view. However, there is only one lateral connecting the utility to the Racetrack and there are no ladder rung switches. Instead, connection of the utility to the Racetrack is controlled via one dedicated ring-bus switch and the neighboring ring-bus switch belonging to another switchboard section. The UC switchboard section includes just the one dedicated ring-bus switch.

In addition to the switchboard laboratory sections, the REDB Racetrack also includes sections of conductor to complete the circle on the ring-bus. These are called ring-ties and consist of cabling routed within the switchboard enclosures for the 250-A buses, and busway located above the switchboard enclosures for the 1,600-A and 2,500-A buses. The one-line diagrams for each of the eight REDB Racetracks are shown in ESIF Drawing Sheets E-604 through E-611. The one-line diagram of 250-A AC REDB #1 is reproduced in Figure 6 with the ring-ties and the PSIL and UC switchboard sections and laterals highlighted.

One-line diagrams, such as the one shown in Figure 6, for lateral terminations to all laboratories are shown in ESIF Drawing Sheets E-612 through E-622. The laterals for the GSE, LBE, and future PVE laboratories terminate directly to their respective RCD. The laterals for each physical laboratory/OTA provide connectivity for additional fixed equipment or for EUT through either a section of lateral busway or a lateral connection board (distribution switchboard). Busways are provided in the PSIL, ESL, and SPL and will also be provided for the future OCL connections. Lateral connection boards are provided in the MVOTA, LVOTA, ESIL, ECL, and FCDTL and will also be provided for the future RTA connections. Conductors may be connected to lateral busway using cable tap boxes or, for AC connections only, bus plugs. The bus plugs will include either an integral circuit breaker or fused disconnect and can only be used on the AC busway at amperages less than or equal to 600 A. For AC connections greater than 600 A, cable tap boxes allowing direct lugging to the busway are used. Cable tap boxes are also used for all connections to the DC busway. The DC cable tap boxes are provided with cam lock connectors rated for the busway's maximum ampacity to facilitate connections. Conductors may be connected into lateral connection boards by direct lugging, fuse, circuit breaker, or fused disconnect. Only direct and fuse-only connections are allowed for DC connection boards. Where protective devices are present, they allow the use of conductors rated below the full bus ampacity to connect equipment to the lateral. In cases where there is no protective device at the lateral connection, a conductor rated at the full ampacity of the respective bus must be used unless the tap rule (National Electric Code [NEC] 240.21(B)) can be invoked. The protective devices located at the lateral terminations may also be used to increase the maximum allowable fault current contribution for a specific experiment setup. Refer to section 3.3.2.4 on fault current ratings and protection for additional information.

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Regardless of whether the lateral connection includes protection or not, all equipment (whether fixed equipment [FE], DUT, or the UC) must connect to the laterals through an RCD. The RCD must include electrically operated switches that have make/break capability (i.e., are capable of closing with voltage applied or opening under load) over all expected voltage, current, and frequency ranges, and must be capable of being opened by command from the REDB Master PLCs under overload or emergency conditions. The RCD must also include local overload protection and, for equipment capable of contributing significant fault current, must include short-circuit protection. There may be experiments for which the RCD requirements can be relaxed, but these will need to be evaluated on a case-by-case basis.

The RCDs for FE are the AC and DC FESBs. The AC and DC FESBs allow the FE to connect to any one of the AC and DC buses, respectively, and include hardwired interlocks to prevent the FE from being placed on more than one bus at the same time. Depending on the nature of the FE, the FESB may use an electrically operated circuit breaker, or electrically operated switch or contactor with overcurrent trip by local controller, and may or may not include fuses. The protective limits must be based on the ampacity of the FE or the ampacity of the REDB being connected to, whichever is lower. Examples of FESBs included on Day One are the GSE, MVOTA, LBE, and AV-900 FESBs. These FESBs all rely on compact real-time embedded industrial (cRIO) controllers with MODBUS over transmission control protocol/internet protocol capability to respond to open/close commands from the REDB Master PLCs.

The RCD for the UC is the AC REDB Service Entrance Switchboard, Alternating Current Research Bus–Main Distribution Switch Board (ACRB-MDSB). The ACRB-MDSB uses electrically operated circuit breakers that are interlocked to prevent the UC from being placed on more than one bus at a time. The ACRB-MDSB breakers are controlled by the AC REDB Master PLC via PLC Remote input/output (IO) located within the ACRB-MDSB switchboard.

Finally, the RCDs for DUTs can consist of any equipment that meets the switching and protection requirement described above and includes additional provisions to identify the DUT location on the REDB bus. Depending on the nature of the DUT, the RCD may use an electrically operated circuit breaker or electrically operated switch or contactor with trip by external controller, and may or may not include fuses. The protective limits must be based on the ampacity of the DUT or the ampacity of the REDB bus being connected to, whichever is lower. Examples of DUT RCDs included on Day One are the 250-A AC and 250-A DC DAQ carts. These devices rely on cRIO controllers with MODBUS over transmission control protocol/internet protocol capability to respond to open/close commands from the REDB Master PLCs and to implement a “ping test” to identify location on the REDB. During the ping test, the DAQ cart applies 24 volts direct current (V_{dc}) onto the REDB lateral to allow the REDB SCADA Server to verify location via voltage transducers located at the ladder rung switches.

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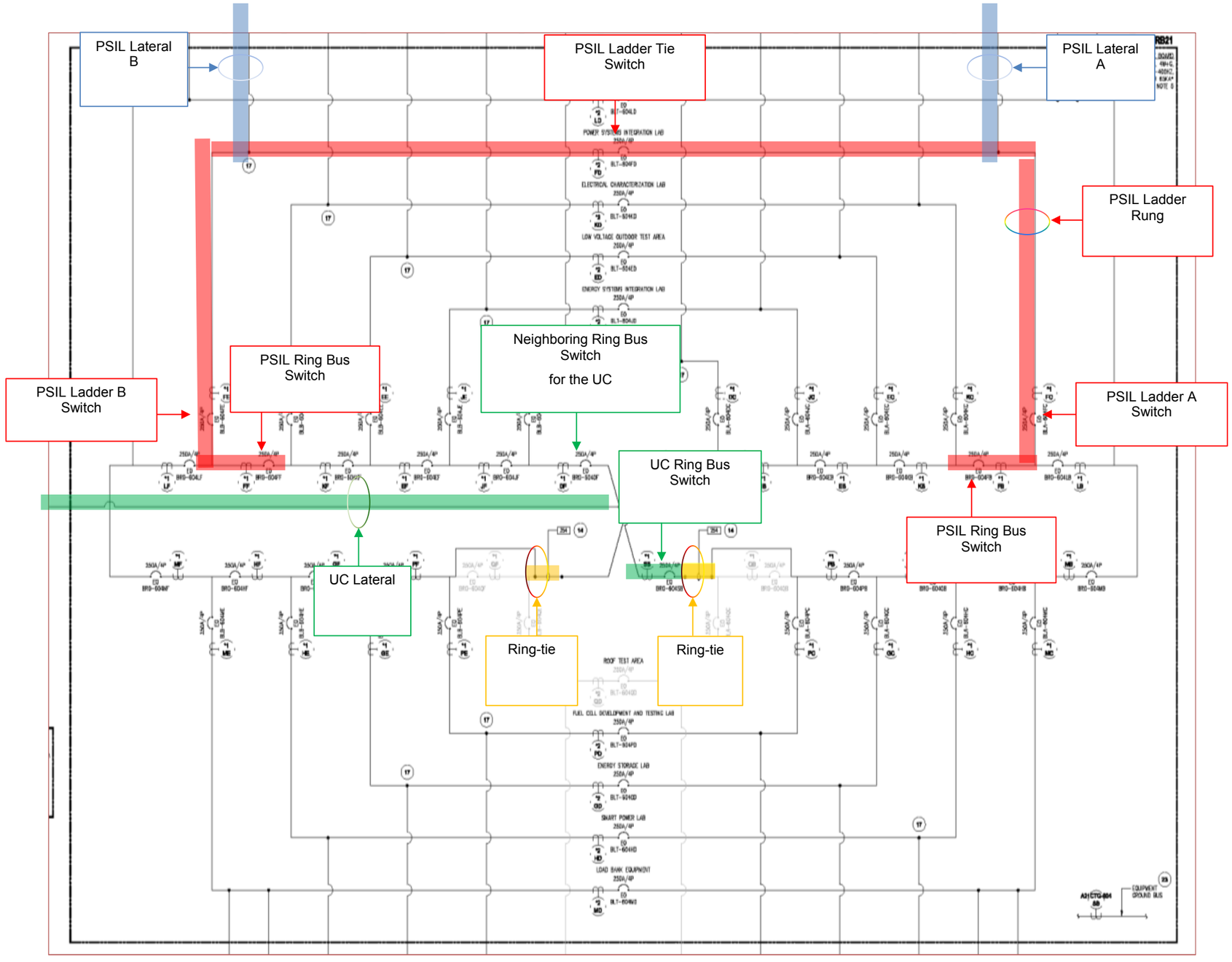

Figure 6. 250-A AC REDB #1 one-line diagram with ring-ties and PSIL and UC switchboard sections highlighted

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3.3.2.3.1 Day One Configuration

As of Day One (March 2013), installation of the following REDB laboratory sections was complete:

ECL	Electrical Characterization Laboratory
ESIL	Energy Systems Integration Laboratory
ESL	Energy Storage Laboratory
FCDTL	Fuel Cell Development and Testing Laboratory
GSE	Grid Simulator Equipment (AC REDB only)
LBE	Load Bank Equipment
LVOTA	Low Voltage Outdoor Test Area
MVOTA	Medium Voltage Outdoor Test Area
PSIL	Power Systems Integration Laboratory
PVE	Photovoltaic Equipment (DC REDB only)
SPL	Smart Power Laboratory
UC	Utility Connection (AC REDB only)

In addition, design but not installation of the following REDB laboratory sections is complete:

OCL	Optical Characterization Laboratory
RTA	Rooftop Test Area

Table 6 provides the Day One lateral schedule for each of the laboratories/OTAs/FE listed above. The table indicates which laterals are fully installed and what physical provisions have been installed for future laterals.

3.3.2.3.1.1 Switchgear

The Racetrack switching devices are circuit breakers without integral trip function; therefore, they are referred to as switches. The AC REDB switches are four-pole, with one pole per phase and a full-rated neutral pole. The DC REDB switches are three-pole, with one pole each for the positive, negative, and common bus. All 250-A buses use molded case switches, while the 1,600-A and 2,500-A buses use LVPSs. The specific devices and their specifications are listed in Table 7. It should be emphasized that the 0 – 1,000 V_{dc} rating listed in the table for the DC devices reflects the *static* capability of the switches only, i.e., the voltage to which the switches may be exposed when either already open or already closed. As previously noted, the DC switches are not rated for make/break operation over this voltage range and must therefore only be opened or closed under dead-bus conditions. The AC devices are make/break rated over the voltage and frequency ranges specified; however, the devices must be de-rated for operation at frequencies greater than 60 Hz. In addition, Table 7 shows manufacturer-provided de-rating for operation at 400 Hz, as well as the required de-rate for continuous-load (≥3 hours) operation of molded case switches.

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Table 6. REDB Day One Lateral Schedule

	AC								DC								REDB Lateral Connnection Type in Lab	Remarks
	250A		250A		1600A		2500A		250A		250A		1600A		2500A			
	A Lateral	B Lateral	A Lateral	B Lateral	A Lateral	B Lateral	A Lateral	B Lateral	A Lateral	B Lateral	A Lateral	B Lateral	A Lateral	B Lateral	A Lateral	B Lateral		
POWER SYSTEMS INTEGRATION LAB (PSIL)	FULL	C&BS	CO	CO	FULL	B&BS	BO	BO	FULL	C&BS	CO	CO	FULL	B&BS	BO	BO	Plug-in Busway	
ENERGY STORAGE LAB (ESL)	FULL	C&BS	CO	CO	FULL	B&BS	BO	BO	FULL	C&BS	CO	CO	FULL	B&BS	BO	BO	Plug-in Busway	
LOW VOLTAGE OUTDOOR TEST AREA (LVOTA)	FULL	C&BS	CO	CO	FULL	C&BS	CO	CO	FULL	C&BS	CO	CO	C&BS	C&BS	CO	CO	Outdoor Rated Panelboard	
MEDIUM VOLTAGE OUTDOOR TEST AREA (MVOTA)	FULL	C&BS	CO	CO	FULL	C&BS	CO	CO	FULL	C&BS	CO	CO	CO	CO	CO	CO	Outdoor Rated Panelboard	
SMART POWER LABORATORY (SPL)	FULL	C&BS	CO	CO	FULL	B&BS	NC	NC	FULL	C&BS	CO	CO	FULL	B&BS	NC	NC	Plug-in Busway	
ELECTRICAL CHARACTERIZATION LAB (ECL)	FULL	C&BS	BO	BO	FULL	C&BS	NC	NC	FULL	C&BS	BO	BO	CO	CO	BO	BO	Panelboard located outside of Class I Div II Space	
ENERGY SYSTEMS INTEGRATION LAB (ESIL)	FULL	C&BS	NC	NC	FULL	C&BS	NC	NC	FULL	C&BS	CO	CO	CO	CO	CO	CO	Panelboard located outside of Class I Div II Space	
ROOF TEST AREA (RTA)	BO	BO	BO	BO	BO	BO	NC	NC	BO	BO	BO	BO	BO	BO	NC	NC	Outdoor Rated Panelboard	
OPTICAL CHARACTERIZATION LAB (OCL)	NC	NC	NC	NC	NC	NC	NC	NC	BO	BO	BO	BO	BO	BO	BO	BO	Future Plug-in Busway	
FUEL CELL DEVELOPMENT AND TESTING LAB (FCD&T)	FULL	C&BS	NC	NC	NC	NC	NC	NC	FULL	C&BS	NC	NC	NC	NC	NC	NC	Panelboard located outside of Class I Div II Space	
GRID SIMULATOR EQUIPMENT (GSE)	FULL	FULL	BO	BO	FULL	FULL	BO	BO	NC	NC	NC	NC	NC	NC	NC	NC	Plug-in Busway	Busway routed through AC REDB room to pick up 4 Grid Simulator FESB
LOAD BANK EQUIPMENT (LBE)	FULL	FULL	BO	BO	FULL	FULL	BO	BO	NC	NC	NC	NC	NC	NC	NC	NC	Plug-in Busway	Busway routed through AC REDB room to pick up 4 Load Bank FESB
PHOTO VOLTAIC EQUIPMENT (PVE)	NC	NC	NC	NC	NC	NC	NC	NC	BS	BS	BO	BO	BS	BS	NC	NC	TBD	
XCEL UTILITY GRID CONNECTION (GRID)	FULL		BO		FULL		BO		NC		NC		NC		NC		N/A	

KEY:	
COMPLETE CONNECTION WITH REDB SWITCHBOARD CONFIGURED WITH CORRESPONDING BREAKERS. LATERAL PANELBOARD OR PLUG-IN BUSWAY FULLY INSTALLED.	FULL
EMPTY CONDUIT AND REDB SWITCHBOARD CONFIGURED WITH CORRESPONDING BREAKERS FOR FUTURE LAB CONNECTION. NO CONDUCTORS, LATERAL PANELBOARD OR LATERAL PLUG-IN BUSWAY PROVIDED.	C&BS
REDB SWITCHBOARD CONFIGURED WITH CORRESPONDING BREAKERS FOR FUTURE LAB CONNECTION. NO LATERAL PANELBOARD OR LATERAL PLUG-IN BUSWAY PROVIDED. FUTURE CONNECTION FROM REDB SWITCHBOARD TO LAB IS FUTURE BUSWAY. NO CONDUIT PROVIDED.	B&BS
REDB SWITCHBOARD CONFIGURED WITH CORRESPONDING BREAKERS FOR FUTURE LAB CONNECTION. NO LATERAL PANELBOARD OR LATERAL PLUG-IN BUSWAY PROVIDED. FUTURE CONNECTION FROM REDB SWITCHBOARD TO LAB IS FUTURE BUSWAY OR CONDUIT. NO BUSWAY OR CONDUIT PROVIDED.	BS
EMPTY CONDUIT ONLY. NO EQUIPMENT OR CONDUCTORS. FLOOR AND LAB SPACE RESERVED FOR FUTURE REDB SWITCHBOARD AND LATERAL PANELBOARD OR BUSWAY.	CO
NO EQUIPMENT OR CONDUCTORS. FLOOR AND LAB SPACE RESERVED FOR FUTURE REDB SWITCHBOARD AND LATERAL PANELBOARD OR BUSWAY. FUTURE CONNECTION FROM REDB SWITCHBOARD TO LAB IS FUTURE BUSWAY OR CONDUIT. NO BUSWAY OR CONDUIT PROVIDED.	BO
NO CONNECTION, NO CONDUIT ROUGH-IN, NO PROVISIONS FOR FUTURE CONNECTION	NC
NOT APPLICABLE	N/A

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Table 7. REDB Racetrack Switches

REDB	Bus	Device	Type	Voltage Rating	Continuous Load Rating	Frequency Rating [Hz]	$16^2/_3$ Hz Current Rating	400 Hz Current Rating
AC	250-A	GE Record Plus 400 AF	MCS	600 V_{rms}	80%	$16^2/_3$ – 400	100%	80%
	1,600 A	GE Entelliguard 1600 AF	LVPS	600 V_{rms}	100%	$16^2/_3$ – 400	100%	80%
	2,500 A	GE Entelliguard 2500 AF	LVPS	600 V_{rms}	100%	$16^2/_3$ – 400	100%	80%
DC	250-A	GE Record Plus 250-AF	MCS	1,000 V_{dc}	80%	NA		
	1,600 A	GE Entelliguard 1600 AF	LVPS	1,000 V_{dc}	100%			
	2,500 A	GE Entelliguard 2500 AF	LVPS	1,000 V_{dc}	100%			

MCS = molded case switch

In addition to the Racetrack switches, the REDB systems also include additional devices where the laterals terminate in each of the individual laboratories. For a plug-in busway, these include circuit breaker and fused disconnect type bus plugs. For lateral panel boards, these include fuses for the DC REDB and circuit breakers and fused disconnects for the AC REDB.

Finally, because the Racetrack switches do not provide either short-circuit or overload protection, short-circuit and overload protection must in general be supplied by RCDs connecting each piece of equipment to the REDB, with monitoring for overload of the overall system provided by the REDB Control System. Depending on the nature of the equipment, the RCDs may use electrically operated circuit breakers, or electrically operated switches or contactors with trip by local controller, and may or may not include fuses. The switching devices and protection mechanisms for the Day One supplied FESBs, ACRB-MDSB, and DAQ Carts are shown in Table 8. Table 9 lists the relevant continuous-load and frequency dependent de-rates for each of these RCDs.

A detailed description of each RCD can be found in the *ESIF Operations and Maintenance Manual*. The GSE, MVOTA, LBE, and AV-900 FESBs are detailed in the following submittals: *ESIF_FESB-ACRB_ Grid Simulator 8, 9, 10, 11 REDB.FD.014*; *ESIF_FESB-ACRB_MVOTA 1 and 2 REDB.FD.014*; *ESIF_FESB ACRB Load Banks 3, 4, 5, 6 REDB.FD.014*; and *ESIF_FESB-DCRB_AV900 1, 3 REDB.FD.014*. The ACRB-MDSB is detailed in the Submittal *ESIF_MDSB-ACRB 4000A Utility Board*. The 250-A AC and 250-A DC DAQ carts are detailed in ESIF Drawing Sheets DP-860-100 through 170.2 and DP-870-100 through 170.2. The DAQ cart ping test is described in detail for the AC and DC DAQ carts in ESIF Drawing Sheets DP-860-132

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and DP-870-132, respectively. Additional DAQ cart details are provided in Submittals *ESIF_DAQ CARTS_250AC REDB.FD.012* and *ESIF_DAQ CARTS_250DC REDB.FD.012*.

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Table 8. Day One Supplied RCDs

RCD	Equipment	REDB	Bus	Switching Device	Long-time Trip (Overload Protection)	Short-time Trip	Instantaneous Trip (Short-Circuit Protection)	Voltage Rating	Frequency Rating [Hz]
FESB	Grid Simulator	AC	250 A	400AF/250AT MCCB	CB electronic trip Trip by cRIO[a]	CB electronic trip[b]	CB electronic trip[b]	600 V_{rms}	$16^2/_3$ - 400
			1,600 A	800AF LVPS	Trip by cRIO	NA	NA		
			2,500 A	800AF LVPS					
FESB	MVOTA	AC	250 A	400AF/250AT MCCB	CB electronic trip	CB electronic trip	CB electronic trip	600 V_{rms}	50/60
			1,600 A	1600AF/1,600AT LVPB					
			2,500 A	1600AF/1,600AT LVPB					
FESB	Load Bank	AC	250 A	400AF/250AT MCCB	CB electronic trip Trip by cRIO[c]	CB electronic trip	CB electronic trip	600 V_{rms}	$16^2/_3$ - 400
			1,600 A	800AF LVPS	Trip by cRIO	NA	NA		
			2,500 A	800AF LVPS					
FESB	AV-900	DC	250 A	400 A Contactor	Trip by cRIO	NA	NA	1,000 V_{dc}	NA
			1,600 A	1,500 A Contactor					
			1,600 A	1,500 A Contactor					

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RCD	Equipment	REDB	Bus	Switching Device	Long-time Trip (Overload Protection)	Short-time Trip	Instantaneous Trip (Short-Circuit Protection)	Voltage Rating	Frequency Rating [Hz]
ACRB-MDSB	Utility Connection	AC	250 A	400AF/250AT MCCB	CB electronic trip	CB electronic trip	CB electronic trip	600 V_{rms}	50/60
			1,600 A	1600AF/1600AT LVPB					
			2,500 A	2500AF/2500AT LVPB					
250A AC DAQ Cart	250A AC DUT	AC	250 A	400AF/250AT MCCB	CB electronic trip Trip by cRIO[a]	CB electronic trip Trip by cRIO[a]	CB electronic trip Trip by cRIO[a]	600 V_{rms}	$16^2/_3$ - 400
250A DC DAQ Cart	250A DC DUT	DC	250 A	400 A Contactor	Trip by cRIO	None	20 – 315 A fuse	1000 V_{dc}	NA

[a] Two levels of protection provided – circuit breaker internal trip set at maximum rating, or user-adjustable cRIO trip limit.
[b] Because the grid simulator is current-limited to 125% of rated, short-time and instantaneous trip functions are not required. However, the functionality is available by default on the 250-A bus due to use of molded carbonate circuit breakers (MCCBs) as the switching device.
[c] Because the load bank cannot supply fault current, short-time and instantaneous trip functions are not required. However, the functionality is available by default on the 250A bus due to use of MCCBs as the switching device.

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Table 9. Day One Supplied RCDs De-rates

RCD	Equipment	REDB	Bus	Switching Device	Device Type	Voltage Rating	Continuous Load Current Rating[a]	Frequency Rating [Hz]	$16^2/_3$ Hz Current Rating[b]	400 Hz Current Rating[b]
FESB	Grid Simulator	AC	250 A	GE Record Plus 400AF/250AT	MCCB	600 V_{rms}	80%	$16^2/_3$ - 400	100%	80%[c]
			1,600 A	GE Entelliguard 800AF	LVPS		100%		100%	80%
			2,500 A	GE Entelliguard 800AF	LVPS		100%		100%	80%
FESB	MVOTA	AC	250 A	GE Record Plus 400AF/250AT	MCCB	600 V_{rms}	80%	50/60	NA	
			1,600 A	GE Entelliguard 1600AF/1600AT	LVPB		100%			
			2,500 A	GE Entelliguard 1600AF/1600AT	LVPB		100%			
FESB	Load Bank	AC	250 A	GE Record Plus 400AF/250AT	MCCB	600 V_{rms}	80%	$16^2/_3$ - 400	100%	80%[c]
			1,600 A	GE Entelliguard 800AF	LVPS		100%		100%	80%
			2,500 A	GE Entelliguard 800AF	LVPS		100%		100%	80%
FESB	AV-900	DC	250 A	Secheron 400 A	Contactor	1000 V_{dc}	100%	NA		
			1,600 A	Secheron 1500 A	Contactor		100%			
			1,600 A	Secheron 1500 A	Contactor		100%			

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RCD	Equipment	REDB	Bus	Switching Device	Device Type	Voltage Rating	Continuous Load Current Rating[a]	Frequency Rating [Hz]	$16^2/_3$ Hz Current Rating[b]	400 Hz Current Rating[b]
ACRB-MDSB	Utility Connection	AC	250 A	GE Record Plus 400AF/250AT	MCCB	600 V_{rms}	80%	50/60	NA	
			1,600 A	GE Entelliguard 1600AF/1600AT	LVPB		100%			
			2,500 A	GE Entelliguard 2500AF/2500AT	LVPB		100%			
250-A AC DAQ Cart	250A AC DUT	AC	250-A	GE Record Plus 400AF/250AT	MCCB	600 V_{rms}	80%	$16^2/_3$ – 400	100%	80%[c]
250-A DC DAQ Cart	250A DC DUT	DC	250-A	Secheron 400 A	Contactor	1,000 V_{dc}	100%	NA		

[a] For a circuit breaker, the continuous load de-rate applies to the breaker frame rating.

[b] For a circuit breaker, the frequency de-rates apply to the breaker frame rating. The trip settings may need to be adjusted accordingly.

[c] The Record Plus long-time trip setting may need to be adjusted to ensure current does not exceed specified percentage of the frame rating.

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3.3.2.3.2 Control System

The REDB Control System consists of four levels:

1. WonderWare SCADA Server
2. REDB Master PLCs
3. Bus PLCs
4. Racetrack Laboratory Section controls, each of which includes PLC Remote IO and one (for the DC Laboratory Sections) or two (for the AC Laboratory Sections) cRIO controller(s).

Although not part of the Racetrack, RCD Controllers (provided Day One by FESB and DAQ cart cRIOs, and ACRB-MDSB Remote IO) report and respond to the appropriate REDB Master PLC. In addition, the Safety Master PLC also communicates with each of the REDB Master PLCs. The REDB Control System is shown in Figure 7 and described in detail in the Functional Requirement Specification (*CHS10357E_FunctionalRequirementSpecification_r0.15.pdf*) and in the ESIF Drawing Sheets DP-600 and DP-622.

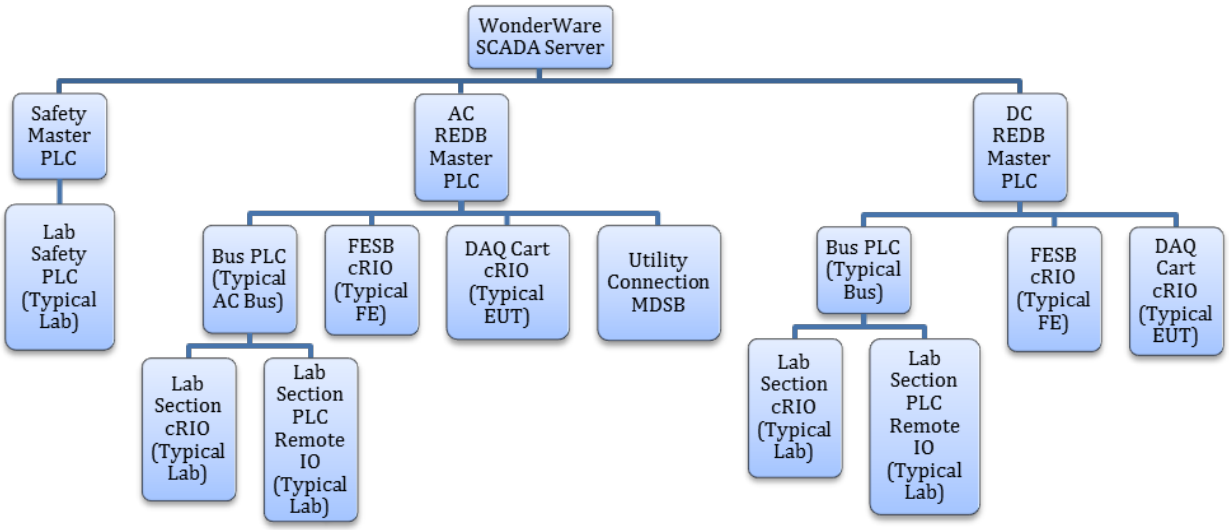

Figure 7. REDB control system

The WonderWare SCADA Server and the Master Safety PLC are located inside the SCADA Closet (C306), the REDB Master PLCs and all the Bus PLCs are located in corridor C223 outside the AC and DC REDB Rooms, and the Lab Section controls (including both PLC Remote IO and cRIO controllers) are located in their respective switchboard sections. The Lab Safety PLCs are located within their respective laboratories; however, the LVOTA and MVOTA Safety PLCs are located in the High Bay House Power Main Electrical Equipment room (C229) adjacent to the AC REDB Room, while the GSE, LBE, and future PVE do not have their own Safety PLCs because they are not physical laboratories. A Safety PLC was not provided for the future RTA laboratory on Day One; however, the SCADA software includes provisions to add a Safety PLC when the RTA laboratory is placed into commission.

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The primary functions of the REDB Control System are to provide an interface to allow researchers to safely configure experiments and to provide critical safety functions: dead bus switching, Racetrack overload protection, and emergency shutdown. It is important to note that all the critical safety functions are implemented entirely at the PLC and cRIO levels and do not require any SCADA Server interaction.

At the highest level, researchers configure experiments using software running on the WonderWare server. The researcher identifies Racetrack switches and desired equipment (both FE and DUT), and sets both RCD and Racetrack switch alarm and trip point settings across the experiment. The server ensures that the experiment is valid with respect to maintaining isolation between experiments. If the experiment is valid, the server grants the researcher ownership of all of the involved Racetrack and RCD switches, as well as the equipment itself.

- Communications between SCADA Server and the REDB Master PLCs

  The SCADA server transmits experiment configuration, including identification of RCDs, RCD alarm/trip point settings, as well as RCD switch open/close requests to the REDB Master PLCs. The SCADA Server receives information back from the REDB Master PLC regarding RCD switch status, RCD diagnostic alarms, and RCD maximum voltage/current root-mean-square values. The SCADA Server also receives information back from the REDB Master PLC regarding REDB room occupancy and door status.

- Communications between SCADA Server and the REDB Bus PLCs

  The SCADA Server transmits experiment configuration, including identification of Racetrack switches and trip point settings, as well as Racetrack switch open/close commands, directly to the Bus PLCs, and receives information back from the Bus PLCs regarding Racetrack switch status, dead bus conditions, and diagnostic alarms.

- Communications between REDB Master PLCs and RCD controllers, plus REDB Master PLC hard-wired signals

  The REDB Master PLCs transmit the RCD trip point settings and RCD switch open/close commands to the RCD controllers: ACRB-MDSB, FESBs, and DUT RCDs such as DAQ carts, and receives information back from these controllers regarding switch status, diagnostic alarms, and maximum voltage/current root-mean-square values. The REDB Master PLCs also receive emergency shutdown command from the Master Safety PLC and experiment overload information from the Bus PLCs. In addition to network communication, the REDB Master PLCs also monitor hard-wired contacts inside the associated REDB room entry panel indicating status of the room entry system, and provide a digital output indicating whether there is a high bay fire alarm to the Room Entry Panel. Finally, the AC REDB Master PLC also includes digital outputs to open the breakers providing house power to the Grid Simulators.

- Communications between REDB Bus PLCs and Lab Section controllers, plus REDB Bus PLC hard-wired signals

  The REDB Bus PLCs transmit Racetrack switch open/close commands to the Remote IO in each laboratory section, and receive information back from the Remote IO regarding

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switch status and status of the hard-wired voltage relays provided as a safety-rated back-up dead bus switching protection (latter included for DC REDB only). The REDB Bus PLCs also receive information from the cRIOs in each laboratory section regarding root-mean-square voltages between each pole and currents through each pole of the switches. The voltages are monitored to ensure dead bus switching. The currents are monitored to provide overload protection for the Racetrack. The cRIOs sample the voltages and currents at 51.2 kHz. The data are decimated by 10, and the decimated data are used to compute root-mean-square quantities based on a fixed 500-ms window. The root-mean-square values are transmitted to the Bus PLCs once every 2 seconds. In addition to network communication, each of the REDB Bus PLCs also provides digital outputs to their associated REDB Room Entry Panel indicating whether all the switches on that bus are open.

3.3.2.3.3 Dead Bus Switching

The Racetrack DC switches as installed, with only one pole per bus, are not rated to allow opening of the switch under load or to allow closing of the switch in the presence of DC voltages greater than 250 V; therefore, dead bus switching must be ensured. Although the Racetrack AC switches are in fact rated for make/break operation over the voltage and frequency range of the AC bus, dead bus switching is similarly required to maintain consistency with operation of the DC REDB and to provide flexibility in future operations. The cRIO-measured root-mean-square voltages are used by the bus PLCs to determine whether the bus is energized. The bus is considered energized if the measured voltages are greater than ~130 – 150 V. The DC laboratory sections include additional Remote IO transmitting the status of voltage relays provided to the control system to create a highly reliable design for dead bus switching. The voltage relays indicate whether the voltage is greater than ~130 – 150 V and are based on a fail-safe design, i.e., loss of control power to the relays themselves will present as a high voltage condition. In addition, the bus PLCs and associated Remote IO used to perform the check and prevent issuance of a command to open/close the switch are a SIL-2 rated system with 99% availability.

3.3.2.3.4 Overload Protection

The use of circuit breakers without integral trip function and the requirement for dead bus switching of the Racetrack switches necessitates that overload protection be provided by other devices. The RCD includes local overload protection to protect the FE or DUT; however, overload protection for the REDB system as a whole is coordinated by the REDB Control System. Specifically, the REDB Bus PLCs use cRIO-measured root-mean-square currents to determine if any experiment is experiencing an overload condition on any section of the bus. The Bus PLCs transmit this information the REDB Master PLC. The REDB Master PLC will then transmit switch open commands to all RCDs connected to the experiment experiencing the overload condition.

3.3.2.3.5 Emergency Shutdown

The Safety PLC System will generate an AC and/or DC REDB EPO upon certain conditions, including operation of an EPO button in any REDB-connected laboratory or OTA, operation of an EPO button in the AC or DC REDB rooms, operation of the “Emergency Break Glass” fire stations located outside the REDB room corridor, or a High Bay fire alarm. The Master Safety PLC will transmit the REDB EPO status to the appropriate REDB Master PLC(s). The REDB

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Master PLC(s) will then transmit switch open commands to all RCDs connected to their respective REDB. This includes all FESBs, DAQ carts and other DUT RCDs, and ACRB-MDSB. In addition, upon an AC REDB EPO, the AC REDB Master PLC will open the breakers providing house power to the Grid Simulators.

3.3.2.4 Fault Current Ratings and Protection

The use of circuit breakers without integral trip function on the AC and DC REDBs requires that fault current protection be provided by other devices, specifically by the RCD connecting the FE, UC, or DUT to the REDB, and/or by any secondary protection located at the lateral busway or connection boards. Furthermore, the wide range of voltages and frequencies for which the REDB was designed, requires that each experiment setup be individually evaluated to determine the maximum allowed level of fault current contribution. For any given experiment setup, the maximum level of fault contribution that can be sustained depends on the experiment voltage and frequency and the ratings of all connected equipment at that voltage and frequency: bus bracing of REDB, short-time withstand of the Racetrack switches, short-time withstand of any other circuit breakers without integral trip function, short-time withstand of any contactors, interrupt rating of any circuit breakers with integral trip function, and interrupt rating of any fuses.

The bus bracing throughout all the AC 250-A, 1,600-A, and 2,500-A systems is designed to withstand 65 kA at 600 V_{rms}, while the bus bracing throughout all the DC 250-A, 1,600-A, and 2,500-A systems is designed to withstand 65 kA at 1,000 V_{dc}. The withstand and interrupt ratings of all the various Day One switches used throughout the REDB, including the Racetrack, lateral busway, and lateral connection board, and RCD devices are listed in ESIF Drawing Sheets E-650 through E-657. Information for the Racetrack switches only is extracted and shown in Table 10.

Table 10. REDB Racetrack Switch Withstand Ratings

REDB	Bus	Device	Type	Voltage	Frequency [Hz]	Withstand	Duration
AC	250 A	GE Record Plus 400 AF	MCS	0 – 600 V_{rms}	16-$^{2}/_{3}$ – 400	5 kA	3 s
	1,600 A	GE Entelliguard 1600 AF	LVPS	0 – 600 V_{rms}	16-$^{2}/_{3}$ – 400	42 kA	3 s
DC	250 A	GE Record Plus 250-AF	MCS	0 – 1,000 V_{dc}	NA	3 kA	3 s
	1,600 A	GE Entelliguard 1600 AF	LVPS	0 – 1,000 V_{dc}		30 kA	½ s

The default maximum supported fault contribution level for any given experiment is the lowest withstand or interrupt rating of all the devices connected to that experiment. However, where available, manufacturer-approved and listed series combinations of overcurrent devices may be used to increase the maximum supported fault contribution beyond the default. The series combinations, and their ratings, are listed in Sheets E-650 through E-657 of the drawing package. For series combinations that have not been explicitly listed and approved by the manufacturer, the maximum supported fault contribution is the value of the lowest withstand or interrupt rating of any device in the combination. In addition, it is important to note that placing

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current-limiting fuses ahead of any molded case switch (MCS) or molded case circuit breaker (MCCB) is not an approved method to obtain a greater fault current level.

Regardless of the overcurrent devices used, including approved series combinations, the bus bracing and/or switch limitations impose absolute maximum fault current levels for each REDB bus as shown in Table 11. In no instance may fault current contribution levels of higher magnitude be placed on the REDB buses.

Table 11. Absolute Maximum REDB Bus Fault Current Levels

REDB	Bus	Frequency [Hz]	Voltage	Absolute Maximum Sustainable Fault Current Contribution
AC	250 A	50/60 Hz	240 V_{rms}	65 kA
			480 V_{rms}	65 kA
			600 V_{rms}	35 kA
		16-2/3 – 400 Hz other than 50/60 Hz	0 – 600 V_{rms}	5 kA
	1,600 A	50/60 Hz	240 V_{rms}	65 kA
			480 V_{rms}	65 kA
			600 V_{rms}	65 kA
		16-2/3 – 400 Hz other than 50/60 Hz	0 – 600 V_{rms}	65 kA
DC	250 A	NA	0 – 1,000 V_{dc}	3 kA
	1,600 A	NA	0 – 1,000 V_{dc}	65 kA

3.3.2.5 REDB Room Entry

Dead bus switching is required to ensure that the Racetrack DC switches, which are not rated for make/break operation, are not opened / closed under load. However, because the hazard associated with make/break operation at significantly high voltages or power levels is High Risk (per NREL Process Hazard Analysis [PrHA] Risk Matrix), access to the DC REDB Room containing the DC Racetrack switchgear is tightly controlled with engineered safety controls. Access to the AC REDB Room is similarly controlled to maintain consistency and to provide flexibility in future operations.

The AC and DC REDB Room Entry wiring is detailed in ESIF Drawing Sheets DP-850-650 through 656 and DP-850-625 through 632, respectively. Entry is controlled by a hard-wired trapped key system and electric door strike locking doors. The AC and DC REDB Room entry panels with trapped keys and status lights are located in the main corridor C223 outside the AC

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and DC REDB Rooms adjacent to the double-door entry to their respective REDB rooms. The REDB room entry systems include the room entry panels, Emergency Break Glass stations near each entry to the corridors, electric door strike locking doors and room status lights at all entry doors, door switches providing status of every door, room EPO buttons inside the room at every door, occupancy sensors distributed throughout each room, and a contactor on the house power panel board providing control power to the respective REDB switchboard enclosures. The room entry panels include relays powered by digital outputs from each of the associated REDB Bus PLCs indicating whether all Racetrack switches on that bus are open as well as a relay powered by a digital output from the associated REDB Master PLC indicating whether there is a high bay fire alarm. In addition, the room entry panel operates relays indicating whether control power has been removed to the associated room switchgear, whether any of the associated room EPO buttons have been pressed or whether either of the two Emergency Break Glass stations has been activated, whether there has been no motion in the associated room for at least 8 to 12 minutes, and the status of all the associated room door switches. The relay contacts are monitored by the associated REDB Master PLC.

The REDB room entry panels include two keys to unlock the associated REDB room doors: a general entry key and a safety override key. Operation of the general entry key requires all breakers on all buses in the associated REDB room to be in the open position, i.e., the key is trapped in the panel until receiving a signal that all breakers are open. If all breakers are open, the key is released, allowing the operator to turn the key. Operation of the key unlocks the doors to the associated REDB room. In addition, operation of the general entry key will open the contactor on the house power panel board providing control power to the respective REDB switchboard enclosures. This will remove all control power inside the switchboard enclosures, including control power to all Racetrack switches, thus preventing automated operation of the switches. For the Racetrack molded case switches, this means no power to the motor operator. For the Racetrack LVPSs, this means no power to the remote close relay as well as the spring charging motors. Manual operation of the molded case switches is prevented a bolted hasp covering the manual operator buttons and/or lever on the motor operator. For the LVPSs, although the spring may be charged, manual operation is prevented by a bolted hasp covering the switch open and close buttons. Note that disconnecting control power to the entire REDB switchgear means that the laboratory section cRIOs and Remote IO will also lose power.

The safety override key does not require the Racetrack switches to be open to operate nor does it remove control power to the switchgear. Therefore, there are no hard-wired controls preventing the switches from being opened or closed. Due the increased risk, access to a REDB room via safety override key will be strictly controlled with administrative safety controls.

In addition to the two entry keys, the room entry systems will also unlock the doors during emergencies. Specifically, if any of the REDB room EPO buttons are pressed, the doors to the associated REDB room will be unlocked regardless of switch position and the contactor providing control power to that room will be opened, thus, preventing any switch from opening or closing. In addition, if either of the two Emergency Break Glass stations is activated or if there is a high bay fire alarm, the doors to both of the REDB rooms will be unlocked regardless of switch position, the contactors providing control power to both rooms will be opened. Furthermore, if any of the REDB Room EPO buttons are pressed, the associated REDB Master PLC will issue an EPO on that REDB, and if either of the two Emergency Break Glass stations is

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activated, both of the REDB Master PLCs will issue EPOs. (Of course, both REDB Master PLCs also issue EPOs during a high bay fire alarm.)

The status lights associated with the REDB rooms essentially indicate whether control power has been removed to the associated REDB switchgear. If the green light is illuminated, control power has been removed. If the red light is illuminated, control power is still present. For the DC REDB room, the green lights are labeled "Access Allowed," and the red lights are labeled "Access Denied." For the AC REDB room, the green lights are labeled "Control Power OFF" and the red lights are labeled "Control Power ON." Note that the red lights will remain illuminated during entry via safety override key, REDB Room EPO, REDB room Emergency Break Glass station, or high bay fire alarm. It is also important to remember that "Access Allowed" or "Control Power OFF" does not indicated dead-bus conditions. The lights merely indicate that the switches are open and cannot be closed. However, the laterals themselves that connect into the REDB switchboard enclosures may be energized.

Table 12 summarizes the actions of each of the REDB room entry mechanisms.

Table 12. REDB Room Entry Mechanisms

Mechanism	Requirements	Removes Control Power to AC REDB Room	Unlocks Doors to AC REDB Room	Removes Control Power to DC REDB Room	Unlocks Doors to DC REDB Room	Causes AC REDB EPO	Causes DC REDB EPO
AC General Entry Key	All AC REDB Racetrack switches open	Yes	Yes	No	No	No	No
AC Safety Override Key	None	No	Yes	No	No	No	No
AC REDB Room EPO button pressed	None	Yes	Yes	No	No	Yes	No
DC General Entry Key	All DC REDB Racetrack switches open	No	No	Yes	Yes	No	No
DC Safety Override Key	None	No	No	No	Yes	No	No
DC REDB Room EPO button pressed	None	No	No	Yes	Yes	No	Yes
Emergency Break Glass Station Activated	None	Yes	Yes	Yes	Yes	Yes	Yes

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Mechanism	Requirements	Removes Control Power to AC REDB Room	Unlocks Doors to AC REDB Room	Removes Control Power to DC REDB Room	Unlocks Doors to DC REDB Room	Causes AC REDB EPO	Causes DC REDB EPO
High Bay Fire Alarm	None	Yes	Yes	Yes	Yes	Yes	Yes

3.3.2.5.1 Lock-out Tag-out

The ladder rung switches used to connect the individual laterals to the Racetrack are also used to lock out those laterals from the Racetrack through hard-wired control connections to the laboratory-specific lockout/tagout (LOTO) panels. The LOTO panels for each physical laboratory or OTA are located inside their respective laboratory or OTA, while the LOTO panels for the GSE, LBE, and future PVE are located in the corridor C223 outside the AC and DC REDB Rooms. The LOTO panels are detailed in the Submittal *ESIF Lock-Out Tag-Out REDB.FD.13_RECORD ONLY*, while wiring to the associated switches is shown in the REDB Switchboard Section Submittals *ESIF_250A AC Switchboard Full Line Up REDB.FD.030*, *ESIF_250A DC Full Line Up_REDB.FD.029*, *ESIF 1600A AC REDB Switchboard Full Line Up*, and *ESIF_1600A DC Switchboard Full Line Up REDB.FD.032*. Although the REDB Bus PLCs monitor whether the switches have been locked out, neither the PLCs nor any other part of the REDB Control System is required for LOTO functionality.

The LOTO panel for each laboratory includes a trapped key and a yellow status light for both the A Lateral and the B Lateral for every AC and DC bus in that laboratory. Each key and light are actually associated with two ladder rung switches: the associated Lateral A or B switch as well as the tie switch used to connect the two laterals (see Figure 6). The key cannot be operated unless both of the switches are open. If both of the switches are open, the associated yellow light will be illuminated and the key can be turned. For the molded case switches, operation of the key disconnects power to the switch motor operators and simultaneously powers the switch shunt trips. Manual operation of the molded case switches is prevented by a bolted hasp covering the manual operator buttons and/or lever on the motor operator. For the LVPSs, operation of the key disconnects power to the switch spring charging motors as well as the remote close relay and simultaneously applies a pulse to the network interlock. Power to the network interlock actuates a physical interlock bar into the breaker close mechanism, physically preventing the breaker from closing. The mechanical interlock bar will not be released until a pulse is applied to the network interlock reset. Operation of the LOTO trapped key also disconnects power to the network interlock reset circuit, preventing the network interlock from being reset. Although the LVPS spring may be charged, manual operation is prevented by a bolted hasp covering the switch open and close buttons.

The UC to the AC REDB is also treated like a unique laboratory from an electrical architecture point of view. However, there is only one lateral connecting the utility to the Racetrack, and there are no ladder rung switches. Instead, connection of the utility to the Racetracks is controlled via one dedicated ring-bus switch and the neighboring ring-bus switch belonging to another switchboard section. To lock out the UC lateral from the Racetrack, personnel must lock out this dedicated ring-bus switch as well as the neighboring laboratory ring-bus switch. Figure 6

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shows the relevant switches for the 250-A AC REDB #1. This must be done on all the AC buses to fully disconnect the UC from the Racetrack. Because these are ring-bus and not ladder-rung switches, the UC does not have a LOTO panel. Instead, the individual switches can be directly locked out using the physical lock out provisions provided on each device. Alternately, the AC REDB room general entry key can be used, as this ensures that *all* of the AC REDB switches are open and cannot be closed.

It is important to note that use of the LOTO panels (or equivalent switches for the UC) disconnects the Racetrack as a source of energy to the laterals. The laterals themselves, which connect into the REDB switchboard enclosures, may still be energized. The complete procedure to de-energize a lateral requires disconnecting all possible sources of energy connected to those laterals, including FESBs, ACRB-MDSB, and/or all equipment connected to the lateral busway and lateral connection boards. Because the laterals originate at the ladder rung switches included inside the Racetrack switchboard enclosures (with the exception of the UC lateral which originates on the Racetrack itself), one implication is that to de-energize any section of the Racetrack switchgear, any lateral entering that section of switchgear must be fully de-energized. Furthermore, that section of the Racetrack must also be isolated from the remainder of the Racetrack. The switchboard labeling on each REDB laboratory section indicates which switches must be locked out to isolate that section. These switches can be directly locked out using the physical lock out provisions provided on each device. Alternately, the respective REDB Room general entry key can be used, as this ensures that *all* of the REDB switches are open and cannot be closed.

Principal Hazards and Controls

The principal hazards and controls associated with operation of the REDB systems are described in Table 13. Specific accident scenarios are described in Section 4.

Table 13. REDB Principal Hazards

Activity	Hazard
Connect/disconnect cabling to a lateral connection	Exposure to arc flash Exposure to arc blast Electric shock
	Fire
	Personnel falling (busway connections only)
	Object falling (busway connections only)
Connect/disconnect cabling to a DUT RCD	Exposure to arc flash Exposure to arc blast Electric shock
	Fire

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Activity	Hazard
Connect/disconnect cabling to a DUT	Exposure to arc flash Exposure to arc blast Electric shock
	Fire
Open/close Racetrack switches via SCADA	Exposure to arc flash Exposure to arc blast Electric shock
	Fire
Energize experiment	Exposure to arc flash Exposure to arc blast Electric shock
	Fire
	Equipment damage

3.4 High Performance Computing/Data Center Hazard Summary

3.4.1 Data Center (B216)

The Data Center provides infrastructure to support advanced energy HPC capability for modeling and simulation needs. This facility also provides a secure data center for sensitive data collected for industry partners.

Principal Hazards:

- Routine office and data center hazards
- The Data Center floor panels open directly to the mechanical room occupying the first floor, presenting an elevated fall exposure should panels be removed. Passive fall protection through the installation of a grid below the floor panels is provided. Additionally, access should be restricted using physical barricades.

3.4.2 Insight Visualization and Collaboration Areas (B308 and B311)

Activities: Provide resources for simulating utility controls and provide visualizations for large power system simulations.

Principal Hazards: Routine office and conference room hazards.

3.4.3 Conference Rooms (B208-B212)

Activities: Provide forum for collaborations and video conferencing.

Principal Hazards: Routine office and conference room hazards.

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3.5 Ventilation and Exhaust Systems

The heating, ventilation, and air conditioning (HVAC) of the ESIF consists of dedicated ventilation and hydronic systems to provide the heating and cooling in the four distinct areas of ESIF: Office, Lobby/Insight Center, laboratories, and Data Center.

The cooling systems for the Office, Lobby/Insight Center, and laboratories are tied into the Primary Cooling Water (PWC) System. The Data Center cooling system is tied into the Energy Recovery Water System, with the exception of the Data Center MAU-DC1, which is tied into the PCW System. The PCW System consists of three cooling towers, two remote basins, two plate and frame heat exchangers, and pumps on either side of the heat exchangers. The plate and frame heat exchanger, HX-604A (standby) and HX-603A (primary) have two systems: hot side and cold side. Heat exchanger HX-604A is a standby heat exchanger for both the PCW System and the Energy Recovery Water System. The cold side consists of cooling towers, CT-601A, B, and C; remote basins, RB-601A and B; and pump P-601A and B. All three cooling towers will operate and have a maximum capacity of 267 tons each (total of 801 tons) and are designed to deliver the entering water temperature of 67°F to the heat exchanger HX-603A. Each remote basin has a capacity of 3,000 gallons of water storage and stores the cooling tower water. From the remote basin, the pump delivers the water to the heat exchanger and circulates the tower water back to the cooling tower. The heat exchanger is designed to have a 2°F rise; the entering water temperature from the cooling tower will provide a 69°F water supply to the hot side. The hot side of the heat exchanger can be considered the PCW System and consists of pumps P-603A and P-603B, cooling coils in MAUs, fan coil units, active chilled beams, and another heat exchanger, HX-603C, which is tied to the Campus Chilled Water System. The Campus Chilled Water System heat exchanger, HX-603C, provides supplemental cooling to the system at a lower supply water temperature of 55°F, known as the Primary Cooling Water Supply–Low Temperature (PCWS-LT). The PCWS-LT is distributed through pumps P-603D and P-603E, which are also tied into all MAU cooling coils, fan coil units, and active beam systems. The PCWS-LT does not tie into air handling units (AHUs) of specialty laboratories; these air-handling units are only tied into the higher Primary Cooling Water Supply temperature of 69°F. Accommodations have been made to allow for future build-out of the tower water system that supports the PCW System.

The Primary Heating Water (PHS) System, which consists of pumps P-605A and P-605B and two heat exchangers, HX-605A and HX-605B, provides all of the heating for the building. There are two heat sources: the Energy Recovery Water System, HX-605A, and the Campus Heating Water System, HX-605B. The Energy Recovery Water System heat exchanger, HX-605A, provides the Primary Heating Water Supply–Low Temperature (PHWS-LT) of 93°F and the Campus Heating Water System heat exchanger, HX-605B, provides the higher PHS Supply temperature of 130°F. After the two heat exchangers, there is a mixing valve that will modulate to increase the PHWS-LT to 95°F. All the heating equipment at building entry points, heating coils of AHUs of specialty laboratories, and heating coils in MAUs for the high bay laboratories, and Data Center are tied into the 130°F PHW Supply. All other heating equipment, such as the heating coils in Office, Lobby/Insight Center and active beam systems in the Office, are tied into the PHWS-LT system.

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3.5.1 Office HVAC

The Office HVAC consists of an AHU that delivers the conditioned ventilation air thru the under-floor air distribution system and an active beam system. The Office AHU, OF1, has a design capacity of 24,000 cubic feet per minute (cfm) (a minimum outside air of 6,500 cfm) and consists of a pre-filter, heating coil, fan section, cooling coil, and a final filter. While the mechanical ventilation provided by AHU-OF1 provides the minimum ventilation of 6,500 cfm at all times, the office space also has supplemental natural ventilation that consists of operable windows at the perimeter, return fans, and a set of relief air louvers at the center of the office space. The active-beam system provides both heating and cooling within the space. The active-beam system consists of pipes that are passed through a "beam" and a transfer fan that supplies air to the beam. The active beams are located along the perimeter and can changeover from heating to cooling and vice versa. The heating for the active beam and heating coil for the AHU-OF1 is tied into the 95°F (PHWS-LT) piping system. The cooling for the active beam and cooling coil for the AHU-OF1 are tied into both the 69°F (PCWS) and 55°F (PCWS-LT) piping system.

3.5.2 Lobby/Insight Center HVAC

The Lobby/Insight Center area houses the main lobby, conference rooms, and the center break room. The Lobby/Insight Center HVAC consists of a makeup air unit that delivers 100% outside conditioned air to fan coil units. The fan coil unit maintains the heating/cooling temperature set points for their respective zones. The Lobby/Insight Center makeup air unit, MAU-OF1, has a design capacity of 12,000 cfm and consists of a pre-filter, heating coil, fan section, cooling coil, and a final filter. The heating for the fan coil units and heating coil for the MAU-OF1 are tied into the 95°F (PHWS-LT) piping system. The cooling for the fan coil units and cooling coil for the MAU-OF1 are tied into both 69°F (PCWS) and 55°F (PCWS-LT) piping systems.

3.5.3 Data Center HVAC

The Data Center HVAC consists of a MAU, AHUs, pumps, heat exchangers, and cooling towers. The Data Center cooling load is met with an air system and a hydronic system. The air system, which consists of the makeup air unit, MAU-DC1, and two AHUs, AHU-DC1 and DC2, meets 10% of the cooling load. The MAU-DC1 has a design capacity of 2,000 cfm and consists of a pre-filter, final filter, heating coil, humidifier section, cooling coil, and a fan section. The heating coil in MAU-DC1 is tied into the 130°F (PHWS) piping system. The cooling coil of MAU-DC1 is tied into both 69°F (PCWS) and 55°F (PCWS-LT) piping systems. MAU-DC1 delivers 100% outside conditioned air to the cold aisle of the Data Center and will allow the Data Center to be positive pressure to the adjacent space. AHU-DC1 and AHU-DC2 have a design capacity of 24,000 cfm and consist of a pre-filter, final filter, cooling coil, and fan section. The cooling coil is tied into the Energy Recovery Water (ERW) System, a different cooling water system than the PCWS. AHU-DC1 and AHU-DC2 re-circulate the air from the hot aisle to the cold aisle. The Data Center has incorporated space for future AHUs, AHU-DC3 through DC15.

The hydronic system, which meets 90% of the cooling load in the Data Center and is similar to the PCWS, consists of four cooling towers, two remote basins, two plate and frame heat exchangers, and pumps on either side of the heat exchangers. The plate and frame heat exchangers, HX-604A (standby) and HX-604B (primary), have two systems—a hot side and a cold side. The cold side consists of cooling towers CT-602A, CT-602B, CT-602C, and

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CT-602D; remote basins RB-602A and RB-602B; and pumps P-602A and P-602B. The configuration is such that three of the cooling towers will operate while one tower remains on standby. Each cooling tower has a maximum capacity of 267 tons (total of 801 tons) and is designed to deliver the entering water temperature of 69°F –71°F to the heat exchanger, HX-604B. Each remote basin has a capacity of 3,000 gallons of water storage and stores the cooling tower water. From the remote basin, the pump delivers the water to the heat exchanger and circulates the tower water back to the cooling tower. The heat exchanger is designed to have a 2°F rise; the entering water temperature from the cooling tower will provide a 71°F–73°F water supply to the hot side. The hot side of the heat exchanger is considered the Energy Recovery Water System and consists of pumps (P-604A and P-604B), water-cooled server racks, AHU-DC1 and 2, cooling coils and another heat exchanger, HX-605A, which is tied to the building primary heating water system. The ERW supply temperature is approximately 71°F–73°F, which provides the cooling for the Data Center water-cooled server racks and the cooling coils for the Data Center AHUs. From the Data Center water-cooled server rack and the cooling coils from the AHU-DC1 and DC2, the ERW return temperature is approximately 95°F, which can go through the heat exchanger, HX-605A, to heat the primary heating water loop to approximately 93°F. Accommodations have been made to allow for future build-out of the tower water system that supports the ERW System.

3.5.4 Laboratory HVAC

The laboratory HVAC consists of two MAUs, three AHUs, fan coil units, and the laboratory exhaust system, which is detailed in Section 3.4.3.6. The High Bay MAUs (MAU-HB1 and MAU-HB2) provide 100% outside conditioned air to all the laboratories, with the exception of three specialty laboratories: C317 – ECL, C328 – Environmental Chamber, and C339 – ESIL. The High Bay MAUs (MAU-HB1 and MAU-HB2) have a design capacity of 42,000 cfm and consist of a pre-filter, final filter, future energy recovery heating coil, heating coil, fan section, direct evaporative cooling section, and a cooling coil. Fan coil units are used within each laboratory to provide supplemental heating or cooling within the laboratory to maintain space temperature. The heating coil for MAU-HB1 and MAU-HB2 are tied into the 130°F (PHWS) piping system. The heating for the fan coil units are tied into the 95°F (PHWS-LT) piping system. The cooling for the fan coil units and cooling coil for the MAU-HB1 and MAU-HB2 are tied into both 69°F (PCWS) and 55°F (PCWS-LT) piping systems.

In each specialty laboratory (C317, C328 and C339), the ventilation is provided by dedicated AHUs (AHU-C317, AHU-C328, and AHU-C339, respectively). The ESIF hazards within the HVAC systems are summarized in Table 14.

Table 14. Hazard Analysis for HVAC Units

Equipment Tag	Preliminary Hazard Type								
	Air/ Water Emissions	Con-fined Space	Electrical	Moving Parts	Temp – Hot/Cold	Pressure High/Low	Noise	Falling	Access
AHU-OF1	X		X	X	X	X	X		
AHU-DC1 and 2	X		X	X	X	X	X		
MAU-OF1	X		X	X	X	X	X		

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Equipment Tag	Preliminary Hazard Type								
	Air/ Water Emissions	Con-fined Space	Electrical	Moving Parts	Temp – Hot/Cold	Pressure High/Low	Noise	Falling	Access
MAU-DC1	X	X	X	X	X	X	X		
MAU-HB1 and 2	X	X	X	X	X	X	X		
AHU-C317	X	X	X	X	X	X	X	X	X
AHU-C339	X	X	X	X	X	X	X	X	X
CT-601A, B, and C		X	X	X	X				
RB-601A and B		X							
P-601A and B			X	X					
P-603A, B, D and E			X	X					
CT-602A, B, C and D		X	X	X	X				
RB-602A and B		X							
P-602A and B			X	X					
P-604A and B			X	X					
P-CHW1 and 2			X	X					
P-HHW1 and 2			X	X					

Hazard controls include machine and electrical guarding, railings, fall protection, warning signage and other standard industrial controls. Administrative controls are implemented through existing NREL safety procedures and work control.

3.5.5 Laboratory Exhaust

Laboratory hoods and ventilated enclosures in the Level 3 laboratories, except the ESL, are exhausted through a dedicated high-efficiency particulate air filter (HEPA) system that is independent of the general laboratory exhaust system. The HEPA system is designed to maximize safety and flexibility associated with nanomaterials. Three exhaust fans with reserve capacity support the HEPA exhaust system. One fan is on standby power. Snorkels are provided in the laboratories for local ventilation of nuisance odors and smoke. All exhaust systems have polyvinyl chloride (PVC)-coated ducting, with the exception of the perchloric acid hood.

The perchloric acid hood is a purpose-manufactured system with acid-resistant cabinet, exhaust ducting, and inductive fan unit. The exhaust system ducting has an integral, automated washdown system.

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The HEPA system has a bag-in/bag-out glove bag system to facilitate removal of HEPA filter assemblies to minimize the possibilities of releases and exposures. Filter change-out procedures are addressed in the operation and maintenance manual for these filters.

3.6 Fire Protection, Detection and Suppression

NREL has performed a detailed fire hazard analysis for the ESIF, which contains greater details on the fire detection and suppression systems. The level of fire protection for the ESIF fulfills the requirements of the best-protected class of industrial risks (Highly Protected Risk or Improved Risk). This includes meeting the applicable building codes and NFPA codes and standards or exceeding them when necessary to meet safety objectives. The applicable codes and standards are those in effect when facility design commences ("code of record").

NREL facilities are designed to incorporate both active and passive fire protection features; reliance has not been placed on only one means to achieve an acceptable level of fire safety. The ESIF provides the necessary fire protection systems and features to achieve "defense-in-depth." The fire protection system consists of heat and smoke detection, alarm, and automatic sprinkler systems installed throughout the building. Much of the smoke detection in the laboratory and data center is an early warning aspirated smoke detection system. Underfloor areas in the offices and the plenum above the HPC/DC drop ceiling are equipped with full area smoke detection. The fire suppression system includes automatic sprinkler protection throughout the facility (note: in-line dampers provide isolation to the HPC/DC plenum, which is not equipped with sprinkler protection). The drop ceiling above the HPC/DC is equipped with in-grid dampers to prevent the potential heat sink of the computer hot aisle containment. Much of the sprinkler protection is wet pipe, with some dry pipe for areas under the office overhangs and a pre-action system for the HPC/DC. A gaseous system was not used for any areas due to asphyxiation risks. Detection and fire protection alarm systems are integrated. A fire pump is installed to ensure adequate standpipe pressure at the most hydraulically remote location. The laboratories are designed for Ordinary Hazard Group 2, with Extra Hazard Group 1 in the H-2 areas; the offices and like areas are Ordinary Hazard Group 1.

A fire access road is provided around most of the facility to provide manual fire-fighting and rescue access to all areas around the building. Because of excessive grades on the eastern leg of the fire access road, the northern part of this road segment is not completely continuous with the southern half; however, West Metro Fire Protection District and the NREL authority having jurisdiction deemed the compensatory hammerheads and length of road segments appropriate and sufficient to support firefighting efforts and emergency access.

Local duct-mounted smoke detectors will close duct smoke dampers in the event of smoke detection. Smoke detectors mounted in AHUs will also deactivate their respective AHUs upon detection of smoke. AHUs will continue to operate upon activation of the building fire alarm system.

The preaction system in the HPC/DC has manual activation stations at all exits from the HPC/DC, which trips the deluge valve and shunts all power in the HPC/DC.

Manual firefighting of wildland fires on the east side of the ESIF is enhanced by the addition of four external hose connection points outside the fire pump room. The hose connection points are

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part of the fire pump header. Most other areas around ESIF are paved to reduce the potential of wildland fire exposure to the ESIF. The hydrogen storage yard consists of a concrete pad with a retaining wall separating it from wildland areas.

The ESIF is equipped with a code-compliant lightning protection system. Surge suppression and protection are provided on laboratory electrical systems. The laboratory area outside the H-2 Occupancy area is identified as a B-Occupancy by IBC (2009). There are four control areas within the B-Occupancy area as delineated in Figure 8. Flammable and toxic gases are stored in sprinklered and ventilated gas cabinets. “Smart” gas cabinets will shut down gas manifolds if an EPO is activated (through manual, gas detection, or high bay fire detection), ventilation is lost, or low gas pressure is detected.

The open-to-all-floors lobby area design relies on multiple code exceptions. It is used as a horizontal egress route; hence, combustible loading must be rigorously controlled. The decorative pine wood in the atrium has a class C flame spread rating; however, non-combustible construction on treated plywood (class A) has been wrapped around the bottom portion of the elevator core and exit enclosure so as to maintain the integrity of the exit and minimize the potential for flame spread up the wall.

Hydrogen distribution systems and pressure regulation stations have been installed on the roof so as to minimize the extent of piping within confined spaces. With this configuration, laboratory ventilation and system detection are sufficient to control any release event in the laboratories and substantially prevent development of flammable concentrations in confined areas.

The ESIL and ECL are equipped with UV/IR cameras to ensure early detection of hydrogen ignition or jet fires and facilitate timely shutdown of systems.

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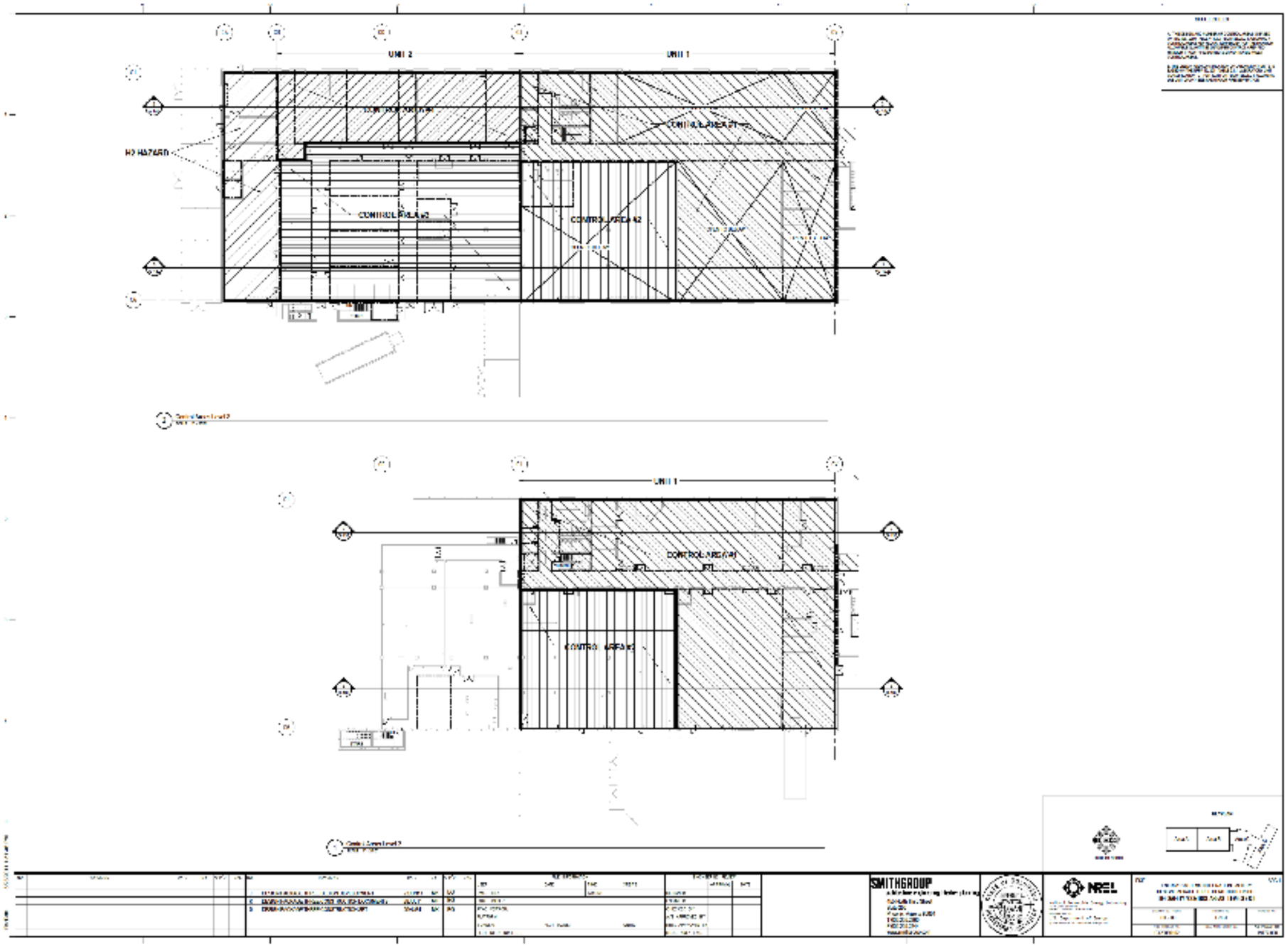

Figure 8. ESIF IBC (2009) control areas from DP-3A Drawing G-131

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3.7 Gas Detection

The ESIF uses a very early warning aspirated smoke detection (VESDA) aspirating sample system for both smoke and gas detection throughout most of the laboratories. Some of the VESDA piping systems are only used for smoke detection, labeled on drawings as "VLP." Systems labeled as "ECO" on drawing sets represent the gas detection modules added to the VESDA system. Each ECO sensor can monitor up to two types of gas.

Air is drawn past the ECO detectors (located immediately outside most laboratories[5]) through a network of air sampling pipes connected to a high-efficiency aspirator. Each pipe inlet on the aspirator unit has an airflow sensor that monitors airflow changes in the pipes. Air is exhausted from the detector and vented back into the protected laboratory.

The gas detectors monitor the room and report to the safety PLC for each laboratory. The local safety PLC directly controls all associated safety functions within the laboratory. The local safety PLC also communicates with the master PLC, which provides sister PLCs with the PLC state information. The gas detection system is equipped with both warning levels and action levels. For warning levels, upon reaching the desired set points as outlined in Table 15 (DP-710-0), an Alert alarm will be generated by the PLC. The alarm will be displayed through the supervisory control and data acquisition (SCADA) system, and the light tree for that laboratory will turn on the yellow light. If the gas concentration continues to rise, then an Action alarm is generated to the SCADA system, and the safety PLC will initiate the defined safety functions, which include sending a request to the BAS to increase ventilation (where applicable), shutting down gas manifolds, closing house header systems, and initiating an alarm in the laboratory (red EPO light, blue gas alarm light, and horn). Qualified staff can address the alarm via the SCADA system and established Alarm Response Desk Procedure. Additionally, if the gas detector requires maintenance as indicated by the onboard electronics of the detector, a trouble signal is generated to the SCADA. The VESDA pumps are connected to the fire alarm system as they provide the air sampling system for the gas detectors and smoke detection. The fire alarm system sends reports to the SCADA system via the BAS, allowing the SCADA system to notify a trouble or failure condition. During trouble alarms, a yellow warning light is activated.

Gas detectors have standby battery backup for 24 hours operation during normal operation, and at least 5 minutes under alarm state. Gas detectors have approximately 2 GB memory for event and data logging. The gas detection system and smoke detection system will be calibrated according to the manufacturers' and NFPA 72 requirements. All drawing sets are on file in Sustainability, Infrastructure Transformation, and Engineering (SITE) Operations.

[5] Except near the H-2 occupancy laboratories.

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Table 15. Initial Gas Detection Set Points

		User Alarm Set Point/Action					System Action Set Point					
Gas	**Labs with Detector**	**User Alarm Set Point (Adjustable)**	**Yellow Light[a]**	**SCADA system Alarm[b]**	**Alarm Set Point**	**EPO**	**Red Light**	**Blue Light**	**Lab Horn**	**Gas Manifold**	**House Hydrogen Block/Bleed Valves**	**SCADA system Alarm[b]**
Hydrogen	ECCL (C329), ESFL (C321), FCDTL (C323), ML (C324), ESSL (C330), MCL (C319), ESIL (C339 and C340), ECL (C317), ESL (C325), TSML (C331), TSPL (C332)	20% LFL	X	X	25% LFL	X	X	X	X	X	X	X
Oxygen	FCDTL (C323), PSIL (C221), ESL (C325)	20% v/v	X	X	19.5% v/v		X		X	X		X
Carbon Monoxide	ECCL (C329), FCDTL (C323), PSIL (C221), ESL (C325)	30 ppm	X	X	200 ppm		X		X	X		X
Ammonia	FCDTL (C323)	25 ppm	X	X	35 ppm		X		X	X		X
Hydrogen Sulfide	FCDTL (C323)	5 ppm	X	X	10 ppm		X		X	X		X
Nitrogen Dioxide	PSIL (C221)	1 ppm	X	X	2 ppm		X		X	X		X

a. Yellow light also is illuminated when a sensor Trouble from the detector's self-diagnostics occurs.
b. SCADA will alert via computer operation stations and log the time/date of event, and user that acknowledges alarm. NOTE: Gas set points based on recommended defaults from Xtralis unless stated otherwise. System action set points are configured in the gas detector.

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CONSULTANTS

PROJECT NAME:
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ENERGY SYSTEM INTEGRATION FACILITY
15301 DENVER WEST BLVD.
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FIRE ALARM SUPPLIER:
FIRE PROTECTION CONCEPTS, INC.
9223 BOOKER LANE
CONIFER, COLORADO 80433
PHONE: 303-679-1679
CONTACT: MARK NEAL

REFERENCES:
2010 NFPA 72
2008 N.E.C.
2009 I.B.C.
2009 I.F.C.
WEST METRO AMENDMENTS

CODE ANALYSIS:
OCCUPANCY: B OFFICE
CONSTRUCTION TYPE: I FULLY SPRINKLERED
SPRINKLERS: YES
NUMBER OF STORIES: 4 STORIES PLUS BASEMENT

ELECTRICAL CONTRACTOR:
ENCORE ELECTRIC INC.
2107 WEST COLLEGE AVE.
PHONE: 303-934-1234

NATIONAL RENEWABLE ENERGY LABORATORY
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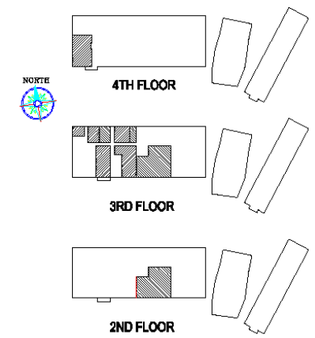
REVISION 0
SCOPE OF WORK:

WE ARE ADDING A NEW VESDA GAS DETECTION SYSTEM TO THE 3RD AND 4TH FLOORS. ALL DETECTORS WILL BE MONITORED TO MAIN FIRE ALARM CONTROL PANEL. ALL MONITOR MODULES WILL BE SUPPLIED BY OTHERS.

REVISION 1

REVISED DRAWINGS PER ENGINEER'S COMMENTS.



KEY PLAN
NOT TO SCALE

WIRING METHODS

NATIONAL ELECTRICAL CODE

ARTICLE 300 WIRING METHODS
GENERAL REQUIREMENTS
300-11. SECURING AND SUPPORTING.
(1) WIRING LOCATED ABOVE A FIRE-RATED FLOOR/CEILING OR ROOF/CEILING ASSEMBLY SHALL NOT BE SECURED TO, OR SUPPORTED BY, THE CEILING ASSEMBLY, INCLUDING THE CEILING SUPPORT WIRES. AN INDEPENDENT MEANS OF SECURE SUPPORT SHALL BE PROVIDED
EXCEPTION: THE CEILING SUPPORT SYSTEM SHALL BE PERMITTED TO SUPPORT WIRING AND EQUIPMENT THAT HAVE BEEN TESTED AS PART OF THE FIRE-RATED ASSEMBLY.
(2) WIRING LOCATED ABOVE A NONFIRE-RATED FLOOR/CEILING OR ROOF/CEILING ASSEMBLY SHALL NOT BE SECURED TO, OR SUPPORTED BY, THE CEILING ASSEMBLY, INCLUDING THE CEILING SUPPORT WIRES. AN INDEPENDENT MEANS OF SECURE SUPPORT SHALL BE PROVIDED
EXCEPTION: THE CEILING SUPPORT SYSTEM SHALL BE PERMITTED TO SUPPORT BRANCH CIRCUIT WIRING AND ASSOCIATED EQUIPMENT WHERE INSTALLED IN ACCORDANCE WITH THE CEILING SYSTEM MANUFACTURER'S INSTRUCTIONS.
CABLES AND RACEWAYS SHALL NOT BE PERMITTED TO BE SUPPORTED BY CEILING GRIDS.
(B) RACEWAYS USED AS MEANS OF SUPPORT. RACEWAYS SHALL NOT BE USED AS A MEANS OF SUPPORT FOR OTHER RACEWAYS, CABLES OR NONELECTRIC EQUIPMENT.
300-14 LENGTH OF FREE CONDUCTORS AT OUTLETS, JUNCTIONS, AND SWITCH POINTS. AT LEAST 6 IN, (152mm) OF FREE CONDUCTOR SHALL BE LEFT AT EACH OUTLET, JUNCTION, AND SWITCH POINT FOR SPLICES OR THE CONNECTION OF FIXTURES OR DEVICES.
EXCEPTION: CONDUCTORS THAT ARE NOT SPLICED OR TERMINATED AT THE OUTLET JUNCTION, OR SWITCH POINT.
300-15 BOXES, CONDUIT BODIES, OR FITTING - WHERE REQUIRED.
(A) BOX OR CONDUIT BODY. A BOX OR CONDUIT BODY COMPLYING WITH SECTIONS 370-16 AND 370-28 SHALL BE INSTALLED AT EACH CONDUCTOR SPLICE CONNECTION POINT, SWITCH POINT, JUNCTION POINT, OR PULL POINT FOR THE CONNECTION OF CONDUIT, ELECTRICAL METALLIC TUBING, SURFACE RACEWAY, OR OTHER RACEWAYS.
EXCEPTION NO. 1: A BOX OR CONDUIT BODY SHALL NOT BE REQUIRED FOR A CONDUCTOR SPLICE CONNECTOR IN SURFACE RACEWAYS, WIREWAYS, HEADER-DUCTS, MULTIOUTLET ASSEMBLIES, AUXILIARY GUTTERS, AND CABLE TRAYS. COVERS OF WIRING METHODS USED FOR THIS PURPOSE SHALL BE REMOVABLE AND ACCESSIBLE AFTER INSTALLATION.
EXCEPTION NO. 2: AS PERMITTED IN SECTION 410-31 WHERE A FIXTURE IS USED AS A RACEWAY.
760-54. INSTALLATION OF CONDUCTORS AND EQUIPMENT.
(A) SEPARATION FROM ELECTRIC LIGHT, POWER, CLASS 1, AND NPLFA CIRCUIT CONDUCTORS.
(3) OTHER APPLICATIONS. POWER-LIMITED FIRE ALARM CIRCUIT CONDUCTORS SHALL BE SEPARATED AT LEAST 2 IN. (50.8mm) FROM CONDUCTORS OF ANY ELECTRIC LIGHT, POWER, CLASS 1, OR NONPOWER-LIMITED FIRE ALARM CIRCUIT CONDUCTORS.
EXCEPTION NO. 1: WHERE EITHER (1) ALL OF THE ELECTRIC LIGHT, POWER CLASS 1, OR NONPOWER-LIMITED FIRE ALARM CIRCUIT CONDUCTORS OR (2) ALL OF THE POWER-LIMITED FIRE ALARM CIRCUIT CONDUCTORS ARE IN RACEWAY OR IN METAL-SHEATHED, METAL-CLAD, NONMETALLIC-SHEATHED, OR TYPE UF CABLES.
EXCEPTION NO. 2: WHERE THE ALL OF THE ELECTRIC LIGHT, POWER, CLASS 1, OR NONPOWER-LIMITED FIRE ALARM CIRCUIT CONDUCTORS ARE PERMANENTLY SEPARATED FROM ALL OF THE POWER-LIMITED FIRE ALARM CIRCUIT CONDUCTORS BY A CONTINUOUS AND FIRMLY FIXED NON-CONDUCTOR, SUCH AS PORCELAIN TUBES OR FLEXIBLE TUBING IN ADDITION TO THE INSULATION ON THE WIRE.

SYSTEM CONDITION	ALARM SIGNAL INDICATOR	ALARM SIGNAL TO VESDA REMOTE ANNUNCIATOR	SUPV. SIGNAL INDICATOR AT (FACP)	TROUBLE SIGNAL INDICATE AT (FACP)	AIR SAMPLING SYSTEM ALRT (SUPERVISORY)	AIR SAMPLING SYSTEM ACTION (TROUBLE)	AIR SAMPLING SYSTEM FIRE (FIRE ALARM 1)	CONTROL FUNCTIONS			
ALL AIR SAMPLING SYSTEM PRE ALARM (0.0125% OBSC.) ALERT			●		●						
ALL AIR SAMPLING SYSTEM PRE ALARM (0.2000% OBSC.) ACTION				●		●					
ALL AIR SAMPLING SYSTEM IN ALARM 1 (1.0000% OBSC.) FIRE 1	●	●					●				
ALL AIR SAMPLING SYSTEM PANEL IN TROUBLE CONDITION				●							

AIR SAMPLING SYSTEM
SEQUENCE OF OPERATION MATRIX

DRAWING DIRECTORY

SHEET NO.	SHEET INFORMATION:
FA-01	GENERAL COVERING SHEET, BILL OF MATERIALS, ELECTRICAL NOTE AND SEQUENCE OF OPERATION
FA-02	3RD FLOOR GAS DETECTION SYSTEM LAYOUT AND NOTES
FA-03	4TH FLOOR GAS DETECTION SYSTEM LAYOUT AND NOTES
FA-04	GAS DETECTION SYSTEM ISOMETRIC DETAILS
FA-05	GAS DETECTION SYSTEM ISOMETRIC DETAILS
FA-06	GAS DETECTION SYSTEM ISOMETRIC DETAILS
FA-07	GAS DETECTION MOUNTING DETAILS AND NOTES
FA-08	GAS DETECTION MOUNTING DETAILS AND NOTES
FA-09	GAS DETECTION WIRING DIAGRAMS AND BATTERY CALCULATIONS
FA-10	ONE LINE DIAGRAM AND WIRING LEGEND

BILL OF MATERIAL

SYMBOL	EXISTING	NEW	TOTAL	PART NUMBER	DESCRIPTION	COMMENTS
	0	5	5	VLC-500	VESDA DETECTOR	VESDA
	0	5	5	VPS-300US-120	VESDA POWER SUPPLY	VESDA
PS	0	5	5	VLP-002	VESDA DETECTOR	VESDA
	0	5	5	VPS-300US-120	VESDA POWER SUPPLY	VESDA
H2 EX	0	7	7	ECO-D-B-14-EX	H2 EX ECO GAS DETECTOR	VESDA
H2	0	10	10	ECO-D-B-14	H2 ECO GAS DETECTOR	VESDA
H2S	0	1	1	ECO-D-B-43	H2S ECO GAS DETECTOR	VESDA
NH3	0	1	1	ECO-D-B-42	NH3 ECO GAS DETECTOR	VESDA
NO2	0	1	1	ECO-D-B-45	NO2 ECO GAS DETECTOR	VESDA
CO/IO2	0	3	3	ECO-D-B-31-41	CO/IO2 ECO GAS DETECTOR	VESDA
CO	0	1	1	ECO-D-B-41	CO ECO GAS DETECTOR	VESDA

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NO.	DATE	BY	PER	REVISION
0	12-15-11	E.C.	M.N.	RELEASED FOR APPROVAL.
1	01-3-12	E.C.	M.N.	REVISED DRAWINGS PER ENG. COMMENTS

COVER SHEET
GENERAL
INFORMATION

ENG'G DPT: E.C. ENG'G DPT: M.N.
SCALE: NOTED
ENG: BILL BRUINER
ENG. REV.: X
PHONE NO.: 303-588-2686
FA-1
DATE: 12-15-11 SHEET: 1 OF 10

Figure 9. Gas detection drawing, general information

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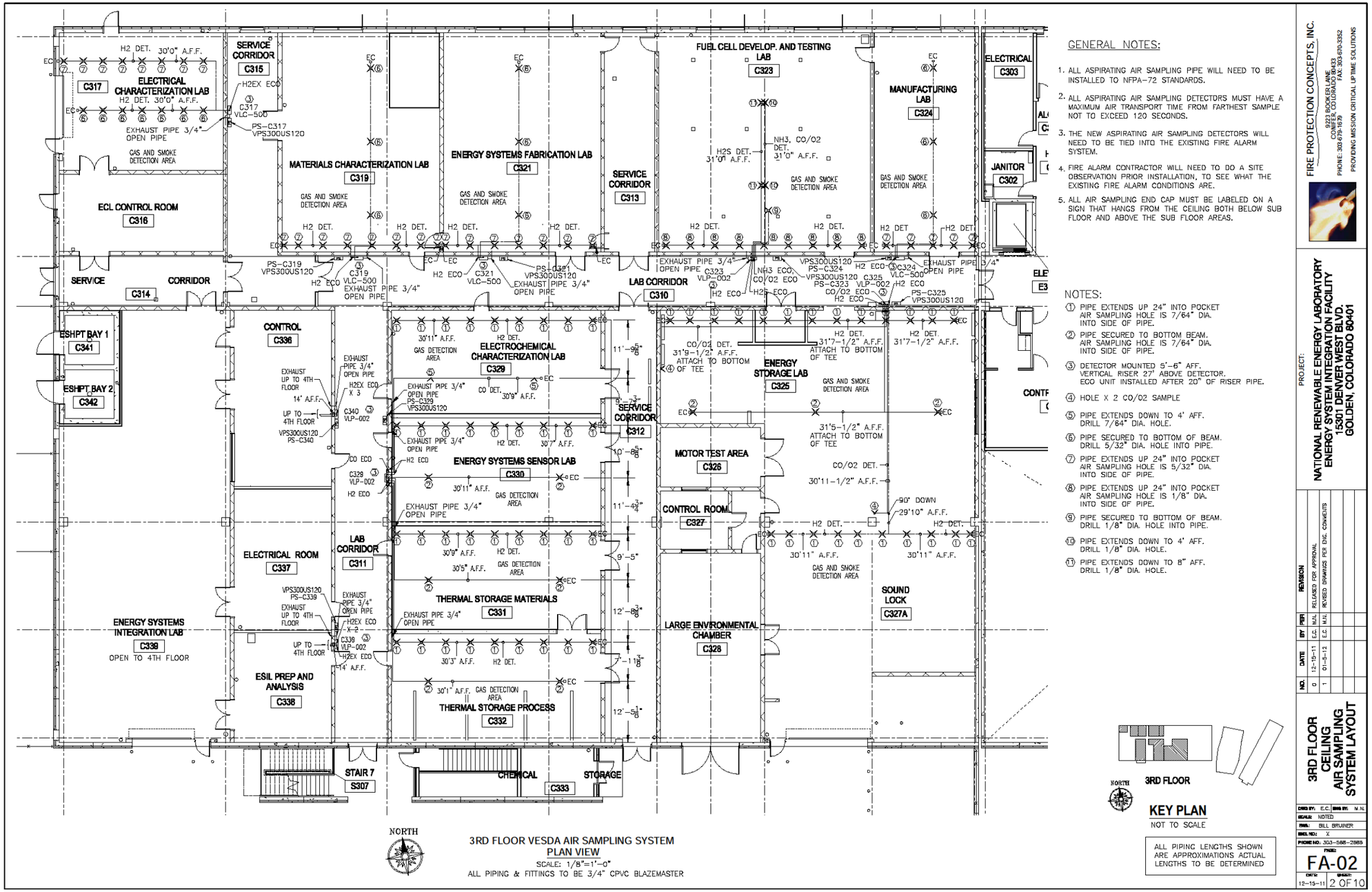

Figure 10. Gas detection drawing, third floor ceiling

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3.8 Building Standby/Emergency Power System

Diesel generators provide the ESIF building with standby/emergency power. When loss of utility power is sensed, automatic transfer switches enable startup and connection of the backup generators to the ESIF. However, back-up generators power only critical loads connected to the backup power network.

Diesel backup generators require diesel fuel be at the ready, necessitating on-site fuel storage per NREL and DOE guidelines. Documented and regular (monthly) maintenance is required to ensure the generators remain in good operating condition.

See Section 3.8.2 for further discussion on building emergency power.

3.8.1 Systems Control and Communications

Three major and important computer-based systems protect and control systems within the ESIF:

- The PLC system contains the core of the safety protection algorithms for research systems at the ESIF. An array of PLCs interacts to implement critical safety functions that assure reliable and safe use of the REDB, gas detection, gas delivery, and associated systems and experiments.
- The SCADA system acts as a wrapper used to interact with the user-controllable systems in the ESIF. In addition to facilitating core safety PLC functionality, the SCADA system provides a powerful platform to perform monitoring and control functions on a large number of test points and control options for laboratory operations.
- The BAS is a Delta Controls system using the BAC-net protocol and controls, and monitors the facility infrastructure systems, e.g., ventilation.

3.8.1.1 Safety PLCs

The PLC system hardware consists of safety (SIL 2) level safety and reliability protocol components. A system of 17 safety PLCs—a master and 16 laboratory PLCs—makes up the backbone of the ESIF Laboratory Safety System. Each of the 16 laboratory PLCs executes logic and responds locally to gas alarms, EPO actions, and controlled stop (C-stop) actions independent of the master safety PLC. Table 16 lists the 16 ESIF laboratories containing safety PLCs and the detection inputs to those PLCs. The master safety PLC is the point of entrance for software-generated EPO and C-stop signals, which originate from the SCADA system. The master PLC also collects and distributes EPO and C-stop signals with other peer PLCs such as the REDB, RHC, and RFL PLCs.

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Table 16. ESIF Laboratories with Safety PLCs

	Number of Detection Inputs								
			Gas Detection Sensors						
Laboratory	**EPO**	**Door Interlocks**	**H_2**	**CO**	**O_2**	**CO/ O_2**	**NO_2**	**NH_3**	**H_2S**
Power Systems Integration	4					1	1		
Smart Power	5								
Energy Storage	7		2			2			
Electrical Characterization	4		1						
Energy Systems Integration	10		6						
LVOTA	5								
MVOTA	8								
Thermal Storage Process and Components	3		1						
Thermal Storage Materials	2		1						
Energy Systems Fabrication	3		1						
Manufacturing	2		1						
Materials Characterization	2		1						
Electrochemical Characterization	3		1	1					
Energy Systems Sensor	2		1						
Fuel Cell Development and Test	2		1			1		1	1
Energy Systems High Pressure Test		1	2						

CO = carbon monoxide
H_2 = hydrogen
H_2S = hydrogen sulfide
NH_3 = ammonia
NO_2 = nitrogen dioxide
O_2 = oxygen

The Siemens S7 Safety PLCs have two main areas of logic execution: the standard logic program and the safety program. The safety program has many restrictions in terms of access and programming rules. Therefore, only a limited subset of the full PLC logic is run in the safety program, namely that which is needed to implement a safety-instrumented function. By design,

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the standard program redundantly executes the functionality of the safety program, but provides alarming and annunciation, scheduling, and other functions. The standard program passes requests for particular actions, such as breaker actions in the REDB system, to the safety program. The safety program then executes only the safety-instrumented functions. If the safety-instrumented function logic is satisfied, the safety program modifies the SIL-2 rated outputs. The safety program does not control non-safety outputs. This architecture is summarized in Figure 11 and further detailed in Appendix B.

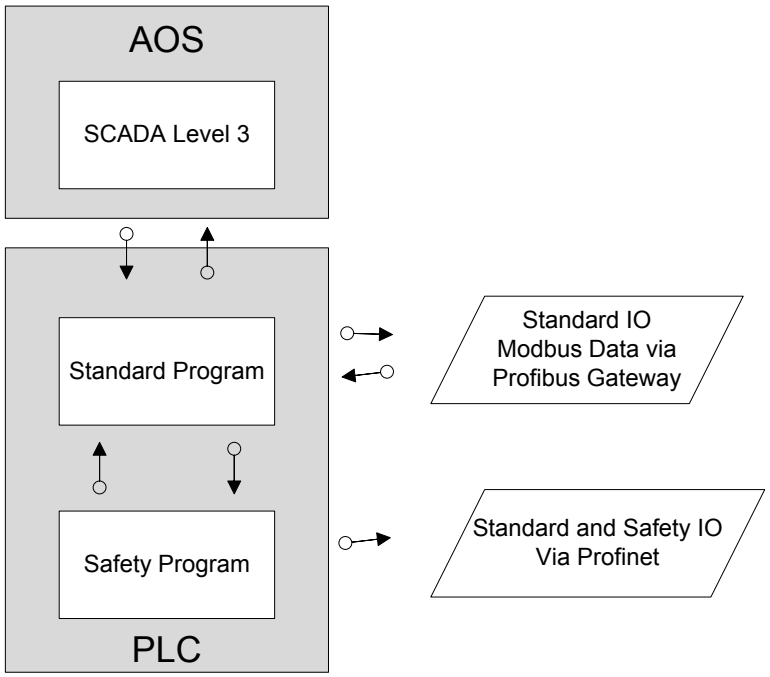

Figure 11. Safety PLC architecture

Each laboratory is equipped with at least one EPO switch (red button) that can be manually activated. Additionally, EPO actuation can also be initiated via a software emergency power off (SEPO) switch provided on each of the laboratory SCADA screens for convenience. A SEPO is an experiment-specific collection of SCADA alarms that trigger a configured set of EPO actions, often in multiple laboratories. A SEPO is effectively pressing a selected set of EPO buttons. Each laboratory safety PLC logically ORs the hardware EPO input with this SEPO input flag, and this combined EPO state is transmitted to all other system safety PLCs. The resulting action of an EPO for each of the ESIF support systems in a laboratory will be detailed in the following sections, but generally an EPO action consists of:

- The red light and alarm horn turn on.
- Any gases present in the laboratory are isolated.
- If the laboratory has REDB connections, an EPO signal is sent to the REDB system.
- The house power supply for the area is interrupted.
- Security is notified.

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A C-stop is an experiment-specific collection of SCADA alarms that triggers a common reaction. During experiment configuration, the user selects which alarms are triggered by the C-stop. Any readable alarm can be added, and the C-stop can be configured to open or close any rated switches that are owned by the experiment. A C-stop, which can be initiated either from a SCADA screen or a yellow button in most laboratories, is not a credited safety control. Instead, its use is intended to provide a C-stop capability to protect equipment.

3.8.1.2 Safety PLC System's Interaction with REDB

The Safety PLC system is the critical supervisory entity that ensures safe operation of the REDB and associated connections and experiments. Specific to the REDB, the critical safety functions that the PLC is responsible for include:

- Ensuring "dead bus switching" for the REDB. This function monitors voltage and current sensors on all REDB sections and allows operation of switches only when these parameters are within acceptable ranges. This ensures switches are not operated with voltage or current present so as not to risk the safety of users or damage components.
- Overvoltage/undervoltage protection to prevent any section of the REDB from operating beyond its rated voltage limit.
- Overcurrent protection to prevent any section of the REDB from operating beyond its rated current limit.

Each REDB bus network has an associated safety PLC dedicated to its protection and control. In addition, a "master" PLC acts as the coordinator of actions and protection among REDB networks. This master PLC also handles communication of controls and monitoring data with the higher-level SCADA system.

The SCADA system has a variety of functions, many of which are instituted to ensure safe and reliable operation of the REDB and associated systems. Specific to the REDB, some of the major SCADA functions include:

- Coordination of bus configuration to ensure independent experiment configurations may not be connected. This involves managing configuration requests from users for bus configuration by checking the validity of the request, and then communicating the requested configuration to the safety PLC system.
- Coordination of experiment setups using RCDs. This function of the SCADA system checks the validity of a requested experimental setup by "pinging" the data network to verify the correct connection and presence of a compatible RCD connection. This action also initiates SCADA functions involving the RCD to allow the user to control and monitor parameters and operation of an experiment via RCD interfaces.
- Operation of research support services such as hot and cold water, gases, and video feedback.
- Management of data acquisition tools that give the user data acquisition, monitoring, and logging capability.

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The safety PLCs in each laboratory interface extensively with the appropriate REDB PLCs for each laboratory and the SCADA system in coordination of a number of safety-related functions.

3.8.1.2.1 Lock-out/Tag-out Interfaces

For access to the REDB room itself, safety program code releases the general entry key when all LOTO switches are open or if safety override keys are turned. In individual laboratories, safety program code prevents any "open" or "close" digital output commands from occurring when a REDB switch has locked status.

3.8.1.2.2 Monitoring and Control of REDB

Safety program code determines the worst-case status of voltage presence on the REDB from redundant pairs of voltage detection relay inputs. When actuating the breakers on the REDB, switches are prevented from opening or closing if voltage is present on either side of the switch.

3.8.1.2.3 EPO Action

When an EPO command is received by the safety PLC in a laboratory, it is immediately communicated to all REDB PLCs associated with the REDB in that laboratory unless the REDB LOTO panel in the laboratory is in the locked position. In turn, the REDB PLC will command all rated breakers to open. None of the breakers is controlled by SIL-2 digital outputs so the safety program must route breaker commands through the standard program in the REDB PLCs.

3.8.1.3 Safety PLC System's Interaction with the BAS

The BAS, which provides sequence control of the building and laboratory environmental systems, has hardwired safety connections to the safety PLC system for critical sequence operations. These hardwired safety connections are used to communicate gas detection and UV/IR (only in the ESIL) actions. When a laboratory gas detector goes into alarm, an EPO is triggered, but also:

- The fire system interface contact is activated, sending a supervisory alarm to the fire panel.
- The blue alarm light turns on. If there is no blue light in a laboratory, the red light is used.
- If the gas is a flammable gas, the red light is used in addition to the blue light.
- A BAS interface contact is closed to signal the BAS to increase ventilation to the laboratory.

3.8.2 Building Emergency Power

3.8.2.1 Backup Generator

The generator is sized to accommodate the following loads:

- Emergency lighting fixtures and exit signs
- Fire pump
- Fire detection and alarm system
- Central control station and lighting

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- Public address system
- UPS system
- Ten percent of the HPC/DC equipment.

The generator specifications are as follows:

- Diesel generator = 900 kW, 480 V-3 PH [480 volt, 3 phase], sound attenuated enclosure, 4 hours runtime
- Power supply = 160 kVA, 480 V-3 PH, 5-minute battery runtime
- Emergency distribution section rating = 2,000 A, 480 V-3 PH-4 wire way, aluminum bussing
- UPS distribution section rating = 600 A, 480V–3PH-4 wire way, copper bussing
- Module tie cabinet = 600 A, 480 V-3 PH
- Two automatic transfer switches for life safety (NEC 700)
- Two automatic transfer switches for legally required systems (NEC 701)
- Two automatic transfer switches for standby optional systems (NEC 702).

3.8.2.2 Uninterruptible Power Supply

The UPS is sized to accommodate 10% of the HPC/DC equipment loads, which is the minimum necessary to maintain the storage, administration, and networking systems. The equipment and material include:

- UPS – Switch mode double conversion technology, maintenance bypass, emergency power off, valve-regulated lead-acid battery, minimum 93% efficiency at 50% load during double conversion process
- Distribution switchboards/panel boards – copper bussing, circuit breaker type, 100% rated
- Mains, 20% spare capacity, SUSE rated
- Branch panel boards = copper bussing, circuit breaker type, fully rated, 20% spare capacity
- Dry-type transformers – high efficiency, National Electrical Manufacturers Association TPl rated for 115°C rise, aluminum windings, K-rated for “non-linear” loads.

In addition to the HPC/DC loads, UPS is also provided for other select loads such as the security system, SCADA system, and enterprise IT systems. The generator is sized for one air handling supply fan to operate on backup power. During power outages, supply air will be prioritized through the building controls to be delivered to laboratories with fume hoods for make-up air. For exhaust ventilation in general, one of the three fans (50% design capacity) that serve each of the two central exhaust systems will be provided with backup power. Because the one fan cannot provide 100% design capacity, it is assumed that fume hood face velocity may drop below the airflow rate indicated for safe operation during a power grid outage. For the H-2 area, one exhaust fan (that is capable of 100% design capacity) will be on backup power.

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Research equipment, in general, will not be supplied with backup power. During power outages, valves will move to their fail-safe positions. Various other support systems and system controls are on backup power, including SCADA system functions.

3.9 Codes and Standards

This section of the HAR identifies the policies, regulations, codes, and standards relevant to the ESIF facility and describes the compliance of the ESIF with these codes and standards, which are listed in Appendix C.

3.9.1 Policy, Regulations, and Codes

3.9.1.1 NREL Standards and Requirements

Frequently encountered hazards are the subject of specific LLPs and implementing programs developed by the NREL EHS Office and referenced in other EHS policies. NREL develops controls on a case-by-case basis for specific hazards that are unique to a particular activity and do not warrant an LLP or implementing program. These documents align with industry standards and best management practices.

3.9.1.2 Integrated Safety Management System

NREL achieves management of EHS matters through two overlapping and integrated mechanisms. A formal laboratory management system provides the mechanisms for planning and conducting laboratory-wide activities that are critical to the laboratory's mission, including EHS. This laboratory management system is supplemented by, and integrated with, distinct EHS support systems that utilize a graded approach to identify and control individual work hazards and ensure compliance with applicable EHS regulatory requirements. These integrated laboratory management and EHS support systems allow EHS to be simultaneously addressed by all workers at laboratory-wide and task-specific levels, and the combination of the two makes up the NREL ISMS.

3.9.2 ESIF Site Orientation

All individuals accessing laboratory and non-office areas of the ESIF will be oriented to the space, its hazards, and the controls utilized. The orientation process mirrors the requirements set forth in LLP 6-1.4, *Environment, Health and Safety Training*. Site orientation is not intended to qualify or authorize anyone to work in a laboratory, but to provide the necessary information to safely access that space. The orientation process differs depending upon the audience, but achieves the same outcome in that the individual has a sufficient level of knowledge regarding the hazards, controls, and the required response actions in an emergency to safely access that space.

The orientation process for the various audiences is as follows:

- Visitors: These individuals are to be escorted at all times. Visitors are to receive a briefing from their host regarding the space so that they have a general understanding regarding the hazards and alarm response actions.

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- Contractors: Contractors go through a formal orientation process that is documented on an orientation checklist geared towards the type of contractor services they are providing: construction, research/support, and vendor. This orientation is provided by an EHS POC.
- Research/Research Support Staff (includes non-NREL ESIF users): These workers go through a formal orientation process that is documented in the NREL Learning Gateway and on the "Site-Specific Environment, Health, and Safety Orientation for Laboratory and Non-Office Support Areas" form. A knowledgeable and qualified person from that specific area conducts this orientation.
- EHS, SITE Operations, and Security: Workers from these three organizations go through a formal orientation process provided by their supervisor or designee. This orientation process varies by organization due to organizational function, need to access all areas of the site, and response to upset or emergency conditions.

3.9.3 Personal Protective Equipment

NREL Site Procedure 6-4.1, *Personal Protective Equipment,* provides guidance on how to determine the need for personal protective equipment (PPE) and how to select, obtain, use, inspect, clean, maintain, and store PPE. This procedure also identifies the various avenues in which workers receive training on PPE.

PPE training is primarily provided in hazard-specific training classes such as Chemical Safety, Qualified Electrical Worker, and Fall Protection; however, there are PPE-specific training classes such as Respiratory Protection and Self Contained Breathing Apparatus (SCBA).

3.9.4 Emergency Power Off and Alarm Response

3.9.4.1 EPO

Every laboratory has a red EPO button that will take specific actions within that laboratory when physically pushed. These actions may range from shutting off gas flow to a laboratory and opening up emergency vents to shutting down the AC and DC REDB to all electrical laboratories. Activation of an EPO will activate audible and visual alarms. In addition to each laboratory's EPO, there is an overall "Lab EPO" located in the PSIL control room, which, if activated, will initiate an EPO action within every laboratory in the building.

Worker understanding of the EPO actions that will be taken within the laboratory in which they are working is critical to ensure that appropriate response actions are taken in an emergency situation. Alarm response instructions are included in a desk procedure, as well as posted throughout the laboratory facility. Laboratory workers are trained during ESIF General Orientation, ESIF Laboratory Orientation, and laboratory site-specific orientation on the EPO functionality and Alarm Response in the laboratory areas. This information is also referenced within SOPs and SWPs, as appropriate.

A summary matrix defining the typical specific actions that will be taken associated with each laboratory EPO can be found in Appendix D. However, it is important to note that the system can be modified through the change control process; therefore, refer to the most current drawing for the Laboratory Safety System for the most current configuration.

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3.9.5 Worker Authorization

Worker authorization is performed in accordance with LLP 6-1.4, Environment, Health, and Safety Training, Appendix D.

3.10 Institutional Programs

This section describes the institutional programs credited in the ESIF HAR and implemented by ESIF Center personnel to assure that safety and environmental requirements are integrated through all the ESIF's activities.

3.10.1 Process Safety Management

The ESIF management team has adopted Process Safety Management (PSM) as a best management practice to provide a framework for safely performing operations using hazardous materials. PSM is the application of management systems to identify, understand, and control chemical and manufacturing process hazards and to prevent process-related injuries and incidents.

Elements of PSM, as recommended by the American Institute of Chemical Engineers/Center for Process Safety, include:

- Accountability: Objectives and goals
- Process knowledge and documentation
- Capital project review and design procedures
- Process risk management
- Management of change
- Process and equipment integrity
- Human factors
- Training and performance
- Incident investigation
- Standards, codes, and laws
- Audits and corrective actions
- Enhancement of process safety knowledge.

3.10.2 Integrated Safety Management System

NREL implements an ISMS defined by LLP 6-1.5, *Integrated Safety Management and Environmental Management Systems*. NREL's activities are guided by integrated safety management to assure compliance with EHS requirements, to prevent occupational illness and injury, to fulfill environmental stewardship obligations and pollution prevention obligations, and to achieve continual improvement of EHS management systems. The laboratory's integrated safety management approach is applied as a continuous cycle with the degree of rigor appropriate to address the type of work activity and the hazards involved.

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Operations at the ESIF comply with the requirements of LLP 6-1.5 for:

- Planning, conducting, and checking work
- Identifying hazards and defining controls
- Development of detailed operating and maintenance procedures
- Defining line management and worker responsibilities for EHS.

3.10.3 Quality Management

A quality management (QM) program is implemented at the facility that assures the delivery of safe, reliable products and services that meet or exceed the customer's requirements, needs, and expectations as required by DOE O 414.1D, *Quality Assurance*, and as defined in DOE G 414.1-2B, *Quality Assurance Program Guide*. Quality assurance requirements at NREL are identified in LLP 2-3.1, *Quality Management Program,* and are implemented by the *ESIF Quality Management Program*.

3.10.4 Integration of EHS, Quality Management, and Process Safety Management

The facility's QM program provides the processes and tools for assuring that integrated safety management objectives and PSM elements are integrated. Table 17 provides a crosswalk between the QM elements derived from LLP 2-3.1, *Quality Management Program*; the ISMS elements derived from LLP 6-1.5, *Integrated Safety Management and Environmental Management Systems;* and the PSM elements derived from the Federal Register Title 29, Code of Federal Regulations (CFR), Part 1910.119, *Process Safety Management of Highly Hazardous Chemicals*.

Table 17. Integration of Quality, Integrated Safety, and Process Safety Elements

Quality Management Element	ISMS Elements	Process Safety Management Elements
Managing requirements	Planning: Objectives and targets	Process knowledge and documentation Capital project review and design procedures Process risk management Management of change Process and equipment integrity Standards, codes, and laws Enhancement of process safety knowledge
Planning	Planning: Hazard identification and control Planning: Legal and other regulatory review Implementation and Operation: Emergency preparedness and response	Accountability: Objectives and goals Capital project review and design procedures Standards, codes, and laws

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Quality Management Element	ISMS Elements	Process Safety Management Elements
Execute Work	Implementation and Operation: Operational control	Process risk management Management of change Process and equipment integrity Enhancement of process safety knowledge
Customer acceptance and delivery	Management Review Implementation and Operation: Communication, participation, consultation	Standards, codes, and laws
Monitoring performance	Checking and corrective action: Monitoring and measuring	Incident investigation Audits and corrective actions
Performance feedback and improvement	Implementation and Operation: Communication, participation, consultation Checking and corrective action: Incident investigation, non-conformity, corrective action	Incident investigation Audits and corrective actions
Workforce management	Implementation and Operation: Resources, roles, responsibilities, authorities Implementation and Operation: Competence, training, awareness	Process risk management Human factors Training and performance
Document and records management	Implementation and Operation: Document control Checking and corrective action: Control of records	
Assessments	Checking and corrective action: Evaluation of compliance Checking and corrective action: Internal assessments	Audits and corrective actions
Material resources	Checking and corrective action: Evaluation of compliance Checking and corrective action: Internal assessments	Enhancement of process safety knowledge

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4 Integrated Hazard Analysis

4.1 Integrated Hazard Analysis Methodology

The objective of the IHA is to identify the preventive and mitigative controls needed to ensure ESIF activities pose no greater than routine or low risk, maintaining the safety envelope defined for the facility and the site. Within those controls, it is also an objective to identify the IROFS, whether they are administrative controls or ESFs. While all controls will be implemented and contribute to risk reduction, it is the IROFS and controls associated with the **bounding events** that are considered to be paramount, and they will therefore be subject to added rigor in their implementation and maintenance. The method used to perform the IHA was shown in Figure 2.

The IHA is composed of two phases: the process hazards analysis (PrHA[6]) and the accident analysis. LLP 6-6.2, *Hazard Identification and Control,* requires the user to contact the EHS POC for any new or significant change to a system or activity. The POC, working with the user, determines whether the new or changed activity/system requires a PrHA to be performed. Those activities and systems adequately controlled using LLPs, e.g., 6-1.46 *Chemical Safety*, are deemed not to require a PrHA. The controls developed in the PrHA are then documented in the SWP or SOP.

The PrHA scenarios are captured on an ESIF-specific form designed to provided consistency and efficiency during the analysis. The form uses drop-down pick lists for "accident type," "cause or initiating event," and "hazard of concern." These lists are developed following the guidance in the Center for Chemical Process Safety's (CCPS's) *Guidelines for Hazard Evaluation Procedures*, 3rd Edition (2008). The drop-down lists allow the analyst to select multiple items on the list. This was done to reduce the number of forms needed, capture dependent failures on a single form, and show compound events. The form template and instructions are presented in Appendix E along with the likelihood bins, consequence bins, and risk matrix from LLP 6-6.2 and the complete lists of accident types, causes or initiating events, and hazards of concern.

The form is used to capture the hazard evaluation technique used to perform the PrHA. This is done for historical purposes and trending. Most of the PrHAs completed to date have been "what-if" analyses, but several hazard operability studies have also been done. Figure 12 presents a decision logic that can be used to select the appropriate hazard evaluation technique.

[6] The acronym PHA has been used since the 1960s to mean "preliminary hazard analysis." When OSHA promulgated the Process Safety Management rule (29 CFR 1919.119) in 1992, the term "process hazard analysis" was coined. It too is represented by the acronym PHA in most publications. The Center for Chemical Process Safety (CCPS) in its third edition of *Guidelines for Hazard Evaluation Procedures* (2008) speaks to this issue. CCPS has started using PrHA to mean preliminary hazard analysis and PHA is then used exclusively for process hazard analysis. However, in DOE HDBK 1100-2004, *Chemical Process Hazards Analysis*, which was originally published in 1996, DOE uses PrHA to distinguish process hazard analysis from the original PHA. In LLP 6-6.2, *Hazard Identification and Control*, PHA is used for "process hazard analysis." In this HAR, the DOE convention is followed, and PrHA is used for "process hazard analysis" and PHA for "preliminary hazard analysis" even though this is inconsistent with LLP 6-6.2 and the CCPS.

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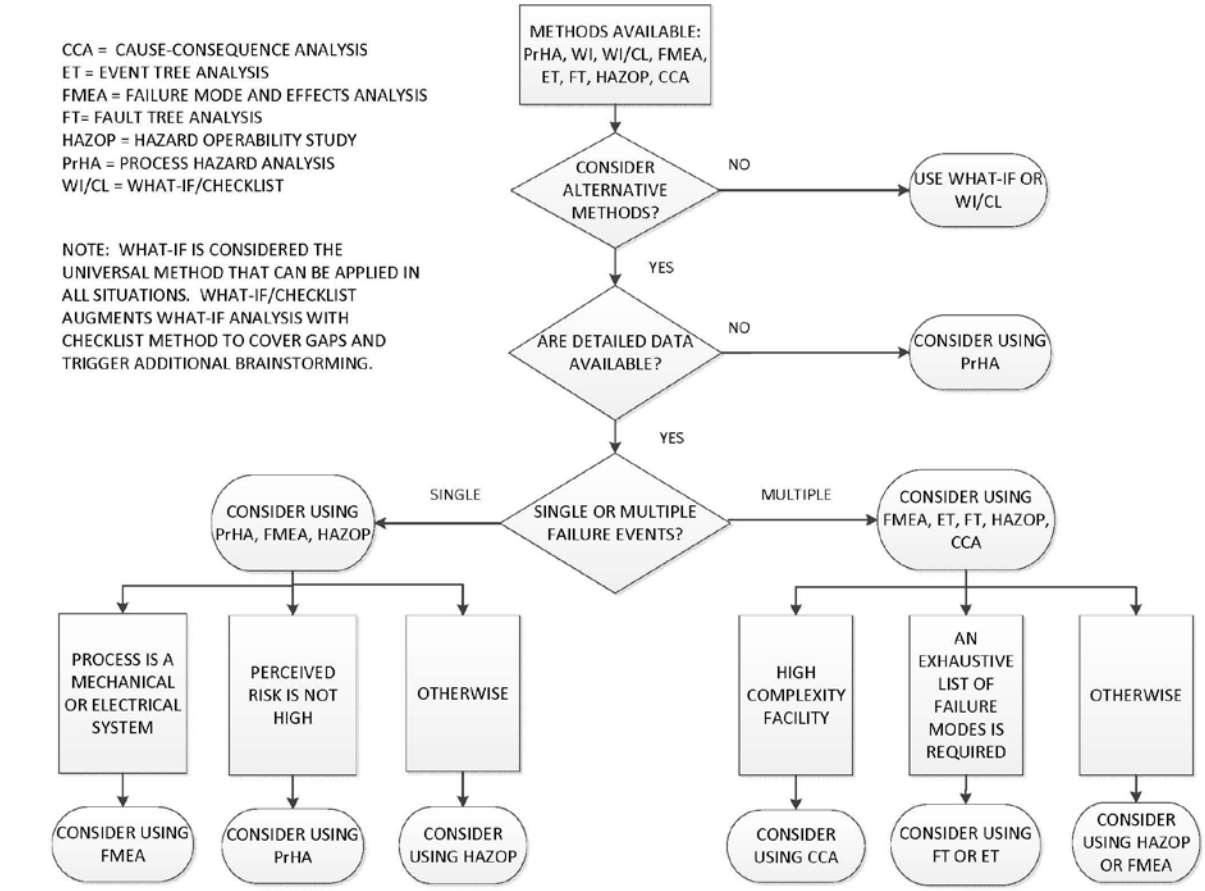

Figure 12. Hazard evaluation technique decision logic

The form is used to calculate the uncontrolled (initial) risk and the controlled (residual) risk after the analyst identifies the controls to be applied. The risk calculation is consistent with the methodology stipulated in LLP 6-6.2, *Hazard Identification and Control*. The controls are classified as either administrative or engineered, and as preventive or mitigative. Some controls can perform both a preventive and a mitigative function, so compound control types are allowed. The instructions for the form stipulate the amount of risk reduction that may be taken for each type of control. Preventive controls act to reduce the frequency, and engineered preventive controls are credited with up to two bins reduction, while administrative controls are credited with up to a single bin reduction for a robust control or one-half bin for ordinary administrative controls. Mitigative controls act to reduce consequences; engineered controls are preferred over administrative ones. The credit allowed for engineered mitigative systems is up two bins and one-half to one bin for administrative controls.

Figure 13 shows a form for a spill scenario of diesel or biodiesel from a day tank. This is a fairly benign hazard, but the form illustrates many of the considerations that the analyst must perform.

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Site: STM			**Facility/Location:** ESIF/C325 (ESL), C221 (PSIL)										
Process: Material handling			**Hazards of Concern:** Hazardous chemicals										
ID No.	**Accident Type**	**Cause or Initiating Event**	**Scenario**	**Control Description & Type**		**Freq**	**Consequence**			**Risk**			**Notes**
							E/F	**P/E**	**W**	**E/F**	**P/E**	**W**	
119	Spill Fire	Human error Equip Malfunction	Diesel/biodiesel spill and fire when it comes in contact with hot surface. 100-gallon day tank could be overfilled, tank could fail, user could pump without proper connection to vehicle, or pipe could fail causing spill.	**UNCONTROLLED →**		B	II	IV	II	H	R	H	
				Secondary containment (double walled day tank)	EM		✓	✓	✓		Double walled tank contains spills from the primary tank.		
Hazard Evaluation Technique		**Hazards of Concern:**		Sprinkler system (fire suppression)	EM		✓		✓		Fire suppression will extinguish or contain fire.		
What if		Combustible materials		Limited volume of day tank	EP		✓		✓		Limited volume of combustible that can be lost into the laboratory, reducing the severity of the resulting event.		
				Leak detection of double wall	EP	✓					Leak detector will notify personnel of a failure in the primary tank. Leak detector requires routine check of functionality.		
				High level switch with auto fill shutoff	EP	✓					High level sensor and automatic shutoff valve prevent overfilling. High level switch requires routine check of functionality.		
				SOP requires users to be present during tank filling	AP/AM	✓	✓	✓	✓		Attended operation provides immediate response to problems.		
				CONTROLLED →		C	IV	IV	IV	R	R	R	*Assumes all controls are in place*
EP = Engineered Preventive; EM = Engineered Mitigative, AP = Administrative Preventive, AM = Administrative Mitigative, ✓ = Contributes to Reduction													

Figure 13. Hazard Identification Form: Example spill scenario (ESIF)

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The example scenario is a cascade event with a spill of diesel/biodiesel leading to a subsequent pool fire. The different spill mechanisms could be due to either equipment malfunction or human error (a compound event). The analyst judged the uncontrolled frequency to be "reasonably probable" or expected to occur several times in the life cycle of the system. Applying engineered preventive controls for leak detection and a high-level switch with auto-fill shutoff were judged to reduce the likelihood to "occasional," or likely to occur sometime in the life cycle of the system. More frequency reduction could have been taken for these controls, but the selection is conservative. The consequence reduction is due to a number of engineered and one administrative control. Little or no consequence reduction is needed for the public/environment receptor, so only the double-walled tank design is credited. For the equipment/facility and worker receptors, tank design, fire suppression, and attended operations are credited. The controlled risk is shown to be routine for all receptors.

For the ESIF IHA, forms were completed for all of the postulated accident scenarios. The scenarios were then classified first by accident type and second by initiating event. Initiating events fell into three general areas: equipment malfunction, human error, and external events. The reason for classifying the scenarios in this manner was that the control set for a given accident type could change depending on the initiating event. For example, the controls for an earthquake-induced fire include structural elements whereas controls for a fire initiated by an equipment malfunction do not necessarily consider structural elements such as seismic restraints.

The distribution of the 88 scenarios generated for the ESIF among the 17 accident type categories is shown in shown in Table 18. The numbers in the table represent the scenario identification numbers. Details of the scenarios analyzed in the PrHA are included in Appendix F.

For each class of scenario, e.g., spill with exposure, equipment damage with injuries, etc., a representative scenario was selected for that class. Typically, the representative scenario was the one with the highest initial (uncontrolled) risk, thereby requiring the most complete set of controls to reduce the risk to acceptable levels.

Another review of the classified scenarios was performed to determine those that were the result of dependent failures. Dependent failures were generally of two types: cascade failures and common cause failures. An example of a cascade failure is presented in Figure 13, where a diesel/biodiesel spill leads to a pool fire. A typical common cause failure is human error. A single human error, such as incorrect performance of periodic instrument calibration, can lead to multiple system failures. Dependent failures are of particular concern because the consequences are typically greater than for single, independent events. This can affect the selection of preventive and mitigative controls. Dependent failure events are strong candidates for becoming bounding events.

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Table 18. ESIF Scenarios by Accident Category

Dropped load	Electric Shock or arc flash	Equipment damage	Equipment damage with injuries	Explosion/ blast over-pressure	Explosion/ fire	Exposure to loud noise	Exposure to high temps	Exposure to low temps	Fire	Fire/Small local fire in work area	Radiation exposure	Release	Release with exposure	Spill	Spill with expo-sure	Std Ind Hazard
115	155	211	156	170	110	241	213	300	110	213	253	110	140	119	222	124
	203	223	167	221	147	264	225		119	224		147	144	215	225	218
	204	228	168	225	149		240		147	228		149	151	223	250	221
	205	239	212	233	150		273		149	232		150	186	224		262
	214	287	229	243	165		289		150	248		177	218	226		300
	216		295	285	177				177	249		189	222	237		
	217			286	218				210	273		190	235	238		
	219				220				225			195	236	265		
	227				221				226			199	251			
	231				234				237			213	252			
	232				240				240			225				
					244				246			239				
					246				247			242				
					276				249			245				
					277				265			246				
					294				276			248				
									277			273				
												276				
												277				
												280				
												288				
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Twenty-six events (highlighted in Table 18) were classified in multiple accident categories or multiple initiating event types. Dependent analysis of these 26 compound scenarios was conducted by the PrHA team to derive the primary accident category, the primary type of initiating event, and whether the events involved a dependent failure such as a common cause or cascade failure. The results of the dependent analysis of the 26 compound scenarios and their final classifications are shown in Table 19.

Table 19. ESIF Compound Scenarios Dependent Analysis

Scenario	Common Cause	Cascade	Treat As
11	N/A	N/A	Explosion-fire
119	no	yes	Spill
147	N/A	N/A	Explosion-fire
149	no	yes	Fire
150	no	yes	Fire
177	no	yes	Explosion-fire
213	no	yes	Release
218	no	no	Release w/exposure
221	no	no	Standard industrial hazard
222	N/A	N/A	Spill w/exposure
223	N/A	N/A	Spill
224	N/A	N/A	Spill
225	N/A	N/A	Spill w/exposure
226	no	yes	Spill
228	no	yes	Equipment damage
232	no	yes	Electric Shock/Arc Flash
237	no	yes	Spill
239	no	yes	Equipment damage
240	yes	no	Explosion-fire
246	yes	no	Explosion-fire
248	no	yes	Release
249	N/A	N/A	Small fire
265	no	yes	Spill
273	no	yes	Release
276	no	yes	Fire
277	N/A	N/A	Explosion-fire

N/A = not applicable

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A representative scenario was selected for each accident classification, typically the scenario with the highest risk and/or loss. The 35 representative scenarios and key supporting information are shown in Table 20.

Table 20. ESIF Representative Scenarios

Represent-ative Scenario Risk ID #	Hazard Category	Lab	Accident Type	Cause or Initiating Event	Scenario Description
115	Physical – Struck by	OCL, PSIL	Dropped load	Equipment malfunction	During a lifting operation on the overhead crane, a cable breaks due to wear, improper maintenance, or improper operation, resulting in load dropping
127	Physical – Electrical	MVOTA	Electric shock or arc flash	Equipment malfunction	Shock, arc flash, explosion result from ground faults, short circuits. (Electrical services at 13.2 kV/200A)
214	Physical – Electrical	REDB Room	Electric shock or arc flash	Equipment malfunction	Flood results from inadvertent sprinkler head operation. (Approx. 200 sq. ft. area of effect)
205	Physical – Electrical	MVOTA, SPL, OCL, PSIL, REDB, ECL, FCDTL, ESL, ESIL, LVOTA, RTA	Common cause	Human error	AC ground faults (phase to ground or phase to phase) result due to insulation damage, mis-wiring, physical damage or equipment failure. Electrical experiments using the REDB with 0 – 600 V_{ac}/ 0 – 2,500A/ 16-2/3 – 400 Hz
228	Physical – Electrical	ECL	Cascade	Equipment malfunction	Destruction of power electronics of DUT occurs from high current or voltage. Small component ejects from test device destruction
287	Equipment Damage – mechanical	ESOTA	Equipment damage	Equipment malfunction	Pressure or flow required by compressor is not provided, resulting in compressor damage and/or release of hydrogen (closed valves, obstruction, failed pressure transmitter, etc.). Hydrogen gas supply to compressor.

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Represent-ative Scenario Risk ID #	Hazard Category	Lab	Accident Type	Cause or Initiating Event	Scenario Description
168	Equipment Damage with Injuries	HPTB1, 2	Equipment damage with injuries	Equipment malfunction, loss of integrity	Component in High Pressure Test Cell ruptures; media can be water, oil, helium, hydrogen or nitrogen gas at 15,000 psi in volumes up to 3.5 liters
212	Equipment Damage with Injuries	ESIL, HPTB1, 2, ESOTA	Equipment damage with injuries	Equipment malfunction, loss of integrity; Equipment malfunction, fail to run, start, or stop	Compressor fails (diaphragms, seals, check valves, loss of cooling), resulting in release of gas and shrapnel from explosion of 1-liter surge vessel, potential jet flame. (Compressor raising pressure to as high as 15,000 psi.)
156	Equipment Damage with Injuries	ESOTA	Equipment damage with injuries	Equipment malfunction, loss of integrity	Catastrophic rupture of high-pressure hydrogen gas storage vessel is caused by overpressure from compressor, back flow, or temperature swings. (200 kg hydrogen at 3,500 to 15,000 psi)
170	Explosion – Blast Over-pressure	ESIL	Explosion-blast over-pressure	Equipment malfunction, loss of integrity	Backflow of hydrogen from storage (outside the building) to ESIL (where hydrogen is generated/compressed) causes overpressure of piping or equipment with release. (200 kg hydrogen at 3,500-15,000 psi)
277	Explosion – Fire	ESIL, HPTB1, 2, RTA	Explosion – fire, not cascade	External event	During venting of hydrogen, hydrogen concentration in air reaches flammable limits and ignites. Flame fronts accelerate in pipe/ducts and detonate at L/D of about 10. Explosive gas concentration of hydrogen in pipe, pipe deflagration. (From equipment/test venting from ESIL and high pressure test bays or roof has block/bleed valves).

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Represent-ative Scenario Risk ID #	Hazard Category	Lab	Accident Type	Cause or Initiating Event	Scenario Description
177	Explosion – Fire	ECL	Explosion – Fire cascade	Equipment malfunction; Equipment malfunction, loss of integrity	Hydrogen gas accumulates in a confined area, reaches flammable concentration, and deflagrates. (The quantity of hydrogen that can be discharged from a 0.25-inch-outer-diameter [OD], 0.109-inch-inner diameter pipe at choke flow.)
294	Explosion – Fire	ESOTA	Explosion – Fire not cascade	Human error	Air or O_2 is accidentally connected to a hydrogen system, resulting in flammable hydrogen concentrations and ignition. (Hydrogen gas for house system, 2,000 psi bottle gas.)
234	Explosion – Fire	ESIL	Explosion – Fire not cascade	Equipment malfunction	Reaction of hydrogen and oxygen produces heat and pressure, rupturing the electrolyzer. Electrolyzer operates at up to 600 psi; rupture of equipment could release oxygen, hydrogen, and caustic.
240	Explosion – Fire	ESOTA	Explosion – fire, exposure to high temperature and fire	External event – fire	Grass fire heats hydrogen storage vessels, compressor, and components, causing pressure relief valve to vent H_2 gas. Approximately 200 kg hydrogen stored, 3,500-15,000 psi
264	Exposure to Loud Noise	SPL	Exposure to loud noise	Equipment malfunction	High frequency noise is produced from power electronics
213	Exposure to High Temperature	TSPCL	Exposure to high temperatures	Equipment malfunction Equipment malfunction, loss of integrity	Heat transfer fluid released from a reactor results in burns and a small local fire.

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Represent-ative Scenario Risk ID #	Hazard Category	Lab	Accident Type	Cause or Initiating Event	Scenario Description
289	Exposure to High Temperature	ESOTA	Exposure to high temperatures	Human error	Heat of compression causes hot surfaces, personnel touches surface causing a burn. Hot tubing/compressor parts due to heat of compression capable of causing severe burns
276	Fire	MCL, FCDTL, ECCL, ESSL	Fire	Equipment malfunction Equipment malfunction, loss of integrity	Hydrogen gas could accumulate in a confined area, build up to a flammable gas concentration, and deflagrate. The quantity of hydrogen that can be discharged from a 0.25-inch-OD pipe at choke flow.
210	Fire	ESOTA	Fire	Equipment malfunction	Hydrogen fire during vehicle filling because connection is not leak-tight (Note: not in Day One build-out.) Release of 10,000 psi hydrogen from filling station.
247	Fire	ECL	Fire	Equipment malfunction	Failure of power electronics board could cause fire and/or damage to laboratory fuel supply lines resulting in sustainable fire. Flammable gas and liquid supply lines (research fuel lines) provide fuel source for fire, ignition source is test being conducted on power electronics.
249	Small Fire	SPL, PSIL, ESFL, ML, ECCL, ESIL	Small fire	Human error	Solvents/flammable storage. Room fire or small local fire in work area. Assume many liter- to gallon-sized bottles in storage cabinet.
253	Exposure to Radiation	ML	Exposure to radiation	Human error	Accidental x-ray exposure. Unspecified energy level, but below the level that would be capable of life-threatening exposures in minutes. Exposure could exceed annual limit of 3 rem.

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Represent-ative Scenario Risk ID #	Hazard Category	Lab	Accident Type	Cause or Initiating Event	Scenario Description
288	Release	ESOTA	Release	Equipment malfunction human error	Release of hydrogen caused by compressor damaging pipe, leaky fittings or valves, leaky pressure safety valve, open vent valves, etc. Hydrogen gas up to 15,000 psi and 200 kg
199	Release	ECL, MCL, ESFL, FCDTL, ML, ECCL, ESSL, ESIL, HPTB1, 2	Release	Equipment malfunction	Over pressurization of vent system caused by freezing, increased flow, plugged vent. Hydrogen released to vent system is unable to vent to roof due to frozen pipe, increased flow, plugged vent (insect/bird)
189	Release	FCDTL	Release	Equipment malfunction, human error	Spill, leak or open liquid nitrogen dewar. Nitrogen dewars used in laboratory can evaporate at a rate creating an oxygen deficient atmosphere, exposure to spill can cause burn
195	Release	MCL, ESSL	Release	Equipment malfunction	Leak of gas from bottle gas system. Carbon dioxide supplied by ½ inch or smaller line, 200–500 psig
40	Release with Exposure	ESL	Release with exposure	Equipment malfunction	Toxic gas release (H_2S) from overcharging batteries. H_2S formed at rate based on charging current.
35	Release with Exposure	PSIL	Release with exposure	Equipment malfunction, human error	Exposure to toxic gas. Typical rate of CO/NO_2 from vehicle exhaust (assume 200 HP engine)
222	Release with Exposure, Spill with Exposure	ECCL	Release with exposure, spill with exposure	Equipment malfunction, human error	Evaporation of acid during use, spill during transport, or spill that seeps out of the hood. Perchloric acid ($HClO_4$), sulfuric acid (H_2SO_4), and other acids in 1-liter to 1-gallon size containers.

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Represent-ative Scenario Risk ID #	Hazard Category	Lab	Accident Type	Cause or Initiating Event	Scenario Description
251	Release with Exposure	FCDTL, ECCL	Release with exposure	Equipment malfunction	Pipe or vessel leak (assumes gas cabinet supplied via permanently installed piping). Volume of standard gas cylinder containing 250 scf (CO concentration 1%) at 2,000 psig.
151	Release with Exposure	ESFL, TSML, TSPCL	Release with exposure	Human error	Release of nanomaterials to room (drop container or spill). Less than 10 grams, probably on a solid substrate, material is between 1 and 100 nanometers in dimension.
238	Spill	LVOTA	Spill	Equipment malfunction, human error	Spill of fuel collects in below-grade trenches. Flammable liquid (gasoline)/flammable gas (propane) from DUT. Less than 50-gallon standard equipment tanks.
224	Spill	ESL	Spill	Human error	Spill of cryogenic liquids or quench of superconducting magnetic energy storage unit (SMESU) creates an oxygen (O_2)-deficient atmosphere. Quench system release of CO_2 or other gas to remove oxygen and quench a fire. Cryogenic liquids can evaporate and displace the oxygen from the room. Volume of both expected to be large enough to create a hazard.
215	Spill	PSIL, ESFL, ESL	Spill	Human error	Small spill of corrosives in work area. Assume liter to gallon-sized non-breakable containers.

4.2 ESIF Process Hazard Analysis: Bounding Event Selection

Bounding events are selected from among the representative events and dependent failure events. Each of the representative scenarios was examined to determine whether it rises to the stature of a bounding event, that is, an event of such significant risk, impact, and loss that it defines an outer boundary of the ESIF safety envelope. Together, the bounding events define the ESIF

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safety envelope and the minimum specifications of the ESIF preventive and mitigative controls required to keep the ESIF within the envelope.

Not all representative events become bounding events even though they "bound" the class they represent. For instance, the representative scenario for "small local fire in work area" is not likely to become the bounding event for "fires" given the various other fires in that class such as pool fires, jet fires, room fires, etc. The bounding events selected should have a comprehensive set of preventive and mitigative controls that will assure adequate risk reduction for all the subordinate events in the applicable class or classes.

A set of eight bounding events was identified from the 37 representative scenarios. A subsequent crosscheck review by the ESIF HAR team determined that four additional bounding events were warranted to address possible high-impact accidents that were not covered in the 37 representative scenarios. The complete set of 12 bounding events defining the ESIF safety envelope is shown in Table 21.

Table 21. Bounding Events Defining the ESIF Safety Envelope

Bounding Event	Location in ESIF
Electric shock, arc flash, explosion resulting from ground faults, short circuits	MVOTA
Electric shock, arc flash, flood from inadvertent sprinkler head operation	REDB
AC ground faults (phase to ground or phase to phase) due to insulation breakdown, mis-wiring, physical damage, or equipment failure	MVOTA, SPL, OCL, PSIL, REDB, ECL, FCDTL, ESL, ESIL, LVOTA, RTA
Rupture of component in High Pressure Test Cell; media can be water, oil, helium, hydrogen or nitrogen gas at 15,000 psi in volumes up to 3.5 liters	HPTB1, 2
Catastrophic rupture of high-pressure hydrogen gas storage vessel, cause by overpressure from compressor, back flow, temperature swings. 200 kg hydrogen at 3,500 to 15,000 psi	ESOTA
Backflow of hydrogen from storage (outside the building) to ESIL (where hydrogen is generated/compressed) causing overpressure of piping or equipment with release. 200 kg hydrogen at 3,500 to 15,000 psi	ESIL
Accidentally connect air or O_2 system to hydrogen system, or other accidental air/hydrogen mixing. Hydrogen gas for house system, 2,000 psi bottle gas.	ESOTA
Grass fire heats hydrogen storage vessels, compressor, components, causing pressure relief valve to vent hydrogen gas. Approximately 200 kg hydrogen stored at 3,500 to 15,000 psi	ESOTA

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Bounding Event	Location in ESIF
Burns from exposure to release of heat transfer fluid and small local fire. Quantity and temperature not mentioned; heat transfer fluids are normal combustible liquids. Temperature expected to be at levels which would burn humans	TSPCL
Hydrogen fire during vehicle filling because connection is not leak-tight. Release of 10,000 psi hydrogen from filling station	ESOTA
Exposure to toxic gas. Typical rate of CO/NO_2 from vehicle exhaust (assume 200 HP engine)	PSIL
Release of nanomaterials to room (drop container or spill.) Less than 10 grams, probably on a solid substrate, material is between 1 and 100 nanometers in dimension. The technology is new, and uncontrolled risks are not fully known. However, certain nanoparticles may be deposited into the respiratory tract and cause damage. Other known hazards are absorption through the skin or lungs via inhalation and entering the bloodstream. NIOSH has determined that titanium dioxide could be considered a potential occupational carcinogen. Based on the preliminary information and recommended controls by OSHA, the uncontrolled risks have been placed in the worst possible selections.	ESFL, TSML, TSPCL

The PrHA and bounding event exercise yielded a set of IROFS, defined as those administrative and physical controls that are credited with either a preventive or mitigative safety function. Preventive controls reduce likelihood and are evaluated in the frequency analysis. Mitigative controls reduce consequences and are evaluated in the consequence analysis. Administrative IROFS that are deemed significant contributors to risk reduction are classified as SACs. Physical IROFS that are deemed significant contributors to risk reduction are classified as ESFs. All other IROFS are implemented through SMPs. The IROFS defined through the PrHA representative and bounding event analysis are presented in Table 2**.**

4.3 Accident Analysis

The ESIF accident analysis exercise began with the selection of certain events (EBAs) from the bounding events or other postulated accidents that define the safety envelope of the ESIF. The postulated accidents that were examined in the accident analysis are presented in Table F-1 in Appendix F.

While the PrHA was qualitative in nature, relying heavily on the analyst's experience, the ESIF accident analysis uses quantitative or semi-quantitative techniques to develop more refined estimates of likelihood and consequences of accidents. The types and quantities of hazards present in the ESIF (and NREL generally) do not require a probabilistic analysis; a deterministic approach with carefully crafted assumptions and detailed initial conditions is sufficient.

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As in the PrHA, the objective of the accident analysis is to identify the controls necessary to prevent or mitigate the hazards to an acceptable level and to evaluate the effectiveness of those controls in reducing or eliminating the hazard risk. The controls identified as having the most impact are deemed to be IROFS and include both engineered and administrative controls. Not all IROFS, however, need to be implemented with the same amount of rigor. The analyst, working with the Facility Manager and EHS POC, will determine which controls will be implemented with added rigor and they are so stipulated in the ESIF HAR. The other IROFS will be implemented through the NREL SMPs, and this commitment is stipulated in the HAR as well. Figure 14 shows the logic described above, and Figure 15 shows the accident analysis process.

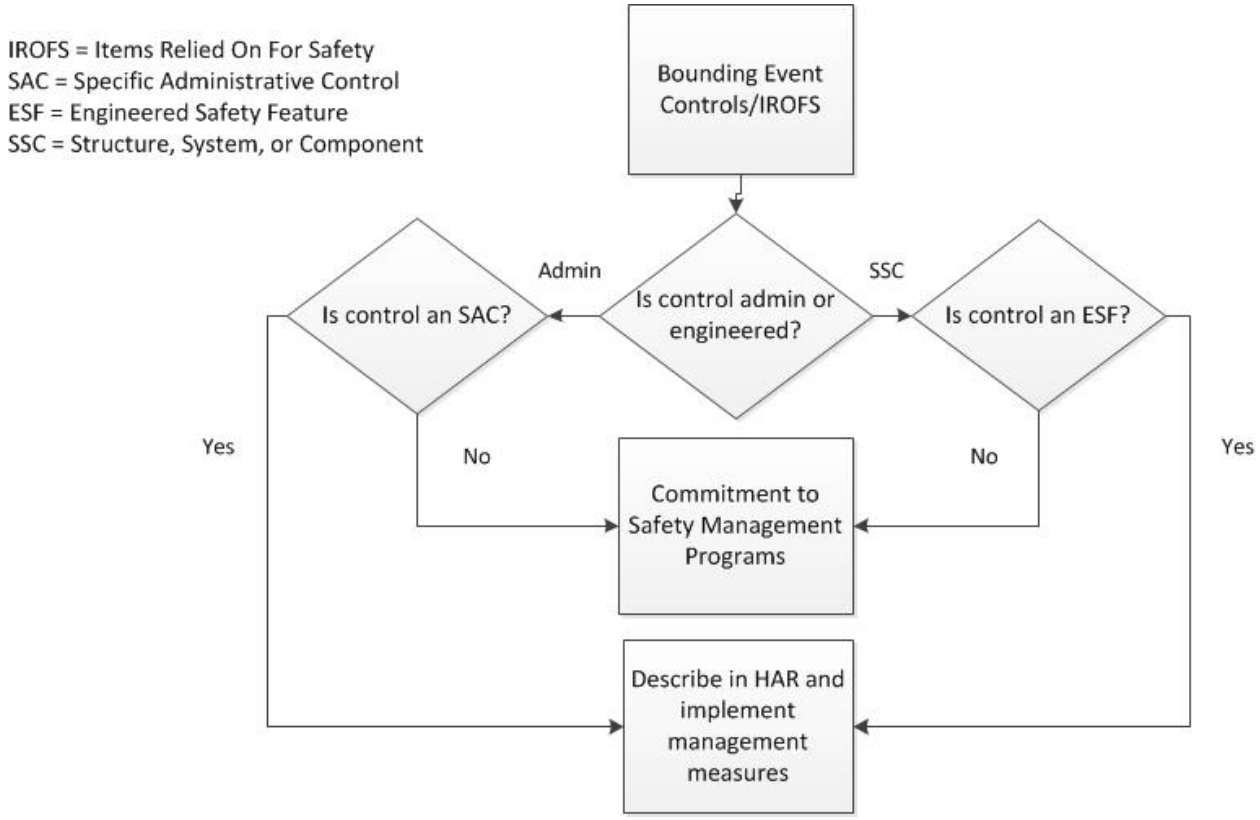

Figure 14. Elevation of some controls

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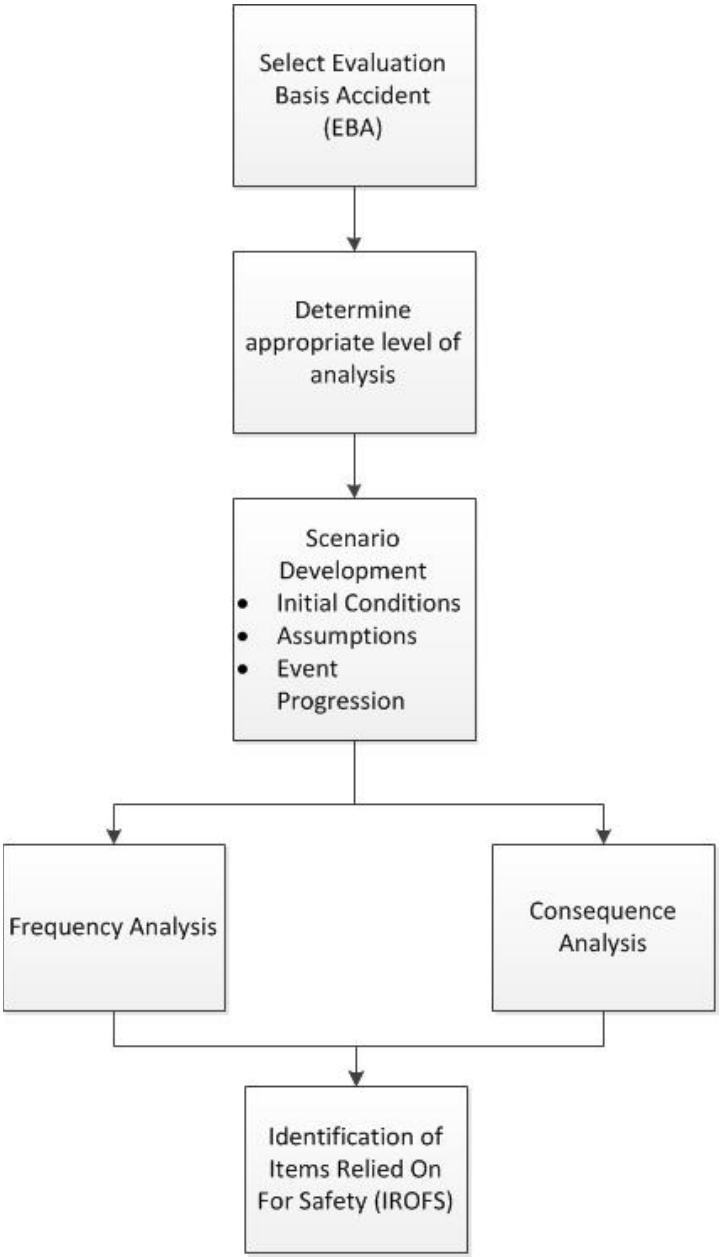

Figure 15. Accident analysis process

All assumptions made in the accident analysis (i.e., defining points in the scenario progression) are validated as part of the accident analysis activity. For example, if an operator is supposed to push Button Z to stop an accident progression, the accident analysis needs to make it clear that the operator can actually do so. Making it clear may simply involve noting there are no physical phenomena associated with the accident that would preclude him or her from doing so. Likewise, basic assurance must be provided that equipment relied upon in unusual or severe environments will function. This assurance does not constitute the need for or expectation of full, formal environmental qualification.

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4.3.1 Accident Analysis Methodology

The EBAs in the following section were either postulated accidents or further refinement of bounding events where a better understanding of the likelihood of occurrence or the consequences was deemed necessary. Generally, the level of analysis is commensurate with the initial risk, with higher risk scenarios receiving a more rigorous treatment than lower risk scenarios. In some cases, only the consequence analysis was performed.

Scenario Development: Typically, the scenario describes the initial conditions and assumptions used to bound the event, describe the hazard, and quantify the material at risk. Next, the accident progression from the initiating event, through the deviations caused by the initiating event, leading to the loss event(s) is described. Preventive and mitigative safeguards are proposed; these are then evaluated in the consequence and frequency analysis.

Consequence Analysis: The consequence analysis uses an appropriate methodology or model for the phenomenon involved. The consequences are quantified initially taking no credit for mitigative features. Subsequent iterations credit the mitigative features until there is a sufficient reduction in the consequences. Typically, it is this final set of conditions that is described in the accident analysis.

Frequency Analysis: For purposes of the HAR, the frequency analysis is limited to quantification through simple means such as event trees and fault trees. The process for frequency analysis consists of estimating the likelihood of the initiating event, identification of preventive and mitigative controls and their probability of success, and the ultimate likelihood of the loss event(s). The process can be iterative, adding additional safeguards until the desired likelihood of the loss event(s) is determined.

Finally, the set of preventive and mitigative safeguards are identified as IROFS.

4.3.2 Items Relied on for Safety from the Accident Analysis

The ESIF accident analysis generated an additional set of IROFS beyond those defined in the PrHA bounding event analysis. The IROFS from the accident analysis were presented in Table 3.

The combined set of IROFS defined through bounding event analysis and accident analysis is listed in Table 22.

Table 22. IROFs Defined through Bounding Event Analysis and Accident Analysis

Item Relied on for Safety	Control Type	System, Laboratory or Activity	Accident Type	Scenario
Design Feature: Components are located in standard NEC-rated electrical enclosures.	EC	REDB System/ Normal Electric Power	Electric shock or arc flash	Flood from inadvertent sprinkler head operation

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Item Relied on for Safety	Control Type	System, Laboratory or Activity	Accident Type	Scenario
Design Feature: All source connections have standard overcurrent protection that will remove the energy in the event of a ground fault.	EC	REDB System/ Normal Electric Power/Fire Suppression; Laboratory Safety	Electric shock or arc flash	Flood from inadvertent sprinkler head operation
Design Feature: Fire suppression flow switch generates a high bay fire alarm. A high bay fire alarm results in an EPO.	EC	REDB System/ Normal Electric Power	Electric shock or arc flash	Flood from inadvertent sprinkler head operation
Design Feature: The compact reconfigurable (cRIO) control modules prevent closing or opening switches if the voltage is greater than 50V.	EC	REDB System	Electric shock or arc flash	Shock, arc flash, explosion resulting from ground faults, short circuits
Work Control Documents require dead bus switching unless a recloser or other device designed for live switching is used.	AC	REDB System/ Normal Electric Power	Electric shock or arc flash	Shock, arc flash, explosion resulting from ground faults, short circuits
Work Control Documents require use of a dedicated industry-standard breaker for any DUT to provide overcurrent protection.	AC	REDB System/ Normal Electric Power	Electric shock or arc flash	Shock, arc flash, explosion resulting from ground faults, short circuits
Design Feature: Dedicated industry-standard breakers are provided for DUTs.	EC	REDB System/ Normal Electric Power	Electric shock or arc flash	Shock, arc flash, explosion resulting from ground faults, short circuits
Design Feature: The REDB and normal electrical power system were designed and installed in accordance with NEC requirements.	EC	REDB System/ Normal Electric Power	Electric shock or arc flash	Shock, arc flash, explosion resulting from ground faults, short circuits
The Preventative Maintenance (PM) program requirements include resistance (ohm) measurement and thermal imaging. (The intent of these PMs is to specify routine inspection and testing of the system that will identify weak spots prior to a failure.)	AC	REDB System/ Normal Electric Power	Electric shock or arc flash	Shock, arc flash, explosion resulting from ground faults, short circuits

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Item Relied on for Safety	Control Type	System, Laboratory or Activity	Accident Type	Scenario
Work Control Documents include Electrical Safety Program requirements for the use of proper PPE and clothing by workers completing dead bus confirmation and changing switch positions.	AC	REDB System/ Normal Electric Power	Electric shock or arc flash	Shock, arc flash, explosion resulting from ground faults, short circuits
Work Control Documents for the REDB System in the laboratories require an operable SCADA System or define compensatory measures if the SCADA System is not operable. (The SCADA System provides remote indication and operation of critical components associated with the Normal Electric Power System. The SCADA System is only credited as an administrative control as design does not include any provisions beyond component status and remote operation requests.)	AC	REDB System/ Normal Electric Power System	Electric shock or arc flash	Shock, arc flash, explosion resulting from ground faults, short circuits
Design Feature: Sweitzer Engineering Laboratories (SEL) protective reclosers are installed in the systems. (These reclosers were specified in accordance with normal standards for medium voltage distribution and have industry standard monitoring and programming that interrupt the source during a fault condition to limit the energy.)	EC	REDB System/ Normal Electric Power	Electric shock or arc flash	Shock, arc flash, explosion resulting from ground faults, short circuits
Work Control Documents include Electrical Safety Program requirements for proper bus labeling and LOTO.	AC	REDB System/ Normal Electric Power	Electric shock or arc flash	Shock, arc flash, explosion resulting from ground faults, short circuits
Flammable liquids are stored in cabinets per the requirements of the Chemical Safety Program.	AC	Flammable liquid handling	Fire - Small local fire in work area	Improper handling of flammable liquids leading to small fire

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Item Relied on for Safety	Control Type	System, Laboratory or Activity	Accident Type	Scenario
Work Control Documents include the requirements defined in the Chemical Safety Program for performing activities handling flammable liquids inside fume hoods whenever possible, and limiting the quantities of flammable liquids used in fume hoods.	AC	Flammable liquid handling	Fire - Small local fire in work area	Improper handling of flammable liquids leading to small fire
Design Feature: Smoke detectors are provided in the labs to notify facility personnel to evacuate prior to exposure to toxic smoke.	EC	Fire Detection System/ Laboratory Safety	Fire - Small local fire in work area	Improper handling of flammable liquids leading to small fire
Design Feature: The Facility Sprinkler System activates to extinguish fires that occur from improper handling of flammable liquids.	EC	Fire Suppression System	Fire - Small local fire in work area	Improper handling of flammable liquids leading to small fire
Work Control Documents require that nanomaterials be transported in containers with sealed or taped lids.	AC	Nanomaterial handling	Release with exposure	Release of nanomaterials to room (dropped or spilled container)
Work Control Documents for nanomaterials include requirements for PPE to protect facility workers from exposure to nanomaterials during normal work or due to a dropped or spilled container.	AC	Nanomaterial handling	Release with exposure	Release of nanomaterials to room (dropped or spilled container)
Design Feature: Nanomaterials are handled in enclosures with HEPA filtration on the exhaust system. If the use of an enclosure is not possible, local exhaust with HEPA filtration is used.	EC	Nanomaterial handling/ Laboratory Exhaust Ventilation	Release with exposure	Release of nanomaterials to room (dropped or spilled container)
LLP 6-1.46, *Chemical Safety*, complies with DOE/ NIOSH guidelines for safe handling of nanomaterials. Work Control Documents associated with nanomaterials incorporate requirements in accordance with this LLP.	AC	Nanomaterial handling	Release with exposure	Release of nanomaterials to room (dropped or spilled container)

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Item Relied on for Safety	Control Type	System, Laboratory or Activity	Accident Type	Scenario
Design Feature: The House Hydrogen System is designed per the requirements of LLP 6-1.62, *Pressure Safety*, including ASME Pressure Vessel Code requirements.	EC	House Hydrogen System	Equipment damage with injuries	Catastrophic rupture of high-pressure hydrogen storage vessel, caused by overpressure from compressor, back flow, temperature swings
Work Control Documents for the House Hydrogen System define the required preventive maintenance requirements including monitoring the tanks for UV damage.	AC	House Hydrogen System	Equipment damage with injuries	Catastrophic rupture of high-pressure hydrogen storage vessel, caused by overpressure from compressor, back flow, temperature swings
Work Control Documents for the House Hydrogen System define the requirements for filling the hydrogen storage tank to the desired pressure based on the outside temperature.	AC	House Hydrogen System	Equipment damage with injuries	Catastrophic rupture of high-pressure hydrogen storage vessel, caused by overpressure from compressor, back flow, temperature swings
Design Feature: Bollards or other approved means of protection are installed according to code around the hydrogen storage tanks to protect the tanks from normal vehicle traffic.	EC	House Hydrogen System	Equipment damage with injuries	Catastrophic rupture of high-pressure hydrogen storage vessel, caused by overpressure from compressor, back flow, temperature swings
Design Feature: The House Hydrogen System is designed and installed per the ICC and NFPA code requirements.	EC	House Hydrogen System	Equipment damage with injuries	Catastrophic rupture of high-pressure hydrogen storage vessel, caused by overpressure from compressor, back flow, temperature swings
Design Feature: Pressure relief devices are provided on the hydrogen storage vessels to protect against over-pressurization.	EC	House Hydrogen System	Equipment damage with injuries	Catastrophic rupture of high-pressure hydrogen storage vessel, caused by overpressure from compressor, back flow, temperature swings
Work Control Documents for the House Hydrogen System require isolation valves to pressure relief devices to be in the open position.	AC	House Hydrogen System	Equipment damage with injuries	Catastrophic rupture of high-pressure hydrogen storage vessel caused by overpressure from compressor, back flow, temperature swings.

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Item Relied on for Safety	Control Type	System, Laboratory or Activity	Accident Type	Scenario
Work Control Documents for the House Hydrogen System require isolation valves to pressure relief devices to be in the open position.	AC	House Hydrogen System	Explosion – blast over-pressure	Backflow of hydrogen from storage (outside the building) to ESIL (where hydrogen is generated/compressed) causing over pressure of piping or equipment with release.
Work Control Documents for the House Hydrogen System specify pressure relief device calibration frequencies; these requirements are incorporated in the preventive maintenance requirements for the system.	AC	House Hydrogen System	Equipment damage with injuries	Catastrophic rupture of high-pressure hydrogen storage vessel, caused by overpressure from compressor, back flow, temperature swings.
Work Control Documents for the House Hydrogen System specify pressure relief device calibration frequencies; these requirements are incorporated in the preventive maintenance requirements for the system.	AC	House Hydrogen System	Explosion – blast over-pressure	Backflow of hydrogen from storage (outside the building) to ESIL (where hydrogen is generated/compressed) causing overpressure of piping or equipment with release. Hydrogen fire during vehicle filling because connection is not leak-tight (Note: not in Day 1 buildout)
Work Control Documents for the House Hydrogen System specify pressure relief device calibration frequencies; these requirements are incorporated in the preventive maintenance requirements for the system.	AC	House Hydrogen System	Fire	Hydrogen fire during vehicle filling because connection is not leak-tight (Note: not in Day 1 buildout)
Work Control Documents for the House Hydrogen System specify pressure relief device calibration frequencies; these requirements are incorporated in the preventive maintenance requirements for the system.	AC	House Hydrogen System	Fire Explosion – fire Exposure to high temper-ature	Grass fire heats hydrogen storage vessels, compressor, components, causing pressure relief valve to vent H_2 gas
Work Control Documents for the House Hydrogen System require restricted access to hydrogen tanks through a locked gate.	AC	House Hydrogen System	Equipment damage with injuries	Catastrophic rupture of high-pressure hydrogen storage vessel, caused by overpressure from compressor, back flow, temperature swings

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Item Relied on for Safety	Control Type	System, Laboratory or Activity	Accident Type	Scenario
Design Feature: Check valves are installed on the House Hydrogen System to provide reverse flow protection.	EC	House Hydrogen System	Equipment damage with injuries.	Catastrophic rupture of high-pressure hydrogen storage vessel, caused by overpressure from compressor, back flow, temperature swings.
Design Feature: Check valves are installed on the House Hydrogen System to provide reverse flow protection.	EC	House Hydrogen System	Explosion – blast over-pressure	Backflow of hydrogen from storage (outside the building) to ESIL (where hydrogen is generated/compressed) causing over pressure of piping or equipment with release.
Design Feature: The high-pressure hydrogen storage tanks are installed at the required separation from other facilities.	EC	House Hydrogen System	Equipment damage with injuries	Catastrophic rupture of high-pressure hydrogen storage vessel, caused by overpressure from compressor, back flow, temperature swings
Design Feature: The hydrogen storage vessels are designed to meet the ASME Pressure Vessel Code.	EC	House Hydrogen System	Explosion – blast over-pressure	Backflow of hydrogen from storage (outside the building) to ESIL (where hydrogen is generated/compressed) causing overpressure of piping or equipment with release.
Design Feature: The hydrogen compressors are designed and installed according to ICC and NFPA code requirements.	EF	House Hydrogen System	Explosion – blast over-pressure	Backflow of hydrogen from storage (outside the building) to ESIL (where hydrogen is generated/compressed) causing over pressure of piping or equipment with release.
Design Feature: Pressure relief devices are provided on the House Hydrogen System to protect against over-pressurization.	EC	House Hydrogen System	Explosion – blast over-pressure	Backflow of hydrogen from storage (outside the building) to ESIL (where hydrogen is generated/compressed) causing over pressure of piping or equipment with release.
Design Feature: Pressure relief devices are provided on the House Hydrogen System to protect against over-pressurization.	EC	House Hydrogen System	Fire Explosion – fire Exposure to high tempera-ture	Grass fire heats hydrogen storage vessels, compressor, components, causing pressure relief valve to vent H_2 gas

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Design Feature: The vent pipes from the House Hydrogen System pressure relief devices are raised vertically to release any hydrogen above people / property.	EC	House Hydrogen System	Equipment damage with injuries	Catastrophic rupture of high-pressure hydrogen storage vessel, caused by overpressure from compressor, back flow, temperature swings
Design Feature: The vent pipes from the House Hydrogen System pressure relief devices are raised vertically to release any hydrogen above people / property.	EC	House Hydrogen System	Explosion – blast over-pressure	Backflow of hydrogen from storage (outside the building) to ESIL (where hydrogen is generated/compressed) causing over pressure of piping or equipment with release.
Design Feature: The vent pipes from the House Hydrogen System pressure relief devices are raised vertically to release any hydrogen above people / property.	EC	House Hydrogen System	Fire Explosion – fire Exposure to high tempera-ture	Grass fire heats hydrogen storage vessels, compressor, components, causing pressure relief valve to vent H_2 gas
Specific Administrative Control: Requirements for the control of ignition sources in accordance with classification of the hydrogen station (C1D2 Group B) are defined in the House Hydrogen System work control documents.	SAC	House Hydrogen System	Fire	Hydrogen fire during vehicle filling because connection is not leak-tight (Note: not in Day 1 buildout)
Design Feature: EPA/NFPA safety standards for hydrogen refilling stations are incorporated into the hydrogen filling station design.	EC	House Hydrogen System	Fire	Hydrogen fire during vehicle filling because connection is not leak-tight (Note: not in Day 1 buildout)
Design Feature: The hydrogen filling station is designed according to NFPA guidelines including the installation of pressure relief devices.	EC	House Hydrogen System	Fire	Hydrogen fire during vehicle filling because connection is not leak-tight (Note: not in Day 1 buildout)
Design Feature: The hydrogen filling station is located outside to allow ventilation and dispersion of any released hydrogen.	EC	House Hydrogen System	Fire	Hydrogen fire during vehicle filling because connection is not leak-tight (Note: not in Day 1 buildout)

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Design feature: A UV/IR camera is provided that covers the hydrogen dispensing area and will activate a shut-off valve if a hydrogen fire is detected.	EC	House Hydrogen System/Gas Detection System/ Laboratory Safety System	Fire	Hydrogen fire during vehicle filling because connection is not leak-tight (Note: not in Day 1 buildout)
Work Control Documents for the House Hydrogen System specify preventive maintenance requirements for the UV/IR camera and shut off valve.	AC	House Hydrogen System/Gas Detection System	Fire	Hydrogen fire during vehicle filling because connection is not leak-tight (Note: not in Day 1 buildout)
Specific Administrative Control: Requirements for the control of combustible materials around the vessel storage area are defined in House Hydrogen System work control documents.	SAC	House Hydrogen System	Fire Explosion – fire Exposure to high tempera-ture	Grass fire heats hydrogen storage vessels, compressor, components, causing pressure relief valve to vent H_2 gas
Design Feature: The hydrogen storage pad design is concrete to prevent a fire directly under a tank.	EC	House Hydrogen System	Fire Explosion – fire Exposure to high tempera-ture	Grass fire heats hydrogen storage vessels, compressor, components, causing pressure relief valve to vent H_2 gas
Design Feature: The hydrogen control system has feedback on automated valves to alert the system of a failure (i.e., valve failing to open).	EC	House Hydrogen System	Equipment damage	Pressure or flow required by compressor is not provided resulting in compressor damage and/or release of hydrogen (closed valves, obstruction, failed pressure transmitter, etc.).
Work Control Documents for the House Hydrogen system specify preventive maintenance requirements for the automated valves and these requirements are incorporated in the preventive maintenance requirements for the system.	AC	House Hydrogen System	Equipment damage	Pressure or flow required by compressor is not provided resulting in compressor damage and/or release of hydrogen (closed valves, obstruction, failed pressure transmitter, etc.).

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Design feature: the House Hydrogen System includes pressure transmitters that monitor and shut off the hydrogen compressor.	EC	House Hydrogen System	Equipment damage	Pressure or flow required by compressor is not provided resulting in compressor damage and/or release of hydrogen (closed valves, obstruction, failed pressure transmitter, etc.).
Work Control Documents for the House Hydrogen system specify pressure transmitter calibration frequencies and these requirements are incorporated in the preventive maintenance requirements for the system.	AC	House Hydrogen System	Equipment damage	Pressure or flow required by compressor is not provided resulting in compressor damage and/or release of hydrogen (closed valves, obstruction, failed pressure transmitter, etc.).
Design Feature: The hydrogen compressor's supply pressure switch low cut off is interlocked with the compressor.	EC	House Hydrogen System	Equipment damage	Pressure or flow required by compressor is not provided resulting in compressor damage and/or release of hydrogen (closed valves, obstruction, failed pressure transmitter, etc.).
Design Feature: The standard design for gas bottles requires fittings for oxygen bottles and air bottles that are incompatible with hydrogen system connections.	EC	House Hydrogen System	Explosion – fire	Accidentally connect air or O_2 cylinder to H_2 system
Work Control Documents for the House Hydrogen System define the requirements and procedure for attaching gas bottles to the House Hydrogen System if onsite generated hydrogen is not used.	AC	House Hydrogen System	Explosion – fire	Accidentally connect air or O_2 cylinder to H_2 system
Design Feature: The oxygen detectors in the FCDTL will alarm prior to achieving an oxygen-deficient atmosphere.	EC	Gas Detection System/ Nitrogen (House) System/ Laboratory Safety/ FCDTL	Release	Spill, leak, or open liquid nitrogen dewar
Work Control Documents include PPE requirements in accordance with the Chemical Safety Program to protect workers from exposure due to spills or leaks.	AC	Nitrogen (House) System/ FCDTL	Release	Spill, leak, or open liquid nitrogen dewar

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Work Control Documents include requirements and procedures for correct handling to prevent spills, and procedures for cleaning up spills.	AC	Nitrogen (House) System	Release	Spill, leak, or open liquid nitrogen dewar
Design Feature: The Laboratory Ventilation Supply and Exhaust Systems provide adequate air change rate to remove released inert gas.	EC	Nitrogen (House) System/ Laboratory Supply Ventilation and Laboratory Exhaust Ventilation Systems/ Laboratory Safety	Release	Spill, leak, or open liquid nitrogen dewar
Design Feature: The size of ESIF laboratories where nitrogen dewars are used creates a large volume that will not be easily replaced with inert nitrogen in the event of a bottle spill.	EC	Nitrogen (House) System	Release	Spill, leak, or open liquid nitrogen dewar
Design Feature: Dewars are designed so that they will not tip over, causing a spill. The material of construction for dewars prevents leaks.	EC	Nitrogen (House) System	Release	Spill, leak, or open liquid nitrogen dewar
Design Feature: The High Pressure Test Bays are constructed with blowout panels to relieve pressure in the laboratories caused by an overpressure event or explosion.	EC	High Pressure Test Bay	Equipment damage with injuries	Rupture of component in High Pressure Test Cell; media can be water, oil, helium, hydrogen or nitrogen gas
Design Feature: Areas in front of the panels are fenced for restricted access.	EC	High Pressure Test Bay	Equipment damage with injuries	Rupture of component in High Pressure Test Cell; media can be water, oil, helium, hydrogen or nitrogen gas
Design Feature: The panels are located at an elevation to prevent introducing additional hazards to personnel in the area.	EC	High Pressure Test Bay	Equipment damage with injuries	Rupture of component in High Pressure Test Cell; media can be water, oil, helium, hydrogen or nitrogen gas

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Design Feature: The panels are tethered to prevent them from blowing past the restricted area boundary.	EC	High Pressure Test Bay	Equipment damage with injuries	Rupture of component in High Pressure Test Cell; media can be water, oil, helium, hydrogen or nitrogen gas
Design Feature: Shutoff valves and control components are located outside the High Pressure Test Bays (to prevent damage to these components during an event and to assure that hazards can be removed at the end of a test).	EC	High Pressure Test Bay	Equipment damage with injuries	Rupture of component in High Pressure Test Cell; media can be water, oil, helium, hydrogen or nitrogen gas
Design Feature: Duct work inside of the High Pressure Test Bays is designed to handle expected pressures generated by a release. (Additional exhaust duct work provides an additional means of venting to relieve pressure.)	EC	High Pressure Test Bay/ Laboratory Exhaust Ventilation System	Equipment damage with injuries	Rupture of component in High Pressure Test Cell; media can be water, oil, helium, hydrogen or nitrogen gas
Design Feature: Ignition sources inside the High Pressure Test Bays are controlled (designed, installed, maintained) in accordance with the hazard classification of the test bays.	EC	High Pressure Test Bay	Equipment damage with injuries	Rupture of component in High Pressure Test Cell; media can be water, oil, helium, hydrogen or nitrogen gas
Design Feature: Hydrogen gas detection is provided inside the High Pressure Test Bays. Work Control Documents address the following test design requirements: Experiments that require continuous hydrogen supply gas require design and installation of an automated valve that will shut off the hydrogen supply to the test bays if hydrogen is detected.	EC	High Pressure Test Bay/Gas Detection System/House Hydrogen/ Laboratory Safety	Equipment damage with injuries	Rupture of component in High Pressure Test Cell; media can be water, oil, helium, hydrogen or nitrogen gas
Work Control Documents address the following test design requirements: Experiments that require continuous hydrogen supply gas require design and installation of an automated valve that will shut off the hydrogen supply to the test bays if hydrogen is detected.	EC/AC	High Pressure Test Bay/Gas Detection System/House Hydrogen/ Laboratory Safety	Equipment damage with injuries	Rupture of component in High Pressure Test Cell; media can be water, oil, helium, hydrogen or nitrogen gas

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Work Control Documents for the Gas Detection System in the High Pressure Test Bays require an operable SCADA System or define compensatory measures if the SCADA System is not operable. (The High Pressure Test Bays have oxygen detection reported via the SCADA so that personnel can confirm that the space has returned to acceptable conditions prior to entering the space. The SCADA System is only credited as an administrative control as design does not include any provisions beyond monitoring and remote operation requests.)	AC	High Pressure Test Bay/Gas Detection System/ SCADA/ Laboratory Safety	Equipment damage with injuries	Rupture of component in High Pressure Test Cell; media can be water, oil, helium, hydrogen or nitrogen gas
Design Feature: The walls of the High Pressure Test Bays are designed to contain the pressure from the expansive gas and shrapnel from a failed component.	EC	High Pressure Test Bay	Equipment damage with injuries	Rupture of component in High Pressure Test Cell; media can be water, oil, helium, hydrogen or nitrogen gas
Work Control Documents for the High Pressure Test Bays include requirements for inspection after a rupture event to assure that the strength of the walls has not been compromised.	AC	High Pressure Test Bay	Equipment damage with injuries	Rupture of component in High Pressure Test Cell; media can be water, oil, helium, hydrogen or nitrogen gas
Design Feature: The primary containment enclosure in the high pressure test bays is designed to absorb most of the energy from a rupture event.	EC	High Pressure Test Bay	Equipment damage with injuries	Rupture of component in High Pressure Test Cell; media can be water, oil, helium, hydrogen or nitrogen gas
Work Control Documents for experiments conducted in the High Pressure Test Bays address access restrictions to the cells during testing. Fencing and general security controls restrict access so that only trained personnel are allowed access into the area.	AC	High Pressure Test Bay/ Laboratory Safety System	Equipment damage with injuries	Rupture of component in High Pressure Test Cell; media can be water, oil, helium, hydrogen or nitrogen gas

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Work Control Documents for the High Pressure Test Bays include setting limits for the testing media volume at 3.5L @15,000 psi.	AC	High Pressure Test Bay	Equipment damage with injuries	Rupture of component in High Pressure Test Cell; media can be water, oil, helium, hydrogen or nitrogen gas
Design Feature: The Laboratory Ventilation and Exhaust Systems provide an adequate air change rate to remove released gases.	EC	High Pressure Test Bay/ Laboratory Supply Ventilation and Laboratory Exhaust Ventilation Systems	Equipment damage with injuries	Rupture of component in High Pressure Test Cell; media can be water, oil, helium, hydrogen or nitrogen gas
Design Feature: Code-compliant low resistance grounding of the test article reduces the heat generated during an event.	EC	Destructive testing of electronic components and devices	Fire	Failure of power electronics board could causes fire and/or damage to lab fuel supply lines resulting in a sustainable fire
Work Control Documents define the process for elimination of residual flammable gases in fuel lines during testing.	AC	Destructive testing of electronic components and devices.	Fire	Failure of power electronics board could causes fire and/or damage to lab fuel supply lines resulting in a sustainable fire
Design Feature: Fuel shut-off valves are located outside laboratories that contain fuel lines.	EC	Destructive testing of electronic components and devices	Fire	Failure of power electronics board could causes fire and/or damage to lab fuel supply lines resulting in a sustainable fire
Work Control Documents address the following test design requirement: Power electronics must be in a robust enclosure when being surge tested.	AC	Destructive testing of electronic components and devices.	Fire	Failure of power electronics board could causes fire and/or damage to lab fuel supply lines resulting in a sustainable fire
Work Control Documents prohibit the coincident use of fuels and surge testing of articles that have the potential to produce shrapnel.	AC	Destructive testing of electronic components and devices.	Fire	Failure of power electronics board could causes fire and/or damage to lab fuel supply lines resulting in a sustainable fire
Work Control Documents require that articles being tested that have the potential to produce shrapnel have a restricted access zone around them.	AC	Destructive testing of electronic components and devices.	Fire	Failure of power electronics board could causes fire and/or damage to lab fuel supply lines resulting in a sustainable fire

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Work Control Documents address the following test design requirement: Articles being tested that have the potential to produce shrapnel are required to have physical barriers to protect piping from shrapnel.	AC	Destructive testing of electronic components and devices.	Fire	Failure of power electronics board could causes fire and/or damage to lab fuel supply lines resulting in a sustainable fire
Work Control Documents require inspection of fuel tanks and fueled equipment before use.	AC	Low Voltage Outdoor Test Area	Spill	Spill of fuel collects in below grade trenches.
Work Control Documents define the spill prevention measures required when refueling equipment.	AC	Outdoor use and storage of liquid fuels.	Spill	Spill of fuel collects in below grade trenches.
Work Control Documents require that a spill cart be provided at the LVOTA.	AC	Outdoor use and storage of liquid fuels.	Spill	Spill of fuel collects in below grade trenches.
Work Control Documents address the following test design requirement: Only DOT-approved fuel tanks, 50-gallon maximum capacity, are to be supplied with equipment.	AC	Outdoor use and storage of liquid fuels.	Spill	Spill of fuel collects in below grade trenches.
Design Feature: The Laboratory Supply and Exhaust Ventilation systems provide an adequate air exchange rate to remove toxic gases.	EC	Laboratory Supply Ventilation and Laboratory Exhaust Ventilation Systems/ Laboratory Safety	Release with exposure	Exposure to toxic gas resulting from indoor use of combustion engines.
Design Feature: Toxic gas monitoring (CO) equipment is provided in laboratories used to test combustion engines. The equipment will alarm to alert personnel of a potential release.	EC	Gas Detection System/ Laboratory Safety	Release with exposure	Exposure to toxic gas resulting from indoor use of combustion engines.
Design Feature: Toxic gas monitoring equipment is provided in laboratories used to test combustion engines. The equipment will alarm to alert personnel of a potential release.	EC	Gas Detection System/ Laboratory Safety	Release with exposure	Exposure to toxic gas resulting from indoor use of combustion engines.

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Design Feature: The Laboratory Exhaust Ventilation System provides the capability to connect to vehicle/DUT exhaust. The Work Control Documents for operating vehicles or DUT indoors define the requirements for making the connection.	EC	Laboratory Exhaust Ventilation System/ Laboratory Safety	Release with exposure	Exposure to toxic gas resulting from indoor use of combustion engines.
Design Feature: The design of laboratories provides a large space relative to the exhaust rate. (This reduces the likelihood that toxic gas levels can be reached due to a leak, failure of vent system, or failure to connect the vent to the exhaust.)	EC	Laboratory Exhaust Ventilation System	Release with exposure	Exposure to toxic gas resulting from indoor use of combustion engines.
Work Control Documents address the following test design requirement: Heat transfer fluid boilers must be supplied with a pressure relief device and an enclosure (i.e., spray shield) that would minimize the spray of the heated fluid from failed components.	AC	High-temperature materials handling (molten salts and metals)	Exposure to high tempera-ture Fire – small local fire in work area	Burns from exposure to release of heat transfer fluid and small local fire
Work Control Documents address the following test design requirement: Noncorrosive construction materials must be used for thermal testing equipment containing corrosive materials.	AC	High temperature materials handling (molten salts and metals)	Exposure to high tempera-ture Fire –- small local fire in work area	Burns from exposure to release of heat transfer fluid and small local fire
Work Control Documents define periodic inspection and maintenance of thermal testing equipment.	AC	High-temperature materials handling (molten salts and metals)	Exposure to high tempera-ture Fire – small local fire in work area	Burns from exposure to release of heat transfer fluid and small local fire
Work Control Documents define the PPE requirements when working with thermal testing equipment.	AC	High-temperature materials handling (molten salts and metals)	Exposure to high tempera-ture Fire – small local fire in work area	Burns from exposure to release of heat transfer fluid and small local fire

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Design Feature: The Fire Detection System will detect a significant release and alarm, alerting personnel to evacuate.	EC	High-temperature materials handling (molten metal and salts)/Fire Detection System/ Laboratory Safety	Exposure to high tempera-ture Fire – small local fire in work area	Burns from exposure to release of heat transfer fluid and small local fire
Design Feature: Hot vapors or fire will activate the Fire Suppression System and alarm, alerting personnel to evacuate.	EC	High-temperature materials handling (molten metal and salts)/Fire Suppression System/Laboratory Safety	Exposure to high tempera-ture Fire – small local fire in work area	Burns from exposure to release of heat transfer fluid and small local fire
Design Feature: REDB and Normal Electric Power breakers provide industry standard overcurrent protection.	EC	REDB System/ Normal Electric Power	Electric shock or arc flash	AC Ground Faults (phase to ground or phase to phase) due to insulation breakdown, mis-wiring, physical damage or equipment failure
Design Feature: Design and installation of the REDB and Normal Electric Power is per the NEC.	EC	REDB System/ Normal Electric Power	Electric shock or arc flash	AC Ground Faults (phase to ground or phase to phase) due to insulation breakdown, mis-wiring, physical damage or equipment failure
The Preventative Maintenance (PM) program requirements for the REDB System and Normal Electric Power include resistance (Ohm) measurement and thermal imaging. (The intent of these PMs is to specify routine inspection and testing of the system that will identify weak spots prior to a failure.)	AC	REDB System/ Normal Electric Power	Electric shock or arc flash	AC Ground Faults (phase to ground or phase to phase) due to insulation breakdown, mis-wiring, physical damage or equipment failure
Design Feature: SCADA provides remote indication and operation of critical components. (SCADA is only credited as an administrative control for this area as design does not include any provisions beyond component status and remote operation requests.)	EC	REDB/Normal Electric Power/SCADA System	Electric shock or arc flash	AC Ground Faults (phase to ground or phase to phase) due to insulation breakdown, mis-wiring, physical damage or equipment failure

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Design Feature: Barriers prevent damage to nearby equipment.	EC	House Hydrogen	Compressor Failure	A compressor with an internal volume of 1 liter operating at 15,000 psi fails catastrophically generating a pressure pulse equivalent to 22 grams of TNT. The greatest hazard would be from the shrapnel produced.
Work Control Documents require that access to the Energy Storage Outside Test Area during compressor operation is restricted to essential personnel.	AC	House Hydrogen	Compressor Failure	A compressor with an internal volume of 1 liter operating at 15,000 psi fails catastrophically generating a pressure pulse equivalent to 22 grams of TNT. The greatest hazard would be from the shrapnel produced.
Design Feature: The vessel is rated at 15,000 psig and constructed in accordance with ASME BPVC Section XIII, Division 3 and/or Section X, Class III standards and tested to at least 125% MAWP.	EC	House Hydrogen	Hydrogen Storage Vessel Rupture	The ESOTA includes a FIBA vessel rated for 15,000 psig with a maximum operating pressure of 13,500 psig. The rupture will be assumed to occur at 15,000 psig due to corrosion, defect, cyclical failure, or impact.
Design Feature: Compressor pressure controls, pressure relief valves and pressure reducing stations prevent over pressurization of the vessel. Installation is in accordance with NFPA 2 for risk-based separation distances	EC	House Hydrogen	Hydrogen Storage Vessel Rupture	The ESOTA includes a FIBA vessel rated for 15,000 psig with a maximum operating pressure of 13,500 psig. The rupture will be assumed to occur at 15,000 psig due to corrosion, defect, cyclical failure, or impact.
Design Feature: Electrical systems are classified Class 1, Division 2 and ignition sources have been eliminated	EC	House Hydrogen	Hydrogen Storage Vessel Rupture	The ESOTA includes a FIBA vessel rated for 15,000 psig with a maximum operating pressure of 13,500 psig. The rupture will be assumed to occur at 15,000 psig due to corrosion, defect, cyclical failure, or impact.

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Design Feature: Interlocked UV/IR sensors detect hydrogen fires within the ESOTA and initiate alarms and shutdown sequences.	EC	House Hydrogen/ Laboratory Safety	Hydrogen Storage Vessel Rupture	The ESOTA includes a FIBA vessel rated for 15,000 psig with a maximum operating pressure of 13,500 psig. The rupture will be assumed to occur at 15,000 psig due to corrosion, defect, cyclical failure, or impact.
Design Feature: The ESIL is continuously monitored by a hydrogen detection system. At 10% of LFL, the system causes the basic ventilation to double its exhaust flow rate from 7,000 cfm to 14,000 cfm. At 25% LFL, the system generates an EPO that halts hydrogen production and transfer.	EC	House Hydrogen/ Laboratory Ventilation/Laboratory Safety	Leakage of hydrogen into a confined space	The failure of a hydrogen supply line in the ESIL results in the contents of the 3000 psig storage vessel (a maximum of 10.3 kilograms hydrogen) being released into the laboratory. The LFL will be exceeded.
Design Feature: The ESIL ceiling T-beams create 13 2-foot deep channels that have hydrogen detection system sample ports and forced (push/pull) ventilation. Design Feature: The ESIL was constructed with Class 1, Division 2 electrical systems. Non-classified test articles are allowed below 15 feet above floor level.	EC	House Hydrogen/ Laboratory Ventilation/Laboratory Safety	Leakage of hydrogen into a confined space	The failure of a hydrogen supply line in the ESIL results in the contents of the 3000 psig storage vessel (a maximum of 10.3 kilograms hydrogen) being released into the laboratory. The LFL will be exceeded.
Design Feature: A check valve prevents backflow from the hydrogen storage vessel.	EC	House Hydrogen/ Laboratory Ventilation	Leakage of hydrogen into a confined space	The failure of a hydrogen supply line in the ESIL results in the contents of the 3000 psig storage vessel (a maximum of 10.3 kilograms hydrogen) being released into the laboratory. The LFL will be exceeded.

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Item Relied on for Safety	Control Type	System, Laboratory or Activity	Accident Type	Scenario
Design Feature: The ESIL was constructed with Class 1, Division 2 electrical systems. Non-classified test articles are allowed 15 feet above the floor level.	EC	House Hydrogen/ Laboratory Ventilation	Leakage of hydrogen into a confined space	The failure of a hydrogen supply line in the ESIL results in the contents of the 3000 psig storage vessel (a maximum of 10.3 kilograms hydrogen) being released into the laboratory. The LFL will be exceeded.
Work control documents require a second REDB control room engineer will verify the configuration entered before energizing the experiment is allowed.	AC	REDB	Misconfiguration of REDB racetrack and laterals from REDB control system HMI	The wrong REDB laboratory lateral is inadvertently energized after an electrical source is connected to a misconfigured REDB system line-up due to human error.
Work control documents require that a second REDB control room engineer verifies that the intended limits were properly entered.	AC	REDB	Improper operating limits are entered into the REDB control system HMI	A current overload on a portion of the REDB resulting from human error
The safety PLC system is under configuration management.	AC	REDB	Corrupt or compromised control logic is introduced into the REDB control system	Normal software-controlled safety functions performed by the REDB control system fail due to human error, malicious human intervention, or controller corruption
Design Feature: The flow battery has on-board leak detection that provides notification.	EC	Testing devices that have a large volume of corrosive liquid	Release of a large volume of corrosive liquid.	A large-scale electrolyte leakage due to rupture of the containment vessel due to mechanical impact, over-pressurization, or a material defect or corrosion.

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Item Relied on for Safety	Control Type	System, Laboratory or Activity	Accident Type	Scenario
Design Feature: The leak detector interlock shuts off electrolyte transfer pumps.	EC	Testing devices that have a large volume of corrosive liquid	Release of a large volume of corrosive liquid.	A large-scale electrolyte leakage due to rupture of the containment vessel due to mechanical impact, over-pressurization, or a material defect or corrosion.
Design Feature: The room is equipped with a containment berm, sized to contain the entire contents of the flow battery.	EC	Testing devices that have a large volume of corrosive liquid	Release of a large volume of corrosive liquid.	A large-scale electrolyte leakage due to rupture of the containment vessel due to mechanical impact, over-pressurization, or a material defect or corrosion.
Work control documents require that containers are limited to a maximum size of 1 gallon.	AC	Strong acid handling	Toxic Spill Inside	A container of strong acid is dropped during transportation causing rupture of the container and subsequent release.
Work control documents require that labs where acids are handled have at least 6 air changes per hour.	AC	Strong acid handling	Toxic Spill Inside	A container of strong acid is dropped during transportation causing rupture of the container and subsequent release.
Work control documents require that only DOT approved tanks or drums are used.	AC	Outdoor refueling	Hazardous Material Spill Outside	Diesel, bio-diesel, or gasoline driven equipment can experience a spill during fueling or transfer, or a failure of a storage tank or on-board fuel tank.
Work control documents require that all fueling and transfers are attended operation.	AC	Outdoor refueling	Hazardous Material Spill Outside	Diesel, bio-diesel, or gasoline driven equipment can experience a spill during fueling or transfer, or a failure of a storage tank or on-board fuel tank.
Work control documents require that transfers are by hand pump only.	AC	Outdoor refueling	Hazardous Material Spill Outside	Diesel, bio-diesel, or gasoline driven equipment can experience a spill during fueling or transfer, or a failure of a storage tank or on-board fuel tank.
Work control documents require that all connections to toxic gas cylinders are made within a vented and purged gas cabinet or hood, located in the service corridor.	AC	Toxic gas cylinder handling Laboratory Exhaust System Laboratory Gas Supply	Toxic Gas Leak	The contents of a 170-pound H_2S cylinder leak into the FCDTL, the result of impact/mechanical damage of the process tubing.

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Item Relied on for Safety	Control Type	System, Laboratory or Activity	Accident Type	Scenario
Design Feature: Stainless steel tubing transporting toxic gas between the gas cabinet, fume hoods, and any enclosures has fully-welded construction and is doubly contained within a carrier pipe.	EC	Laboratory Gas Supply Laboratory Exhaust System	Toxic Gas Leak	The contents of a 170-pound H_2S cylinder leak into the FCDTL, the result of impact/mechanical damage of the process tubing.
Design Feature: The FCDTL has an occupied air change rate of at least 6 per hour, resulting in a minimum exhaust flow rate of 1967 scfm.	EC	Laboratory Exhaust System	Toxic Gas Leak	The contents of a 170-pound H_2S cylinder leak into the FCDTL, the result of impact/mechanical damage of the process tubing.
Work control documents require that the process tubing and carrier pipe are pressure tested annually and between usage campaigns before introducing the toxic gas.	AC	Laboratory Gas Supply	Toxic Gas Leak	The contents of a 170-pound H_2S cylinder leak into the FCDTL, the result of impact/mechanical damage of the process tubing.
Work control documents require that gas cabinets and fume hoods are inspected regularly and tested annually to ensure proper operation.	AC	Laboratory Gas Supply Laboratory Exhaust System Gas Detection system	Toxic Gas Leak	The contents of a 170-pound H_2S cylinder leak into the FCDTL, the result of impact/mechanical damage of the process tubing.
Design Feature: FCDTL (C323) is equipped with an aspirating air sampler equipped with the appropriate toxic gas detectors. At 50% of the NIOSH or OSHA threshold for the toxic gas, the system generates a warning light and alarm. At 100% of the threshold, the system automatically triggers an alarm, including a red alarm light, SCADA system interdiction, lab alarm horn, maximizing the lab exhaust flow rate and closing the gas manifold valve.	EC	Laboratory Exhaust System Gas Detection system/ Laboratory Safety	Toxic Gas Leak	The contents of a 170-pound H_2S cylinder leak into the FCDTL, the result of impact/mechanical damage of the process tubing.

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Item Relied on for Safety	Control Type	System, Laboratory or Activity	Accident Type	Scenario
Work control documents require that solvents are limited to a maximum container size of 1 gallon and are stored in flammable storage cabinets when not being used.	AC	Flammable material handling	Toxic Fumes from Combust-ion of Power Electron-ics or Solvents	Research activities in a number of laboratories have the potential to create small fires that are not self-sustaining. These fires are created from the overheating of power electronics or the spill of solvents contacting an ignition source. Smoke from these fires can contain toxic substances as well as the products of combustion.
Work control documents define administrative controls require laboratories to be kept clean and free of combustible debris such as cardboard boxes.	AC	Flammable material handling	Toxic Fumes from Combust-ion of Power Electron-ics or Solvents	Research activities in a number of laboratories have the potential to create small fires that are not self-sustaining. These fires are created from the overheating of power electronics or the spill of solvents contacting an ignition source. Smoke from these fires can contain toxic substances as well as the products of combustion.
Design Feature: Fire extinguishers are located throughout the facility allowing users to quickly extinguish a small fire.	EC	Fire Suppression System	Toxic Fumes from Combus-tion of Power Electron-ics or Solvents	Research activities in a number of laboratories have the potential to create small fires that are not self-sustaining. These fires are created from the overheating of power electronics or the spill of solvents contacting an ignition source. Smoke from these fires can contain toxic substances as well as the products of combustion.
Design Feature: Construction of the laboratories utilize low flammable materials to prevent the spread of any small fires (epoxy coated concrete floors, open steel structure, concrete ceilings, drywall walls, etc.)	EC	All ESIF laboratories	Toxic Fumes from Combus-tion of Power Electron-ics or Solvents	Research activities in a number of laboratories have the potential to create small fires that are not self-sustaining. These fires are created from the overheating of power electronics or the spill of solvents contacting an ignition source. Smoke from these fires can contain toxic substances as well as the products of combustion.

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Item Relied on for Safety	Control Type	System, Laboratory or Activity	Accident Type	Scenario
Design Feature: Ventilation is designed to keep any release in the associated lab and exhaust the smoke to the roof stacks.	EC	Laboratory Exhaust System	Toxic Fumes from Combus-tion of Power Electron-ics or Solvents	Research activities in a number of laboratories have the potential to create small fires that are not self-sustaining. These fires are created from the overheating of power electronics or the spill of solvents contacting an ignition source. Smoke from these fires can contain toxic substances as well as the products of combustion.
Design Feature: Ventilation removes any smoke (toxins) from the facility and provides safe egress routes and time for personnel to exit the facility, limiting the exposure to toxins.	EC	Laboratory Exhaust System	Toxic Fumes from Combus-tion of Power Electron-ics or Solvents	Research activities in a number of laboratories have the potential to create small fires that are not self-sustaining. These fires are created from the overheating of power electronics or the spill of solvents contacting an ignition source. Smoke from these fires can contain toxic substances as well as the products of combustion.
Design Feature: The fire alarm system with smoke detectors will sense and alarm, leading to evacuation of the facility.	EC	Fire Detection System	Toxic Fumes from Combus-tion of Power Electron-ics or Solvents	Research activities in a number of laboratories have the potential to create small fires that are not self-sustaining. These fires are created from the overheating of power electronics or the spill of solvents contacting an ignition source. Smoke from these fires can contain toxic substances as well as the products of combustion.

4.4 Accident Risk Analysis

A comprehensive risk analysis has been performed for the ESIF. For each event, or transient, an estimate of the event probability and consequence was determined. Risk analysts at NREL use a risk assessment matrix, found in the NREL Hazard Identification and Control Program and included below, to combine the probability and consequence into a semi-quantitative measure of risk. The NREL management team selected this approach because of the dynamic nature of the laboratory programs. If the analysis identifies an event to be moderate or high risk, then designs are derived to achieve a low or routine risk designation.

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The activities proposed for the ESIF are very similar to those currently taking place in various laboratories elsewhere on the NREL campus; hence, much of the ESIF HAR was derived from extensive practical working experience. Despite this fact, the scale of these activities is greater in some cases, and the integration and potential collocation of these operations in one facility pose challenges that must be understood and managed in detail. Given the nature of design-build projects and the design challenges of this facility, it is important that a rigorous process hazard analyses are performed and that thorough application of NREL's hazard identification and control program be continued.

The goal of this analysis was to identify the bounding events relating to life safety and property protection. All other proposed and future work must have a level of risk below the bounding events, or a new assessment would be required to determine the significance of impact to the site. It is important to note that the ESIF bounding events analysis is necessarily an iterative process; hence, the risk scenarios, hazards, controls, mitigations, and the risks themselves may change, evolve, or be refined as the design progresses.

4.5 Hazardous and Potential Events (Original Programming)

The original programming for the ESIF considered the following hazards and potential events. The accident analysis was updated for current programming as described in Section 4.6.

4.5.1 Hydrogen

As indicated previously, the generation, storage, and use of significant quantities of hydrogen at high pressures represent the major hazard at the ESIF. The following discussion is a review of the more significant events associated with handling hydrogen at high pressures, and of their consequences, without considering the probability of their occurrence.

The ESIF includes enough storage capacity for 200 kg hydrogen. Storage pressures range from 3,500 to 15,000 psi. The ESIF hazards analyses builds off the extensive National Aeronautics and Space Administration (NASA) experience handling large quantities of gaseous hydrogen at high pressures. Metals fabrication facilities also use large quantities of hydrogen, as does the petroleum refining industry. Moreover, there are many recent studies, regulations, and specific experience in hydrogen compression, storage, and refueling operations that were reviewed as part of the ESIF hazard analysis. Overall, there have been many years of safe operation, as well as some spectacular failures. The hazards of handling hydrogen are well known, and NREL operations will employ engineering and administrative controls to facilitate its safe use.

The hazards of handling hydrogen stem from its large flammability range—4 % to 75 % (Lees 1996, Table 16.4)—and its very low spark ignition energy—0.019 mJ (Lees 1996, Table 16.6). The *Fire Protection Handbook* (Cote and Linville 1986) states: "Although its wide flammability range and high burning rate accentuate these hazards, its low ignition energy, low heat of combustion on a volume basis and its nonluminous (low thermal radiation level) flame exert counteracting influences in many instances. Hydrogen also has high ignition energy, a low heat of combustion and a hydrogen flame is almost invisible." The *Handbook* (p. 5-52) further states:

> "Because of its low ignition energy, when gaseous hydrogen is released at high pressure, normally small heat producing sources, e.g., friction and static generation, often result in prompt ignitions. Accordingly, hydrogen is often

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> thought of as self-igniting under these circumstances. A record of releases at high pressure reveals that fires rather than combustion explosions occur. When hydrogen is released at low pressure, self-ignition is unlikely and combustion explosions occur which are often characterized by very rapid pressure rises which are extremely difficult to vent effectively. Open air or space explosions have occurred from large releases of gaseous hydrogen."

The combustion explosions are often referred to as deflagrations. While some damage can result from the flame front, such as secondary ignition of combustible materials, most of the damage from a deflagration occurs from rapid pressure buildup from the heating of the reactants (hydrogen and oxygen), the combustion product water vapor, and the air. The pressure rise is limited by the extent to which the gases are confined. The pressure buildup is never greater than about 10 times the absolute pressure before ignition. While the peak pressure might be quite high, its duration is normally quite limited because of venting and the heat transfer between the hot gases and cold surfaces in the area where the fire occurred.

Because of its broad flammable range, if there is a leak of hydrogen in any area where hydrogen can accumulate, from a safety perspective it should be assumed that there will be a location where the hydrogen concentration is within the flammability range and that a spark source of sufficient energy to ignite the hydrogen will also be present. Given that it would be difficult to totally prevent leaks from occurring (the ESIF is, after all, a developmental facility), designs must take advantage of the rapid dissipation of released hydrogen. Specifically, the design must ensure that 1) released hydrogen cannot rise into an enclosed area, and 2) vent pipes designed to remove any hydrogen are not venting a flammable mixture of hydrogen and air. The metal fabrication industry places large holes in the roofs of its facilities, and the petroleum industry places much of its equipment outdoors to take advantage of the rapid diffusion and resultant dispersion of hydrogen gas to the atmosphere. Both of these design approaches avoid the difficult issue of ensuring adequate venting should a deflagration occur in a confined area.

It has been shown experimentally and theoretically that the flame front produced in an unconfined three-dimensional flammable gas cloud will not accelerate and produce a much more damaging explosive shock wave. That is not the case if the plume is confined in one or two of the three dimensions. Numerous detailed accident investigations have concluded that the damage resulting from partially confined plumes is much greater than would be expected for an unconfined vapor cloud deflagration. Similarly, if the flammable mixture is in a pipe of sufficient diameter (typically 1 inch or greater) and ignition occurs, the flame front rapidly accelerates; after about 10 pipe diameters, the flame front will reach sonic velocity and the resultant shock wave will split the pipe open.

Regarding the storage of hydrogen at high pressures, the failure of a vessel is judged to be in the Improbable range using the NREL risk matrix. A NASA-authored report discussing catastrophic storage vessel failure states: "Although there is a very low probability for catastrophic occurrence, selecting a site that will minimize the effects of such an event is prudent." (NASA 2004). The analysis then assumes a catastrophic failure of the pressure vessel and establishes a safe distance to the nearest building from the storage location. The basis for the distance comes from a modeling of the release plume. The objective is to place the storage location far enough away from any adjacent structure such that the release plume will be unconfined should it be

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ignited. NFPA standards for hydrogen handling incorporate these distances, and these requirements have been met.

High-pressure hydrogen is stored in tube racks consisting of a number of cylinders, usually four to six, each about 20 feet long and 1 to 2 feet in diameter. The tube configuration is not unlike the tube trailers used to deliver high-pressure gases to facilities like NREL. Failure of a hydrogen storage cylinder is not anticipated. If a cylinder did fail, it would not be expected to cause an adjacent pressure cylinder to fail because such vessels are often made of ductile metals.

Under this failure scenario, one of the pressure cylinders fails and generates a large gas cloud. While such failures are rare, those that have occurred are often the result of hydrogen embrittlement in an area sensitized following welding. Accumulation of combustibles, trash, or a fuel spill around the pressure cylinders could also result in cylinder failures if a fire occurred. Failure of a pressure relief device may also occur. The 20-foot-long storage vessels are long enough to make it possible for a fire to overheat one end of a vessel; if the pressure safety valve is at the other end, or if one is not present, the vessel could fail catastrophically before it vented to the atmosphere. Even in this case, although several vessels might be close to failing, it is not expected that they would fail simultaneously. The maximum quantity in one vessel is approximately 20 kg, which limits the energy that would be released should one or more of the storage vessels fail.

Another hydrogen hazard that must be considered is the quantity of hydrogen that could be released should a high-pressure hydrogen pipe be damaged and fail. The system would be provided with a quick-acting isolation valve that would isolate the hydrogen in the line from the storage vessels when the pressure in the piping drops rapidly. Often, the volume of hydrogen that exits the system before shutdown is initiated and the volume that exits after shutdown are great enough to cause all or a large portion of the atmosphere in a laboratory room to exceed the LFL for hydrogen in just a few seconds. An ignition source, if present, would ignite the gas cloud, and because the cloud is confined, the pressure in the room would rapidly rise. If the whole room were in the flammable range at the time of ignition, the pressure would breach the walls and potentially damage adjacent laboratories. As previously discussed, if the vented hydrogen accumulates in a pipe and the flammable mixture ignites, an even more damaging detonation could occur.

There are other properties of hydrogen that present some hazards. Explosions have occurred within a pressure cylinder if air is not purged from the cylinder before hydrogen is added. Static electricity could ignite the hydrogen concentration if within the flammability range. The flame front formed would accelerate down the cylinder and detonate. Such a detonation would be violent enough to cause the remaining cylinders to fail. This risk is documented.

Another hazard of hydrogen is associated with its interaction with the pressure cylinder. If the hydrogen is extremely pure, which is the case with hydrogen generated on site, the pressure vessel would be more susceptible to hydrogen embrittlement.

Hazard controls for hydrogen use and other safety precepts applied to hydrogen systems generally include the following:

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- Engineered controls:
    - Providing adequate ventilation, as well as designing and operating hydrogen systems to prevent leakage, and eliminating potential ignition sources
    - Installing barriers or safeguards to minimize risks and control failures
    - Installing safety systems to detect and counteract or control the possible effects of such hazards as vessel failures, leaks and spills, embrittlement, collisions during transportation, ignitions, fires and explosions, cloud dispersions, and exposure of personnel to flame temperatures
    - Maintaining a safe interface under normal and emergency conditions so at least two failures occur before hazardous events could lead to personal injury, loss of life, or equipment or property damage
    - Installing warning systems to detect abnormal conditions, measure malfunctions, and indicate incipient failures. Providing warning system data transmissions with visible and audible signals that have sufficient redundancy to prevent any single-point failure from disabling the warning system
    - Installing safety valving and flow regulation that will adequately respond and protect personnel and equipment during hydrogen storage, handling, and use
    - Using automated control systems with caution and warning feedback inputs. Also, constraining manual controls within the systems by using automatic limiting devices to prevent over-ranging
    - Applying a system of verifications of equipment, power, and other system services for safe performance in the design and normal operational regimes
    - Applying "fail-safe" system design, meaning that any single point failure from which potentially hazardous conditions are a risk must cause the system to revert to conditions that will be safest for personnel and with the lowest property damage potential
    - Applying redundant safety features to prevent a hazardous condition when a component fails.
- Administrative Controls:
    - Subjecting all plans, designs, and operations associated with hydrogen use to an independent, safety review. Safety reviews should be conducted on effects of fluid properties, training, escape and rescue, fire detection, and firefighting
    - Establishing operating procedures for normal and emergency conditions and reviewing these procedures as appropriate
    - Performing hazards analyses to identify conditions that may cause injury, death, or property damage
    - Assuring continuous improvement of systems through reporting, investigating, and documenting the occurrences, causes, and corrective actions required for mishaps, incidents, test failures, and mission failures in accordance with standardized procedures.

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All of these safety controls and precepts are currently used at NREL. NREL's ISMS provides a rigorous administrative structure to ensure that these safety precepts are successfully applied to the ESIF.

4.5.2 Natural Gas

Natural gas presents some of the same flammability and explosive hazards as hydrogen; however, the flammability range of natural gas in air is narrower, mainly at the high end—the lower flammability limit is 5% and the upper limit is 15%. The confined-space deflagrations associated with natural gas are just as severe when they occur. For this analysis, the assessments are bounded by the hydrogen scenarios.

4.5.3 Electrical

The REDB poses electrical arc flash and shock hazards. Robust system monitoring, stability control, and dead bus switching are key requisites for safe design and operations. This is discussed in greater detail in section 4.6.5.

Various electrical exposures unrelated to the REDB are also present in laboratories and are associated with low and medium voltage testing and experimental component assessment and modification activities.

4.5.4 Toxic Gases

The facility will contain limited quantities of toxic gases, such as hydrogen sulfide, whose release could pose a risk to workers' health should it occur. Any hydrogen sulfide contained in high-pressure gas cylinders would be diluted with a carrier gas such as argon or nitrogen, such that any accidental discharge is unlikely to exceed any exposure limits. The concentration of the hydrogen sulfide in the gas cylinders would not exceed 40 ppm and the Emergency Response Planning Guideline (ERPG)-2 limit of 30 ppm. The turbulent jet caused by a release would likely induce enough mixing with the surrounding air to limit the volume above 30 ppm to a very small volume. These releases are not considered to be bounding accidents.

4.5.5 Nanomaterials

Limited quantities of nanomaterials may be used in the ESIF. It is expected that fewer than 10 grams of nanomaterials would be present at any location; these materials are, in most cases, immobilized on a solid substrate or in liquid suspension. Because the hazards of these materials are not completely understood, NREL personnel will follow LLP 6-1.46, *Chemical Safety*, which incorporates DOE and National Institute for Occupational Safety and Health (NIOSH) guidelines on nanomaterials. Based on these guidelines, NREL personnel would handle the nanomaterials in ventilated enclosures with HEPA filtration, and the nanomaterials would be transported, if necessary, in properly sealed containers within secondary containment.

4.5.6 Spills and Other Hazards

Spills of diesel and gasoline pose a lesser threat but are sufficiently different from a gas release to be considered separately.

There is a small risk from spills of acids and caustic materials that mainly present a risk to workers; such risks could be largely controlled by having workers don protective equipment

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(such as gloves and face shields) and performing the work in a hood or other type of enclosure. Furthermore, whenever multiple chemicals are present in a facility, there is a risk of incompatible reactions; however, based on the list of chemicals that could be present in the ESIF, the risk of incompatible chemicals mixing and causing a violent reaction is low.

Because ESIF workers would deal with full-sized equipment that would be prototypic of equipment to be used on an industrial scale, the risk of over-pressurization and subsequent failure would be present. Such failures are largely a risk to workers; however, they can also cause damage to adjacent equipment when they occur.

Finally, there are risks associated with stored energy sources, which includes electrical energy and compressed gas. The ESIF management team has developed systems to manage high-voltage and high-amperage electrical circuits. More common industrial hazards, such as high-pressure gas cylinders, present a significant source of stored energy should a valve be sheared off during handling.

4.5.7 Summary

Overall, the vast majority of the potential ESIF hazards is known and is well understood. Section 4.6 presents a more detailed analysis for several accidents that are believed to be the bounding events for the ESIF. Some effort was made to identify a location where these bounding events might occur. *In general, any location mentioned is considered to be representative of analogous areas.* In any future detailed safety assessment, the adequacy of safety features for every process that could result in the accidents described in Section 4.6 will be assessed.

4.6 Postulated Accident Analysis

Many of the hazards that could be present in the ESIF are discussed in Section 4.5. This section attempts to list some accident scenarios where these hazards might be realized during ESIF operations. The goal of the accident analysis is to identify a sufficient number of plausible event scenarios from the many classes of events, external accidents, equipment failures, procedural errors, etc., to identify the bounding events for the ESIF.

When discussing hydrogen storage, NASA analyzes the catastrophic failure of a storage vessel even though such an event falls in the Improbable probability range on the NREL risk matrix. NASA states that such assessments are prudent given the potentially severe consequences.

4.6.1 Compressor Failure

It is assumed that the compressor has a volume of 1 liter and is operating at a pressure of 15,000 psi. The energy generated by the failure can be estimated using the equation (Lees 1996, Equation 17.4.28, page 17/26):

$$E = \frac{PV}{\gamma - 1} \qquad \textbf{Eqn. 1}$$

where:

E is the energy generated

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P is the pressure (Pa)
V is the volume (m^3)
γ is the heat capacity ratio (C_p/C_v), which equals 1.4 for a diatomic gas such as hydrogen

The key assumption is the free volume inside the compressor. The energy released from the compressor failure is 0.26 megajoules (MJ), or the equivalent of 62 grams of trinitrotoluene (TNT). The energy of the pressure pulse from this event would be equivalent to about 22 grams of TNT and would cause damage for a few tens of meters. The biggest threat would be from the potential shrapnel produced. More details regarding the mass and internal volume of the compressor are needed to quantify the extent of the impact.

The arrangement of the compressor relative to other equipment and the presence of any barriers could also significantly affect the extent of impacts. Overall, if the volumes are correct, this is a relatively small explosion that could be effectively limited. The greater concern would be the shrapnel generated from the explosion. Note that if the internal volume in the compressor is significantly greater than 1 liter, an estimated value, then the failure would cause proportionately greater impacts.

4.6.2 Hydrogen Storage Vessel Rupture

Installation: The hydrogen storage zone will consist of one cylinder pressurized with a rated pressure of 3,000 psig (20.8 megapascals [MPa]). It is oriented east to west along the north edge of the storage pad, and includes a bank of six cylinders each pressurized to 6,000 psig (41.4 MPa) providing cascade filling capacity for cars with 35-MPa fuel systems and a high-pressure FIBA tank rated for 15,000 psig (103.4 MPa) with a maximum operating pressure of 13,500 psig (93.2 MPa). Up to three additional high-pressure FIBA tanks are planned to be installed in the future and will be considered in this analysis.

The most catastrophic event is the rupture of a high-pressure storage cylinder. Although the presence of pressure safety valves will likely limit the pressure to the maximum operating pressure, it is desirable to perform this analysis for the maximum rated pressure of the tanks to provide the greatest flexibility for future changes in operating conditions. The rupture will be assumed to occur at 103.4 MPa due to corrosion, defect, cyclic failure, or impact. Distances between equipment and other potential damage receptors are estimated; the exact distances and cylinder configurations will affect the outcomes of the posited events.

Probability of Rupture: Using a Bayesian analysis of hydrogen component leak frequencies, LaChance et al. (2009) estimates an annual cylinder rupture frequency for cylinders in hydrogen service to be 5.0×10^{-7}. LaChance et al. also reports the generic annual cylinder rupture frequency is 2.1×10^{-6} based on previous operations data. The NREL risk matrix suggests that based on probabilities alone, the worst-case risk profile would be Low. Based solely on component failure rates, a catastrophic rupture scenario is so remote that it could be argued that *this event is not reasonably credible under most normal operating scenarios.*

However, it is important to note that the component failure rates reported by LaChance at al. are determined from a Bayesian analysis of very limited data set for high-pressure hydrogen installations weighted against failure rates reported for a broad range of industries. The predicted

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leakage rate for these components is significantly lower than those for the other industries, often by several orders of magnitude in some cases. While some consideration may be given to some of the inherently safer technologies used in high pressure hydrogen systems, there may be bias in the data due to low sample size and inclusion of data from conservative-practice prototype facilities. The potential for tank rupture due to unforeseen scenarios, equipment failures, or other rare events cannot be fully discounted. LaChance et al. specifically excludes escalation of fire scenarios from consideration. Conceivable scenarios that result in vessel rupture include:

- Mechanical impact
- Impinging jet fire from nearby leak
- Catastrophic rupture of a nearby lower-pressure vessel
- Pool fire of externally supplied fuel
- Direct attack with explosives.

These scenarios could conceivably cause a rupture of the high-pressure cylinder. Therefore, this scenario is semi-quantitatively evaluated here to provide an extreme bounding condition and to provide a general estimation of the most egregious off-site consequences.

Several of the listed initiating events would be considered lower-severity process failures; although failure of the high-pressure cylinder does not occur each time the initiating event occurs, it represents an escalation in the event severity colloquially known as the "domino effect." Jet fires are of particular concern due to the fact that hydrogen undergoing rapid decompression through a restriction has been observed to self-ignite. Some studies have shown that jet fires have significant probabilities (~45%) of leading to further explosions, though the data may be biased due to underreporting of jet fire incidents that did not lead to subsequent events (Gómez-Mares, Zárate, and Casal [2008]).

The composite pressure vessels are vulnerable to external flame and high temperatures; the structural composite wrapping layer may fail if directly impinged upon by fire, leading to vessel rupture. Several authors have experimentally determined flame length and heat flux for high pressure hydrogen jets into air for pressures up to 70 MPa, with good agreement between data (LaChance et al. [2009], Mogi and Horiguchi [2009], Proust et al. [2011], Schefer et al. [2006]). For a circular orifice, Mogi and Horiguchi (2009) found that the flame length could be given by the following relation:

$$\frac{L_f}{d} = 0.530 {P_1}^{0.43}$$

where:

L_f = flame length (m)
d = orifice equivalent diameter (millimeter [mm])
P_1 = hydrogen pressure (MPa)

It is expected that this correlation can provide reasonable estimates of flame length when extrapolated to the 103.5 MPa, and essentially states that flame length is proportional to the

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orifice diameter for a given pressure. Following LaChance et al. (2009), the large majority of leakage events will have flow areas between 0.1% to 10%, with 3% being selected by the Institute of Electrical and Electronics Engineers Task Group 6 committee as the basis for safe distance calculations. The inner diameter of ¼-inch tubing rated for a 103.5-MPa system is approximately 3 mm. Flow areas of 0.1% and 10% are equivalent to orifice diameters ranging from 0.01 mm to 1 mm, with a flow area of 3% corresponding to 0.5 mm. It is worth noting that industry experience suggests that under high pressure, small-diameter leaks have been known to expand in size due to the erosive effects of large frictional forces on the edges of the leak.

Based on this relation for a 103.5-MPa system, for orifices with diameter 0.01 mm and 1 mm, the flame length can be estimated to be between 4 centimeters and 4 m, with 2 m corresponding to the selected value of 3%. For the 20.8-MPa system, for the same orifice diameter range, the flame lengths can be estimated as 2 centimeters to 2 m, with 1 m corresponding to a 3% flow area.

In the current equipment arrangement for the storage pad, high-, medium-, and low-pressure storage tanks are sited together, with separation distances of approximately 2 ft. between the high-pressure tanks and medium-pressure tanks and piping. These distances are within jet flame distances for 3% flow area leaks. Due to the arrangement of the storage vessels and piping elements on the pad, it is possible for a jet flame from low- or high-pressure piping and vessels to impinge on the high-pressure hydrogen tank. This risk may be limited through increased separation distances of components with higher probability of leaking, such as flanges and valves. Mogi and Horiguchi (2009) also measured the flame lengths for high aspect ratio slit, to simulate flames emanating from a crack. The observed flames were markedly shorter and wider, indicating that the use of circular orifices as a basis for flame length is likely conservative. Thus, it would be desirable to extend the quantitative risk assessment and risk-informed engineering processes to estimate the probability and overall risk level of these types of escalating events. This analysis may be affected by inadequate data of the probability of rupture for composite vessels under jet fire.

Severity of Rupture: The severity of the event depends on the overpressure wave created from a cylinder rupture and the physics of "primary" projectiles from the cylinder or "secondary" projectiles induced by the blast.

Blast Energy*:* There are several ways to estimate blast energies. According to Lees (1996), the two most widely used relations for estimating explosion energies are those given by Brode (1959) and Baker (1973), with the preferred method for the estimation of explosion energy of gas-filled vessels being Brode (Lees pages 17/25 and 17/27). In the pressure regime of this cylinder, Brode's relation, which is based on an isobaric expansion, predicts the blast energy to be approximately 25% higher than Baker's estimations, which is based on isentropic expansion of an ideal gas. From Brode:

$$E_{blast,br} = \frac{(P_1 - P_0)\,V}{\gamma_1 - 1}$$

where:

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P_1 = Initial vessel pressure (absolute)
P_0 = Atmospheric pressure (absolute)
V = Volume of vessel
Υ_1 = Ratio of specific heats of the gas (1.4 for hydrogen)

Some authors, including Baum (1988), recommend the use of actual gas enthalpy-entropy data when available to most accurately estimate the available explosion energy. Due to the high storage pressure of hydrogen, significant deviations from the ideal gas equations of state are expected, e.g., a 30% deviation in density. This assessment will also consider the impact of departure on Brode's constant volume expansion.

From the definition of enthalpy for constant volume processes, we may derive:

$$E_{blast,r} = \Delta H - V\Delta P = (H_1 - H_0) - V(P_1 - P_0)$$

where:

H_1 = Enthalpy evaluated at vessel conditions P_1 and V
H_0 = Enthalpy evaluated at P_0 and V

The height of the cylinder from the ground is approximately 2 ft. The approximate dimensions of the cylinder are: inner diameter = 14.536 in.; L = 14.5 ft.; wall thickness = 1.482 in.; approximate water volume is 0.343 m^3. Substitution yields:

$$E_{blast,br} = \frac{(103.5\ \text{MPa})\ (0.343\ \text{m}^3)}{1.4 - 1}$$

$$\rightarrow \qquad E_{blast,br} = 86.5\ \text{MJ} \qquad \text{Eqn. 2}$$

For the real gas modification, enthalpies and other physical properties were evaluated using the National Institute of Standards and Technology REFPROP software. The density of hydrogen at any given tank pressure is found using the program REFPROP, which is a product from National Institute of Standards and Technology. The REFPROP program uses equations for the thermodynamic and transport properties to calculate the state points of the fluid or mixture. These equations are the most accurate equations available worldwide.

$$H_1(103.5\ \text{MPa}, 50.497\ \text{kg/m}^3) = 4636.9\ \text{kJ/kg}$$

$$H_0(0.08067\ \text{MPa}, 50.497\ \text{kg/m}^3) = -4.44\ \text{kJ/kg}$$

$$E_{blast,r} = \left(4.6369 - -0.00444\frac{\text{MJ}}{\text{kg}}\right) - 0.343\ \text{m}^3(103.5 - 0.08067\ \text{MPa})$$

$$E_{blast,r} = 44.9\ \text{MJ}$$

As is shown in these calculations, consideration of the real gas states results in a 48% reduction in the estimated blast energies, based on the departure of density and enthalpy from the ideal gas case. For the rest of this assessment, the conservative estimate of Brode's ideal gas expansion

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will be used, with the understanding that the blast energy may be over-predicted by a factor of nearly two. The blast energy for the high pressure vessel is substantially higher than the energy previously calculated for the low pressure vessel (35 MJ). Thus, an update of the overpressure calculation and blast damage calculations is required.

To put the selected blast energy in some context, the TNT equivalent for the blast energy estimated above is:

$$E_{blast,br} = 86.5 \text{ MJ} \times \frac{1 \text{ kg}_{TNT\ eq}}{4.184 \text{ MJ}} \times \frac{2.205 \text{ lbs}}{1 \text{ kg}}$$

$$\rightarrow \qquad E_{blast,br} \cong 45.6 \text{ lbs}_{TNT\ eq}$$

The CCPS (2010) states that the TNT equivalence method is a poor representation for estimating pressure and impulse in bursting vessels in most practical cases: the method over-predicts overpressure close in to the vessel and under-predicts overpressure in the far field (CCPS 2010, Section 7.4, Methods for Predicting Blast Effects from Vessel Bursts). This same source states that the TNT method also under-predicts the impulse at all distances except very near the vessel. CCPS (2010) gives attention to the blast curve method for bursting pressure vessels, which is the treatment that is applied in this assessment.

The blast energy given in Eqn. 1 represents a spherical, free-air explosion. Because the cylinders are close to the ground, wave reflection may occur. Wave reflection due to walls and other planar surfaces is separate from ground reflection and must be considered separately. Pressure vessels near the ground are modeled by doubling the energy to account for ground reflection, though it should be noted that this conclusion is based on limited data (CCPS 2010, p. 262). Hence, the energy of the blast that will be used in the estimation of overpressure is given below:

$$E_{blast} = 2 \times 86.5 \text{ MJ} = 173.0 \text{ MJ} \qquad \text{Eqn. 2}$$

Overpressure and Impulse: The resultant overpressures and impulse of a blast are determined based on the vessel burst curves provided by CCPS (2010), which cites Tang et al. (1996). The scaled distance is given by CCPS to be:

$$\bar{R} = R\left(\frac{P_0}{E_{blast}}\right)^{1/3}$$

where:

$\bar{R}$ = Scaled blast distance to receptor
R = Distance to receptor

Substituting the initial cylinder pressure,

$$\bar{R} = R\left(\frac{0.08067 \text{ MPa}}{173.0 \text{ MJ}}\right)^{1/3}$$

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$\rightarrow \quad \bar{R} = (0.078/\mathrm{m})R$ Eqn. (3) {This is the scaled distance to the receptor}

The scaled overpressure, $\bar{P}$, and scaled impulse, $\bar{I}$, are determined using the pressure and impulse curves provided in section 7.4 of CCPS (2010), which cites Tang et al. (1996). For the purposes of this investigation, P_1/P_0 = 1,288, hence, the P_1/P_0 = 1,000 curve is utilized.

The scaled overpressure and scaled impulse can also be adjusted for the cylindrical geometry of the vessel. This can be done by applying the adjustment curves presented in section 7.4 of CCPS (2010), which cites Geng (2009). The highest pressure ratio curve provided is P_1/P_0 = 100, well below the calculated P_1/P_0. Based on the trends, overpressure and impulse will be under-predicted in the close field while over-predicted in the far field. As most of the receptors are in the far field, the adjustment factors for the P_1/P_0 = 100 curve may be considered as a conservative approximation for the overpressure calculations.

CCPS (2010) provides that the blast wave from a cylindrical vessel is weakest along its axis. For the cylindrical case, the blast is non-uniform. In the near field, the overpressure along the axis of symmetry (0 degrees) remains higher than for the spherical case. As distance increases, however, it drops to a value that is less than the corresponding overpressure for the sphere. Conversely, overpressures along the direction normal to cylinder axis (90 degrees) are initially lower than the corresponding values for the sphere but deteriorate less rapidly after $\bar{R}$ = 0.1, remaining higher than the overpressures for the sphere out to $\bar{R}$ = 10. Based on the equipment layout of the high-pressure cylinders, these calculations assume the receptor is normal to the cylinder axis and this additional overpressure is applied. Along the direction of 45 degrees, overpressure is similar to that for the sphere, particularly in the far field ($\bar{R}$ > 1). Similar trends are observed when comparing the radial distributions of impulse for the two cases (CCPS, p. 259).

In this case, all persons, STM campus facilities, and offsite public areas (e.g., conservation space hiking trail, Whitaker subdivision, and Richards Heights subdivision are in the far field (see Table 23) relative to the hydrogen storage area. Where the scaled distance, $\bar{R}$, is greater than 10, the overpressure and impulse can be estimated, or at least bounded, by a spherical blast. Thus, for this specific case, the adjustments for cylindrical geometry are not indicated and not included for the far field.

The estimated peak overpressure, P_s , and pressure impulse, I_s, are calculated using the scaled values incorporated in the following relations provided in CCPS (2010), with results tabulated in Table 23.

$P_s = \bar{P}P_0$ Eqn. 4 {Side-on peak overpressure at the receptor}

$\rightarrow \quad P_s = \bar{P} * 80.67 \text{ kPa}$

$I_s = \frac{\bar{I}\, P_0^{2/3}\, E_{blast}^{1/3}}{a_0}$ Eqn. 5 {Side-on impulse at the receptor}

where:

a_0 = speed of sound in the ambient air (assumed to be 330 m/s)

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$$I_s = \bar{I} * \frac{(80{,}670\ \text{Pa})^{2/3}\ (70 \times 10^6\ \text{J})^{1/3}}{330\ \text{m/s}}$$

$$\rightarrow \qquad I_s = \bar{I} * 2400\ \text{Pa-s}$$

Table 23. Summary of Overpressures and Impulse Using Vessel Burst Scaling Curves (Tang et al., 1996) Corrected for Cylindrical Vessel Geometry (Geng, 2009)

Receptor	Receptor Distance R (m)	Scaled Distance $\bar{R}$	Scaled Overpressure[a] $\bar{P}$	Scaled Impulse[b] $\bar{I}$	Side-on Peak Overpressure[c] P_s (kPa)	Side-on Impulse[25] I_s (Pa-s)	Reflection Factor
North Access Roadway, Edge	12	0.9	0.62	0.067	79.6 (AF=1.6)	287 (AF=1.35)	1
Facility Trail, NW Pad Edge	12	1.17[7]	0.45	0.054	54.1 (AF=1.5)	234 (AF=1.35)	1
ESIL N_2 storage Tank	23	1.8	0.25	0.036	28.2 (AF=1.4)	149.0 (AF=1.3)	1
ESIF North Wall	27	2.1	0.20	0.031	21.8 (AF=1.35)	128.0 (AF=1.3)	2
Facility Trail, Property Line	61	6.06	0.05	0.011	4.4 (AF=1.2)	49.4 (AF=1.2)	1
MVOTA	65	5.0	0.06	0.014	5.7 (AF=1.2)	52.2 (AF=1.2)	1
S&TF H_2 Gas Storage	115	8.9	0.027	0.0079	2.6 (AF=1.2)	30.0 (AF=1.2)	1
Conservation Space North trail	~120	9.3	0.025	0.0076	2.4 (AF=1.2)	28.8 (AF=1.2)	1
S&TF Toxic Gas Bunker	130	10.1	<.025 [0.022]	0.0071	<2	22.2	2
Richards Heights Subdivision	400	31	<<0.025 [0.005][e]	<<0.0071 [0.0024][26]	<<2	<<14	1
Whitaker Subdivision	610	47	<<0.025 [0.003][26]	<<0.0071 [0.0016][26]	<<2	<<14	1

a. CCPS Figure 7.6 (Tang et al. 1996). Scaled ranges above 10 are beyond the range presented by Figure 7.6, and 0.0025 represents the limit of quantification for positive overpressure.

b. CCPS Figure 7.7 (Tang et al. 1996). Scaled ranges above 10 are beyond the range presented by Figure 7.6, and 0.0071 represents the limit of quantification for positive impulse.

c. The tabular value includes an adjustment multiplier for cylindrical vessels per Figure 7.10 (CCPS cites Geng [2009]). The value in parenthesis following the value is the adjustment factor (AF).

d. Ground reflection factor is not included due to partial shielding by retaining wall.

e. The value in brackets is based on the linear extrapolated value provided for the scaled overpressure and impulse values.

[7] Ground reflection factor is not included due to partial shielding by retaining wall.

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***Overpressure Effects**:* Hazardous overpressures can damage sensitive organs, such as ruptured eardrums and hemorrhaged lungs. Overpressures can also cause injuries from whole body displacement (e.g., knocking a person over or into other objects). A person standing next to a wall orthogonal to the blast wave may be subject to additional overpressure, as in-phase wave reflection may substantially increase the overpressure experienced. For the purposes of this analysis, wall reflection will increase the overpressure experienced by the most conservative factor of 2. Several receptor sites have been identified as meeting the criteria for reflection, and the assigned "Reflection Factor" is given in Table 23. Workers directly within the pad area are at severe risk of injury or death due to projectiles and the overpressure wave. Fortunately, this area will typically be unoccupied and thus is not quantitatively considered here.

Hearing effects: From Moore (1967), temporary ear damage can occur at a threshold of 0.2 psi (1.38 kPa). According to Lees (1996), relations for eardrum rupture are given in the vulnerability model described by Eisenberg, Lynch and Breeding (1975), citing data from Fugelso et al. (1972), presented in Table 24. The data were correlated with a simple logarithmic fit to provide interpolated ear damage probabilities.

Table 24. Probability of Eardrum Rupture due to Overpressure (Fugelso et al. [1972], cited by Lees 17/224)

	Peak Overpressure	
Probability of eardrum rupture (%)	**(psi)**	**(Pa)**
1 (threshold)	2.4	16,500
10	2.8	19,300
50	6.3	43,500
90	12.2	84,000

From this information, receptors at the north access roadway may suffer an 85% chance of eardrum rupture while workers at the north side ESIF wall may suffer approximately a 53% chance. Workers in other areas beyond the immediate area (e.g., MVOTA) may suffer temporary hearing effects. A person standing on NREL property at the closest point of the facility trail would suffer a 65% chance of eardrum rupture. A person standing on the same path at the NREL property line may suffer temporary hearing loss. Workers in facilities near the ESIF (e.g., the Science and Technology Facility) are not likely to suffer any hearing affects. Receptors offsite may hear a loud noise, but they are unlikely to suffer any adverse effects to their hearing.

Lung effects. From Lees (1996), relations for death due primarily to lung hemorrhage are given in the vulnerability model by Eisenberg, Lynch and Breeding (1975). These relations are based on data from Fugelso, Weiner, and Schiffman (1972) reproduced in Table 25, and are presented only as a function of peak overpressure. In White et al. (1971), survivability is estimated as a function of peak overpressure and blast wave duration. When Fugelso et al.'s data are compared with White et al.'s data to determine an implicit pressure wave duration, it is found that the duration is 5 seconds or greater, a conservative assumption.

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Table 25. Probability of Fatality from Lung Injuries due to Overpressure (Fugelso et al. [1972], cited by Lees 17/225)

	Peak Overpressure	
Probability of fatality	**(psi)**	**(Pa)**
1 (threshold)	14.5	100,000
10	17.5	120,000
50	20.5	140,000
90	25.5	175,000
99	29.0	200,000

Based on these criteria, the peak overpressures from this bounding event are not expected to cause a worker fatality at the selected receptor points. Using the scaled peak overpressure/scaled impulse diagram (P-I diagram) from Baker et al. (1983), this scenario is well below the threshold level for lung injury outside of the pad (Lees, Figure 17.107, page 17/228).

Whole body displacement: At the predicted overpressure for this tank catastrophically bursting, Moore (1967) and Lawrence Livermore National Laboratory (1993) predict that persons outside on the North Access Road may be knocked down. Several probit relations exist for different types of potential injuries. From the TNO "Green Book" (*Methods for The Determination of Possible Damage to People and Objects Resulting from Releases of Hazardous Materials,* first edition 1992) (as cited by Lees [1996]) the lethal injury probit for skull impact with a hard surface (e.g., ground) is given as (Lees [1996], page 17/229):

$$Y = 5 - 8.49\ln(S)$$

where:

$$S = \frac{2.43x10^3}{P_s} + \frac{4x10^8}{P_s I_s}$$

Using the values for overpressure and impulse from Table 23, the probit values and the corresponding probability for fatality were calculated. At the North Access Road, which is the closest receptor point, the probit variable was -19, indicating that lethal injury is improbable.

For whole body impact, the TNO Green Book provides:

$$Y = 5 - 2.44\ln(S)$$

where:

$$S = \frac{7.38x10^3}{P_s} + \frac{1.3x10^9}{P_s I_s}$$

The probit value was calculated as -4.9 for the North Access Road; hence, a lethal injury is not anticipated.

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Structural damage to ESIF: Much of the information for structural damage is based on peak overpressure. Lees (1996) and Baker (1983) suggest that the applicability of data based on overpressures is more applicable to quasi-static loading than impulsive loading, and that relying on overpressures alone may result in considerable overestimation of damage (Lees 1996, 17/188). Hence, the following evaluation may be very conservative.

Eisenberg et al. (1975) derived a probit relation relating to structural damage and peak overpressures:

$$Y = -23.8 + 2.92\ln(P_s)$$

Using Table 23 and the distance to the ESIF north wall, the probit is approximately 5.36, which correlates to a 64% chance of structural damage to ESIF at this overpressure. This result indicates a high potential for significant structural damage at the ESIF north wall.

Overpressure damage to process equipment: A catastrophic rupture of a high pressure tank can generate a pressure wave that may seriously damage nearby process equipment. This study is primarily concerned with the safety of workers and the general public during such a catastrophic event, and thus will not cover the potential for property damage. However, it is important to quantitatively understand the risks for secondary events, including catastrophic vessel failure, which may escalate the range or severity of the incident, colloquially known as a "domino effect" event. Domino events are by definition rarer than the initiating event, but may have a greater severity.

Rausch et al. (1977) suggests that overpressures of 8–12 psi (55–83 kPa) are required to damage pressure vessels, with higher values cited for severe damage. Work by Cozzani and Salzano (2004) assigns probit values for severe damage to various types of process equipment based solely on peak overpressure. The general form of the probit equation is given below; values for constants k_1 and k_2 are given in Table 26.

$$Y = k_1 + k_2 \ln V$$

Table 26. Probit Coefficients for Severe Equipment Damage (after Cozzani and Salzano [2004])

Equipment Class	k_1	k_2	Regression Coeff
Atmospheric vessels	-18.96	2.44	0.573
Pressure vessels	-42.44	4.33	0.852
Elongated Equipment and Piping	-28.07	3.16	0.690
Small equipment	-17.79	2.18	0.776

Although the regression coefficients show high variability, the results of the functions match well with the values reported in Lees (1996) and Rausch et al. (1977). Based on the results of Table 23 and the probit equation above, the failure probability for pressure vessels, piping, and small equipment located near the high pressure tank during a rupture event has been calculated, with the results displayed in Figure 16. This probability-distance relationship shows that pressure vessels within 10 m have a high probability of failure, rapidly falling below the damage

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threshold by 20 m distance. The effect on smaller equipment and piping is more severe, with high probabilities of damage out to 25 m distance.

Based on the latest site layout, this generally limits the damage to equipment on the Zone 300 outdoor pad. The equipment within the destructive zone includes any other installed high-pressure tanks, medium-pressure six-pack tanks, the PBNL-301 low-pressure tank, the CNM-351 compressor, and the associated piping. No single piece of equipment located within this zone has a compressed gas potential energy exceeding the high pressure tanks. However, simultaneous rupture of nearby vessels and piping would result in a large release of hydrogen. Although no ignition sources are normally present on the pad, during a catastrophic rupture event there is the potential for spark generation from fragments or debris striking metal objects on the pad. The chemical energy available in the hydrogen is far greater than the potential energy of compression, emphasizing the need to prevent catastrophic rupture.

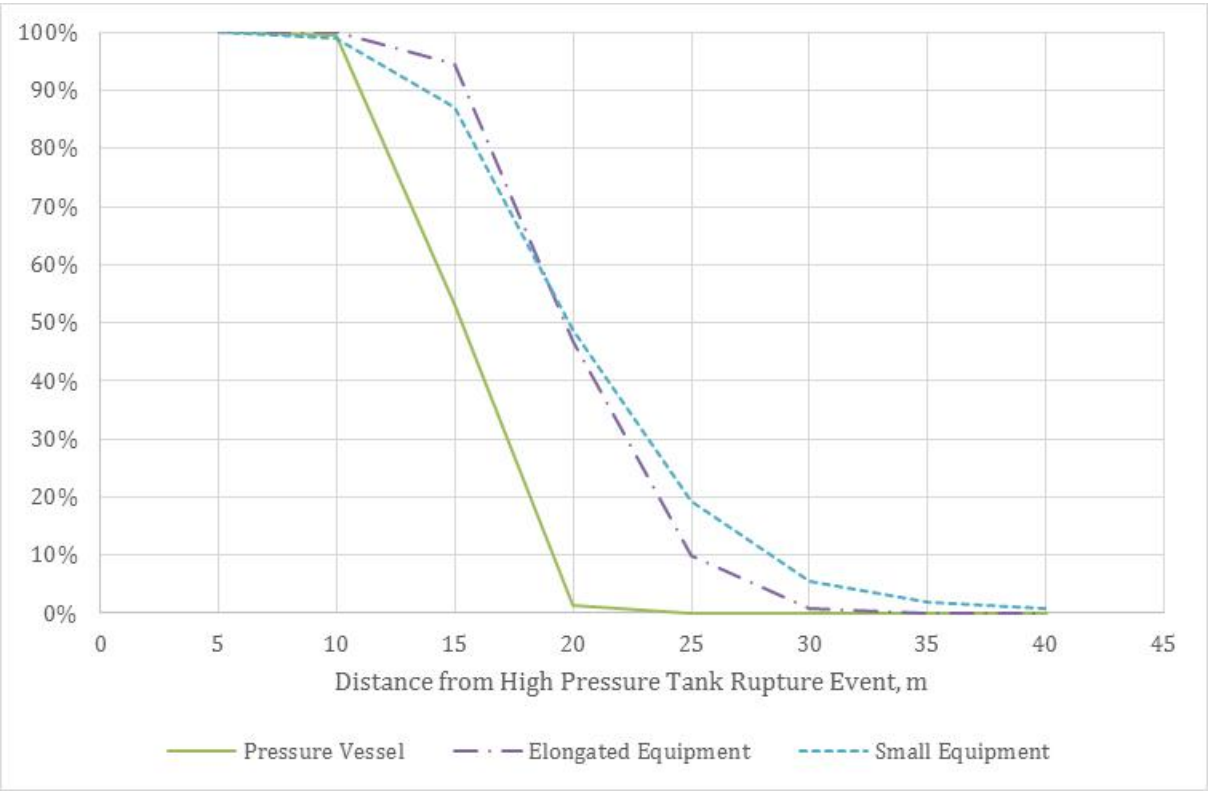

Figure 16. Probability–distance curves of overpressure catastrophic equipment damage resulting from high-pressure hydrogen tank rupture

Fragment Hazard Evaluation: For this particular event and general causal mechanisms, CCPS indicates that it is common to have small numbers of fragments, from two to ten. If there are more than two fragments and the vessel is cylindrical, strip fragments that expand radially about the axis of symmetry can be posited based on Baker et al. (1983) as discussed by CCPS (p. 282). The profiles of these strips generally have a relatively large drag coefficient (CCPS, Table 7.1). Only a fraction of the blast energy appears as kinetic energy (Lees [1996], p. 17/200). For a sudden rupture of a vessel filled with an ideal gas, assuming adiabatic expansion, the highest fraction of energy available for translation to kinetic energy of fragments can be calculated using Baum (1984):

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$$E_{kinetic} = k\frac{P_1 V_1}{\gamma_1 - 1}$$

Based on experimental results, CCPS recommends using a k value of 0.2 (CCPS [2010], p. 280); hence,

$\rightarrow \quad E_{kinetic} \cong 17.3$ MJ {Estimated kinetic energy transmitted to fragments}

The vessel's total mass is known, so the mass-weighted average initial velocity can be determined from the definition of kinetic energy:

$$v_{avg} = \sqrt{\frac{2E_{kinetic}}{m}} = \sqrt{\frac{(2)(17.3 \text{ x } 10^6 \text{ J})}{(1851 \text{ kg})}}$$

$$v_{avg} = 136.7 \text{ m/s}$$

Further estimates for the estimated maximum velocities are from Baum (1988) for total vessel failure:

$$v_f = 0.88 {f_f}^{0.55} a_{H2} \qquad \text{Eqn. (6)}$$

where:

a_{H2} is the speed of sound within the vessel at operating conditions
f_f is the initial acceleration on the fragment, given by:

$$f_f = \frac{P_1 A_f r_i}{m_f a_{H2}^2}$$

The speed of sound for real gases is most simply given by the expression:

$$a_{H2} = \sqrt{\gamma \frac{P}{\rho}} = \sqrt{\frac{(1.41)(103.4 \text{ x } 10^6\ Pa)}{50.453\ kg/m^3}}$$

$$a_{H2} = 1700\ m/s$$

Because the wall thickness is known, a reasonable estimate of (A_f/m_f) is the quantity: $(1/\rho_f t_f)$ (DOE [1993], page 27); hence:

$$f_f \cong \frac{P_1 r_i}{\rho_f t_f a_{H2}^2}$$

$$f_f \cong \frac{(103{,}400{,}000\ Pa)(0.222\ m)}{(7900\ kg/m^3)(0.0376m)(1700\ m/s)^2}$$

$$f_f \cong 0.027$$

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Substituting into Eqn. 6:

$$v_f = 0.88 {f_f}^{0.55} a_{H2}$$

$$\rightarrow \qquad v_f \cong 204\ m/s$$

The range of the fragment can be estimated from CCPS (2009), which ignores air resistance/drag:

$$R = \frac{v_f^2 \sin(2\alpha)}{g} \qquad \text{Eqn. (7)}$$

For cylinders with horizontal axes, CCPS (2010) indicates the initial trajectory will be low, typically 5° or 10° (CCPS [2010], page 309). Hence, typically fragment ranges can be estimated as follows:

$$R_5 = 736\ m$$

$$R_{10} = 1{,}450\ m$$

If unobstructed, these fragments could easily reach all areas of the site as well as nearby public areas, including nearby residential subdivisions. However, assuming a cylinder height of 2 ft., the distance to the ESIF north wall (approximately 90 ft.), and the height of the ESIF north wall (38.5 ft.), any projectile normal to the cylinder's axis of symmetry with an angle less than approximately 20 degrees will be constrained from offsite transport by the ESIF wall. With the storage pad retaining wall (height of approximately 7 ft.), a projectile with an angle less than about 14 degrees will be similarly constrained by the wall.

Due to the high velocities, long transport distances, and potentially great consequences, it is worthwhile to check the impact of air resistance. CCPS cites the work of Baker et al. (1975, 1983), which numerically solves for the maximum fragment range based on initial velocities and estimates of the fragment drag coefficients. These curves are developed for pressure vessels, but do not indicate any correction for the vessel geometry. Scaled maximal range $\bar{R}$ and scaled initial velocity $\bar{v_i}$ are calculated by the following equations:

$$\bar{R} = \frac{\rho_0 C_D A_D R}{M_f}$$

$$\bar{v} = \frac{\rho_0 C_D A_D {v_f}^2}{M_f g}$$

where:

ρ_0 = density of ambient atmosphere = 1.068 kg/m^3
R = maximal range
C_D = drag coefficient of fragment = 1.17 for a flat plate member
A_D = cross sectional area of fragment

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g = gravitation acceleration = 9.807 m/s^2
M_f = mass of fragment

Similarly to the initial velocity analysis above, $\frac{M_f}{A_D}$ may be approximated by $\rho_f t_f$.

Carrying out these calculations yields $\bar{v} = 17.8$, corresponding to $\bar{R} \cong 3.5$. Back-solving gives:

$$R = 833.1\ m$$

Although this range is greatly reduced when compared to results neglecting wind resistance, at this distance a number of public receptors surrounding the ESIF may be reached. This is in line with historical catastrophic vessel ruptures, where fragments were found greater than 1 km away from the source of the initial blast (Mébarki et al. 2012). This indicates that one or more public fatalities may occur as a result of a high pressure vessel rupture.

For workers in the ESIL or ECL OTAs, DOE (1993) predicts that there is better than a 50% probability that all but very small fragments (less than 0.003 lbs_m) will cause serious injury. The MVOTA is in direct line of sight of the hydrogen storage pad and is within range of the fragments, leading to the possibility of equipment damage. The Science and Technology Facility and the gas storage bunkers are within direct line of site of the storage pad. Based on Eqn. 7 as well as when wind-resistance is included, these storage bunkers are within the range of the fragments. Detailed study would be required to determine the probability of impact with the toxic gas and hydrogen storage bunkers. However, based on similar studies and the results of Eqn. 7, it can be expected that the probability of impact is significant. At the velocities predicted during a full rupture, a direct impact could cause loss of containment of the toxic or flammable gases, potentially further escalating the incident. The gases in the other facility have not been disclosed for this study, and thus the impact cannot be fully characterized.

Glass breakage: The probit for glass breakage is given by Eisenberg et al. (1975) as:

$$Y = -18.1 + 2.79\ln(P_s)$$

Using the data in Table 23, this predicts that any glazing treatments on the north wall of ESIF will almost certainly fragment. Many of the glazings on the north wall have been replaced with blow-out panels, and as such may be resistant to breakage. Based on the Lees (1996) information, Lees (1996) provides a formula relating serious injury from missiles, particularly glass to impulse as (Lees [1996], 17/242)[8]:

$$Y = -27.1 + 4.26\ln(I_s)$$

Again, using Table 23 and the probit relation above, a serious wound from glass fragments is unlikely; however, glass fragments resulting from the overpressure may cause skin lacerations for persons in the ESIL or ECL.[9]

[8] Note that Lees' equation 17.40.31 identifies the impulse variable "J," which for consistency in this evaluation has been kept as "I."
[9] See Department of Army (1969) table in Lees 17/242.

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The Science and Technology Facility is located approximately 130 m from the hydrogen pad. The probit value at this distance is 3.34, corresponding to a 5% chance of breakage. This indicates that some of the glazings may shatter. The probit value for serious injuries due to secondary missiles such as glass is -13.05, indicating that such injuries are not likely to occur.

Ground Shock Estimates*:* The amplitude, in inches, of the potential ground shock estimate as a result of cylinder burst is provided by Lees (1996, p. 17/187):

$$A = 0.001\ \frac{K(E_{TNT\ Eq})^{1/2}}{d}$$

where:

K = soil constant (assume clay, where K = 300)
$E_{TNT\ Eq}$ = TNT equivalent mass (lb)
d = distance to structure (ft.)

At close range, blast wave damage is far more damaging than ground shocks. For distant receptors outside of the range of damage from overpressure, ground shock is worth consideration. Based on the same distances as used in Table 23, the Science and Technology Facility has an amplitude of 0.0048 in. For the Richards Heights Subdivision, which is the closest to the ESIF, the amplitude is estimated at 0.0015 in., while the Whitaker Subdivision would have an amplitude of approximately 0.001 in. Lees (1996) indicates ground shock amplitude of less than 0.008 in. is generally needed for avoiding damage to an average structure. Hence, no property damage is anticipated due to ground shock at either subdivision, although the amplitude at the wall of the Science and Technology Facility is nearing the damage threshold.

Risk Summary: The probability is Extremely Remote, given a conservative estimate of probability. The severity of the events is Critical; hence, the risk profile is Low.

Controls: The tank/cylinder is rated to 15,000 psig by the manufacturer (the current maximum operating pressure is 13,500 psig), constructed in accordance with ASME BPVC Section XIII, Div. 3 and/or Section X, Class III standards, and proof tested to at least 125% MAWP. The cylinder is a robust, seamless tube construction with continuous, spin-forged, non-welded end caps. Testing funded by NREL has indicated that these tanks are highly resistant to mechanical damage. Even with 40% scoring to the composite layer, the vessel retains integrity through pressure cycling and results in burst pressures well in excess of the MAWP (Makinson and Newhouse [2011]). In addition, non-destructive, external inspection protocols are in development to monitor high-pressure composite vessels to ensure maximum vessel integrity (National Board of Boiler and Pressure Vessel Inspectors (undated); Newhouse et al. [2012]).

The only source of pressure that could generate pressures exceeding 15,000 psig is the system compressors, and these source pressures are controlled by a system of pressure relief valves and pressure reducing stations. These compressors may also be equipped with compressed air pressure control units limit the discharge pressure of the compressor by the use of spillback to suction.

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The cylinder is positioned on the extreme north end of the ESIF development area, separated from the ESIF and other STM installations in accordance with risk-based separation distances prescribed in NFPA 2. The pad is partially shielded on three sides by the geography of the mesa, limiting the impact radius of projectiles. The pad and cylinder will be protected by bollards and fencing, to minimize the probability of impact with vehicles and mobile equipment. The pad is sloped to prevent the accumulation of flammable liquids beneath the tanks. The area is electrically classified, and potential ignition sources have been eliminated. Interlocked UV/IR flame sensors are used to detect fires within the area and to initiate alarms and emergency shut-down sequences to limit the severity of the event.

4.6.3 Leakage of Hydrogen into a Confined Space

Leaks of hydrogen into confined spaces are characterized by many different event scenarios as presented below.

4.6.3.1 Hydrogen Leak in Gas Cabinet

Event Description: Leak at the hydrogen Compressed Gas Association (CGA) connection resulting in ignition of hydrogen inside the gas cabinet.

Probability: This event is due to a mechanical failure of a manifold or connection due to such factors as over-pressure, vibration, misalignment or thermal expansion and contraction. The probability of an automated valve failing to operate or remain open is quite high (~10^{-1} faults per year). These failures, however, will not result in a leak in the gas distribution cabinet. The probability of a leak from the manifold and associated connectors to the gas cabinet is substantially smaller. Mean annual leak frequencies for even very small leaks (e.g., 0.01% of total flow area, which is much less than posited in this scenario) range from 10^{-3} to 10^{-6} (LaChance et al. [2009], Table 4-2). The most likely fault scenario stems from human errors of commission in making connections (~10^{-1}). Consequently, it is possible, but not likely that this transient will occur in the life cycle of the system.

This transient is possible for any hydrogen cylinder. NREL has standardized gas cylinder procedures in effect laboratory-wide, and tens of thousands of hydrogen cylinders have been used without incident during the laboratory's history.

The overall probability is Remote.

Consequences: The consequences of a hydrogen leak in a gas cabinet could be critical because the maximum initial flow out of a cylinder at 2,500 psi with a valve opening of 0.25 in. is approximately 25,000 standard liters per minute (4.9 lb/min). The flow decreases as pressure decreases, and in less than five minutes the cylinder will empty. Fire and/or explosion are then possible.

A worst case scenario involves the release of hydrogen through a wide-open valve at maximum cylinder pressure, when the cylinder is not connected, to any flow restricting lines. Potential leaks through a cylinder 0.25-in. open valve were considered. At P = 2,000 psig, cylinder size 1A, 216 ft^3 under standard temperature and pressure, the maximum flow release flow rate would be 25,000 liters per minute, or 4.9 lb/min.

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The concentration buildup in gas cabinets with and without ventilation functioning exceeds the LFL for hydrogen gas in only a fraction of a minute. Exceeding the LFL is dangerous although ignition is not expected without an ignition source present (hydrogen auto-ignition temperature is 752°F). Although hydrogen is suspected of self-ignition during high pressure drop flows, often associated with sudden releases such as during burst of a ruptured disc, typically this ignition takes place immediately after release occurs, consuming the hydrogen and preventing accumulation that might result in a flash fire (Dryer et al. [2007]). Although the lower limit for an explosion of hydrogen can be debated, we can say that given the very rapid concentration built up by a worst case release, if an ignition source is present, explosion is possible.

To prevent such an event, cylinder change safety procedures are strictly enforced.

The consequence was categorized as Critical.

Risk Summary: This event presents a Low Risk profile, as a conservative estimate of the likelihood is Remote, and the consequence is Critical.

Controls: The most likely cause of leaking hydrogen in a gas cabinet is operator failure to properly tighten the CGA connection during a cylinder change. Therefore, this connection must be checked with a hydrogen detector after every cylinder change.

An excess flow valve at the CGA connection would stop the flow of hydrogen downstream in the event of a serious leak. A significant leak upstream (at the CGA connection) would be detected by the operator when the valve is opened.

Smaller leaks would be contained by the gas cabinet and diluted by the exhaust flow to prevent the buildup of a flammable hydrogen mixture. In the event of ventilation failure, a system-wide interlock is triggered and the flow of hydrogen would be immediately stopped at the source. Additionally, gas detection of fractional concentrations of the LFL in the cabinet will initiate shutdown of the control valve and laboratory EPO and alarm.

No ignition source is allowed inside a gas cabinet, and only intrinsically safe electrical components are allowed; this minimizes sources of ignition.

If a large leak were to develop with subsequent ignition, the cabinet would contain the fire and an internal sprinkler system would be activated to reduce damage.

4.6.3.2 Failure of Gas Supply Line within the ESIL

This accident scenario includes an administrative or mechanical failure that would allow hydrogen an open pathway from the 3,000-psig hydrogen storage vessel through the piping manifold into the ESIL room volume. Mechanical failures can be characterized as a rupture event resulting in an opening as high as 100% of the piping flow area.

The ESIL is designed and built to NEC 70, Articles 500 and 501 Class I, Division 2 standards. Administrative controls are detailed within the ESIL SOP to help assure safe practices and maintain the integrity of the safety systems. In addition, many engineering controls exist to maintain a safe operating environment within the ESIL space. Therefore, a number of

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engineering and administrative controls would need to fail before this accident scenario would be realized.

Accident Assumptions

- Initial concentration of hydrogen within the ESIL is zero.
- Tank pressure is maximum at 3,000 psig resulting in:
  - Maximum 10.3 kg of hydrogen in the tank
- Tank volume is known to be 0.681 m^3.
- Density of air and hydrogen is calculated with REFPROP.
- Ambient temperature of 20°C.
- Atmospheric pressure, P_{atm}, of 11.7 psi absolute (80.67 kPa).
- Mechanical or administrative control failure results in opening within the ESIL for hydrogen to flow from storage tank.
- Pressure-relieving valves have been configured for rated pressure of 3,000 psig for the laboratory manifold, or are not operational at the time of the accident.
- Laboratory tubing has maximum inner diameter of 0.18 in. (4.57 mm).
- Discharge coefficient, C_d
  - $C_d = 0.63$ for choked flow
  - $C_d = 1$ for subsonic flow

Probability: Considering the likelihood from the Sandia National Laboratories report, *Analyses to Support Development of Risk-Informed Separation Distances for Hydrogen Codes and Standards* (LaChance et al. [2009]), we propose the mean yearly frequencies indicated in Table 27 for hydrogen piping component rupture.

Table 27. Rupture Failure Rates for Various Piping Components (after LaChance et al. [2009])

Piping	Valves	Joints	Flanges
5.6×10^{-7}	1.4×10^{-5}	6.1×10^{-6}	Not Available

The overall probability of rupture is given by the sum of the rupture probability of each fitting within the space. However, even with a number of fittings, these probabilities are still generally far lower than those typically assigned to human factors for gross error, which are typically on the order of 10 to 10^{-2} for quantitative risk assessments. Thus, in the design and installation of these systems, it is critical to utilize reliable protocols to prevent user error and to ensure intrinsic safety. If these errors can truly be eliminated through administrative procedure, the probability of incident is reduced to less than 10^{-4} based on the presence of a few valves within the ESIL space. According to the NREL Risk Assessment Matrix (see Appendix D), frequencies below 10^{-4} through 10^{-6} are considered extremely remote. Even if the consequence is determined to be Catastrophic, the resulting risk would fall into the Low category.

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Consequences: Two different equations were used to determine the concentration of hydrogen inside the ESIL given the assumptions listed above. The approach uses Eqn. 3 to determine the initial concentration inside the ESIL. After that, Eqn. 1 does not account for the existing or build-up of hydrogen within the ESIL volume. After the first step of the simulation, Eqn. 4 is then used to show the impact of hydrogen buildup and recovery due to the ventilation system of the space.

The simulations were conducted in Microsoft Excel using a 1-second time step. The pressure of the tank is recalculated for every time step based on the amount of mass flow from the tank during the previous time step. The density of hydrogen at any given tank pressure is found using the program REFPROP.

$$C = \frac{G}{Q}\left(1 - e^{\frac{-Qt}{V}}\right)$$ Eqn. 3 (time step 1, only)

$$C_i = \frac{1}{Q}\left\{G - (G - Q * C_{i-1}) * e^{\frac{-Q*(t_2-t_1)}{V}}\right\}$$ Eqn. 4 (All subsequent time steps)

where:

$$G = Contaminant\ Generation\ Rate\ \left[\frac{kg}{min}\right]$$

$$Q = Air\ Evacuation\ Rate\ \left[\frac{m^3}{min}\right]$$

$$V = Room\ Volume\ [m^3]$$

$$C = Concentration\ in\ Air\ \left[\frac{kg_{H_2}}{m^3{}_{air}}\right]$$

$$k^* = Safety\ Factor$$

$$t = time\ [min]$$

* The safety factor, k, represents a range of practical inefficiency, variability in conditions and layout, system error and degradation of the ventilation system. This k provides a margin of safety by derating the ventilation effectiveness.

H_2 Flow Rate into ESIL (choked flow)

$$S = C_D * A_h * \left(P * \rho_o * k * \left(\frac{2}{r+1}\right)^{\frac{r+1}{r-1}}\right)^{\frac{1}{2}}$$

$$G\ \left[\frac{kg}{min}\right] = S\left[\frac{kg}{s}\right] * 60\ \left[\frac{s}{min}\right]$$

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H_2 Flow Rate into ESIL (not choked flow) P < 1,585 psi absolute

$$S = C_D * A_h * \left(2 * P * \rho_o * \left(\frac{k}{k-1}\right) * \left\{\left(\frac{P_{atm}}{P}\right)^{\frac{2}{k}} - \left(\frac{P_{atm}}{P}\right)^{\frac{k+1}{k}}\right\}\right)^{\frac{1}{2}}$$

Hydrogen Concentration Conversion

$$Concentration\ Percent = C\left[\frac{kg_{H_2}}{m^3{}_{air}}\right] * \frac{1}{2.01588}\left[\frac{kmol_{H_2}}{kg_{H_2}}\right] * \frac{1}{0.99149}\left[\frac{m^3{}_{air}}{kg_{air}}\right] * 28.97\left[\frac{kg_{air}}{kmol_{air}}\right]$$

$$Concentration\ Percent = (C * 14.494)\left[\frac{kmol_{H_2}}{kmol_{air}}\right] * 100\ [\%]$$

Constants

The volume of the ESIL is:

$$V_{ESIL} = 27060\ [ft^3]$$

$$V_{ESIL} = 27060\ [ft^3] * 0.028317\left[\frac{m^3}{ft^3}\right]$$

$$V_{ESIL} = 766.3\ [m^3]$$

If we consider only using a quarter of the ESIL for this analysis:

$$V = V_{ESIL} * \frac{1}{4}$$

$$V = 191.6\ [m^3]$$

The ESIL air system circulates at:

$$Q = 30{,}000\left[\frac{ft^3}{min}\right]$$

$$Q = 849.51\left[\frac{m^3}{min}\right]$$

Conclusion: This accident scenario allows all 10.3 kg of hydrogen to flow into the ESIL starting at the storage vessel's maximum pressure of 3,000 psig. The results provided in Figure 17 show two concentrations of hydrogen using Eqns. 1 and 2 and the assumptions listed above. The maximum concentration is found to be 18.7%, well above the LFL for hydrogen in air of 4%. In this simulation, the amount of time spent above 4% is 56 seconds.

According to the commissioning report, there exists a 52-second time delay from the furthest remote sampling point before the gas is received at the sensor. Following that, there is a total of 10 seconds delay of accounting for the internal electronics of the hydrogen detector and the ESIF monitoring system. Not accounted for here is the diffusion time from the point of release inside

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the ESIL until reaching the sampling port of the hydrogen detection system, which is estimated to be 6 seconds. This vertical transit time to the sample ports at the ceiling structure tees was estimated based on an earlier computational fluid dynamics simulation of hydrogen released at 2,000 psig conducted by the design team.

Next Steps: Update the ESIL ventilation rate to 7,000 ft^3/min (198.2 m^3/min), 68-second maximum propagation delay through furthest sample port (use 7,000 ft/min vent during that time), 3-second delay for vent fan ramp up from 7,000 to 14,000 ft^3/min (use 10.5k ft^3/min average for 3 min) and the remaining time of event at 14,000 ft^3/min. Determine time spent above 4% concentration of hydrogen in air.

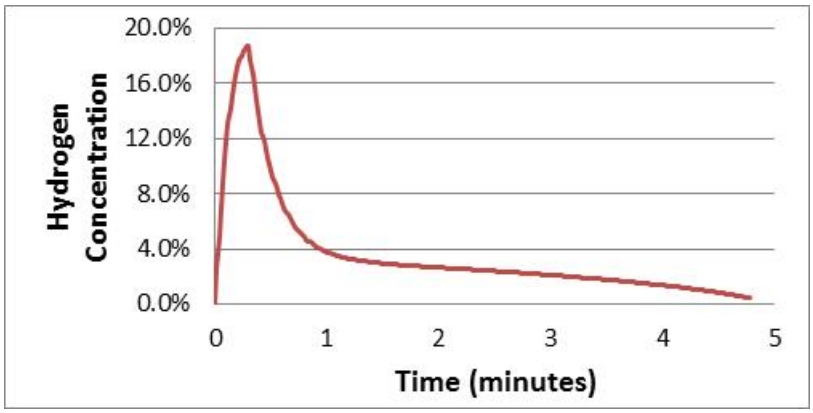

Figure 17. Resulting hydrogen concentration inside ESIL

Risk Summary: This event scenario ranks as a Low Risk.

Controls

Volume: The ESIL has a large 5,000 sq. ft. area with roughly 30-foot ceilings. This resulting large volume improves the overall safety of the testing area to allow hydrogen to disperse freely. Hydrogen gas is highly diffusive (0.61 cm^2/s) and positively buoyant; it rapidly mixes with the ambient air upon release. The ceiling of the ESIL consists of structural tee sections that create 13 long channels of air. Each of these structural tees creates a channel that is roughly 2 feet deep. In the case of hydrogen and its positive buoyancy, the gas becomes essentially isolated from the other channels as there is only a small amount of mixing occurring. The ESIL is continually monitored by a hydrogen detection system and includes basic and advanced ventilation systems.

Basic Ventilation: Much like the other laboratories, the ESIL is designed with a basic ventilation system to meet the ASHRAE 62 standard for acceptable indoor air quality. Upon detection of 4,000 ppm, which equals 10% of the LFL of hydrogen, the ventilation system roughly doubles its flow rate.

Advanced Ventilation: The structural tees discussed earlier pose a special circumstance where hydrogen could stratify and accumulate within the isolated channels. To mitigate this situation, ventilation supply and return ducts extend up into the 2-foot channels and provide a push-pull action to sweep out the channels. Air sampling ports also extend up into these channels.

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Hydrogen Detection: In each of the 13 channels, an air sampling port extends up into the 2-foot space to pull air towards a hydrogen gas detector located in the adjacent corridor. The detector analog signal is monitored by the ESIF supervisory control system, which monitors and provides two alarm levels. The first alarm occurs at 10% LFL of hydrogen in air and causes the room ventilation to double, illuminates an amber beacon for the ESIL, and provides an update of this condition on the ESIL human machine interface. The second alarm level occurs at 25% LFL of hydrogen in air. At this point, an internal relay to the hydrogen gas detector opens, causing an EPO for the ESIL. The EPO removes all power from the ESIL except for the ventilation system. The loss of power immediately halts all hydrogen production and compression within the ESIL, while also closing the fail safe (spring return) isolation valve out on the storage tank.

Check Valve: The design of the ESIL hydrogen production, compression, and storage system to provide house hydrogen to the other ESIF laboratories is designed to protect against reverse flow. The small orifice of a check valve also provides a limiting action on the flow of hydrogen. Check valves are opened when a differential pressure across the two-port device is reached. This "cracking" pressure is determined by an internal spring or other flexing mechanism that is specified depending on the application

A check valve with a nominal 25 psig cracking pressure is specified for the hydrogen storage tank located at the ESIL OTA. This particular check valve has an internal spring that will crack open with pressures ranging from 20 – 30 psig. Due to spring and gas inertia hysteresis, this check valve will close or reseal when the upstream pressure is about 17 psig higher. However, check valves can fail open due to debris on the poppet or O-ring sealing surface. Regular inspection and replacement programs are recommended to limit check valve failure.

4.6.4 Spill of Nanomaterials

Nanomaterials will typically be manufactured at other facilities and brought to the ESIF in liquid suspension or bound on a substrate. More typically, micron-sized structures of nanomaterials may be present in small quantities at the ESIF. The materials will be handled in chemical fume hoods and negative pressure glove boxes. Nanomaterials will be routinely handled between laboratories at ESIF and between other facilities on the NREL campus.

Probability: The probability of spills is somewhat analogous to handling any hazardous chemistry. This is largely governed by errors of commission or omission (~10^{-3} or 10^{-2}) or primary containment failures during handling and transport. The possibility of a spill, however, does not, in itself, result in a harmful exposure in that the vast majority of nanomaterials are suspended in solution or bound in a matrix. This coupled with the increased procedural rigor for handling these materials should decrease the probabilities of a harmful exposure.

Consequences: NIUOSH's report titled *Approaches to Safe Nanotechnology: Managing the Health and Safety Concerns Associated with Engineered Nanomaterials* (NIOSH 2009) points out the great uncertainty in estimating the consequences should a person be exposed to nanomaterials. Given the lack of good impact estimates, it must be assumed that a spill of nanomaterials during transfer could result in serious long-term health effects to any individual who came in contact with or inhaled the particles. The NIOSH report also states that the properties of nanomaterials are often different from those of other materials having the same

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composition; as a result, nanomaterials present an increased handling risk. Overall, given the uncertainties, the effects of exposure to nanomaterials must be classified as Critical.

Controls: NREL's *Chemical Safety Procedure* strictly regulates the handling of nanomaterials. Nanomaterials at the ESIF will be handled in negative-pressure glove boxes and chemical hoods. A ventilation canopy, which is connected to the HEPA filtration bank, is installed in the Thermal Storage Process Laboratory specifically for off-normal event mitigation during integrated process testing of heat transfer fluids utilizing nanomaterials. All the critical chemical exhaust systems in the ESIF are connected to the central HEPA system on the roof of the ESIF. Between control areas, nanomaterials are handled in secondary containments to further lessen the likelihood of an uncontrolled release to the environment. The ESIF is equipped with laboratory service corridors to facilitate the safe handling of nanomaterials and other chemicals so as to better contain/mitigate any spills. All of the ESIF is equipped with smooth epoxy floors with an integral cove base to facilitate proper remediation of spilled chemicals. Moreover, the design of the ESIF attempted to maximize adjacencies and control inter-laboratory handling of chemicals to minimize handling in areas that could increase exposures. Finally, the ESIF has a designated chemical handling dock and a hazardous waste area that are purposely situated to minimize travel distances for chemical transport and further mitigate the consequences of spills.

4.6.5 Misconfiguration of REDB Racetrack and Laterals from REDB Control System Human-Machine Interface

Description of Event: During the initiation of an experiment, the wrong REDB laboratory lateral is inadvertently energized after an electrical source is brought online to a misconfigured REDB configuration.

Probability: Because of the uniqueness of this system, quantitative analysis of the likelihood of such an event is difficult. From a qualitative standpoint, the probability is considered to be Occasional. This event would be the result of human error on the part of multiple people on the REDB operations team. With the layered controls in place, multiple human errors must simultaneously occur for any consequences to occur.

Consequence: Inadvertently energizing a laboratory lateral, by itself, will not result in injury, occupational illness, or system damage. Personnel injury and/or equipment damage are possible, but would require that multiple layered controls be defeated and that multiple events occur simultaneously. Thus, the consequences of this transient event alone are negligible.

Controls: Any and all configurations of the REDB Racetrack and lateral systems must be pre-verified by multiple individuals on the REDB operations team. The REDB operations lead also verifies that a proposed configuration will not cause interference between multiple experiments or inadvertently energize unintended locations of the REDB. Once these verifications have been made, one REDB control room engineer will execute the configuration using the REDB control system human-machine interface. As the configuration is entered into the REDB control system human-machine interface, the system requires the control room engineer to verify the configuration point by point. A second REDB control room engineer will verify the configuration entered before energizing the experiment is allowed.

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REDB laterals that are not in active use for the experiment for which the REDB is being configured are required to be maintained in a safe state:

- The REDB lateral itself must be locked and tagged out.
- All potential points of contact by personnel with the laboratory lateral are to be properly locked and tagged out.
- Any equipment in that laboratory that may connect to that lateral is also required to be disconnected, locked, and tagged out when not actively part of an experiment.

Risk: Based on this analysis, the risk level is considered to be Routine.

4.6.6 Improper Operating Limits Are Entered into the REDB Control System Human-Machine Interface

Description of Event: REDB protective devices fail to prevent a current overload on a portion of the REDB.

Probability: Because of the uniqueness of this system, quantitative analysis of the likelihood of such an event is difficult. From a qualitative standpoint, the probability is considered to be Occasional. This event is due to human error on the part of multiple people on the REDB operations team.

Consequence: Minor system damage is possible to REDB electrical conductors in the event of an overload. Thus, the consequences of such an event are considered to be Marginal.

Controls: In designing and configuring any and all REDB experiments, multiple individuals from the REDB operations team, as well as the experiment's principal investigator, verify all electrical sources and sinks that will be placed onto the REDB and the maximum current that will be present at all locations on the REDB configuration at all times. Using this information, appropriate operating limits, which include a factor of safety, that will limit the current at any point along the REDB to within its rating are chosen. These limits are then verified by the REDB operations team lead and entered into the REDB control system human-machine interface by a REDB control room engineer. A second REDB control room engineer verifies that the intended limits were properly entered.

All unproven REDB experiments with multiple sources will be attended-operation only. Those attending a REDB experiment will be monitoring the current at various points in the experiment and should be able to quickly respond to any overload event.

Risk: Based on this analysis, the risk level is considered to be Routine.

4.6.7 Corrupt or Compromised Control Logic is Introduced to the REDB Control System

Description of Event: Normal software-controlled safety functions performed by the REDB control system fail to operate.

Probability: This event is caused by human error (introduced when modifying the original, tested-as-working, control logic to make an approved change), malicious human intervention

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(purposely replacing working controller logic with modified control logic), or by communications or controller corruption. System-wide consequences are only possible if multiple controllers are compromised, which is extremely remote. In all, there is a remote probability of occurrence with the controls in place.

Consequences: Minor system damage resulting from an overload event, which would otherwise have been detected and acted upon by the controller, is possible; however, such damage is limited to the local area that a particular controller is responsible for (the main REDB raceway is monitored by multiple controllers). Injury would not occur as a result of just this event; another event would have to simultaneously occur for injury to occur. Thus, the consequences of such an event are considered to be Negligible.

Controls: Access to modify control code is closely controlled. All changes must be reviewed and approved per the change management process, and any changes require extensive testing, review, and verification before the system can go live.

Any access to the REDB control system communications network that is required to modify controller logic is very tightly controlled and monitored. An initial cyber security assessment has verified that the risk of attack to this network is low. Continuing cyber security monitoring and audits will be conducted.

All points of the REDB, except for selected sources and sinks without their own controller, are monitored by multiple controllers that are all capable of initiating an EPO.

Maintenance of critical hardware is performed at manufacturer-recommended intervals as part of the ESIF *Operations and Maintenance Plan*.

Risk: Based on this analysis, the risk level is considered to be Low.

4.6.8 Flow Battery Leakage

The ESIF is expected to test flow batteries as grid energy storage devices up to the megawatt scale. A number of electrolyte systems have been demonstrated at smaller scales, of which vanadium/vanadium (V/V), vanadium/iron (V/Fe), and zinc-bromide (Zn-Br) electrolytes have shown promise and have been piloted at scales in the tens of kilowatts. During commercialization of these batteries, a number of leakage events have occurred. Although the precise hazard level depends on the selected electrolyte solutions, a general understanding of the risks for worker safety and environmental damage of a large-scale electrolyte leak may be studied.

Additional initiating events and safeguards that are specific to an individual flow battery technology must be handled through the use of PrHA of the particular technology before installation to manage the risks of each individual system. For example, in some systems and scenarios, hydrogen or toxic gas (e.g., bromine, ammonia) evolution is possible during certain conditions, leading to potential over-pressurization and loss of containment if pressure control devices fail. Another internal failure mode that must be considered in the PrHA is the accidental mixing of the catholyte and the anolyte, resulting in a rapid reaction and energy release.

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Ultimately, these different initiating events typically lead to large-scale containment loss as their worst-case consequence, which is discussed in detail here.

Installation: Flow batteries consist of catholyte and anolyte solutions that are pumped from storage tanks in circuits through battery stacks. Storage tanks are typically held at a pressure nominally above atmospheric pressure. For most types of flow batteries (notably excepting Zn/Br), energy storage and the power output may be decoupled as the size of the vessel is more or less independent of the size of the battery stacks. The storage capacity of the battery is largely determined by the quantity of chemicals stored and the energy density of the electrolyte solutions.

Most vendors of flow cell storage units have chosen to modularize their units, typically mounting the battery stacks, storage tanks, power electronics, and controls within shipping containers to provide easy installation and transport for systems providing total power ratings greater than 100 kW. Some designs mount a number of smaller, self-contained cells within these enclosures, while other designs utilize a single large system.

Based on the quantities of chemicals required, the flow battery must be located within an H-4 Occupancy. Based on the occupancy ratings of the various laboratories, the ECL has been identified as one of the best rooms to locate battery testing equipment as it was built as an H-2 Occupancy and is large enough to accommodate the flow reactors. The room is equipped with a 4-inch sealed edge on each wall, excluding the doorways. The room is approximately 33 ft. × 28 ft., yielding an area of 924 sq. ft. Assuming 4-inch berms or other means of sealing are added to the doors, this means that the room could contain up to 2,300 gallons of liquid in the event of a spill without modifications. The only other room meeting H-4 Occupancy requirements is the ESIL, which is currently occupied by electrolyzers and other hydrogen equipment. Before installation of any battery, consideration would have to be given to the safety implications of collocating a specific flow battery with an operating hydrogen system, particularly if alkaline electrolyzers are in use.

The base large-scale unit of the Gildemeister CellCube V/V is a 200-kW unit with 400 kW-hr of storage capacity. Based on an approximate energy storage density of 22.6 W-hr/L (Li et al., 2011), this indicates a minimum volume of 35.4 m^3 (4,700 gal) of stored electrolyte (sum of anolyte and catholyte). Each unit contains catholyte and the anolyte stored in two separate plastic storage tanks, each with its own pumping system. The pressures are expected to be nominally atmospheric. A gas barrier is used to prevent oxygen ingress while allowing evolved gases to escape from the system.

Installations of Zn-Br batteries have been developed up to 500 kW-hr. These consist of ten 50-kW-hr independent Zn-Br battery modules installed in a single enclosure. Zn-Br systems may achieve 15.7 – 39.0 W-hr/L energy density; thus, each module may contain approximately 850 gallons of electrolyte solution, while each enclosure may contain as much as 8,500 gallons.

Probability: By utilizing inherently safe design concepts, manufacturers can nearly completely eliminate the likelihood of large-scale leakage of electrolyte from the pumps and piping system. Although these vary by manufacturer and should be examined on a case-by-case basis, these may

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include utilizing top entry nozzles, leak detection systems, automatic shut-off valves, and interlocked action to stop pump flows in the event of a leak.

The most likely way that large-scale electrolyte leakage may occur is due to rupture of the containment vessel. The most likely scenarios of rupture resulting in large releases are mechanical impact by a vehicle, over-pressurization, material defect, or corrosion. Over-pressurization will not be covered within this analysis but will be covered within a PrHA of the battery unit. Although other scenarios, such as overfilling or leaking connections, may be more likely, they are unlikely to result in large-scale releases.

An accepted failure rate for atmospheric storage tanks is given as 3×10^{-5} (Lees 1995, Appendix 14: Failure and Event Data, p. 12), although other sources have estimated this failure rate to be between 4×10^{-4} to 3×10^{-6}. Proper selection of the tank's material of construction to resist the dilute acidic environment of the electrolyte solutions is a critical part of reducing the probability of failure.

The overall risk is judged to be Extremely Remote.

Consequences: A major leakage of electrolyte solution may result in substantial property damage, environmental contamination, and potential exposure of workers to hazardous chemicals. The leakage has the potential to empty one of the electrolyte tanks. In the 400 kW-hr CellCube example, this means that up to 2,350 gallons of electrolyte may spill, filling the room to a height of 4 inches, and potentially leaking into the crawl-space below if not contained. The electrolyte can short circuit electrical components and corrode susceptible materials. Furthermore, if the electrolyte solution reaches the foundation of the building, the solution may contaminate the soil with high concentrations of metals or chemicals, forcing costly soil remediation.

Both vanadium and zinc solutions can produce acute toxicity and are harmful if swallowed in large quantities. Zinc bromide solutions also have the potential to evolve bromine and/or ammonia gas, a reactive and toxic vapor. Even in the event of a spill, it is unlikely that a worker would be exposed to enough electrolyte to produce an acute response. Injury and skin irritation due to gross exposure are more likely outcomes.

Overall, the consequence is judged to be Critical.

Controls: The flow batteries incorporate a number of leak detection and containment features that can alert operators to a developing leak and to limit the loss of electrolyte. These systems use interlock action to shut off pumps if leaks are detected.

The low pressure tanks are fabricated from plastic to resist corrosion and to offer a long service life. Properly sized, water-tight enclosures and containment dikes can completely mitigate many of the environmental and facility damage hazards. Even if a single event damages the integral secondary containment of the flow battery and the storage tanks, the large-scale spill may be contained within the room by a containment berm, greatly limiting the impact of the spill.

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Facility operations and practices must ensure that vessels are thoroughly inspected and leak-tight before operations are begun and that secondary containment safeguards are in place before any filling or emptying operations are undertaken.

4.6.9 Toxic Spill Indoors (Acid in Liquid form)

Laboratory usage of strong acids, while conducted in fume hoods, requires handling of containers outside of the hoods for delivery and storage. A spill can occur outside the fume hood during these activities. Additionally, a catastrophic spill or container failure, while having some secondary containment from the hood, could flow into the laboratory space.

Installation: The ESIF contains no permanent installation of acids in the liquid form. All liquids are brought into the facility in small containers, 1 liter to 1 gallon in size. Containers are designed and approved for transportation and delivery purposes. Sulfuric acid would only be used in the wet laboratories (MCL, ESFL, ML, ECCL, ESSL, TSML, and TSPL) within fume hoods. Perchloric acid can only be used in the ECCL where the facility contains a hood specifically designed for the acid, per code, to handle the associated hazards.

Probability: The primary hazard associated with handling the acids is dropping the container during transportation, causing a rupture and subsequent release of the acid. Because handling is completed by personnel, the probability is listed at 10^{-1}, Reasonably Probable.

Consequences: The PrHA has identified the consequences of a spill as Marginal to the Facility and Public/Environment and Critical to the Worker. The following hazards are identified in each chemical's Material Safety Data Sheets (MSDS) for each acid:

- Sulfuric Acid (MSDS, Revision 1, 12-Nov-2010, Fisher Scientific, *Sulfuric acid, 73–98%*)

  Causes severe burns by all exposure routes (eyes, skin, inhalation, ingestion). Reacts with water. May ignite combustibles (wood paper, oil clothing, etc.). Contact with metals may evolve flammable gas.

- Perchloric Acid (MSDS, Revision 8, 06-June-2006, Fisher Scientific, *Perchloric acid, 50–72%*)

  Causes severe burns by all exposure routes (eyes, skin, inhalation, ingestion). Reacts with water. May ignite combustibles (wood paper, oil clothing, etc.). Contact with metals may evolve flammable gas.

Controls: The limited quantity available is the major control for the usage of acids. At a maximum of 1 gallon of liquid, if the entire container is spilled to the laboratory floor, a spill the size of about 13 sq. ft. in area will be produced (assumes 1/8-inch thickness of liquid on the horizontal surface). Because the laboratories are 800 sq. ft. or larger and all floors are epoxy-coated concrete, the spill is easily contained within a small area of the laboratory, never causing exposure to the general public. The epoxy-coated floor and painted hoods and cabinetry provide protection to the facility from exposure to the acids.

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The vapor pressures of both acids are relatively low: sulfuric acid is less than 0.133 Pa at 20°C (MSDS, Revision 1, 12-Nov-2010, Fisher Scientific, *Sulfuric acid, 73–98%*), and perchloric acid is less than 0.9 kPa at 20°C (MSDS, Revision 8, 06-June-2006, Fisher Scientific, *Perchloric acid, 50–72%*), which means the acids will have a slow evaporation rate. All laboratories where acids are used have at least a six air change per hour ventilation rate and are high bay laboratories (32-foot height), providing a large volume of air. Thus, only the area localized to the spill would have dangerous concentrations. All air being discharged to the environment (via exhaust stacks) would have no greater concentration than present under normal usage of the acids in the fume hoods per the design.

Administrative controls are in place for how personnel should handle acids under both normal conditions and for any spill cleanup. These require the use of PPE to protect personnel from exposure and increased PPE for cleanup of spills. Recommendations from the MSDSs are as follows:

- Sulfuric Acid (MSDS, Revision 1, 12-Nov-2010, Fisher Scientific, *Sulfuric acid, 73–98%*)

  PPE (general use): Use in fume hood; wear chemical safety goggles, protective gloves, and clothing to prevent skin exposure.

  Spill Cleanup: Use PPE. Ensure adequate ventilation. Evacuate personnel to safe areas. Do not get in eyes, on skin, or on clothing. Soak up with inert absorbent material. Keep in suitable and closed containers for disposal.

- Perchloric Acid (MSDS, Revision 8, 06-June-2006, Fisher Scientific, Perchloric acid, 50–72%)

  PPE (general use): Use in fume hood; wear chemical safety goggles and face shield, protective gloves, and clothing to prevent skin exposure..

  Spill Cleanup: Clean up spills immediately, observing precautions in Section 3.9.3, *Personal Protective Equipment*.

  - Remove all sources of ignition.
  - Absorb spill using an absorbent, noncombustible material such as earth, sand, or vermiculite.
  - Do not use combustible materials such as sawdust.
  - Flush spill area with water.
  - Keep area wet and prevent it from drying out.
  - Provide ventilation.
  - Keep combustibles (wood, paper, oil, etc.) away from spilled material.
  - Keep unnecessary and unprotected personnel away.
  - Use only non-sparking tools and equipment.
  - Spill may be carefully neutralized with soda ash (sodium carbonate).

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Laboratories include eyewash/showers in the event of personnel having direct contact with the acid. E-stops in each laboratory, when activated, will sound a horn and indicate a red light at all entries to the laboratory. Personnel can activate the E-stop system in the event of a spill to warn other personnel to leave the area and to not enter the laboratory.

4.6.10 Toxic Spill Outside (Flammable/Combustible Fuels)

The ESIF has a diesel fuel system for laboratories that includes an outdoor fueling station where trucks can supply fuel to day tanks for laboratory use. OTAs also have experiment test pads where fuel-driven equipment can be used. Thus, fuel will be stored, refilling operations completed, and fuel used as part of experimentation. Spilling, storage container failure, or equipment fuel tank failure would result in the loss of a flammable or combustible fuel to the environment.

Installation: The ESIF has two diesel day tanks (100-gallon capacity each) that reside inside the building, one in the ESL and another in the PSIL. Level 2, outside the PSIL, has a truck refueling station for these tanks that includes a small spill containment box. Fuel delivery trucks could contain up to 6,000 gallons of fuel, but are handled in a DOT-rated tanker. No other flammable or combustible fuels are permanently installed at the facility. Fuels used at outdoor test pads in the LVOTA and MVOTA will use DOT-approved tanks as supplied on the equipment or a 55-gallon drum. Gasoline, diesel, and bio-diesel blends are the only fuels expected. Fuel transfers from 55-gallon drums to equipment tanks shall be accomplished via hand pumps.

Probability: Drum fueling and transportation activities are a manual procedure completed by personnel. Additionally, the OTAs can have a variety of vehicular traffic, making the probability of a spill 10^{-1}, Reasonably Probable, due to the dependence on personnel.

Consequences: The PrHA has identified the consequences of a spill as Catastrophic to the Facility, Critical to the Public/Environment, and Catastrophic to the Worker. The catastrophic ratings are associated with ignition of the liquid and/or vapor causing a significant fire and in the case of gasoline, potentially a flash fire and/or explosion. Loss of the fuels to the environment is considered an environmental pollution that requires reporting to the relevant authorities as these fuels contaminate soil and groundwater. Large spills can cause vapors that are hazardous to personnel.

Controls: NFPA 30, Table 15.3 provides allowable storage quantities and distances to property lines and public ways. The standard requires a minimum distance from any storage/usage of 50 ft to a property line and 10 ft to a public way for Class IA liquids, which are the most flammable (i.e., gasoline). Maximum pile storage is 2,200 gallons in metal containers (40 drums). These distances provide a good guidance to the exposure and risk range for an event. The outdoor test pads all meet the recommended distances, and there are expected to be two to four drums in either area.

Secondary containment shall be used for all 55-gallon drums, both during storage and any use. Equipment fuel tanks are DOT rated, thus not requiring secondary containment. Manual fueling processes (i.e., hand pump use) limit the quantity of liquid spilled from hose and transfer issues as personnel have to provide the motive force to displace liquid. Additionally, manual operation ensures SOP requirements for attended operation while transferring of fuels. It is expected that

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nozzles will be used to access 55-gallon drums, thus limiting the amount of liquid that can escape if a drum is tipped over. All containers shall be fully closed during any transportation.

Access to below-grade trench and areas: All have raised curbs to prevent liquid flow into the space. Standard below-grade confined space practices per OSHA are utilized to assure heavy fumes have not collected in the spaces prior to entry.

E-stop buttons located at each pad remove power from the pad and stop experimentation to reduce the potential ignition sources. General fencing and bollards provide protection to reduce the likelihood of an external event causing catastrophic failure of the fuel tanks/drums (e.g., impact from vehicular traffic). These barriers also limit the personnel to those involved in the experiment and trained for the appropriate hazards of the OTAs. General public and non-related personnel are kept from entering the test pads. E-stop buttons also indicate a red light at the test pads to warn personnel not to approach or enter the space.

4.6.11 Toxic Gas Leak

A number of toxic gases may be handled within the FCDTL. In the event of an accidental release, these gases may pose a significant hazard to workers within these laboratories. Hydrogen sulfide (H_2S) is a highly toxic and flammable gas that will be handled within FCDTL. In rats, the inhalation LC50% has been determined to be 712 ppm over 1 hour. Although it has a strong, unpleasant odor at even low concentrations, at concentrations greater than 100 ppm it is known to quickly cause olfactory fatigue, increasing a worker's risk of overexposure. In addition, its density is greater than air, causing it to settle and potentially accumulate to dangerous levels in quiescent areas. Based on these toxic properties, a large leak of hydrogen sulfide into the laboratory space has been selected as the representative accident analysis for toxic gas leakages in the facility.

Installation: Hydrogen sulfide cylinders and all connections must be made within a vented and purged gas cabinet or hoods, which are located in hallway spaces. Stainless steel tubing transporting hydrogen sulfide between the gas cabinet, fume hoods, and any enclosures shall have fully welded construction and further shall be contained within a carrier pipe. For the majority of applications, this tubing will be ¼ in. with a minimum thickness of 0.028 in. Three sizes of cylinders are commercially available, containing 20, 60, or 170 lbs of >99.0% purity liquefied gas at pressures of 252 psig, or 266.7 psia, respectively, accounting for cylinders filled at sea-level. For this analysis, it is assumed that the largest cylinder, containing 170 lbs of H_2S, is involved in an accident.

Probability: A number of initiating events may lead to the accidental release of hydrogen sulfide into the laboratory space, primarily envisioned as mechanical failure of the piping system due to over-pressure, vibration, misalignment, impact, or thermal expansion and contraction.

The most likely fault scenario is due to human errors in making cylinder or experimental connections, approximately 10^{-1} faults per year. However, when working properly, the gas cabinets and fume hoods should be capable of containing leaks without severe impacts on the laboratory environment. Gas cabinet failure (10^{-1} faults per year) on its own will not result in leakage; therefore, simultaneous failure of the cabinet at the same time as an improper connection is required to result in a leakage scenario. The need for these events to occur

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simultaneously reduces the likelihood by at least another order of magnitude for a well-maintained system equipped with hydrogen sulfide detectors, reducing the probability of leakage events to 10^{-3}. The greatest risk of leakage may be during a cylinder change-out operation, as a worker is expected to be present while opening the gas cabinet to replace the cylinder. These additional risks may be mitigated through proper gas cabinet pressure monitoring and regulator installation procedures.

Gross failure of the piping system outside of the gas cabinet would result in a direct path for the pressurized hydrogen sulfide gas to the room, quickly leading to dangerously high concentrations of hydrogen sulfide within the room. The most likely initiating cause is impact/mechanical damage, perhaps caused by failure of another experiment within the laboratory. The carrier pipe system further reduces the likelihood of catastrophic damage to the piping system. The likelihood of this type of failure has been estimated at 10^{-4}.

The probability of a large release is thus Extremely Remote.

Consequences: In the event of a gross mechanical failure of the tubing system, the 170-lb hydrogen sulfide gas cylinder at 267 psia would depressurize into the laboratory room, in this case assumed to be the FCDTL, C323, with an effective room volume of 19,670 ft^3. With the inner diameter of the tubing at 0.194 in. and atmospheric pressure at 11.7 psia, the instantaneous flow may be determined by:

$$Q_l = CYA\sqrt{\frac{2g(144)\Delta P}{\rho}}$$

where:

Q_l is the volumetric flowrate at upstream conditions, ft^3/s
C is the resistance coefficient, safely assumed as 1.0 for nozzles
A is the restriction area, sq. ft.
Y is the expansion factor, a fraction <1 based on the pressure drop divided by the absolute pressure[10]
g is the acceleration due to gravity, ft/s^2
$\Delta P = (P_{cyl} - P_{atm})$, the difference between the cylinder pressure and ambient, psi
ρ is the gas density at upstream conditions, lb/ft^3

For small restrictions, while $\frac{P_{cyl}-P_{atm}}{P_{cyl}} > 0.475$, the flow is "choked," and ΔP must instead be considered as $0.525P_{cyl}$, and Y considered to be 0.72.

Utilizing this instantaneous rate equation, the system may be modeled differentially with a small time-step (e.g., 0.1 min) to determine the depressurization rate and the room concentration. The FCDTL has an occupied air change rate of 6 air changes per hour, resulting in an exhaust flow of

[10] See Crane, pg. A-21.

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1,967 scfm. Interlock actions to increase the air flow were not confirmed and thus were not considered in this analysis. The room is considered to be well-mixed, although this is not a conservative assumption as local concentrations may exceed the room-average concentration.

As the pressure falls within the cylinder, the liquefied hydrogen sulfide vaporizes, with temperature and pressure approximately following the saturated vapor pressure curve. This vaporization takes up a substantial amount of latent heat and causes the temperature to quickly fall to 220 K within the cylinder, reducing the vapor pressure and thus the gas pressure within the cylinder. As a simplifying assumption, the cylinder is assumed to be at a single temperature and pressure; in reality, transient temperature gradients in the liquid would likely slow the evaporation rate somewhat, although this effect is likely insignificant. As the cylinder cools below ambient temperatures, heat is gained from the environment. For simplicity, a reasonable constant heat transfer coefficient (25 W/m^2-K) was selected to model this heat transfer. Correlations for hydrogen sulfide latent heat, liquid specific heat, and vapor pressure were used to determine the heat and mass balance and cylinder pressure at each time step.[11] Finally, the worst case scenario occurs when the cylinder is almost full, and this case was selected for this calculation. A significant reduction in both the flow-rate and the peak concentration is observed for partially filled cylinders.

The results of this differential analysis are presented graphically in Figure 18. The cylinder releases much of its volume in the first 5 minutes, where the concentration reaches its peak at over 16,000 ppm, creating a lethal environment within seconds after the incident begins. As the cold cylinder regains heat from the environment, hydrogen sulfide is released from the cylinder until the liquid is fully vaporized, extending the time a lethal hazard is present. The prolonged lethal concentrations of hydrogen sulfide would pose a threat to nearby laboratories and would likely require a full evacuation of the facility while the affected laboratories could be checked and cleared.

Controls: A number of controls are in place to limit the likelihood and impact of this type of toxic gas release event. All cylinders are contained within approved gas-cabinets to ensure that cylinder connections and changeovers can be accomplished without leakage into the laboratory environment. All-welded construction and double containment of all gas system piping greatly limits the possibility of damage and leakage.

By implementing protocols to conduct pressure testing of both the process tubing and the carrier pipe annually and between usage campaigns, the integrity of the piping system can be ensured before introduction of toxic gases. Procedures must ensure the reliable operation and regular inspection of gas cabinets and fume hoods. Work with hydrogen sulfide must not be undertaken when the reliability of these systems is in question.

[11] Properties correlated based on West, J.R., 1948.

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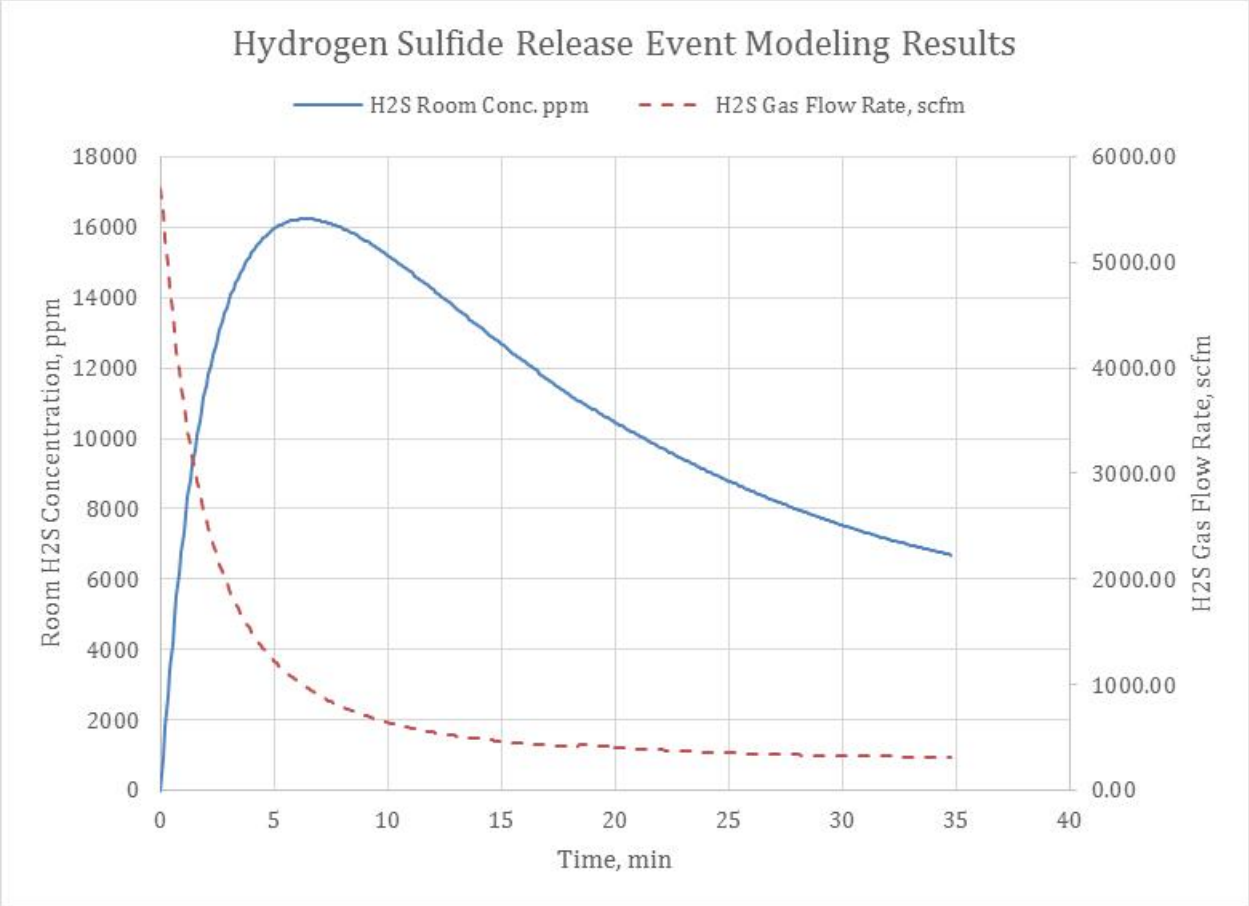

Figure 18. Hydrogen sulfide release event modeling results

The FCDTL (C323) is equipped with an aspirating air sample detector equipped with an Xtralis hydrogen sulfide detector. This detector has a user-configurable alarm at 5 ppm that triggers a yellow alarm light and a SCADA system alarm. At 10 ppm, the detector is configured to take automatic action, including lighting a red alarm light, alerting the SCADA system, sounding the laboratory horn, maximizing the airflow, and closing an automated gas manifold valve. Based on the monitoring system piping and flow rates, it is expected that the system will trigger within 70 s of the incident beginning. In the full release case described above, a potentially lethal concentration of 6,890 ppm is reached before action is taken. In the case of a full release, workers in the room will likely be immediately alerted to the leak by the noise of the escaping gas and should evacuate immediately. The alarm system should prevent accidental entry by others unaware of the incident.

4.6.12 Toxic Fumes Release from Combustion of Power Electronics or Solvents

Research activities in a number of laboratories have the potential to create small fires that are not self-sustaining. These fires are created from the overheating of power electronics or small solvent fires. Smoke generated from these small fires has been identified as the largest potential hazard in such an event. Overheating of power electronics can release toxic components and particles from the electronics into the atmosphere, exposing workers to many compounds, some of which are toxic. Solvent fires similarly release chemicals contained within them and combustion products into the air.

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Installation: Testing of power electronics is primarily done in Power Electronics Bays 1, 2, and 3 contained within SPL. However, the ECL, MCL, ESFL, FCDTL, ML, ESIL, ECCL, ESSL, TSML, TSPL, ESL, SPL, and PSIL could all experience a failure. Power electronics are installed as components in many devices tested and utilized in auxiliary devices required to monitor the experiment.

The ECL, MCL, ESFL, FCDTL, ML, ESIL, ECCL, ESSL, TSML, TSPL, ESL, SPL, and PSIL in the ESIF can use solvents from small containers. These solvents are limited to a maximum container size of 1 gallon and are stored in flammable cabinets when not being used. During usage, personnel handle the containers, transporting them from point A to B as needed, using them on laboratory benches and in laboratory hoods or ventilated enclosures.

Probability: Failure of power electronics varies for different laboratories. Testing of these devices for reliability, new to market, and under abnormal conditions is performed in the Power Electronic Bays in the SPL. As such, they have a probability of Frequent for overheating and creating toxic smoke. The rest of the facility uses power electronics that have already passed rigorous testing for the expected operation. As such, the probability of failure in laboratories outside the Power Electronics Bays is expected to be Reasonably Probable based on past experience.

Solvent fires are expected to have a Remote probability due to being a secondary event to solvent spills. To have a solvent fire, an ignition source must also be present during a spill event. Laboratories that are electrically classified, with the exception of ESIL and ECL, contain ignition sources such as electrical systems and hot surfaces. However, laboratories do not have open flames such as Bunsen burners.

Consequences: Combustion of power electronics or solvents creates toxic smokes that can contain components such as antimony, beryllium, cadmium, chromium hexavalent, lead, mercury, brominated flame retardants, PVC, polychlorinated biphenyls, phthalates, and organotins[12,13] for power electronics. Salts, heavy metals, and any compound contained within a solvent are potential toxins that are released during a fire, as well as a large number of combustion products, including carbon monoxide, hydrogen cyanide, dioxins, etc.

Due to the wide range of potential situations, the analysis is conducted in a more general format to demonstrate the effectiveness of the facilities safeguards. Release of toxic smoke due to either a power electronics failure or solvent fire would have the following consequences. The ESIF laboratories are designed as an industrial facility, and as such, smoke would cause minimal permanent damage to any of the laboratories. Consequences from an event are expected to be Negligible, as room cleanup would only require cleaning of surfaces and/or repainting due to smoke damage. Ventilation is designed to keep any release in the associated laboratory and exhaust the smoke to the roof stacks. Similarly, smoke exposure to the environment and public would also be negligible. The non-self-sustaining and fuel-limited properties of these events inherently limit the quantity of smoke that can be produced. Release of smoke either outside or from the ventilation exhaust systems will quickly dissipate into the natural environment. As such

[12] Toxic Tech, "The Dangerous Chemicals in Electronic Products." Greenpeace Briefing.
[13] Five Winds International, LP. *Toxic and Hazardous Materials in Electronics, An Environmental Scan of Toxic and Hazardous Materials in IT and Telecom Products and Waste, Final Report*

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the consequence to the environment and general public is also considered Negligible. However, workers in a laboratory could be exposed to fatally toxic concentrations of smoke, which could cause death or permanent disability resulting in a Catastrophic consequence. More likely consequences would only be injury.

The Society of Fire Protection Engineers (SFPE) *Handbook of Fire Protection Engineering* provides various tables and data (for example, Tables 28 and 29) to allow estimation of an event, potential level of hazards, and personnel escape times prior to incapacitation. These tables are used along with other assumptions to produce a potential bounding event scenario.

Table 28. Classification of Toxic Hazards in Fires as Revealed by Large Scale Fire Simulation Tests (SFPE, 1992)

Fire	Rate of Growth	CO_2/CO	Toxic Hazard	Time to Incapacitation	Escape Time Available
Smoldering/non-flaming: victim in room of origin or remote	Slow	≈1	CO 0 to 1500-ppm, low O_2 15 to 21%, irritants, smoke	Hours	Ample if alerted
Flaming: victim in room or origin	Rapid	1,000 decreasing toward 50	CO 0 to 1%, CO_2 0 to 10%, low O_2 10 to 21%, irritants, heat, smoke	A few minutes	A few minutes

The smoke conversion factor, ε, is defined as the mass of smoke produced/mass of fuel burned.

Table 29. Smoke Production for Plastics (SFPE, 1992)

Type	Smoke Conversion Factor, ε	Combustion Conditions	Fuel Area, m^2
PVC	0.03-0.12	Pyrolysis	0.005
PVC	0.12	flaming	0.005

The smoke conversion factor was used for creating a general mass balance on laboratories to determine a general concentration (by mass) and required time for an event to clear a laboratory for safe re-entry. Calculations were completed on the Power Electronics Bay 3, which is the smallest volume room, and the PSIL which is one of the larger high bay laboratories but has the lowest air changes per hour. These two laboratories provide good basis for review.

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The following assumptions and values were used to create the concentration versus time graphs presented in Figure 19:

- General Modeling.
  - Fire would generate smoke for 5 minutes.
    - Automated response systems will cut off sources of ignition (electrical power, REDB, etc.) at 2 minutes. The longest laboratory smoke detection response time is estimated at 2 minutes on the VESDA systems. Laboratories with standard smoke detectors will respond faster as they do not have the sample transport lag time.
    - Smoke generation will continue past the removal of the ignition source, but the fire is not self-sustaining, thus smoke generation will end at the 5 minute mark.
    - The buildings sprinkler system is an additional safeguard to validate the non-self-sustaining model. If the event generates enough heat where combustion of the surrounding room becomes feasible, the sprinkler heads would also trip, providing another control to limit the length of the fire.
  - Laboratories are fully mixed.
- PVC smoke generation was used as the basis. PVC is a significant component used in power electronics and creates hydrogen chloride fumes under combustion, thus making it the bounding compound.
  - The highest density of PVC (90.5 lb/ft^3).
  - A surface area of 0.05 sq. ft. and a thickness of ½ inch with a resulting 0.2 lb mass.
  - A smoke factor of 0.12 was used for flaming cases, and 0.03 was used for pyrolysis cases.
- Power Electronics Bay 3
  - Laboratory volume 2,028 cubic feet (123 lbs of air)
  - 9 lb/min minimum air flow rate (~4 air changes per hour)
  - 13 lb/min maximum air flow rate (~6 air changes per hour)
- PSIL
  - Laboratory volume 274,336 cubic feet (16,625 lbs of air)
  - 359 lb/min minimum air flow rate (~1 air change per hour)
  - 536 lb/min maximum air flow rate (~2 air changes per hour)

Figure 19 shows the resulting mass balance of smoke-generating events. Note the following items in the graphs as they support the expected results discussed in the control section of this analysis. In large high bay laboratories such as the PSIL, concentrations of smoke may never

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reach toxic levels throughout the laboratory allowing significant evacuation times. Laboratories fully clear themselves of the smoke in less than 2 hours.

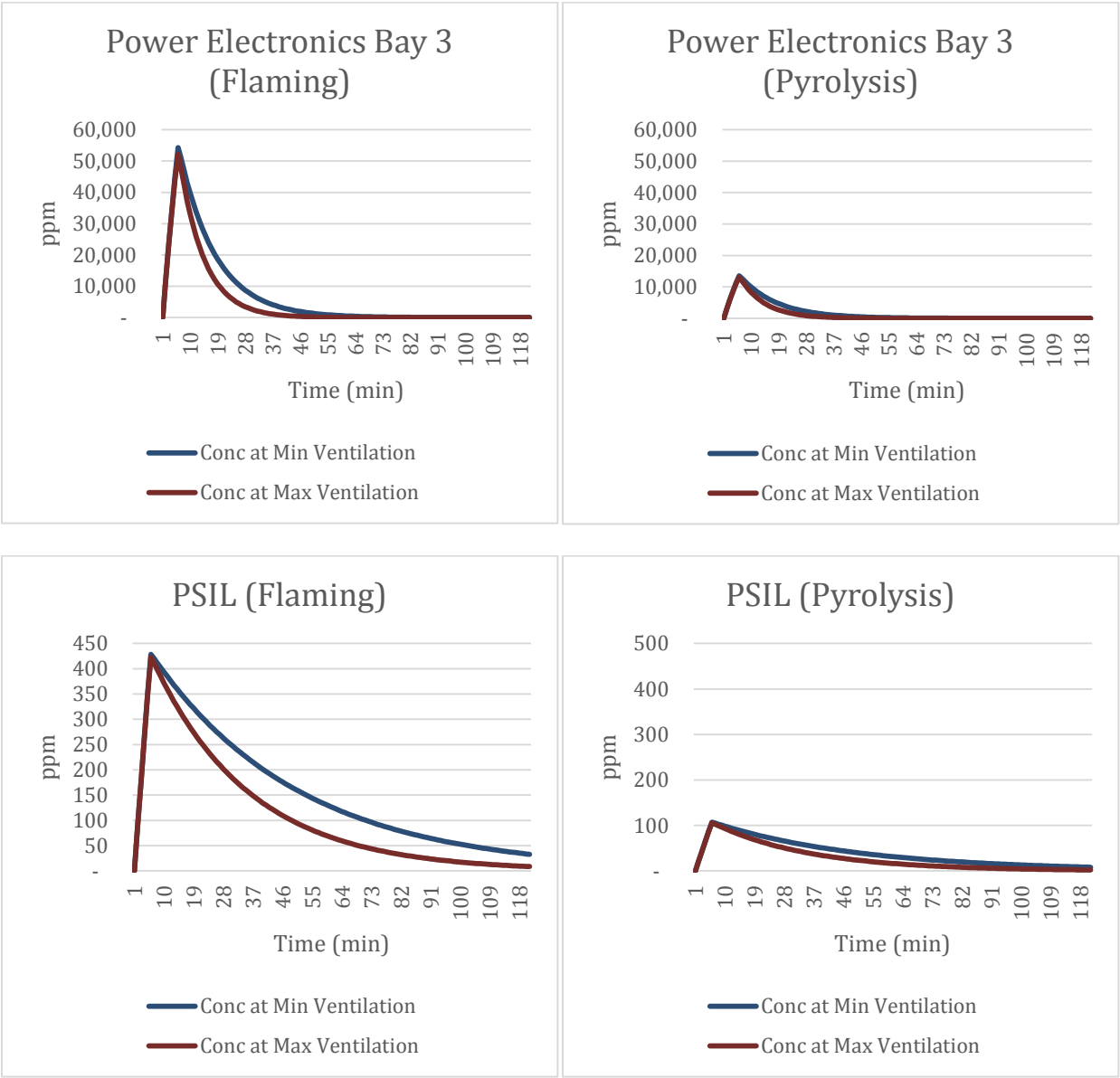

Figure 19. Resulting mass balance of smoke generating events

Controls: The ESIF laboratories have design features that protect the facility and worker from smoke events. The primary safeguard is the ventilation inside the laboratory. Ventilation removes any smoke (toxins) from the facility and provides safe egress routes and time for personnel to exit the facility, limiting any exposure to toxins. Local snorkels can be used during high-likelihood tests to further reduce any worker exposure.

A critical requirement of the bounding event is that the fires are not self-sustaining. Several engineered and administrative safeguards exist to assure these events remain limited. ESIF has a

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fire alarm system with smoke detectors that will sense and alarm all personnel of an event to evacuate the building. The system also is tied into the laboratory safety systems that will cause an E-stop of all laboratories. This removes all ignition sources and energy from the laboratories. Removal of energy limits the size of the event when dealing with power electronics fires. Power electronics fires require electrical energy to be present to continue to overheat a component or provide a short in the system that produces high current and subsequently the burning of material. Upon removal of that energy, the fire will become non-self-sustaining. Solvent fires have a limited quantity of fuel to the maximum size of the container being used (1 gallon).

Construction of the laboratories utilized low-flammable materials to prevent the spread of any small fires (epoxy coated concrete floors, open steel structure, concrete ceilings, drywall walls, etc.). Administrative controls require laboratories to be kept clean and free of combustible debris such as cardboard boxes. Additionally, fire extinguishers are located throughout the facility allowing users to quickly extinguish a small fire. Laboratory personnel are trained in the use of fire extinguishers.

The completed analysis supports the general recommendations of the *SFPE Handbook* indicting that smoke generated from these types of events is escapable by personnel prior to reaching a catastrophic level of exposure. Workers are trained to evacuate the facility when the fire alarm is activated. Ventilation and room volumes provide adequate dilution of the smoke being generated to provide ample time for such evacuations. As such the consequence to workers is reduced from the Catastrophic level down to Marginal or less due to the reduced exposure to any toxic materials. The above modeling also provides a guideline for acceptable times to wait prior to reentering a laboratory after an event.

4.6.13 Summary and Conclusions

The accident analysis has identified many possible events that could occur at the ESIF and has analyzed in detail several of the more severe event sequences. The analysis concludes that several events have the potential for significant impacts to site workers and possibly the general public and emphasizes the importance of the safety features that have been incorporated into the facility.

The ESIF is a complex facility with thousands of feet of piping and numerous safety devices of varying types that must function with high reliability to ensure safety. All results depend on material quantities and the conditions under which ESIF materials will be handled. As activities change, these bounding events should be reassessed.

Except for nanomaterials, decades of experience in safely handling materials have resulted in the development of a highly reliable suite of adequate preventive, protective, and mitigative safety features to ensure that the ESIF can be operated safely.

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5 Safety Management Programs

NREL has developed and implemented an Integrated Safety Management System, which fulfills applicable requirements in a manner that adequately protects workers, the public, and the environment from hazards associated with the operation of the ESIF. The ISMS is defined in LLP 6-1.5, *Integrated Safety Management and Environmental Management Systems.* Subsidiary documents implement the requirements of the NREL ISMS. These subsidiary documents include procedures that define the SMPs. The SMPs are developed and implemented for functional safety areas, inform workers of recognized hazards in the workplace, describe the potential adverse effects of these hazards, and specify the required protective measures.

The ESIF management team takes credit for controls established in the SMPs to assure worker safety and to protect the public and the environment. Figure 20 defines the approach used by the ESIF management team to establish if a control required to mitigate the impact of a hazard is addressed by an SMP or if an SAC or an ESF is required to mitigate the hazard. Hazards and controls specific to the ESIF that are not addressed in an SMP are described in Section 4 of this HAR.

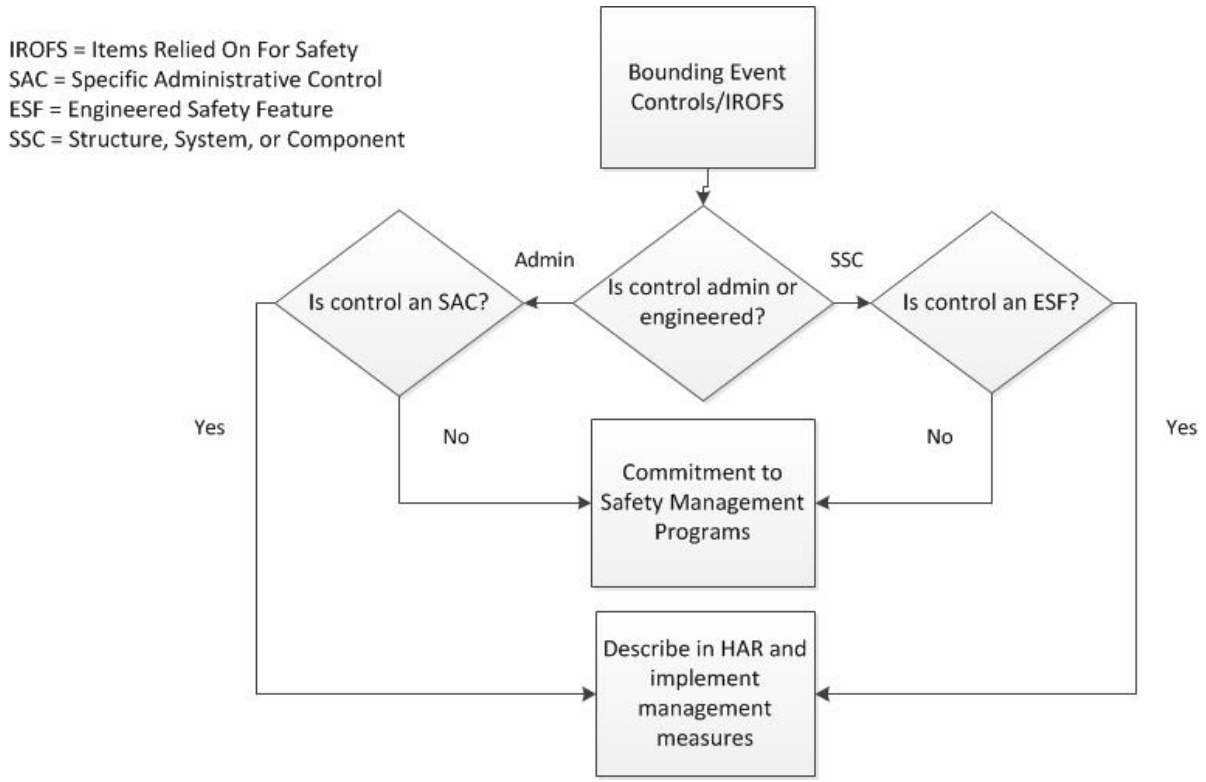

Figure 20. Elevation of some controls

The ESIF management team implements all SMPs applicable to the work in the facility, including:

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- LLP 6-1.46, Chemical Safety
- LLP 6-1.36, Fire Protection
- LLP 6-1.47, Compressed Gas Safety
- LLP 6-1.48, Local Exhaust Ventilation
- LLP 6-1.54, Electrical Safety
- LLP 6-1.55, Lockout/Tagout
- LLP 6-1.56, Hoisting and Rigging
- LLP 6-1.62, Pressure Safety
- LLP 6-6.2, Hazard Identification and Control.

The primary SMPs associated with working safely in the ESIF are *Chemical Safety*, *Fire Protection*, *Pressure Safety*, *Hydrogen Safety*, and *Electrical Safety*. The implementation of these SMPs is discussed in more detail below.

5.1 Chemical Safety

Chemical safety at the ESIF is implemented in accordance with LLP 6-1.46, *Chemical Safety.* The procedure has been developed to inform workers of recognized chemical hazards in the workplace, describe the known adverse health effects of these chemicals, and specify the protective measures to use chemicals safely. This procedure incorporates all appropriate requirements and guidance from DOE orders, guides, and standards.

Implementation of this procedure in the ESIF is the responsibility of ESIF Center personnel. All workers who perform activities with hazardous chemicals complete chemical safety training before being released to work in an ESIF laboratory without the direct supervision of a trained and qualified worker. Training requirements are defined in LLP 6-1.46. Additional training requirements are defined in the SOPs for working with extremely hazardous chemicals. Verification of adequate implementation of LLP 6-1.46 is the responsibility of the Chemical Safety Officer. This is accomplished through periodic self-assessments of both the content and implementation of the procedure.

As required by LLP 6-1.46, SOPs are required for working with extremely hazardous chemicals. Chemicals in this category at the ESIF include nanomaterials, highly toxic chemicals, and perchloric acid. Controls identified in LLP 6-1.46 and credited in this HAR include:

- For nanomaterials, ESIF performs a safety assessment per LLP 6-6.2, *Hazard Identification and Control*, and develops an SOP to handle nanomaterials. Engineering controls are employed, including the use of ventilated enclosures with HEPA air filtration and properly sealed containers for transport. Administrative controls associated with housekeeping requirements, work practices, signage, and labeling are defined by the SOP. PPE is worn as a precaution when the failure of a single control, including an engineering control, poses a risk of exposure to workers. Nanomaterials are handled in the ESFL, the TPSL, and the TSML.

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- Quantities and concentrations of toxic gases such as hydrogen sulfide are limited. An SOP defining safe handling requirements is required. Highly toxic gases are used in the MCL, the ECL, and the ESSL. The use of PPE when using acids and caustic materials is required as defined by Industrial Hygiene. The use of hoods or other ventilated enclosures is required. Hazardous chemicals are present at the ESIF in the ESIL, the Energy Systems High Pressure Testing Bays, the MCL, the ESFL, the FCTDL, the ECL, the ESSL, the TSML, the TPSL, the ESL, the PSIL, the SPL, the Hazardous Waste Room, and the Machine Shop.
- An SOP defining safe handling requirements for perchloric acid is required. Engineering controls are employed, including acid-resistant cabinets and exhaust ducting, inductive fan units, and automated ducting wash-down systems. Perchloric acid is present in the FCDTL and the ECL.

5.2 Fire Safety

Fire protection at the ESIF is implemented in accordance with LLP 6-1.36, *Fire Protection.* This procedure has been developed to reduce the level of risk to an acceptable level for the potential for bodily injury, property damage or loss, and programmatic interruption due to fire or explosion. This procedure incorporates all appropriate requirements and guidance from DOE orders, guides, and standards.

Implementation of this procedure in the ESIF is the responsibility of line management. As part of new employee orientation, employees are educated on the selection and use of fire extinguishers. LLP 6-1.36 requires hands-on training for specific laboratory workers and recommends hands-on training for other workers in the laboratories. The ESIF follows this recommendation and requires hands-on training for laboratory workers. Verification of adequate implementation of LLP 6-1.36 is the responsibility of the EHS Fire Authority Having Jurisdiction. This is accomplished through periodic self-assessments of both the content and implementation of the procedure and through independent fire and life safety assessments of the ESIF as appropriate.

The design, construction, and commissioning of the ESIF were accomplished such that the as-constructed facility meets the requirements of LLP 6-1.36. The procedure provides direction on code compliance, preparation of a formal fire hazard analysis, and control of facility modifications that could impact life safety requirements. The procedure addresses design requirements for facilities, including construction type, compartmentalization to limit damage from a fire, suppression and detection systems, and the use of state-of-the-art equipment that has been listed or tested by a nationally recognized test laboratory. Basic laboratory fire safety requirements associated with the use of flammable and combustible materials are defined. As required by LLP 6-1.36, a safety assessment must be completed before undertaking activities involving combustible materials. The required safety assessments have been completed as part of the safety analysis used to develop this HAR.

SACs are established to adequately implement fire protection in the ESIF. These controls are discussed in Section 1 of this HAR and include:

- Implementation of a combustible control program for the control of combustible materials in the hydrogen vessel storage area.

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Controls identified in LLP 6-1.36 and credited in this HAR include:

- Routine Testing and Inspection: Fire suppression, detection, and alarm systems are inspected, maintained, and tested per the applicable NFPA standard. Testing and inspection are performed by SITE Operations and qualified subcontractors.
- Building Inspection: The ESIF line managers routinely inspect laboratory, computing, common, and office areas and address fire prevention issues and concerns.
- Building Evacuations: The ESIF maintains facility evacuation procedures, and Security and Emergency Preparedness conducts periodic evacuation drills to minimize fire exposure to workers and visitors.
- System Outages and Impairments: Outages and impairments of fire suppression, detection, or alarm systems are minimized. Necessary fire system outages are conducted in accordance with *SITE Operations BAE-PMEC Handbook* and incorporate appropriate compensatory measures to achieve a commensurate level of fire protection.
- Fire Extinguishers: Fire extinguishers are located throughout the ESIF for workers to use in the event of a fire. Security is responsible for inspection and maintenance of these fire extinguishers.
- Wildfire Control Areas: Wildfire control areas are established and maintained by SITE Operations. Vegetation is maintained at a height of 4 to 6 inches within a distance of 30 feet around facilities and equipment; within a distance of 8 feet around transformers and electrical switchgear; within a distance of 4 feet along road, driveway, and parking lot shoulders; and in the roadbed of unpaved roads, driveways, and parking lots.
- Winterization: The ESIF has been designed for winterization of fire systems subject to freezing. SITE Operations performs an annual inspection of the ESIF to verify adequate winterization.
- Small Appliance Requirements: The ESIF follows NREL requirements for the purchase, installation, and use of space heaters, coffee makers, and cooking appliances.
- Hot Work: The ESIF generates a *Hot Work Permit* for welding, cutting, grinding, or other hot work for temporary activities as prescribed by LLP 6-6.5, *Safe Work Permits.* Hot work for routine activities and a fixed location is controlled by SOPs.
- Fire Safety for Heated Food Service Events: The ESIF follows fire safety measures for the use of Sterno and electrical heating appliances.

5.3 Pressure Safety

Pressure safety at the ESIF is implemented in accordance with LLP 6-1.62, *Pressure Safety.* This procedure provides rules and processes to protect NREL workers, property, and the environment by establishing a uniform safety system for activities involving pressure vessels and pressure systems (PV/Ss) or systems under vacuum. NREL PV/Ss, and the ESIF PV/Ss specifically, are designed, built, tested, maintained, and operated in accordance with regulations and applicable consensus codes and standards (National Codes and Standards), specifically the ASME Boiler and Pressure Vessel Code and ASME B31-series Piping Codes. This procedure incorporates all appropriate requirements and guidance from DOE orders, guides, and standards.

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Implementation of this procedure in the ESIF is the responsibility of line management. LLP 6-1.62 requires that users of PV/Ss are also trained in the specific requirements contained in the SOP.

Verification of adequate implementation of LLP 6-1.62 is the responsibility of the ESIF Facility Manager with the support of the ESH Pressure Safety Manager. This is accomplished through periodic self-assessments of both the content and implementation of the procedure and through the oversight of the design, fabrication, installation, testing, and operation of PV/Ss.

The design, construction, and commissioning of the ESIF was accomplished such that the as-constructed facility meets the requirements of LLP 6-1.62. This procedure identifies the general requirements for PV/S safety, including safety principles and MAWP and maximum operating pressure requirements. The procedure defines requirements for the design, selection, installation, and testing of pressure relief devices, valves, fittings, pressure gages, piping and tubing, piping and tubing support, and pressure regulators. Design considerations for PV/Ss are identified, including loading evaluation, provision for worker access, minimization of attachments, use of pressure relief devices, material selection on the basis of proven compatibility, restrictions on the use of non-code PV/Ss, and requirements for repairs or alteration of ASME code-stamped items. As required by LLP 6-1.62, a risk assessment must be completed prior to the design, purchase, delivery, or acceptance of a PV/S. The ESIF PV/Ss underwent risk assessments as part of the design process and as part of the IHA process documented in this HAR.

Controls identified in LLP 6-1.62 and credited in this HAR include:

- Pressure vessel design factors, including requirements for adequate factor of safety, contained fluid leak rate for hazardous materials, equipment access, realistic MAWP determination, overpressure protection, low pressure tank design standards, and flammable and combustible tank design standards. All pressure system design work conducted at the ESIF is performed by responsible designers with advanced pressure safety training, and reviewed by the Pressure Safety Manager and is compliant with the ESIF configuration management processes.
- Welding considerations, including ASME certification for welders and the impact of welding and repair welding on material qualities. All pressure system welding conducted at the ESIF is performed by ASME-certified welders. The ESIF employs the services of welding engineers or material specialists for the specification of weld parameters.
- Material selection requirements, including compatibility, use of ductile materials, and precautions associated with hydrogen embrittlement. The ESIF PV/S designs specify materials that consider the compatibility reference chart, Attachment D to LLP 6-1.47, *Compressed Gas Safety.*
- Design, operation, and test requirements for vacuum-only systems (MAWP less than or equal to 2 psig) and for pressure vessels also used for vacuum (MAWP greater than 2 psig). Operation and testing of vacuum systems are conducted in accordance with SOPs.
- Design, operation, and test requirements for inert cryogenic systems, cryogenic oxygen systems, and cryogenic hydrogen systems. Operation and testing of cryogenic systems are conducted per SOP.

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- Design, fabrication, operation, testing, and safety considerations for dewars per DOT regulations, including cryogenic liquid cargo tanks (mobile dewars) and mobile and stationary dewars (cargo tanks). Operation and testing of dewars are conducted per SOP.
- Design, testing, and safety considerations for refrigerator systems. Operation and testing of refrigeration systems are conducted per SOP.
- Requirements for facility boiler systems.
- Requirements for steam systems.
- Design, testing, and safety considerations for hydraulic systems. Testing and use of hydraulic systems are conducted per SOP.
- Documentation and record keeping requirements for PV/Ss. SITE Operations maintains records of required inspections and calibrations for PV/Ss.

5.4 Hydrogen Safety

Hydrogen safety requirements are identified in three LLPs. LLP 6-1.36, *Fire Protection* (see Section 5.2) defines the active and passive fire protection features such that an acceptable level of fire safety associated with the ESIF hydrogen activities is achieved through multiple means. Fire prevention as well as immediate detection and suppression are emphasized. LLP 6-1.62, *Pressure Safety* (see Section 5.3), prescribes the ASME Boiler and Pressure Vessel Code requirements and the ASME B31-series Piping Code requirements for the ESIF systems that contain pressurized hydrogen. Pressurized hydrogen systems are operated, maintained, tested, and inspected in accordance with LLP 6-1.62 to minimize the risk to the worker, the public, and the environment as a result of ESIF Operations. LLP 6-1.47, *Compressed Gas Safety*, applies to the ESIF Center personnel associated with the distribution and use of compressed hydrogen and provides the requirements for the design and operation of gas distribution systems.

The ESIF employs ESFs to prevent and mitigate the potential impacts of a hydrogen release and deflagration. These ESFs include flammable-gas detectors, rapid gas shutoffs on hydrogen supply lines, design limits on the quantity of hydrogen that could be released before shutoff, deflagration venting, laboratory ventilation, and SCADA control of the DUT. A SAC is employed at the ESIF to augment the prevention and mitigating functions of the ESFs:

- Requirements for the control of ignitions sources in accordance with classification of the hydrogen station are defined in the House Hydrogen System work control documents.

NREL has established a Hydrogen Safety Working Group under the direction of EHS. The ESIF team, as a major user of hydrogen, participates in this working group.

5.5 Electrical Safety

Electrical safety at the ESIF is implemented in accordance with LLP 6-1.54, *Electrical Safety*. This procedure identifies the general safety requirements for activities involving electrical systems and equipment and describes the cautionary measures to maintain an acceptable level of risk. Electrical equipment used at ESIF is required to incorporate the design requirements of applicable consensus standards and the NEC. This procedure incorporates these requirements and guidance from applicable DOE orders, guides, and standards.

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Implementation of this procedure in the ESIF is the responsibility of ESIF Center personnel. LLP 6-1.54 identifies electrical safety training requirements based on the worker's potential electrical exposure level. All NREL workers receive basic electrical safety training via online training. Workers with a moderate level of electrical exposure are required to complete the electrical worker training, LOTO training, LOTO field "practical" demonstration of proficiency (annual requirement), and cardiopulmonary resuscitation (CPR)/automated external defibrillator (AED) training. Workers with a high electrical exposure potential must complete the training noted above and additional specialty training (e.g., NFPA 70E, medium voltage, etc.) provided by qualified external providers. Electrical worker qualification and authorization are documented through a card system that includes knowledge verification by an Electrical Safety Officer and clear delineation of authorized activities from line management.

The design, construction, and commissioning of the ESIF were accomplished such that the as-constructed facility meets the requirements of the NEC and the authority having jurisdiction. Commercially available equipment must bear the approval of a nationally recognized test laboratory. Research equipment must be designed in accordance with the general requirements of the NEC as well as the applicable standards of the ANSI, Underwriters Laboratories, NFPA 70E and 79, National Electrical Manufacturers Association, and/or Institute of Electrical and Electronics Engineers. Electrical equipment is subject to inspection and approval by the NREL Electrical Authority Having Jurisdiction prior to use. LLP 6-1.54 also defines the requirements for the installation, inspection and installation approval, and maintenance and testing of electrical equipment, including requirements for safety system testing.

NREL and ESIF policy is to avoid work on energized systems unless that work is justified in accordance with the requirements in NFPA 70E, Standard for Electrical Safety in the Workplace. As required by LLP 6-1.54, an SOP, safe work permit, or an Energized Electrical Work Permit is required for work on electrical systems. Controls identified in LLP 6-1.54 and credited in this HAR include:

- NREL policy is to implement programs to assure compliance with general electrical work safety requirements, including the provisions of NFPA 70E and the DOE Electrical Safety Handbook, work planning and hazard assessment, job briefings, LOTO requirements per LLP 6-1.55, *Lockout/Tagout*, equipment maintenance, emergency procedures, equipment and work area inspections, and use of boundaries and electrical tools and PPE.
- Staff members at ESIF are supported by several embedded Electrical Safety Officers. These individuals have received advanced electrical safety training and are approved by the NREL Electrical Authority Having Jurisdiction. Electrical Safety Officers are available to assist staff with equipment design, inspections, procedure development, and implementation of safe work practices. NREL also has several individuals who have passed the ICC Electrical Inspector Exam.
- Electrical work on distribution systems at the ESIF is required to be performed by licensed electricians approved by the Site Operations Office.

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- LLP 6-1.54 *Appendix A, Electrical Safety Inspection Guidelines*, is incorporated at the ESIF in quarterly work area inspections performed by line managers and supported by Electrical Safety Officers.

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6 Management Measures

Management measures are activities performed by ESIF management on a continuing basis to provide reasonable assurance that items relied on for safety will perform their intended safety function. IROFS include ESFs and administrative controls as defined in this HAR. The ESIF management team takes credit for controls established in the management measures to assure worker safety and to protect the public and the environment.

The ESIF Center Director used information provided in NUREG-1520, *Standard Review Plan for the Review of a License Application for a Fuel Cycle Facility,* as a guide to determine the management measures that should be developed and incorporated to provide reasonable assurance. The management measures are:

- Configuration management (CM)
- Maintenance management (MM)
- Quality management (QM)

The ESIF has developed facility-specific programs for each of these management measures. These programs are integrated and coordinated with each other and with other ESIF and NREL-wide policies and procedures.

6.1 Configuration Management

The ESIF Center implements a CM program that ensures consistency in the facility design and operational requirements, the physical configuration, and the facility documentation. The ESIF CM Program is integrated into the work processes at the ESIF. The CM Program maintains this consistency throughout the life of the ESIF, particularly as changes are made. The CM Program is based on DOE-STD-1073-2003, *Configuration Management.* While this standard was developed for nuclear facilities, because of the complexity of the ESIF systems and because of the requirements to adjust the ESIF's capabilities for research purposes, the ESIF implements elements of this standard. This implementation is graded based on the significance of the systems to safety. The CM Program meets the requirements of NREL Policy 8-3, *Configuration Management,* to apply configuration management methods to enhance safety, improve effective utilization, and control costs. The ESIF CM Program meets the requirements of NREL Implementing Program 2-3.1, *Quality Management Plan*, for planning and executing work.

6.1.1 Program Management

NREL and ESIF management are committed to the support of the CM Program. CM assures consistency among design requirements, physical configuration, and systems documentation, thereby enhancing safety and operational efficiency. Key responsibilities for implementation of the CM Program are defined in the CM Program document. These responsibilities are documented in roles, responsibilities, authorities, and accountabilities (R2A2) for each position per the ESIF Desk Procedure, *ESIF Roles, Responsibilities, Authorities, and Accountabilities*.

The ESIF Facility Manager is responsible for the implementation of configuration management in ESIF. The Facility Manager establishes the CM Program requirements, prioritizes CM Program activities, provides resources for CM Program implementation, and assesses the CM

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Program implementation. The Facility Manager defines the mission critical and high cost systems managed under CM-3. The Facility Manager establishes the controls that assure that the engineered safety features and administrative controls credited in the HAR Summary will perform their intended safety functions. The Facility Manager approves changes that impact the ESIF safety envelope or the ESIF mission. The Facility Manager works with the Systems Engineering Lead to assign system owners for safety-related systems and non-safety-related systems. For systems with no designated owner, the Facility Manager assigns the Building Area Engineer or the Research Line Manager as System Owner.

6.1.2 Identification of Items under Configuration Management

Identification of items under configuration management includes identifying which systems and documents require configuration management, assigning a CM level to systems and documents under configuration management, and assigning an owner for each system and document under configuration management.

The ESIF maintains an Approved System List under CM. The Approved System List includes both facility systems and research systems. The level of CM applied to each of the systems in these categories is specified. Not all systems at the ESIF require the same level of configuration control.

The ESIF maintains an Approved Document List under CM. The Approved Document List includes documentation associated with facility system and research systems.

Development and use of the Approved System List and the Approved Document List are defined in the ESIF Desk Procedures *Approved System List* and *Approved Document List.* The CM levels for ESIF systems are defined as follows:

- CM-1: The facility or research system or software is an item relied on for safety of the worker, the public, or the environment as credited in the safety analysis section of the HAR.
- CM-2: Failure of the facility or research system to perform its function could impact the safety functions of a CM-1 system as defined in the HAR.
- CM-3: Mission critical (failure of the system could cause a substantial interruption to the operation of the ESIF) or high cost (if the system fails, it would be expensive to fix or replace).

Systems that do not fall into one of these CM categories are not required to be under configuration management.

The Approved System List contains the following information for each CM-level system:

- System name
- System identification number
- System owner
- System boundaries

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- System CM level
- Sub-system or component CM levels if different from the overall system
- Basis for system CM level
- System description and function
- SDD number (if applicable)
- System design, operation, and maintenance documents required to be on the Approved Document List
- Location of controlled copies of system design, operation, and maintenance information.

The Approved Documents List is a listing of controlled documents requiring configuration management. Each document on the Approved Documents List has a document owner. For system-related documents, the document owner is the System Owner. Controlled documents include:

- HAR
- LLPs credited as SMPs in the HAR
- ESIF procedures that implement SACs defined in the HAR
- ASL
- Master facility drawings
- CM system-specific documents defined in the Approved System List.

6.1.3 Design Control

Design activities at the ESIF are assigned based on the specific systems, as defined in the *SITE Operations BAE–Project Management/Engineering/Construction (PMEC) Handbook*. The *SITE Operations PMEC* establishes boundary interfaces on facility systems. In general, design and design modifications for facility systems at the ESIF are the responsibility of the SITE Operations BAE and PMEC. Designs and design modifications for research infrastructure systems and research equipment are the responsibility of the ESIF Center personnel or Research Line Manager. ESIF Desk Procedure *Control of ESIF Engineering* establishes the design process used at the ESIF.

The ESIF has established the ESIF Facility Manager as the Design Authority for facility and research systems. The ESIF Facility Manager formally delegates this responsibility when required. The Design Authority identifies and establishes the processes and procedures used at the ESIF for generating and controlling design requirements, documenting design requirements, implementing the design process, and controlling design outputs. The processes and procedures identified and established by the Design Authority are implemented by all organizations performing engineering in the ESIF in accordance with the *Control of Engineering* desk procedure.

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6.1.4 Work Planning and Control

The ESIF implements work control processes to assure that when work activities are performed, consistency is maintained between the documents, the procedures, and the physical configuration of the facility. The integrated safety management process, defined in Policy 6-1, *Integrated Safety Management and Environmental Management*, is used to integrate safety into all aspects of work planning and execution. The work planning and control process meets the requirements of LLP 8-6.1, *Safe Conduct of Operations*, and Policy 4-8, *Conduct of Research and Analysis*. Work Control is an administrative process by which work activities are identified, initiated, planned, scheduled, coordinated, performed, approved, validated, reviewed for adequacy and completeness, and documented.

Work on the ESIF systems is performed by SITE Operations, ESIF Center personnel, or research staff. For work performed by SITE Operations, maintenance work planning and control are conducted in accordance with LLP 8-11.3, *Site Maintenance Program,* and the ESIF Desk Procedure *Work Planning and Control*. For work performed by ESIF Center personnel and research staff, work planning and control are conducted in accordance with the ESIF Desk Procedure *Work Planning and Control*. System interfaces are established that clearly define the boundaries between facility systems and research systems.

The ESIF management team uses work control documents to plan, control, and execute work. Work planning identifies the technical and administrative requirements to complete a work activity and provides the materials, tools, and support activities to perform the work safely and correctly. Planning includes the appropriate level of detailed work instruction so that workers can carry out the activities as planned. The planning system identifies the hazards and mitigating controls, provides the required design engineering input, and defines the required post maintenance testing or post modification testing (PMT) and acceptance criteria.

6.1.5 Change Control

The ESIF implements a change control process, defined in ESIF Desk Procedure *Work Planning and Control*, as part of the CM Program to maintain consistency among design requirements, the physical configuration, and the related facility documentation as various types of changes are made. All temporary or permanent changes in the design requirements, design basis, physical configuration, or documentation within the CM Program are identified, controlled, and reviewed through this formal change control process. Changes include facility and equipment modifications, maintenance changes, operational changes, procurement changes, document changes, and computer hardware and software changes.

As part of the formal change control process, the ESIF management team uses a defined review process to determine the individuals or organizations that must review the proposed change. Identification of responsible reviewers is based on the type of change, CM level of the system or document, impact of the change on controlled documents, impact on operations, and impact on training.

6.1.6 Document Control

The ESIF implements a document control process, defined by ESIF desk procedure *Document Management,* which supports CM. The ESIF document control process meets the requirements

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of Policy 3-5, *Records Management.* The ESIF document control process utilizes the SITE Operations Facility Engineering CM System as defined in the *SITE Operations Project Management Manual* to control the record set of drawings for the facility.

CM baseline documents maintained in the ESIF CM document control system include the HAR, key drawings, master facility drawings, design requirement and design basis information, maintenance and operations documents, records, SDDs, change control requests, change control packages, and SAC-related procedures, documents, and records. The specific CM documents included in the document control system are defined for each CM-level system.

All documents under configuration management are identified on the ESIF Approved Document List. The ESIF Approved Document List is established as a controlled document data management system. The ESIF Approved Document List identifies the specific documents managed under change control and includes the revision level, current status, document owner, pending changes, storage location, and outstanding document action requests.

ESIF CM-level drawings are stored in accordance with NREL policies for records management to assure documents are protected. Electronically stored documents are backed up on an established basis. Documents managed in the document control process relate to the system and are easily retrievable. The ESIF document control process assures that only approved revisions of CM documents are used.

6.1.7 Assessment

The ESIF implements an assessment program to measure the effectiveness of CM. The CM assessment program is integrated with the overall ESIF assessment program. Assessments are conducted consistent with the requirements of LLP 2-3.10, *Assessments.* The objective of assessing CM is to detect, document, determine the cause of, and correct inconsistencies among design requirements, documentation, and the physical configuration.

The ESIF management team performs programmatic assessments of the implementation of the CM function. Assessments are performed for each CM element: design control, work planning and control, change control, and document control. These assessments measure effectiveness and determine whether the CM controls are adequate.

The ESIF management team performs physical configuration assessments to verify that change control processes are effective and that physical configurations are adequately reflected in as-built documentation.

6.2 Maintenance Management

The ESIF implements a maintenance management program that ensures real property is maintained in a manner that promotes operational safety, worker health, environmental protection and compliance, property preservation, and cost effectiveness while meeting the ESIF missions as required by DOE O 430.1B, *Real Property Asset Management*. The ESIF MM Program assures that systems relied on for safety, as defined in this HAR, are inspected, calibrated, tested, and maintained commensurate to the item's importance to safety. This is accomplished through the tailored application (graded approach) of specific requirements for maintenance of DOE nuclear facilities as defined in DOE O 433.1B, *Maintenance Management*

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Program for DOE Nuclear Facilities, and DOE G 433.1A, *Nuclear Facility Maintenance Management Program Guide.*

The elements of the ESIF MM Program are:

- Maintenance organization and administration
- Master Equipment List
- Planning, scheduling, and coordination
- Types of maintenance
- Maintenance procedures
- Training and qualification
- Configuration management
- Procurement
- Non-conforming, suspect, and counterfeit items
- Maintenance history
- Aging degradation
- Seasonal facility preservation
- Performance measures
- Facility condition inspection
- Post modification/maintenance testing.

Maintenance activities at NREL are accomplished per the requirements of LLP 8-11.3, *Site Maintenance Program.*

The ESIF adheres to the requirements and processes defined in this procedure. The ESIF develops additional desk procedures as required to implement all elements of the ESIF MM Program.

6.2.1 Maintenance Organization and Administration

The ESIF adheres to the requirements and processes defined in LLP 8-11.3, *Site Maintenance Program.* This procedure describes the roles and responsibilities of the participants in maintenance work performed at the ESIF. This procedure identifies and describes the functions of the Work Control Center to plan, approve, schedule, and coordinate maintenance work in the ESIF. LLP 8-11.3 describes site maintenance activities and does not include maintenance of program /research equipment. As identified in the CM Program described above, research program maintenance work is controlled as defined in the ESIF Desk Procedure *Work Planning and Control.*

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6.2.2 Master Equipment List

The ESIF Approved System List, identified in the CM Program, includes all systems that are CM level. The Approved System List is used to develop the ESIF MEL. All CM-level systems (facility and research system) are included in the MEL. Non CM-level systems are included in the MEL as determined by the Facility Manager and BAE. The MEL is maintained in a computerized maintenance management system (CMMS). The ESIF BAE develops and maintains the MEL. The MEL is used by maintenance, operations, and research personnel to identify and apply appropriate controls to maintenance and modification of CM-level equipment.

6.2.3 Planning, Scheduling, and Coordination

The ESIF plans, schedules, and coordinates maintenance activities to ensure maintenance is accomplished in a timely manner, improve maintenance efficiency, reduce chemical and physical hazards, increase equipment availability, ensure worker safety through training and the proper use of PPE, and ensure hazardous waste is properly segregated. The ESIF plans, schedules, and coordinates maintenance work as described in the CM Program.

6.2.4 Types of Maintenance

The ESIF conducts corrective maintenance, preventive maintenance (PM), predictive maintenance (PdM), and surveillance and testing to provide a high degree of confidence that equipment degradation is identified and corrected and that systems relied on for safety are capable of performing the required safety functions. System owners define the PM and PdM requirements for equipment based on the manufacturer's recommendations and system history collected in the CMMS. The requirements for PM and PdM are captured in the ESIF MEL and in the CMMS database.

6.2.5 Maintenance Procedures

As addressed in DOE O 433.1B, "maintenance procedures" are documents providing maintenance direction, including work packages, procedures, and design outputs.

The ESIF management team prepares and uses maintenance procedures and other work-related documents to provide direction for safe and efficient maintenance work performance. SITE Operations LLP 8-11.3, *Site Maintenance Program*, includes the work planning and control processes used by the ESIF for maintenance work on facility systems. The ESIF Desk Procedure *Work Planning and Control* establishes the work planning and control processes used by operations and research organizations.

6.2.6 Configuration Management

The ESIF maintains the configuration of the system and administrative controls relied on for safety in accordance with the CM Program management measure section of this HAR. CM is implemented to control approved modifications and prevent unauthorized modification of systems.

6.2.7 Procurement

ESIF Procedure *Control of ESIF Engineering* establishes the requirements for engineering support to the procurement process and the requirements for procurement of CM-level

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equipment. For CM-level systems, components and the number of each component required for spares are identified in the MEL.

6.2.8 Non-conforming, Suspect, and Counterfeit Items

ESIF Center personnel follow the requirements of LLP 2-3.2, *Nonconforming Items including Suspect and Counterfeit,* to provide effective controls for the prevention, detection, and disposition of nonconforming items, including suspect and counterfeit items. This procedure provides the basic approach for implementing controls for nonconforming items commensurate with the risks within NREL facilities and projects.

6.2.9 Maintenance History

The ESIF management team uses the CMMS maintenance history and trending program to document maintenance performed, provide historical information for maintenance planning, support maintenance and performance trending of facility systems and components, and improve facility reliability. Each system included in the ESIF MEL has a separate maintenance history in the CMMS. Documentation includes all system information defined in the MEL, operating history, performed maintenance, diagnostics, PM and PdM, repairs, in-service testing, and PMT. The ESIF CSEs review and approve in-service testing and PMT on CM-1 systems.

Maintenance records are retained per the requirements of LLP 8-11.3, *Site Maintenance Program* and LLP 3-5.2, *Management of Active and Inactive Records.*

6.2.10 Aging Degradation

The ESIF identifies CM-1 systems subject to aging degradation inspections, defines the specific parameters to be inspected, defines the acceptance criteria, and performs the inspections. These requirements are identified in the SDDs, included in the MEL, entered in the CMMS, and tracked by the system owner. The system owners monitor their assigned systems for performance against required capabilities, physical configuration against the technical baseline, and trending of material conditions.

6.2.11 Seasonal Facility Preservation

To prevent equipment and building damage due to weather conditions, the ESIF performs inspections and PM to protect against cold weather, extreme hot/dry weather, wildfires, flooding, high winds, and lightning. These activities are implemented by SITE Operations. Requirements for the ESIF PM for freeze protection are maintained and tracked in the CMMS.

6.2.12 Performance Measures

The ESIF Center uses maintenance performance monitoring as a management tool to track the reliability of CM-1 systems and to assess the adequacy of maintenance activities. Performance monitoring requirements support the continuous improvement activities and goals defined in LLP 8-11.3. Monitored performance indicators may include safety system availability, maintenance re-work, overdue PM, maintenance backlog, and compliance with the ESIF self-assessment requirements.

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6.2.13 Facility Condition Inspection

The ESIF Center conducts routine assessments to identify issues relating to operability, reliability, housekeeping, and general condition and to assure excellent facility condition and housekeeping.

As identified in LLP 8-11.3, *Site Maintenance Program*, the ESIF supports the real property condition assessments performed at least every five years by SITE Operations per DOE O 433.1B.

- As identified in the CM management measure, the ESIF performs physical configuration assessments to verify that change control processes are effective and that physical configurations are adequately reflected in as-built documentation.
- System owners inspect their assigned CM-1 systems for signs of degradation and aging at least annually.

6.2.14 Post Maintenance Testing

The ESIF Center performs PMT to verify that components will fulfill their design function when returned to service after maintenance. PMTs are integrated into the work-control process. PMTs and acceptance criteria are specified by the System Owner and documented in the work control document. For work on CM-1 systems, the system owner reviews and approves the test and inspection results.

6.3 Quality Management

The ESIF Center implements a QM program that assures the delivery of safe, reliable products and services that meet or exceed the customer's requirements, needs, and expectations. Quality assurance requirements at NREL are implemented by LLP 2-3.1, *Quality Management Program.*

The ESIF follows and adheres to the requirements and processes of LLP 2-3.1. Facility-specific requirements for the ten criteria required by DOE O 414.1D are identified in the ESIF QM Program. Two criteria are credited by the HAR as important to safety and are described in this management measure: Criterion 1, *Program*, and Criterion 2, *Personnel Training and Qualification.*

ESIF-specific desk procedures required by the HAR are documented in the ESIF QM Program.

The ESIF QM Program defines the organization that controls and conducts safe work, documents the R2A2 assigned to key individuals within the organization, and documents the training and qualification requirements for all individuals who control and execute work in the facility.

6.3.1 Organization

The organization structure, shown in Figure 21, identifies the organizational interfaces and functional responsibilities of the ESIF management team. Management retains the primary responsibility and accountability for the scope and implementation of the ESIF QM Program. Every individual in the organization is responsible for achieving quality in his or her activities. Management establishes the process for planning, scheduling, resourcing, and executing work.

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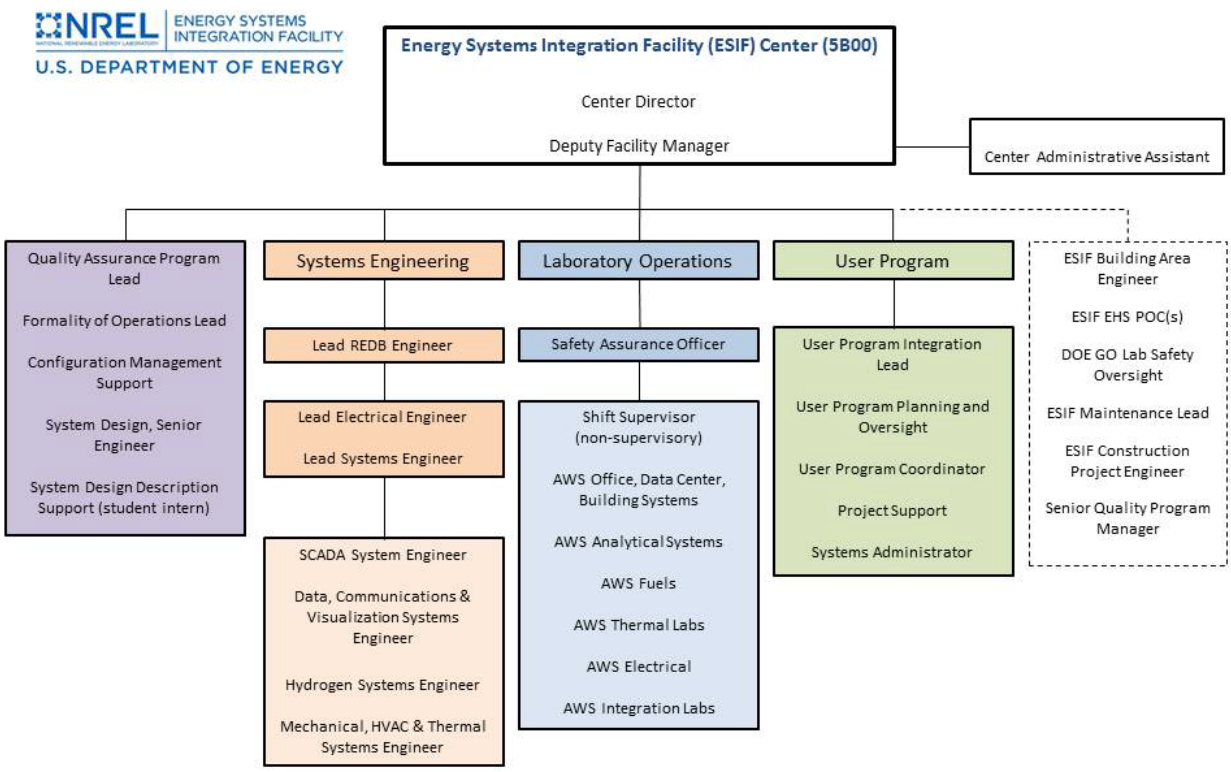

Figure 21. ESIF organization structure

The ESIF organization structure is defined and documented in sufficient detail to allow those inside and outside of the organization to adequately identify its structure, roles, and responsibilities, and the authorities assigned to individuals. The organization structure shows the reporting relationship to the Facility Manager of line organizations, matrix support organizations, and user organizations, with the Facility Manager serving in the role of Facility Manager having overall responsibility and authority for assuring the facility safety envelope is preserved.

The ESIF assigns a system owner to each system. ESIF assigns an area work supervisor to each of the facility's laboratory and support spaces. The system owners and the area work supervisors are responsible for assuring that systems and facility operations are in compliance with the HAR and other safety basis documents.

Research activities are conducted by internal NREL or external facility users. Users work under the administrative control of the ESIF User Program Manager and under the technical control of a system owner or area work supervisor.

6.3.2 Roles and Responsibilities

The ESIF Center establishes functional responsibilities and levels of authority for those managing, performing, and assessing work. The ESIF describes the R2A2 of personnel involved with managing, supporting, and using the facility in the ESIF Desk Procedure *ESIF Roles, Responsibilities, Authorities, and Accountabilities.* The desk procedure applies to personnel in the ESIF center organization, personnel from support organizations assigned to the ESIF management team, other ESIF directorate personnel with a role in managing technical

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capabilities within the ESIF, and the ESIF users (including NREL employees, industrial partners, and collaborators).

6.3.3 Training and Qualification

The ESIF procedures describe personnel selection, training, qualification, and certification requirements for each functional position. These individuals have the potential to impact the facility safety basis through their involvement in operations, maintenance, and technical support. The ESIF workers have individual training plans approved by their managers and tracked in the NREL Learning Gateway. Users external to the ESIF have individual training plans approved by the User Program Manager.

The training includes institutional training, including information about NREL's mission and goals. ESIF-specific training includes safety, emergency plans and necessary operations information, and job-specific training required by work packages, SOPS, and other work control documents.

The ESIF management team uses operations orders to communicate short-term information related to the conduct of facility operations, including notification of work priorities, special operations, data collection campaigns, non-routine tests, upcoming events and audits, announcements of administrative items, policies, procedure changes, and training changes. The ESIF Desk Procedure, *Timely Orders*, defines the preparation and use of operations orders.

The ESIF management team maintains a list of qualified individuals who are trained and authorized by the ESIF Center personnel Manager or designee to operate the ESIF equipment. The list of qualified individuals is a controlled document on the Approved Document List and is posted at the control room.

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Appendix A: (Reserved)

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Appendix B: Safety Architecture

To be provided.

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Appendix C: Codes of Record

The following material on ESIF codes and standards reflect the final design record. The code analysis was performed to reconcile any differences between the IBC and NFPD standards. The ESIF laboratories have been divided into four control areas in accordance with the 2009 International Building Code (IBC) or two laboratory units in accordance with 2011 National Fire Protection Association (NFPA) 45 to accommodate quantities of hazardous materials. H-2 (high hazard) occupancy has been identified for the Energy Systems Integration Laboratory and the Electrical Characterization Lab.

Because laboratory chemical and gas cylinders will be delivered to the facility on an as-needed basis, bulk storage of chemicals and central gas cylinder storage is not required in the building.

The general laboratory areas are adjacent and accessible to a service corridor to minimize the need to pass through an egress corridor to deliver chemicals to and from delivery access points. The service corridor is for the use of chemical delivery per NREL Environment, Health and Safety (EHS) policy; it is not a "service corridor" as defined in the IBC for Group H-5 Occupancy: "semiconductor fabrication and comparable research and development facilities with hazardous product material in excess of those allowed."

The building has fire suppression sprinklers throughout. The High Performance Computing Data Center does not provide enterprise computing support, and as such, it is not provided with non-water–based fire suppression for protection of equipment and information. However, to help preclude accidental activation of the sprinkler system, the area has a pre-action sprinkler system activated by smoke detection. The facility is equipped with a fire detection and alarm system with 100% coverage per NFPA-72. Areas containing unique fire hazards, such as hydrogen, have the appropriate fire detection devices employed. All laboratories are equipped with fire extinguishers located adjacent to the exits at a minimum and as required by code with signs indicating their location. Extinguishers are specified based on the hazards and equipment present in each work area.

Storage cabinets containing flammable materials are made of non-combustible construction with self-closing doors and are grounded. Storage cabinets containing flammable and corrosive materials are required to be ventilated only if the materials being stored are listed as irritants. Storage cabinets containing flammable gas are supplied with a fire sprinkler head. Storage cabinets containing flammable and corrosive materials comply with NREL's Fire Protection Program.

Outdoor test areas are installed as part of the laboratory research areas. They incorporate safety features such as restricting physical access and providing walkways for personnel and fork lift access. Outdoor test areas wide enough to allow vehicular traffic in select areas (such as hydrogen-fueled vehicle fueling).

Applicable Codes

The design complies with all applicable local, state, and federal regulations and ordinances, and applicable utility company requirements as approved and administered by authorities having

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jurisdiction at the project location at the time of construction. Where there was a conflict between the various codes or standards, the most stringent, as determined by NREL, was applied.

The latest editions, as of the time the construction subcontract was awarded, of the following codes and standards were used as references for the basis of design:

1. International Building Code (IBC), 2009
2. International Electrical Code Provisions (IEC), 2009
3. International Energy Conservation Code (IECC), 2009
4. International Fire Code (IFC), 2009, including West Metro Fire Rescue Amendments to the International Fire Code
5. International Plumbing Code (IPC), 2009
6. International Mechanical Code (IMC), 2009
7. Code of Federal Regulations, Title 36, Part 1191 (36 CFR 1191) – Americans with Disabilities Act Accessibility Guidelines for Buildings and Facilities, Final Guidelines and Amendment to Final Guidelines (ADAAG), Architectural and Transportation Barriers Compliance Board; current edition, reprinted compiling all revisions, September 1994
8. FED-STD-795 – Uniform Federal Accessibility Standards, April 1, 1988 (UFAS)
9. DOE 10 CFR 851 (not a code, design criteria reference).

NFPA codes identified were also the most current editions at the time the construction subcontract was awarded and were used in lieu of the 2009 IBC Chapter 35 Referenced Standards:

1. NFPA 10: Standard for Portable Fire Extinguishers, 2010 edition
2. NFPA 13: Standard for the Installation of Sprinkler Systems, 2010 edition
3. NFPA 14: Standard for the Installation of Standpipes and Hose Systems, 2010 edition
4. NFPA 17: Standard for Dry Chemical Extinguishing Systems, 2009 edition
5. NFPA 20: Standard for the Installation of Stationary Pumps for Fire Protection, 2010 edition
6. NFPA 24: Standard for the Installation of Private Fire Service Mains and Their Appurtenances, 2010 edition
7. NFPA 25: Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems, 2008 edition
8. NFPA 30: Flammable and Combustible Liquids Code, 2008 edition
9. NFPA 37: Standard for the Installation and Use of Stationary Combustion Engines and Gas Turbines, 2010 edition
10. NFPA 45: Standard on Fire Protection for Laboratories Using Chemicals, 2011 edition
11. NFPA 52: Vehicular Gaseous Fuel Systems Code, 2010 edition

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12. NFPA 54: National Fuel Gas Code, 2009 edition
13. NFPA 55: Compressed Gases and Cryogenic Fluids Code, 2010 edition
14. NFPA 68: Standard on Explosion Protection by Deflagration Venting, 2007 edition.
15. NFPA 70E®: Standard for Electrical Safety in the Workplace®, 2009 edition
16. NFPA 72: National Fire Alarm and Signaling Code, 2010 edition
17. NFPA 75: Standard for the Protection of Information Technology Equipment, 2009 edition
18. NFPA 77: Recommended Practice on Static Electricity, 2007 edition
19. NFPA 79: Electrical Standard for Industrial Machinery, 2007 edition
20. NFPA 80: Standard for Fire Doors and Other Opening Protectives, 2010 edition
21. NFPA 85: Boiler and Combustion Systems Hazards Code, 2007 edition
22. NFPA 101®: Life Safety Code®, 2009 edition
23. NFPA 110: Standard for Emergency and Standby Power Systems, 2010 edition
24. NFPA 170: Standard for Fire Safety and Emergency Symbols, 2009 edition
25. NFPA 497: Recommended Practice for the Classification of Flammable Liquids, Gases, or Vapors and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas, 2008 edition
26. NFPA 853: Standard for the Installation of Stationary Fuel Cell Power Systems, 2010 edition.

Other Local Standards

1. Consolidated Mutual Water Company Rules
2. Jefferson County Dept. of Health and Environment, Individual Sewage Disposal System Regulations
3. Metro Wastewater Reclamation District Rules and Regulations
4. Pleasant View Water and Sanitation District Rules and Regulations
5. West Metro Fire Rescue Amendments to the international Fire Code
6. Jefferson County Zoning Regulations – Section 11 Lighting.

ESIF Final Code Analysis

I. <u>OCCUPANCY CLASSIFICATION</u>

A. Per IBC Chapter 3, the project will include the following occupancy classifications:

a. 303 – Group A-3 (Assembly), space used for assembly purposes greater than 750 sq. ft. of 50 occupants or more.

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i. A space used for assembly purposes less than 750 sq. ft., less than 50 occupants and accessory to another occupancy can be classified as a Group B occupancy.

b. 304 – Group B (Business), including laboratories for testing and research.

c. 307.4 – Group H-2 (High-Hazard), buildings containing materials that pose a deflagration hazard or hazard from accelerated burning.

B. Per NFPA 45 Section 5.3.1, High Bay Laboratory area will be considered as an Industrial Occupancy as well as group B occupancy per IBC. The most stringent requirements of both codes were applied.

II. CONSTRUCTION

A. The construction will provide Type I-A construction at the High Bay Laboratory and Type II-B construction at the office and data center.

B. The following outlines the allowable building height and area limitations found in Table 503.

a. Type I-A Construction at the High Bay Laboratory

i. Group H-2 height and stories limitation above grade plan is unlimited. Area limitation per floor is 21,000 sq. ft.

1. 415.5 Special Provisions for Group H-2 and H-3 occupancies. Group H-2 and H-3 occupancies containing hazardous materials quantities in excess of Table 415.3.2 will not exceed one story in height and without basements, crawl spaces, or other under-floor spaces.

b. Type II-B Construction at the Office and Data Center

i. Group B height and stories limitation above grade plan is limited to 55 feet and 4 stories. Area limitation per floor is 23,000 sq. ft.

1. 504.2 Where a building is equipped throughout with an approved automatic sprinkler system, the maximum height is increased by 20 feet and the maximum number of stories is increased by one. These increases are permitted in addition to the area increases. *These increases do not apply to fire areas with occupancy in Group H.*

c. Per Table 706.4, a 4-hour fire wall was located to separate the different construction types.

C. Area Modifications. Per 506.3, where a building is equipped throughout with an approved automatic sprinkler system, the building area limitation in Table 503 is permitted to increase an additional 200 percent. Therefore:

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a. Type II-B – Group B Occupancy = 23,000 sq. ft.

i. Area Increase = (23,000 sq. ft. * 200%) + 23,000 sq. ft. = 69,000 sq. ft. allowed per floor

ii. Group H-2 Occupancy is exempt from this increase.

D. 508.3. – Non-separated occupancies are occupancies individually classified. The occupancies within the same building do not need to be separated by fire-resistive rating if the building complies throughout with the most restrictive occupancy classification and applicable provisions. Allowable area and height increases are based on the most resistive occupancy group under consideration for the type of construction.

Non-separated occupancies are considered at the Office and Data Center – Group B Occupancy.

E. 508.4 – Separated occupancies are individually classified. Each fire area will comply with the code based on the occupancy classification. The allowable area for each story will be the sum of the ratios of the actual floor area of each floor divided by the allowable area of each occupancy and will not exceed one. Each occupancy will comply with the height limitations based on the construction type. Individual occupancies will be separated per Table 508.4.

Separated occupancies are considered at the High Bay Lab. Based on the possibility of mixed occupancies (Group B and H). <u>Verification of hazardous materials in laboratory spaces is required.</u>

F. 602 – Construction Classification

a. Table 601 – Minimum Fire Resistance Ratings – 6

i. Exterior Walls

1. Bearing – 3-hour rating

2. Non-bearing – Table 602

b. Group H Occupancy – Separation distances < 5 feet a 3-hour rating is required. For B and U occupancies, 1-hour rating is required.

c. Group H Occupancy – For separation distances of 5 feet to < 10 feet, 3 hour rating is required. For B and U occupancies, 1-hour rating is required.

d. Group H Occupancy – For separation distances of 10 feet to < 30 feet, 2 hour rating is required. For B and U occupancies, 1-hour rating is required.

e. Non-rated at distances greater than 30 feet.

i. Interior Walls

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1. Bearing – 3-hour rating

2. Nonbearing – Non-rated

ii. Structural frame – 3-hour rating

iii. Roof – 1.5-hour rating

iv. Floor – 2-hour rating

f. Table 601 – Minimum Fire Resistance Ratings – Type II-B Construction

i. Exterior Walls

1. Bearing – Non-rated

2. Non-bearing – Table 602

g. Separation distance < 5 feet

i. Group B occupancy – 1-hour rating is required

h. Separation distance 5 feet to < 10 feet

i. Group B occupancy – 1-hour rating is required

i. Separation distance 10 feet to < 30 feet

i. Group B occupancy – Non-rated

j. Non-rated at distances greater than 30 feet.

i. Interior Walls

1. Bearing – Non-rated

2. Nonbearing – Non-rated

ii. Structural frame – Non-rated

iii. Roof – Non-rated

iv. Floor – Non-rated

k. 708.4 – Shaft enclosure will be 1 hour for exit stairs and elevators connecting less than four stories, 2 hours where connecting four stories or more.

i. Shaft enclosure is not required at escalator or stairway opening that is not a portion of the means of egress *protected according to 708.2 exceptions 2.1 or 2.2.*

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l. 708.14.1 – Elevator Lobby – An enclosed elevator lobby is required at each floor where an elevator connects more than three stories.

G. Fire-Resistive Separations

a. Corridor Fire-Resistance Rating per Table1018.1 with sprinkler system.

i. Group B occupancies – Non-rated

ii. Group H-2 occupancies – 1-hour

iii. NREL requires laboratories in the High Bay area to be separated by 1-hour construction. Corridors in High Bay area are rated 1-hour.

b. Exit Passageways – 1023.3 – Exit passageways 1-hour fire barrier or the same rating as the exit stair connected to.

c. Horizontal Exits – 1025.2 – 2-hour fire barrier

d. Elevator machine rooms – 3006.4 – Fire rating not less than the required rating of the hoist-way enclosure.

e. Per Table 508.4, the required separation of occupancies between B and H in a sprinklered building is as follows:

Occupancy	A	B	H-2	S-1	S-2
A	N	1	3	1	N
B		N	2	N	1
H-2		-	N	2	3
S-1				N	1
S-2					N

f. Incidental-use areas to the main occupancy are separated from the main occupancy per Table 508.2.5.

Room or Area	Separation and/or Protection
Furnace room where any piece of equipment is over 400,000 British thermal units	1-hour or provide automatic fire-extinguishing system
Boilers over 15 PSI and 10 HP	1-hour or provide automatic fire-extinguishing system

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Room or Area	Separation and/or Protection
Hydrogen cut-off rooms, not classified as Group H	1-hour in Group B occupancies
Stationary storage battery systems having liquid electrolyte capacity of more than 50 gallons or a lithium-ion capacity of 1,000 pounds used for facility standby power, emergency power, or uninterrupted power supplies	1-hour in Group B occupancies
Rooms containing fire pumps in non-high rise buildings	1-hour in buildings provided throughout with automatic sprinkler system

g. Control areas fire-resistance rating requirements for fire barriers are per Table 414.2.2. The floor construction and the construction supporting the floor of the control area are a minimum 2-hour fire-resistance rating.

Floor Level		% of Maximum Allowable Quantity (MAQ) per Control Area	Number of Control Areas per Floor	Fire-Resistance Rating for Fire Barriers (Hours)
Above Grade Plane	3	50	2	1
	2	75	3	1
	1	100	4	1
Below Grade Plane	1	75	3	1
	2	50	2	1
	Lower than 2	Not Allowed	Not Allowed	Not Allowed

The High Bay Laboratories (Levels 2 and 3) are considered as one level above grade in determining maximum allowable quantities (MAQs) and Control Area due to the slope of the site and because both levels are on grade. This allows 100% MAQ per control area, four control areas, and a minimum 1-hour fire barrier.

H. 715 – Opening Protection

a. Openings in fire-resistive separations are required to be protected in accordance with IBC 715.

b. Summary of Opening Protection Requirements Based on IBC Tables 715.4 and 715.5

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Type of Assembly	Assembly Rating (Hours)	Minimum Door Rating (Hours)	Minimum Window Rating (Hours)
Fire Walls and Fire Barrier	4 3 2	3 3 1 ½	NP NP NP
Fire Barriers that serve as: Shafts, exit enclosures, exit passageways Other fire barriers	 1 1	 1 ¾	 ¾ ¾
Exterior Wall	3 2 1	1 ½ 1 ½ ¾	1 ½ 1 ½ ¾

NP = Not Permitted

c. Fire-protective rated glazing in fire window per Table 715.5 and glazing in fire doors is per section 715.4.6. Fire-protection-rated glazing is tested per NFPA 257 and complies with NFPA 80.

d. Exterior Wall Openings – The building is protected throughout by an automatic sprinkler system; therefore, the allowable areas for unprotected openings are shown in the table below. Exterior walls that are greater than 20 feet from the property line are permitted to have unlimited unprotected openings.

Allowable Exterior Openings – Unprotected

Fire Separation Distance	Percentage of Allowable Openings per Area of Exterior Wall
0-3 ft.	Not Permitted
3-5 ft.	15%
5-10 ft.	25%
10-15 ft.	45%
15-20 ft.	75%
Greater than 20 ft.	No Limit

I. 716 – Duct and Air-Transfer Openings

a. 716.5 – Fire Dampers. Fire dampers are required at locations where ducts or air transfer openings of an air distribution system penetrate fire resistance rated assemblies including:

i. Fire walls

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ii. Fire barriers

iii. Shaft enclosures

iv. Fire partitions

b. Where both a fire and a smoke damper are required, a combination fire/smoke damper is used.

c. 716.5.4.1 – Corridors

i. Smoke dampers are required at locations where ducts or air transfer openings of an air distribution system penetrate a corridor enclosure, and are required to have smoke and draft control doors. Corridor walls with a fire-resistance rating are required to have smoke and draft control doors.

d. 716.4 – Fire and smoke dampers are provided with an approved means of access, not affecting the integrity of the fire resistance rated assemblies.

J. Floor Opening Protection – Entry Lobby

a. Openings through a floor/ceiling assembly are required to be protected in accordance with Section 708.2. Shaft protection is required unless the provisions of exceptions provided in the section are met.

b. Unless specifically stated, the use of multiple exceptions in a building/area is not prohibited.

c. The entry lobby located between the data center and the office area utilizes the following provisions in Section 708.

i. 708.2, Exception 2.1 – A shaft enclosure is not required in a building equipped throughout with an automatic sprinkler system for a stairway opening that is not a portion of the means of egress where the area of the floor opening between stories does not exceed twice the horizontal projected area of the stairway and the opening is protected by a draft curtain and closely spaced sprinklers in accordance with NFPA 13.

ii. 708.2, Exception 7 – A shaft enclosure is not required for a floor opening that:

1. Does not connect more than two stories.

2. Is not part of the required means of egress system.

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3. Is not concealed within the construction of a wall or a floor/ceiling assembly.

4. Is separated from floor openings and air transfer openings serving other floors by construction conforming to required shaft enclosures.

d. For the lobby, a two-fold approach was taken. A stairwell connecting three floors is provided in the space and is protected per Exception 2.1. The three-story communicating floor opening is protected per Exception 7 and uses compliant shaft technology. The first two floors of the communicating opening are unprotected. The opening at the third floor is protected with compliant shaft construction. As such, the number of levels open to each other via the communicating floor openings is limited to two. A detailed analysis by a licensed Fire Protection Engineer was performed to support this approach (reference record drawing ESIF-0000-G-102 for a copy of the analysis).

K. Crawl Space

a. Section 1203.3 Under-floor ventilation. The space between the bottom of the floor joists and the earth under any building except spaces occupied by basements or cellars shall be provided with ventilation openings through foundation walls or exterior walls. Such openings shall be placed so as to provide cross ventilation of the under-floor space.

i. 712.3.3 The crawl space has been identified as an "unusable space." If it is an unusable space, then access will be limited to maintenance and it is considered an unoccupied space.

ii. 1209 Access will require a minimum opening not less than 18 inches by 24 inches.

b. Section 1203.3.1 Openings for under-floor ventilation. The minimum net area of ventilation openings shall not be less than 1 sq. ft. for each 150 sq. ft. (0.67 m^2 for each 100 m^2) of crawl-space area. Ventilation openings shall be covered for their height and width with any of the following materials, provided that the least dimension of the covering shall not exceed ¼-inch (6 mm):

i. Perforated sheet metal plates not less than 0.070 inch (1.8 mm) thick

ii. Expanded sheet metal plates not less than 0.047 inch (1.2 mm) thick

iii. Cast-iron grilles or gratings

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iv. Extruded load-bearing vents

v. Hardware cloth of 0.035 inch (0.89 mm) wire or heavier

vi. Corrosion-resistant wire mesh, with the least dimension not exceeding 1/8-inch (3.2 mm).

c. 1203.3.2 Exceptions. The following are exceptions to Sections 1203.3 and 1203.3.1:

i. Where warranted by climatic conditions, ventilation openings to the outdoors are not required if ventilation openings to the interior are provided.

ii. The total area of ventilation openings is permitted to be reduced to 1/1,500 of the under- floor area where the ground surface is covered with a Class I vapor retarder material and the required openings are placed so as to provide cross ventilation of the space. The installation of operable louvers shall not be permitted.

iii. Ventilation openings are not required where continuously operated mechanical ventilation is provided at a rate of 1.0 cubic foot per minute (cfm) for each 50 sq. ft. (1.02 L/s for each 10 m^2) of crawl space floor area and the ground surface is covered with a Class I vapor retarder.

iv. Ventilation openings are not required when the ground surface is covered with a Class I vapor retarder, the perimeter walls are insulated, and the space is conditioned in accordance with the IECC.

v. For buildings in flood hazard areas as established in Section 1612.3, the openings for under-floor ventilation shall be deemed as meeting the flood opening requirements of ASCE 24, provided that the ventilation openings are designed and installed in accordance with ASCE 24.

III. INTERIOR FINISH

A. Interior finish and floor flame spread and smoke development requirements.

a. The requirements stipulated by NFPA 101-2009 are more stringent and more detailed than those outlined in the 2009 IBC.

b. NFPA 101 stipulates three classes of interior ceiling and wall finishes and two classes of interior floor finishes. The specific properties of each class are outlined at the end of this section.

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c. Per 10.2.8.1 and Table A.10.2.2, unless specifically prohibited elsewhere in the Code, buildings with an approved automatic sprinkler system, Class C interior wall, and ceiling finish materials shall be permitted in any location where Class B is required, and Class B interior wall and ceiling finish materials shall be permitted in any location where Class A is required.

B. Interior Wall and Ceiling Finish

a. 38.3.3.2.1 – Interior wall and ceiling finishes are allowed to be Class A or Class B in exits and exit access corridors.

b. 38.3.3.2.2 – Interior wall finishes are allowed to be Class A, Class B, or Class C in all other areas.

C. Interior Floor Finish

a. 38.3.3.3.2 – Class I and Class II interior floor finishes at exit enclosures.

b. Per 10.2.8.2 and Table A.10.2.2, unless specifically prohibited elsewhere in this Code, buildings with an approved automatic sprinkler system, Class II interior floor finish shall be permitted in any location where Class I interior floor finish is required, and where Class II is required, no critical radiant flux rating shall be required.

D. 10.2.4.1 - Textile Wall Coverings

a. If used, textile wall coverings, including materials having woven or non-woven, napped, tufted, looped, or similar surface, will have a Class A rating.

E. 10.2.5 – Trim and Incidental Finishes

a. The amount of noncombustible decorative material is not limited.

b. 10.2.5.1 – The permissible amount of interior wall, ceiling trim, and incidental finishes, other than wall base, bulletin boards, posters, and paper, will not exceed 10 percent of the aggregate area of walls and ceilings and permitted to be Class C materials.

c. 10.2.5.2 – Interior wall base not exceeding 6 inches in height shall meet the interior wall finish requirements for its location or the requirements for Class II interior floor finish.

d. 10.2.5.3 Bulletin boards, posters, and paper attached directly to the wall shall not exceed 20 percent of the aggregate wall area to which applied.

F. NFPA 101, 2009, 10.2.3.4 Interior Finish Classification Specifications

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a. Class A interior wall and ceiling finish are characterized by the following:

i. Flame spread, 0–25

ii. Smoke development, 0–450

b. Class B interior wall and ceiling finish are characterized by the following:

i. Flame spread, 26–75

ii. Smoke development, 0–450

c. Class C interior wall and ceiling finish are characterized by the following:

i. Flame spread, 76–200

ii. Smoke development, 0–450

d. Class I interior floor finish is characterized by a critical radiant heat flux not less than 0.45 W/cm^2.

e. Class II interior floor finish is characterized by a critical radiant heat flux not less than 0.22 W/cm^2 but less than 0.45 W/cm^2.

IV. MEANS OF EGRESS

A. Occupant load factors are assigned to each room or area to determine total occupant load (see record drawing series ESIF-000-G-XXX). The table below summarizes the Occupant Load Factors that were assigned to each room or area.

Occupant Load Factors based on Table 1004.1.1	
AREA USE	**OCCUPANT LOAD FACTOR (sf/occ)**
Business areas	100 gross
Assembly – Unconcentrated	15 net
Assembly – Concentrated	7 net
Assembly – Standing	5 net
Mechanical Equipment Room	300 gross

B. 1015 – Exit and Exit Access Doorways

a. Per Table 1015.1, a minimum of two exits or exit accesses were provided from each space when the common path of travel would be exceeded, or when the occupant loads exceed the following:

i. A, B occupancies – 49

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ii. H-2 occupancy – 3

b. 1015.2.1 – Where two exits or exit accesses were required, they were separated from one another by not less than one- third the overall diagonal of the space served as allowed for buildings protected by an automatic sprinkler system.

c. 1015.2.2 – Where three or more exits or exit accesses are required, at least two exit doors or exit access doorways were separated from one another by not less than one-t hird the overall diagonal of the space as allowed for buildings protected by an automatic sprinkler system. Additional exits or exit access doorways were arranged a reasonable distance apart so that if one becomes blocked, the others are available.

d. Table 1021.1 – Two exits are required where the occupant load per story does not exceed 500 occupants. Three exits are required where the occupant load exceeds 500, and four exits are required where the occupant load exceeds 1,000.

C. 1016.1 – Travel Distance

a. B occupancy with sprinkler system will not exceed 300 feet.

b. H-2 occupancy will not exceed 100 feet.

D. 1014.3 – Common Path of Travel

a. In occupancies other than Groups H-1, H-2, and H-3, is limited to 75 feet.

b. B occupancies, equipped throughout with an automatic sprinkler system, are limited to 100 feet.

c. Group H-2 is limited to 25 feet.

E. Minimum required egress width per Table 1005.1

a. Group B Occupancy

i. 0.3 inch per occupant for stairs as allowed for buildings protected by an automatic sprinkler system.

ii. 0.2 inch per occupant for other egress components as allowed for buildings protected by an automatic sprinkler system.

b. NFPA 101, 2009

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i. For stairs wider than 44 inches and subject to 0.3 inch per occupant, the capacity is permitted to increase per the following equation:

1. C = 146.7 + (Wn - 44/0.218) where:

C = capacity, in persons, rounded to the nearest integer

Wn = nominal width of stair (inches) as permitted by 7.3.2.2

F. 1018 – Corridors

a. Table 1018.1 – Fire-resistance rating

i. Fire-resistance rating is not required in Group B occupancy corridors for a building protected by an automatic sprinkler system.

ii. 1-hour fire resistance rating is required at Group H Occupancies.

iii. NREL requires laboratories in High Bay area to be separated by 1-hour construction. Corridors in High Bay area are rated 1-hour.

b. 1018.2 – Aisles, corridors, and ramps required for exit access will not be less than 44 inches in clear and unobstructed width.

c. 1018.4 – Dead End Corridors: no dead ends in corridors more than 20 feet.

i. Group B occupancy with automatic sprinkler system throughout not to exceed 50 feet dead end corridor.

G. 1009 – Exit Stairs

a. 1007.3 – Exit stairs that are part of an accessible means of egress will have a clear width of 48 inches between handrails and incorporate an area of refuge or have access to an area of refuge.

b. 1009.1 – Stairs will be a minimum of 44 inches wide.

c. 1009.2 – Minimum headroom within stairway is 80 inches.

d. 1009.4 – Stair riser heights will be 7 inches maximum and 4 inches minimum. The minimum depth is 11 inches.

e. 1009.12 – Handrails will be provided on either side at a height between 34 and 38 inches.

f. 1012.3 – The outside diameter of the handrail shall be not less than 1-¼ inch and not more than 2 inches.

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H. 1008 – Doors

a. Doors serving a means of egress require a minimum width of each opening sufficient for the occupant load and will not be less than 32 inches in clear width.

b. Doors in exit stair enclosures are not less than 32 inches in clear width.

c. Doors swing in the direction of egress travel, where the door serves an occupant load of 50 or more.

d. Doors in the required means of egress can be readily opened without the use of a key, special knowledge, or effort.

e. Exit door hardware complies with IBC 1008.1.8.1 and ADAAG requirements.

I. 1023 – Exit Passageways

a. 1023.1 – Exit passageways will only be used for the purpose of a means of egress.

b. 1023.2 – Minimum width shall be 44 inches.

c. 1023.3 – Exit passageways have a minimum 1-hour fire resistance rating and not less than that required for any connecting exit enclosure.

d. 1023.5 – Openings are limited to those necessary for egress from normally occupied spaces.

J. 1025 – Horizontal Exits

a. A horizontal exit does not serve as the only exit from a portion of the building.

b. Not more than one-half of the total number of exits or total exit width are to be horizontal exits.

c. Horizontal exits are constructed as fire walls per Section 706 or as fire barriers per Section 707.

d. Horizontal exits have a minimum fire resistance rating of 2 hours.

e. Fire doors in horizontal exits are self-closing or automatic-closing.

f. The refuge area of a horizontal exit can be a space occupied by the same tenant or a public area and each such refuge area is adequate to accommodate the original occupant load of the refuge area plus the occupant load anticipated from the adjoining compartment. The capacity

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of the refuge area is computed such that a net floor area allowance of 3 sq. ft. for each occupant is accommodated.

K. 1026 – Exterior Ramps and Stairways

a. 1026.2 – Exterior ramps and stairways are permitted as an element of a required means of egress for buildings not exceeding six stories or 75 feet in height.

b. 1022 – Exit Discharge – Exits shall discharge directly to the exterior of the building, except as allowed below. The exit discharge shall be at grade or shall provide direct access to grade. The exit discharge shall not reenter the building.

i. A maximum of 50 percent of the number and capacity of exit enclosures are allowed to exit through areas on the level of discharge if the following conditions are met:

1. The exit enclosures egress to a free and unobstructed way to the exterior of the building, which is readily visible and identifiable from the point of termination of the exit enclosure.

2. The entire level of discharge is separated from areas below by construction conforming to the exit enclosure fire-resistance rating.

3. The discharge floor is completely sprinklered.

L. 1011 – Exit Signs

a. 1011.1 – Exit and exit access doors are marked by an exit sign, visible from any direction of egress travel. Access to exits is marked by exit signs where the path is not immediately visible to occupants. No point in an exit access corridor is more than 100 feet from the nearest visible exit sign.

b. 1011.3 – Tactile exit signs complying with ICC A117.1 are provided adjacent to each door to an exit stair, exit passageway, and the exit discharge.

c. 1011.4 – Exit signs are illuminated at all times.

d. 1011.5.3 – Exit signs are connected to an emergency power source that can provide 90 minutes of illumination if primary power is lost.

M. 1006 – Means of Egress Illumination

a. 1006.1 – The means of egress, including the exit discharge, is illuminated at all times the building is occupied.

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b. 1006.2 – Illumination level is not to be less than 1 foot-candle at the floor level other than in stairs.

c. 1006.3 – In the event of failure of the normal power supply, emergency electrical systems automatically illuminate for a duration not less than 90 minutes: exit access corridors, exit stairs, exit passageways, and that portion of the exterior exit discharge immediately adjacent to the exit discharge doors.

V. SUPPRESSION

A. 903 - Automatic Sprinkler Protection

a. 903.2.5 Group H – An automatic sprinkler system is provided in high-hazard occupancies.

b. 903.3.1.1 – An automatic sprinkler system is provided throughout the entire building, designed, and installed in accordance with NFPA 13, Standard for the Installation of Sprinkler Systems.

B. 905 – Standpipe Systems

a. A Class 1 standpipe system is installed throughout the building in every required stairway.

b. A hose connection is provided at each floor level above or below grade.

c. Hose connections are located at intermediate landings in each required exit stair.

C. 906 – Portable Fire Extinguishers

a. 906.1 – Fire extinguishers are provided throughout the building in accordance with the International Fire Code and NFPA 10, Standard for Portable Fire Extinguishers.

VI. FIRE ALARM AND DETECTION SYSTEMS

A. 907 – Fire Alarm and Detection Systems

a. The facility is equipped with a fire detection and alarm system with 100% coverage per NFPA-72.

b. 907.2.2 Group B – A manual fire alarm system is required in Group B occupancies having an occupant load of 500 or more persons or more than 100 persons above or below the lowest level of discharge.

B. 415.8.4.6 – Service Corridor – Emergency alarm system will be provided for detection and notification of an emergency condition in Group H occupancies

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C. 414.7.2 – Dispensing, use, and handling – Where hazardous materials having a ranking of 3 or 4 per NFPA 704 are transported through corridors or exit enclosures, these corridors or exit enclosures will have an emergency telephone system, local manual alarm station, or an approved alarm-initiating device at 150-foot intervals and at each exit throughout the transport route. The emergency alarm system will be constantly attended and will initiate an audible and visual signal.

VII. ELEVATORS

A. 3001.3 – Elevators and Escalators conform to ASME A17.1, Safety Code for Elevators and Escalators. Passenger elevators on an accessible route are accessible.

B. 3002.3 – An approved pictorial sign of a standardized design is posted adjacent to each elevator on all floors instructing occupants to use the stairs, not the elevator in case of fire. The sign should read, "IN FIRE EMERGENCY, DO NOT USE ELEVATOR. USE THE STAIRS."

C. 3004.1 – Elevators penetrating more than three stories are provided venting for smoke and hot gases.

D. 3004.4 – Plumbing and mechanical systems are not permitted in an elevator shaft, and plumbing equipment is prohibited in elevator machine rooms.

   a. Floor drains: Sumps and sump pumps are permitted at the base of a shaft if they are indirectly connected to the plumbing system.

E. 3006.1 – An approved means of access is provided to elevator machine rooms and overhead machinery space.

F. 3006.4 – Elevator machine rooms are enclosed in the same construction fire-resistance of the hoist-way enclosure.

G. 3006.6 – Plumbing systems will not be located in elevator equipment rooms.

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VIII. PLUMBING FIXTURE COUNT

A. 2902.1 – A minimum number of plumbing fixtures are provided as shown in the table below.

Description	Water Closets		Lavatories		Bathtubs or Showers	Drinking Fountains	Other
	M	F	M	F			
A-3. Lecture Halls	1 per 125	1 per 65	1 per 200		–	1 per 500	1 service sink
B. Business, Professional Services	1 per 25 for the first 50 and 1 per 50 for the remainder exceeding 50		1 per 40 for the first 80 and 1 per 80 for the remainder exceeding 80		–	1 per 100	1 service sink
S1/S2	1 per 100		1 per 100		Per 411 IPC	1 per 1,000	1 service sink

B. 2902.3 – The required number of plumbing fixtures are distributed equally between the sexes. The occupant load was assumed to be composed of 50 percent of each sex.

Plumbing Fixture Count Calculation							
Description	Water Closets		Lavatories		Bathtubs or Showers	Drinking Fountains	Other
	M	F	M	F			
A-3 Assembly Total Occupants = 552 552 / 2 = 276	2.2	4.2	1.4	1.4	–	1.1	1 service sink
B Offices Total Occupants = 1,376 1376 / 2 = 688	14.8	14.8	9.6	9.6	–	13.76	1 service sink
S1/S2 Storage Total occupants = 81 81 / 2 = 40.5	.81	.81	.81	.81	–	0.08	1 service sink
TOTAL REQUIRED	18	20	12	12	–	15	3
TOTAL PROVIDED	26	26	16	16	3 each	16	5

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IX. NFPA 45 AND IBC LABORATORY REQUIREMENTS

A. This section documents the separation approach for the laboratories. The IBC uses a control area approach for separation of areas storing and using hazardous materials. NFPA 45 uses a laboratory unit approach for separation of laboratory work areas.

A control area is defined as a space within a building where quantities of hazardous materials not exceeding the allowable exempt amounts (IBC Tables 307.7(1) and 307.7(2)) are stored, dispensed, utilized, or handled. Control areas should be separated from all adjacent interior spaces by fire separation assemblies (slab-to-slab) in accordance with IBC 707.0.

A laboratory unit is an enclosed space used for experiments or tests. A laboratory unit can include offices, lavatories, and other incidental contiguous rooms maintained for or used by laboratory personnel, and corridors within the unit. It can contain one or more separate laboratory work areas. It can be an entire building (NFPA 45, 3.3.36). It should be noted that storage areas within laboratories are subject to the requirements of NFPA 30.

The table below lists the areas of overlap between the IBC and NFPA 45, with respect to laboratory separation:

Control Areas (IBC 414.2.2)	**Laboratory Units (NFPA 45, Chapter 5)**
Limit on the number of control areas per	No limit on the number of laboratory units per floor or per building
No limit on the size of a control area	Maximum of 10,000 sq. ft. for Class A and B laboratory units No limit on the size of Class C and D laboratory units
Each control area is limited to the exempt amounts of hazardous materials – IBC Tables 307.7(1) and 307.7(2); amounts decrease for floor levels above and below grade	Each laboratory unit is limited to a maximum quantity of flammable and combustible liquids – NFPA 45, Table 10.1.1
1- or 2-hour fire separation (including glass) between control areas, with 2- hour floors and supporting construction	2-hour fire separation and supporting construction for Class A laboratory units 1-hour fire separation and supporting construction for Class B laboratory units NC separation for Class C and D laboratory units
No dedicated ventilation required for each control area	Each laboratory unit should be exhausted to the outside, to a mechanical penthouse, or to a rated shaft (NFPA 45, 8.2.2)

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B. NFPA 45 includes additional fire protection features that are not necessarily included in the IBC. The following are some of these that are applicable to this facility:

a. Seal or curb all floor openings (NFPA 45, 5.1.6)

b. Provide a second means of access to an exit from a laboratory work area if any of the following conditions exist (NFPA 45, 5.4.1):

i. A work area contains an explosion hazard that would block escape from or access to the work area.

ii. A laboratory work area with a Class A laboratory unit that exceeds 500 sq. ft.

iii. A Class B, C, or D laboratory work area that exceeds 1,000 sq. ft.

iv. A hood in a laboratory work area is located adjacent to the primary means of exit access.

v. There is a compressed gas cylinder in use that is larger than lecture bottle size located such that it could prevent safe egress in the event of accidental release of the cylinder's contents.

vi. There is a cryogenic container in use that is larger than lecture bottle size located such that it could prevent safe egress in the event of accidental release of the container's contents.

c. Exhaust ducts from each laboratory unit will be separately ducted to a point outside the building, to a mechanical room, or to a shaft (NFPA 45, 8.5.10.1).

d. Automatic fire dampers will not be used in chemical fume hood exhaust systems (NFPA 45, 8.10.3.1).

e. Class I liquids will not be stored or transferred from one vessel to another in any exit access corridor, open plan building, or ancillary spaces unprotected from the exit access corridor (NFPA 45, 9.2.2.4).

f. The maximum allowable container capacities should comply with NFPA 45, Table 10.1.4 with the following exceptions:

i. Four (4)-liter glass containers are permitted if there is a purity or corrosion issue with the use of metal or plastic containers.

ii. Sixty (60)-gallon containers are permitted for Class IA and IB flammable liquids if they are stored in a room complying with NFPA 30.

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g. There are additional requirements in NFPA 45 for compressed and liquefied gases (Chapter 11) that will need to be addressed on a case-by-case basis in addition to the detailed requirements found in the International Fire Code.

h. There are additional requirements in NFPA 45 for laboratory operations and apparatus (Chapter 12) that will need to be addressed on a case-by-case basis.

A number of consensus standards were used during design development. These are identified in the architect-engineer's specifications, but a compiled list was not required under the terms of the contract. At this time, the cost/benefit does not warrant performing a design basis reconstitution. However, the SDD development effort will identify, to the extent available, the consensus standards used in the design.

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Appendix D: Laboratory Safety Programmable Logic Controller (PLC) Action Matrices

Nomenclature

ALM	alarm
ARG	argon
BTL	bottle
CH4	methane
CO	carbon monoxide
CO_2	carbon dioxide
DET	detector
H_2	hydrogen
H_2S	hydrogen sulfide
HB	High Bay
HEL	helium
HMI	human machine interface
HP	high pressure
HPTB	High Pressure Test Bay
LCL	lower concentration limit
N_2	nitrogen
NH_3	ammonia
NO_2	nitrogen dioxide
O_2	oxygen
SG[1,2,3]	specialty gas
TP[x]	test pad
TSPL	Thermal Storage Process and Components Laboratory
WKSTN	work station

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ECCL - Electrochemical Characterization Lab

INPUT DEVICES			OUTPUT ACTIONS																	
SYSTEM	Type	TagName	Red	Yellow	Blue	Horn	Fire Notify	BAS Notify	Security Notify	HP H2 Manifold	HP N2 Manifold	O2 Manifold	CO Manifold	H2 Block&Bleed	Natural Gas	Power Shunt	HVAC Purge	AC REDB Trip	DC REDB Trip	EPO
EPO	BUTTON	E-SALPBEPO-329AA		■	■		■	■							■		■	■	■	
	BUTTON	E-SALPBEPO-329BA		■	■		■	■							■		■	■	■	
	BUTTON	E-SALPBEPO-329CA		■	■		■	■							■		■	■	■	
	WKSTN	HMI BUTTON		■	■		■	■							■		■	■	■	
HP H2 BOTTLE	VENT	E-SAMALHH2-312AA		■											■			■	■	
	PRESS	E-SAMALHH2-312AA	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	
	GAS DET	E-SAMALHH2-312AA		■											■			■	■	
	ESTOP	E-SAMALHH2-312AA		■											■			■	■	
N2 BTL	GEN ALM	E-SAMALHN2-312AA	■		■	■	■		■	■	■	■	■	■	■	■	■	■	■	■
O2 BTL	GEN ALM	E-SAMALOXY-312AA	■		■	■	■		■	■	■	■	■	■	■	■	■	■	■	■
CO BOTTLE	VENT	E-SAMALCOM-312AA	■	■			■								■			■	■	■
	PRESS	E-SAMALCOM-312AA	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	GAS DET	E-SAMALCOM-312AA	■	■			■								■			■	■	■
	ESTOP	E-SAMALCOM-312AA	■	■			■								■			■	■	
H2 DET	LEVEL	E-SADETH2R-329AA	■		■	■	■		■	■	■	■	■	■	■	■		■	■	■
	ALARM	E-SAALMH2R-329AB		■											■			■	■	
	TROUBLE	E-SATRBH2R-329AC	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
CO DET	LEVEL	E-SADETCOR-329CA	■		■	■	■		■	■	■	■	■	■	■	■		■	■	■
	ALARM	E-SAALMCOR-329CB	■	■			■								■			■	■	
	TROUBLE	E-SATRBCOR-329CC	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
HB FIRE	ALARM	EPO ACTION		■	■		■	■	■						■		■	■	■	
LAB EPO	ALARM	EPO STATUS		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■

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ECL - Electrical Characterization Lab

INPUT DEVICES			OUTPUT ACTIONS													
SYSTEM	Type	TagName	Red	Yellow	Blue	Horn	Fire Notify	BAS Notify	Security Notify	H2 Block&Bleed	Natural Gas	Power Shunt	HVAC Purge	AC REDB Trip	DC REDB Trip	EPO
EPO	BUTTON	E-SALPBEPO-317AA														
	BUTTON	E-SALPBEPO-317BA														
	BUTTON	E-SALPBEPO-317CA														
	BUTTON	E-SALPBEPO-317DA														
	WKSTN	HMI BUTTON														
CSTOP	BUTTON	E-SALPBSTP-317AA														
	BUTTON	E-SALPBSTP-317BA														
	BUTTON	E-SALPBSTP-317CA														
	BUTTON	E-SALPBSTP-317DA														
	WKSTN	HMI BUTTON														
H2 DET	LCL	E-SADETH2R-317AA														
	ALARM	E-SAALMH2R-317AB														
	TROUBLE	E-SATRBH2R-317AC														
HB FIRE	ALARM	EPO ACTION														
LAB EPO	ALARM	EPO STATUS														

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ESFL - Energy Systems Fabrication Lab (C321)

INPUT DEVICES			OUTPUT ACTIONS														
SYSTEM	Type	TagName	Red	Yellow	Blue	Horn	Fire Notify	BAS Notify	Security Notify	HP H2 Manifold	CO Manifold	H2 Block&Bleed	Natural Gas	Power Shunt	HVAC Purge	AC REDB Trip	DC REDB Trip	EPO
EPO	BUTTON	E-SALPBEPO-321AA																
	BUTTON	E-SALPBEPO-321BA																
	BUTTON	E-SALPBEPO-321CA																
	WKSTN	HMI BUTTON																
CO BOTTLE	VENT	E-SAMALCOM-313AA																
	PRESS	E-SAMALCOM-313AA																
	GAS DET	E-SAMALCOM-313AA																
	ESTOP	E-SAMALCOM-313AA																
H2 DET	LEVEL	E-SADETH2R-321AA																
	ALARM	E-SAALMH2R-321AB																
	TROUBLE	E-SATRBH2R-321AC																
HB FIRE	ALARM	EPO ACTION																
LAB EPO	ALARM	EPO STATUS																

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ESIL - Energy Systems Integration Lab

INPUT DEVICES			OUTPUT ACTIONS																		
SYSTEM	Type	TagName	Gen Red	Gen Yellow	Gen Blue	Gen Horn	HPTB1 Red	HBTB1 Yellow	HBTB1 Blue	HPTB2 Red	HBTB2 Yellow	HBTB2 Blue	Fire Notify	BAS Notify	Security Notify	Natural Gas	Power Shunt	HVAC Purge	AC REDB Trip	DC REDB Trip	EPO
EPO	BUTTON	E-SALPBEPO-339AA		■	■			■	■		■	■	■	■				■			
	BUTTON	E-SALPBEPO-339BA		■	■			■	■		■	■	■	■				■			
	BUTTON	E-SALPBEPO-339CA		■	■			■	■		■	■	■	■				■			
	BUTTON	E-SALPBEPO-339DA		■	■			■	■		■	■	■	■				■			
	BUTTON	E-SALPBEPO-339EA		■	■			■	■		■	■	■	■				■			
	BUTTON	E-SALPBEPO-339FA		■	■			■	■		■	■	■	■				■			
	BUTTON	E-SALPBEPO-339GA		■	■			■	■		■	■	■	■				■			
	BUTTON	E-SALPBEPO-339HA		■	■			■	■		■	■	■	■				■			
	BUTTON	E-SALPBEPO-339JA		■	■			■	■		■	■	■	■				■			
	BUTTON	E-SALPBEPO-339KA		■	■			■	■		■	■	■	■				■			
	WKSTN	HMI BUTTON		■	■			■	■		■	■	■	■				■			
H2 DET	LCL	E-SADETH2R-339AA	■		■	■	■		■	■		■	■		■	■	■		■	■	■
	ALARM	E-SAALMH2R-339AB		■				■			■	■									
	TROUBLE	E-SATRBH2R-339AC	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
H2 DET	LCL	E-SADETH2R-339BA	■		■	■	■		■	■		■	■		■	■	■		■	■	■
	ALARM	E-SAALMH2R-339BB		■				■			■										
	TROUBLE	E-SATRBH2R-339BC	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
H2 DET	LCL	E-SADETH2R-339CA	■		■	■	■		■	■		■	■		■	■	■		■	■	■
	ALARM	E-SAALMH2R-339CB		■				■			■										
	TROUBLE	E-SATRBH2R-339CC	■		■	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■
H2 DET	LCL	E-SADETH2R-339DA	■		■	■	■		■	■		■	■		■	■	■		■	■	■
	ALARM	E-SAALMH2R-339DB		■				■			■										
	TROUBLE	E-SATRBH2R-339DC	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
H2 DET	LCL	E-SADETH2R-339EA	■		■	■	■		■	■		■	■		■	■	■		■	■	■
	ALARM	E-SAALMH2R-339EB		■				■			■										
	TROUBLE	E-SATRBH2R-339EC	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
H2 DET	LCL	E-SADETH2R-339FA	■		■	■	■		■	■		■	■		■	■	■		■	■	■
	ALARM	E-SAALMH2R-339FB		■				■			■										
	TROUBLE	E-SATRBH2R-339FC	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■

ESIL - Energy Systems Integration Lab

INPUT DEVICES			OUTPUT ACTIONS																	
SYSTEM	Type	TagName	Gen Red	Gen Yellow	Gen Blue	Gen Horn	HPTB1 Red	HBTB1 Yellow	HBTB1 Blue	HPTB2 Red	HBTB2 Yellow	HBTB2 Blue	Fire Notify	BAS Notify	Security Notify	Natural Gas	Power Shunt	HVAC Purge	AC REDB Trip	DC REDB Trip	EPO
HPTB1 H2	ALARM	E-SAHB1H2A-684EA																			
HPTB1 O2	ALARM	E-SAHB1O2A-684EB																			
HPTB2 H2	ALARM	E-SAHB2H2A-684FA																			
HPTB2 O2	ALARM	E-SAHB2O2A-684FB																			
HPTB1 DOOR	OPEN	E-SAHB1DOS-684EC																			
HPTB2 DOOR	OPEN	E-SAHB2DOS-684FC																			
H2 VENT	TROUBLE	E-SAH2VHTA-684CG																			
HB FIRE	ALARM	EPO ACTION																			
LAB EPO	ALARM	EPO STATUS																			

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ESL - Energy Storage Lab

INPUT DEVICES			OUTPUT ACTIONS													
SYSTEM	Type	TagName	Red	Yellow	Blue	Horn	Fire Notify	BAS Notify	Security Notify	H2 Block&Bleed	Natural Gas	Power Shunt	HVAC Purge	AC REDB Trip	DC REDB Trip	EPO
EPO	BUTTON	E-SALPBEPO-325AA														
	BUTTON	E-SALPBEPO-325BA														
	BUTTON	E-SALPBEPO-325CA														
	BUTTON	E-SALPBEPO-325DA														
	BUTTON	E-SALPBEPO-325EA														
	BUTTON	E-SALPBEPO-325FA														
	BUTTON	E-SALPBEPO-325GA														
	WKSTN	HMI BUTTON														
CSTOP	BUTTON	E-SALPBSTP-325AA														
	BUTTON	E-SALPBSTP-325BA														
	BUTTON	E-SALPBSTP-325CA														
	BUTTON	E-SALPBSTP-325DA														
	BUTTON	E-SALPBSTP-325EA														
	BUTTON	E-SALPBSTP-325FA														
	BUTTON	E-SALPBSTP-325GA														
	WKSTN	HMI BUTTON														
H2 DET	LCL	E-SADETH2R-325AA														
	ALARM	E-SAALMH2R-325AB														
	TROUBLE	E-SATRBH2R-325AC														
H2 DET	LCL	E-SADETH2R-325DA														
	ALARM	E-SAALMH2R-325DB														
	TROUBLE	E-SATRBH2R-325DC														
O2 DET	LCL	E-SADETO2R-325BA														
	ALARM	E-SAALMO2R-325BB														
CO DET	LCL	E-SADETCOR-325CA														
	ALARM	E-SAALMCOR-325CB														
	TROUBLE	E-SATRBCOR-325CC														
O2 DET	LCL	E-SADETO2R-325EA														
	ALARM	E-SAALMO2R-325EB														

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ESL - Energy Storage Lab

INPUT DEVICES			OUTPUT ACTIONS													
SYSTEM	Type	TagName	Red	Yellow	Blue	Horn	Fire Notify	BAS Notify	Security Notify	H2 Block&Bleed	Natural Gas	Power Shunt	HVAC Purge	AC REDB Trip	DC REDB Trip	EPO
CO DET	LCL	E-SADETCOR-325FA														
	ALARM	E-SAALMCOR-325FB														
	TROUBLE	E-SATRBCOR-325FC														
HB FIRE	ALARM	EPO ACTION														
DIESEL TANK	ALARM	FROM RF PLC														
COMM LOSS	ALARM	TO RF PLC														
LAB EPO	ALARM	EPO STATUS														

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ESSL - Energy System Sensor Lab (C330)

INPUT DEVICES			OUTPUT ACTIONS															
SYSTEM	Type	TagName	Red	Yellow	Blue	Horn	Fire Notify	BAS Notify	Security Notify	CH4 Manifold	HP H2 Manifold	ARG Manifold	H2 Block&Bleed	Natural Gas	Power Shunt	HVAC Purge	AC REDB Trip	DC REDB Trip	EPO
EPO	BUTTON	E-SALPBEPO-330AA																	
	BUTTON	E-SALPBEPO-330BA																	
	WKSTN	HMI BUTTON																	
CH4 BOTTLE	VENT	E-SAMALCH4-312AA																	
	PRESS	E-SAMALCH4-312AA																	
	GAS DET	E-SAMALCH4-312AA																	
	ESTOP	E-SAMALCH4-312AA																	
HP H2 BOTTLE	VENT	E-SAMALHH2-312BA																	
	PRESS	E-SAMALHH2-312BA																	
	GAS DET	E-SAMALHH2-312BA																	
	ESTOP	E-SAMALHH2-312BA																	
ARG BTL	GEN ALM	E-SAMALARG-312AA																	
CO2 BTL	GEN ALM	E-SAMALCOM-312AA																	
H2 DET	LCL	E-SADETH2R-330AA																	
	ALARM	E-SAALMH2R-330AB																	
	TROUBLE	E-SATRBH2R-330AC																	
HB FIRE	ALARM	EPO ACTION																	
LAB EPO	ALARM	EPO STATUS																	

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FCDTL - Fuel Cell Development Lab

INPUT DEVICES			OUTPUT ACTIONS																				
SYSTEM	Type	TagName	Red	Yellow	Blue	Horn	Fire Notify	BAS Notify	Security Notify	CH4 Manifold	NH3 Manifold	CO/H2 Manifold	HP H2 Manifold	HEL Manifold	ARG Manifold	O2 Manifold	CO Manifold	H2 Block&Bleed	Natural Gas	Power Shunt	HVAC Purge	AC REDB Trip	DC REDB Trip	EPO
EPO	BUTTON	E-SALPBEPO-323AA		■	■		■	■											■		■			
	BUTTON	E-SALPBEPO-323BA		■	■		■	■											■		■			
	BUTTON	E-SALPBEPO-323CA		■	■		■	■											■		■			
	BUTTON	E-SALPBEPO-323DA		■	■		■	■											■		■			
	WKSTN	HMI BUTTON		■	■		■	■											■		■			
CH4 BOTTLE	VENT	E-SAMALCH4-313AA		■															■			■	■	■
	PRESS	E-SAMALCH4-313AA	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	GAS DET	E-SAMALCH4-313AA		■															■			■	■	■
	ESTOP	E-SAMALCH4-313AA		■															■			■	■	■
NH3 BOTTLE	VENT	E-SAMALNH3-313AA	■	■			■												■					
	PRESS	E-SAMALNH3-313AA	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	GAS DET	E-SAMALNH3-313AA	■	■			■												■					
	ESTOP	E-SAMALNH3-313AA	■	■			■												■					
CO/H2 BOTTLE	VENT	E-SAMALCHM-313AA		■															■					
	PRESS	E-SAMALCHM-313AA	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	GAS DET	E-SAMALCHM-313AA		■															■					
	ESTOP	E-SAMALCHM-313AA		■															■					
HP H2 BOTTLE	VENT	E-SAMALHH2-313AA		■															■					
	PRESS	E-SAMALHH2-313AA	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	GAS DET	E-SAMALHH2-313AA		■															■					
	ESTOP	E-SAMALHH2-313AA		■															■					
HEL BTL	GEN ALM	E-SAMALHEL-313AA	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
ARG BTL	GEN ALM	E-SAMALARG-313AA	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
O2 BTL	GEN ALM	E-SAMALOXY-313AA	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
CO BTL	GEN ALM	E-SAMALCOM-313AA	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
H2 DET	LCL	E-SADETH2R-323AA	■		■	■	■		■	■	■	■	■	■	■	■	■	■	■	■		■	■	■
	ALARM	E-SAALMH2R-323AB		■															■					
	TROUBLE	E-SATRBH2R-323AC	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■

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FCDTL - Fuel Cell Development Lab

INPUT DEVICES			OUTPUT ACTIONS																				
SYSTEM	Type	TagName	Red	Yellow	Blue	Horn	Fire Notify	BAS Notify	Security Notify	CH4 Manifold	NH3 Manifold	CO/H2 Manifold	HP H2 Manifold	HEL Manifold	ARG Manifold	O2 Manifold	CO Manifold	H2 Block&Bleed	Natural Gas	Power Shunt	HVAC Purge	AC RED8 Trip	DC RED8 Trip	EPO
H2S DET	LCL	E-SADETH2S-323BA	■		■	■	■		■	■	■	■	■	■	■	■	■	■	■	■		■	■	■
	ALARM	E-SAALMH2S-323BB		■															■					
	TROUBLE	E-SATRBH2S-323BC	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
NH3 DET	LCL	E-SADETNH3-323CA	■		■	■	■		■	■	■	■	■	■	■	■	■	■	■	■		■	■	■
	ALARM	E-SAALMNH3-323CB		■															■					
	TROUBLE	E-SATRBNH3-323CC	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
O2 DET	LCL	E-SADETO2R-323DA	■		■	■	■		■	■	■	■	■	■	■	■	■	■	■	■		■	■	■
	ALARM	E-SAALMO2R-323DB	■		■	■	■		■	■	■	■	■	■	■	■	■	■	■	■		■	■	■
CO DET	LCL	E-SADETCOR-323EA	■		■	■	■		■	■	■	■	■	■	■	■	■	■	■	■		■	■	■
	ALARM	E-SAALMCOR-323EB	■	■			■												■					
	TROUBLE	E-SATRBCOR-323EC	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
HB FIRE	ALARM	EPO ACTION		■	■	■	■	■	■										■		■			
LAB EPO	ALARM	EPO STATUS		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■

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LVOTA - Low Voltage Outdoor Test Area

INPUT DEVICES			OUTPUT ACTIONS															
SYSTEM	Type	TagName	TP1 Red	TP1 Yellow	TP2 Red	TP2 Yellow	TP3 Red	TP3 Yellow	TP4 Red	TP4 Yellow	TP5 Red	TP5 Yellow	Fire Notify	Security Notify	Natural Gas	Power Shunt	AC REDB Trip	DC REDB Trip
EPO	TP1 BTN	E-SALPBEPO-T21AA																
	TP2 BTN	E-SALPBEPO-T22AA																
	TP3 BTN	E-SALPBEPO-T23AA																
	TP4 BTN	E-SALPBEPO-T24AA																
	TP5 BTN	E-SALPBEPO-T25AA																
	WKSTN	HMI BUTTON																
CSTOP	TP1 BTN	E-SALPBSTP-T21AA																
	TP2 BTN	E-SALPBSTP-T22AA																
	TP3 BTN	E-SALPBSTP-T23AA																
	TP4 BTN	E-SALPBSTP-T24AA																
	TP5 BTN	E-SALPBSTP-T25AA																
	WKSTN	HMI BUTTON																
HB FIRE	ALARM	EPO ACTION																
TP1 EPO	ALARM	EPO STATUS																
TP2 EPO	ALARM	EPO STATUS																
TP3 EPO	ALARM	EPO STATUS																
TP4 EPO	ALARM	EPO STATUS																
TP5 EPO	ALARM	EPO STATUS																

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MCL - Material Characterization Lab

INPUT DEVICES				OUTPUT ACTIONS																
SYSTEM	Type	TagName	Include?	Red	Yellow	Blue	Horn	Fire Notify	BAS Notify	Security Notify	CH4 Manifold	HP H2 Manifold	ARG Manifold	CO2 Manifold	H2 Block&Bleed	Natural Gas	Power Shunt	HVAC Purge	AC REDB Trip	DC REDB Trip	EPO
EPO	BUTTON	E-SALPBEPO-319AA																			
	BUTTON	E-SALPBEPO-319BA																			
	WKSTN	HMI BUTTON																			
CH4 BOTTLE	VENT	E-SAMALCH4-315AA																			
	PRESS	E-SAMALCH4-315AA																			
	GAS DET	E-SAMALCH4-315AA																			
	ESTOP	E-SAMALCH4-315AA																			
HP H2 BOTTLE	VENT	E-SAMALHH2-315AA																			
	PRESS	E-SAMALHH2-315AA																			
	GAS DET	E-SAMALHH2-315AA																			
	ESTOP	E-SAMALHH2-315AA																			
ARG BTL	GEN ALM	E-SAMALARG-315AA																			
CO2 BTL	GEN ALM	E-SAMALCO2-315AA																			
H2 DET	LCL	E-SADETH2R-319AA																			
	ALARM	E-SAALMH2R-319AB																			
	TROUBLE	E-SATRBH2R-319AC																			
HB FIRE	ALARM	EPO ACTION	X																		
LAB EPO	ALARM	EPO STATUS																			

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ML - Manufacturing Lab

INPUT DEVICES				OUTPUT ACTIONS												
SYSTEM	Type	TagName	Include?	Red	Yellow	Blue	Horn	Fire Notify	BAS Notify	Security Notify	H2 Block&Bleed	Natural Gas	Power Shunt	HVAC Purge	AC REDB Trip	DC REDB Trip
EPO	BUTTON	E-SALPBEPO-324AA														
	BUTTON	E-SALPBEPO-324BA														
	WKSTN	HMI BUTTON														
H2 DET	LCL	E-SADETH2R-324AA														
	ALARM	E-SAALMH2R-324AB														
	TROUBLE	E-SATRBH2R-324AC														
HB FIRE	ALARM	EPO ACTION	X													

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MVOTA - Medium Voltage Outdoor Test Area

INPUT DEVICES				OUTPUT ACTIONS																					
SYSTEM	Type	TagName	Include?	TP1 Red	TP1 Yellow	TP2 Red	TP2 Yellow	TP3 Red	TP3 Yellow	TP4 Red	TP4 Yellow	TP5 Red	TP5 Yellow	TP6 Red	TP6 Yellow	TP7 Red	TP7 Yellow	TP8 Red	TP8 Yellow	Fire Notify	Security Notify	Natural Gas	Power Shunt	AC RED8 Trip	DC RED8 Trip
EPO	TP1 BTN	E-SALPBEPO-T31AA																							
	TP2 BTN	E-SALPBEPO-T32AA																							
	TP3 BTN	E-SALPBEPO-T33AA																							
	TP4 BTN	E-SALPBEPO-T34AA																							
	TP5 BTN	E-SALPBEPO-T35AA																							
	TP6 BTN	E-SALPBEPO-T36AA																							
	TP7 BTN	E-SALPBEPO-T37AA																							
	TP8 BTN	E-SALPBEPO-T38AA																							
	WKSTN	HMI BUTTON																							
CSTOP	TP1 BTN	E-SALPBSTP-T31AA																							
	TP2 BTN	E-SALPBSTP-T32AA																							
	TP3 BTN	E-SALPBSTP-T33AA																							
	TP4 BTN	E-SALPBSTP-T34AA																							
	TP5 BTN	E-SALPBSTP-T35AA																							
	TP6 BTN	E-SALPBSTP-T36AA																							
	TP7 BTN	E-SALPBSTP-T37AA																							
	TP8 BTN	E-SALPBSTP-T38AA																							
	WKSTN	HMI BUTTON																							
HB FIRE	ALARM	EPO ACTION	X																						

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OCL - Optical Characterization Lab

INPUT DEVICES				OUTPUT ACTIONS										
SYSTEM	Type	TagName	Include?	Red	Yellow	Horn	Fire Notify	BAS Notify	Security Notify	Natural Gas	Power Shunt	HVAC Purge	AC REDB Trip	DC REDB Trip
EPO	BUTTON	E-SALPBEPO-220AA												
	BUTTON	E-SALPBEPO-220AB												
	BUTTON	E-SALPBEPO-220AC												
	WKSTN	HMI BUTTON												
CSTOP	BUTTON	E-SALPBSTP-220AB												
	BUTTON	E-SALPBSTP-220BB												
	BUTTON	E-SALPBSTP-220CB												
	WKSTN	HMI BUTTON												
NO2 DET	LCL	E-SADETNO2-220BA												
	ALARM	E-SAALMNO2-220BB												
	TROUBLE	E-SATRBNO2-220BC												
O2 DET	LCL	E-SADETO2R-220AA												
	ALARM	E-SAALMO2R-220AB												
CO DET	LCL	E-SADETCOR-220BA												
	ALARM	E-SAALMCOR-220BB												
	TROUBLE	E-SATRBCOR-220BC												
HB FIRE	ALARM	EPO ACTION	X											

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PSIL - Power Systems Integration Lab

INPUT DEVICES				OUTPUT ACTIONS										
SYSTEM	Type	TagName	Include?	Red	Yellow	Horn	Fire Notify	BAS Notify	Security Notify	Natural Gas	Power Shunt	HVAC Purge	AC REDB Trip	DC REDB Trip
EPO	BUTTON	E-SALPBEPO-221AA												
	BUTTON	E-SALPBEPO-221AB												
	BUTTON	E-SALPBEPO-221AC												
	BUTTON	E-SALPBEPO-221AD												
	WKSTN	HMI BUTTON												
CSTOP	BUTTON	E-SALPBSTP-221AA												
	BUTTON	E-SALPBSTP-221AB												
	BUTTON	E-SALPBSTP-221AC												
	BUTTON	E-SALPBSTP-221AD												
	WKSTN	HMI BUTTON												
SG3 BTL	GEN ALM	E-SAMALSG3-221AA												
NO2 DET	LCL	E-SADETNO2-221BA												
	ALARM	E-SAALMNO2-221BB												
	TROUBLE	E-SATRBNO2-221BC												
O2 DET	LCL	E-SADETO2R-221AA												
	ALARM	E-SAALMO2R-221AA												
CO DET	LCL	E-SADETCOR-221BA												
	ALARM	E-SAALMCOR-221BB												
	TROUBLE	E-SATRBCOR-221BC												
HB FIRE	ALARM	EPO ACTION	X											

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SPL - Smart Power Lab

INPUT DEVICES				OUTPUT ACTIONS											
SYSTEM	Type	TagName	Include?	Red	Yellow	Blue	Horn	Fire Notify	BAS Notify	Security Notify	Natural Gas	Power Shunt	HVAC Purge	AC REDB Trip	DC REDB Trip
EPO	BUTTON	E-SALPBEPO-213AA													
	BUTTON	E-SALPBEPO-213BA													
	BUTTON	E-SALPBEPO-213CA													
	BUTTON	E-SALPBEPO-213DA													
	BUTTON	E-SALPBEPO-213EA													
	WKSTN	HMI BUTTON													
CSTOP	BUTTON	E-SALPBSTP-213AA													
	BUTTON	E-SALPBSTP-213BA													
	BUTTON	E-SALPBSTP-213CA													
	BUTTON	E-SALPBSTP-213DA													
	BUTTON	E-SALPBSTP-213EA													
	WKSTN	HMI BUTTON													
HB FIRE	ALARM	EPO ACTION	X												

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TSML - Thermal Storage Materials Lab

INPUT DEVICES				OUTPUT ACTIONS															
SYSTEM	Type	TagName	Include?	Red	Yellow	Blue	Horn	Fire Notify	BAS Notify	Security Notify	SG1 Manifold	SG2 Manifold	H2 Block&Bleed	Natural Gas	Power Shunt	HVAC Purge	AC REDB Trip	DC REDB Trip	EPO
EPO	BUTTON	E-SALPBEPO-331AA																	
	BUTTON	E-SALPBEPO-331BA																	
	WKSTN	HMI BUTTON																	
SG1 BTL	GEN ALM	E-SAMALSG1-312AA																	
SG2 BTL	GEN ALM	E-SAMALSG2-312AA																	
H2 DET	LCL	E-SADETH2R-331AA																	
	ALARM	E-SAALMH2R-331AB																	
	TROUBLE	E-SATRBH2R-331AC																	
HB FIRE	ALARM	EPO ACTION	X																
LAB EPO	ALARM	EPO STATUS																	
TSPL EPO	ALARM	EPO STATUS																	
TSPL COMM	ALARM	COMM LOSS	X																

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Appendix E: Risk

Table E-1. Risk Matrix

Consequence ↓	**Likelihood →**	**A**	**B**	**C**	**D**	**E**	**F**
		Frequent	Reasonably Probable	Occasional	Remote	Extremely Remote	Improbable
I	Catastrophic	HIGH	HIGH	HIGH	MODERATE	LOW	ROUTINE
II	Critical	HIGH	HIGH	MODERATE	LOW	LOW	ROUTINE
III	Marginal	MODERATE	MODERATE	LOW	LOW	ROUTINE	ROUTINE
IV	Negligible	ROUTINE	ROUTINE	ROUTINE	ROUTINE	ROUTINE	ROUTINE

Table E-2. Likelihood Bins – NREL LLP 6-6.2 Proposed

Level	**Name**	**Frequency**	**Description**
A	Frequent	$F \geq 1.0/y$	Expected to occur one or more times a year; or likely to occur many times in the lifecycle of the system.
B	Reasonably probable	$1.0/y > F \geq 0.1/y$	Expected to occur between once a year and once every few years; or will occur several times in the lifecycle of the system.
C	Occasional	$0.1/y > F \geq 0.01/y$	Expected to occur several times during the lifetime of the facility (50 years); or likely to occur sometime in the lifecycle of the system.
D	Remote	$0.01/y > F \geq 10^{-4}/y$	Expected to occur no more than once during the lifetime of the facility (50 years); or unlikely, but possible to occur in the lifecycle of the system.
E	Extremely remote	$10^{-4}/y > F \geq 10^{-6}/y$	Not expected to occur during the lifetime of the facility (50 years); or so unlikely it can be assumed not to occur in the lifecycle of the system.
F	Improbable	$F < 10^{-6}/y$	Never expected to occur.

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Table E-3. Consequence Bins – NREL LLP 6-6.2 Proposed

Level	Description	Consequences
I	Catastrophic	Could result in one or more of the following: death; permanent total disability; irreversible significant environmental impact; monetary loss equal to or exceeding $10 million; or loss of the system.
II	Critical	Could result in one or more of the following: permanent partial disability; injuries or occupational illness that may result in hospitalization of at least three personnel; reversible significant environmental impact; monetary loss equal to or exceeding $1 million but less than $10 million; or major system damage.
II	Marginal	Could result in one or more of the following: injury or occupational illness resulting in one or more lost work day(s); reversible moderate environmental impact; or monetary loss equal to or exceeding $100K but less than $1 million; or minor system damage requiring repair.
IV	Negligible	Could result in one or more of the following: injury or occupational illness not resulting in a lost work day; minimal environmental impact; monetary loss less than $100K; or minor system damage not requiring repair.

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ESIF Hazard Identification Form

See attachment for instructions.

Facility/Laboratory:

Process:

ID No.	Accident Type	Cause or Initiating Event
	Select	Select

Hazard Evaluation Technique	Scenario
Select	

Hazards of Concern: Select

Material/Condition

	Uncontrolled						
	Frequency	Consequence			Risk		
		E/F	P/E	W	E/F	P/E	W

Control Description	Control Type	Contributes to Reduction				Notes
	Select	☐	☐	☐	☐	
	Select	☐	☐	☐	☐	
	Select	☐	☐	☐	☐	
	Select	☐	☐	☐	☐	
	Select	☐	☐	☐	☐	
	Select	☐	☐	☐	☐	
	Select	☐	☐	☐	☐	
	Select	☐	☐	☐	☐	

SUBMIT

	Controlled							
	Frequency	Consequence			Risk			Assumes all controls are in place
		E/F	P/E	W	E/F	P/E	W	

EP = Engineered Preventive, EM = Engineered Mitigative, AP = Administrative Preventive, AM = Administrative Mitigative, ✓ = Contributes to Reduction	
I = Catastrophic, II = Critical, III = Marginal, IV = Negligible	L = Low, M = Medium, H = High, R = Routine
A = Frequent, B = Reasonably Probable, C = Occasional, D = Remote, E = Extremely Remote, F = Improbable	

Please consider the environment before printing this form.

Figure E-1. ESIF Hazard Identification Form

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Appendix F: PrHA Scenarios

Table F-1. ESIF Items Relied On For Safety (from PrHA)

Risk ID Number	Accident Type	Scenario	System, Laboratory or Activity	Credited Controls (Control Types: EP - Engineered Passive, EA - Engineered Active, AC - Administrative Control)	Control Type	Applicable Location
214-1	Electric shock or arc flash	Flood from inadvertent sprinkler head operation	REDB System	Design Feature: The REDB System components are located in standard National Electric Code (NEC)-rated electrical enclosures.	EP	C224, C225 - REDB Rooms
214-2	Electric shock or arc flash	Flood from inadvertent sprinkler head operation	REDB System	Design Feature: All REDB System source connections have standard overcurrent protection that will remove the energy in the event of a ground fault.	EA	C224, C225 - REDB Rooms
214-3	Electric shock or arc flash	Flood from inadvertent sprinkler head operation	REDB System	Design Feature: Fire suppression flow switch generates a high bay fire alarm. A high bay fire alarm results in an emergency power off (EPO) for the entire C Wing.	EA	C224, C225 - REDB Rooms
227-1	Electric shock or arc flash	Shock, arc flash, explosion resulting from ground faults, short circuits	REDB System	Work Control Documents for the REDB System require dead bus switching unless a recloser or other device designed for live switching is used.	AC	MVOTA
227-2	Electric shock or arc flash	Shock, arc flash, explosion resulting from ground faults, short circuits	REDB System	Work Control Documents require use of a dedicated industry-standard breaker for any device under test (DUT) to provide overcurrent protection.	AC	MVOTA
227-3	Electric shock or arc flash	Shock, arc flash, explosion resulting from ground faults, short circuits	REDB System	Design Feature: Dedicated industry-standard breakers are provided for DUTs.	EA	MVOTA

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Risk ID Number	Accident Type	Scenario	System, Laboratory or Activity	Credited Controls (Control Types: EP - Engineered Passive, EA - Engineered Active, AC - Administrative Control)	Control Type	Applicable Location
227-4	Electric shock or arc flash	Shock, arc flash, explosion resulting from ground faults, short circuits	REDB System	Design Feature: The REDB System was designed and installed in accordance with NEC requirements.	EP	MVOTA
227-5	Electric shock or arc flash	Shock, arc flash, explosion resulting from ground faults, short circuits	REDB System	The Preventative Maintenance (PM) program requirements for the REDB System include resistance (Ohm) measurement and thermal imaging. (The intent of these PMs is to specify routine inspection and testing of the system that will identify weak spots prior to a failure.)	AC	MVOTA
227-6	Electric shock or arc flash	Shock, arc flash, explosion resulting from ground faults, short circuits	REDB System	Work Control Documents for the REDB System include Electrical Safety Program requirements for the use of proper personnel protective equipment (PPE) and clothing by workers completing dead bus confirmation and changing switch positions.	AC	MVOTA
227-7	Electric shock or arc flash	Shock, arc flash, explosion resulting from ground faults, short circuits	REDB System	Work Control Documents for the REDB System in the laboratories require an operable supervisory control and data acquisition (SCADA) System or define compensatory measures if the SCADA System is not operable. (The SCADA System provides remote indication and operation of critical components associated with the REDB System. The SCADA System is only credited as an administrative control as design does not include any provisions beyond component status and remote operation requests.)	AC	MVOTA

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Risk ID Number	Accident Type	Scenario	System, Laboratory or Activity	Credited Controls (Control Types: EP - Engineered Passive, EA - Engineered Active, AC - Administrative Control)	Control Type	Applicable Location
227-8	Electric shock or arc flash	Shock, arc flash, explosion resulting from ground faults, short circuits	REDB System	Design Feature: Protective reclosers are installed in the REDB System. (These reclosers were specified in accordance with normal standards for medium voltage distribution and have industry standard monitoring and programming that interrupt the source during a fault condition to limit the energy.)	EA	MVOTA
227-9	Electric shock or arc flash	Shock, arc flash, explosion resulting from ground faults, short circuits	REDB System	Work Control Documents for the REDB System include Electrical Safety Program requirements for proper bus labeling and lockout / tagout (LOTO).	AC	MVOTA
249-2	Fire - Small local fire in work area	Improper handling of flammable liquids leading to small fire	Flammable liquid handling/ Laboratory Gas Supply System	Design Feature: Flammable gas detectors are provided that are tied into the Laboratory Exhaust Ventilation System as well as automatic shutoff valves on flammable gas lines to further mitigate the consequences of a small local fire.	EA	C213 - SPL C221 - PSIL C321 - ESFL C324 - ML C329 - ECCL C336, C337, C338, C339 - ESIL
249-3	Fire - Small local fire in work area	Improper handling of flammable liquids leading to small fire	Flammable liquid handling/ Laboratory Gas Supply System	Work control documents specify the requirements for operable and calibrated flammable gas detectors.	AC	C213 - SPL C221 - PSIL C321 - ESFL C324 - ML C329 - ECCL C336, C337, C338, C339 - ESIL

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Risk ID Number	Accident Type	Scenario	System, Laboratory or Activity	Credited Controls (Control Types: EP - Engineered Passive, EA - Engineered Active, AC - Administrative Control)	Control Type	Applicable Location
249-4	Fire - Small local fire in work area	Improper handling of flammable liquids leading to small fire	Flammable liquid handling	Personnel are trained in safe handling, storage, and use of flammable liquids.	AC	C213 - SPL C221 - PSIL C321 - ESFL C324 - ML C329 - ECCL C336, C337, C338, C339 - ESIL
249-5	Fire - Small local fire in work area	Improper handling of flammable liquids leading to small fire	Flammable liquid handling	Work Control Documents include the requirements defined in the Chemical Safety Program to perform activities handling flammable liquids inside fume hoods whenever possible, and to limit the quantities of flammable liquids used in fume hoods.	AC	C213 - SPL C221 - PSIL C321 - ESFL C324 - ML C329 - ECCL C336, C337, C338, C339 - ESIL
249-6	Fire - Small local fire in work area	Improper handling of flammable liquids leading to small fire	Flammable liquid handling/Fire Detection System	Design Feature: Smoke detectors are provided in the labs to notify facility personnel to evacuate.	EA	C213 - SPL C221 - PSIL C321 - ESFL C324 - ML C329 - ECCL C336, C337, C338, C339 - ESIL
249-7	Fire - Small local fire in work area	Improper handling of flammable liquids leading to small fire	Flammable liquid handling/Fire Suppression System	Design Feature: The Facility Sprinkler System activates to extinguish fires.	EA	C213 - SPL C221 - PSIL C321 - ESFL C324 - ML C329 - ECCL C336, C337, C338, C339 - ESIL

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Risk ID Number	Accident Type	Scenario	System, Laboratory or Activity	Credited Controls (Control Types: EP - Engineered Passive, EA - Engineered Active, AC - Administrative Control)	Control Type	Applicable Location
151-1	Release with exposure	Release of nanomaterials to room (drop of container or spill)	Nanomaterial handling	Work control documents require that nanomaterials are transported in containers with sealed or taped lids.	AC	C321 - ESFL C331 - TSML C332 - TSPCL
151-2	Release with exposure	Release of nanomaterials to room (drop of container or spill)	Nanomaterial handling	Work control documents for nanomaterials shall include requirements for PPE to protect facility workers from exposure to nanomaterials during normal work or due to a dropped or spilled container.	AC	C321 - ESFL C331 - TSML C332 - TSPCL
151-3	Release with exposure	Release of nanomaterials to room (drop of container or spill)	Nanomaterial handling/ Laboratory Exhaust Ventilation	Design Feature: Nanomaterials are handled in enclosures with HEPA filtration on the exhaust system. If the use of an enclosure is not possible local exhaust with HEPA filtration is used.	EA	C321 - ESFL C331 - TSML C332 - TSPCL
151-4	Release with exposure	Release of nanomaterials to room (drop of container or spill)	Nanomaterial handling	LLP 6-1.46, *Chemical Safety*, complies with DOE/ NIOSH guidelines for safe handling of nanomaterials. Work Control Documents associated with nanomaterials will incorporate requirements in accordance with this LLP.	AC	C321 - ESFL C331 - TSML C332 - TSPCL
156-1	Equipment damage with injuries	Catastrophic rupture of high-pressure hydrogen storage vessel, caused by overpressure from compressor, back flow, temperature swings	House Hydrogen System	Design Feature: The House Hydrogen System is designed per the requirements of LLP 6-1.62, *Pressure Safety*, including ASME Pressure Vessel Code requirements.	EP	ESOTA

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Risk ID Number	Accident Type	Scenario	System, Laboratory or Activity	Credited Controls (Control Types: EP - Engineered Passive, EA - Engineered Active, AC - Administrative Control)	Control Type	Applicable Location
156-2	Equipment damage with injuries	Catastrophic rupture of high-pressure hydrogen storage vessel, caused by overpressure from compressor, back flow, temperature swings	House Hydrogen System	Work Control Documents for the House Hydrogen System define the required preventive maintenance requirements including monitoring the tanks for UV damage.	AC	ESOTA
156-3	Equipment damage with injuries	Catastrophic rupture of high-pressure hydrogen storage vessel, caused by overpressure from compressor, back flow, temperature swings	House Hydrogen	Work Control Documents for the House Hydrogen System define the requirements for filling the hydrogen storage tank to the desired pressure based on the outside temperature.	AC	ESOTA
156-4	Equipment damage with injuries	Catastrophic rupture of high-pressure hydrogen storage vessel, caused by overpressure from compressor, back flow, temperature swings	House Hydrogen System	Design Feature: The House Hydrogen System is designed and installed per the ICC and NFPA code requirements.	EP	ESOTA
156-5	Equipment damage with injuries	Catastrophic rupture of high-pressure hydrogen storage vessel, caused by overpressure from compressor, back flow, temperature swings	House Hydrogen System	Design Feature: Pressure relief devices are provided on the hydrogen storage vessels to protect against over-pressurization.	EA	ESOTA
156-6	Equipment damage with injuries	Catastrophic rupture of high-pressure hydrogen storage vessel, caused by overpressure from compressor, back flow, temperature swings	House Hydrogen System	Design Feature: The vent pipes from the pressure relief devices are raised vertically to release any hydrogen above people / property.	EP	ESOTA

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Risk ID Number	Accident Type	Scenario	System, Laboratory or Activity	Credited Controls (Control Types: EP - Engineered Passive, EA - Engineered Active, AC - Administrative Control)	Control Type	Applicable Location
156-7	Equipment damage with injuries	Catastrophic rupture of high-pressure hydrogen storage vessel, caused by overpressure from compressor, back flow, temperature swings	House Hydrogen System	Work Control Documents for the House Hydrogen System require isolation valves to pressure relief devices to be in the open position.	AC	ESOTA
156-8	Equipment damage with injuries	Catastrophic rupture of high-pressure hydrogen storage vessel, caused by overpressure from compressor, back flow, temperature swings	House Hydrogen System	Work Control Documents for the House Hydrogen System specify pressure relief device calibration frequencies and these requirements are incorporated in the preventive maintenance requirements for the system.	AC	ESOTA
156-9	Equipment damage with injuries	Catastrophic rupture of high-pressure hydrogen storage vessel, caused by overpressure from compressor, back flow, temperature swings	House Hydrogen System	Work Control Documents for the House Hydrogen System require restricted access to hydrogen tanks through a locked gate and also restrict personnel from being inside the gated area during certain activities.	AC	ESOTA
156-10	Equipment damage with injuries	Catastrophic rupture of high-pressure hydrogen storage vessel, caused by overpressure from compressor, back flow, temperature swings	House Hydrogen System	Design Feature: Check valves are installed on the House Hydrogen System to provide reverse flow protection.	EA	ESOTA
156-11	Equipment damage with injuries	Catastrophic rupture of high-pressure hydrogen storage vessel, caused by overpressure from compressor, back flow, temperature swings	House Hydrogen System	Design Feature: The high pressure hydrogen storage tanks are installed at the required separation from other facilities.	EP	ESOTA

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Risk ID Number	Accident Type	Scenario	System, Laboratory or Activity	Credited Controls (Control Types: EP - Engineered Passive, EA - Engineered Active, AC - Administrative Control)	Control Type	Applicable Location
170-1	Explosion - blast overpressure	Backflow of hydrogen from storage (outside the building) to ESIL (where hydrogen is generated/compressed) causing over pressure of piping or equipment with release.	House Hydrogen System	Design Feature: The hydrogen storage vessels are designed to meet the ASME Pressure Vessel Code.	EP	C341 - HPTC
170-2	Explosion - blast overpressure	Backflow of hydrogen from storage (outside the building) to ESIL (where hydrogen is generated/compressed) causing over pressure of piping or equipment with release.	House Hydrogen System	Design Feature: The hydrogen compressors are designed and installed according to ICC and NFPA code requirements.	EA	C341 - HPTC
170-3	Explosion - blast overpressure	Backflow of hydrogen from storage (outside the building) to ESIL (where hydrogen is generated/compressed) causing over pressure of piping or equipment with release.	House Hydrogen System	Design Feature: Pressure relief devices are provided on the House Hydrogen System to protect against over-pressurization.	EA	C341 - HPTC
170-4	Explosion - blast overpressure	Backflow of hydrogen from storage (outside the building) to ESIL (where hydrogen is generated/compressed) causing over pressure of piping or equipment with release.	House Hydrogen System	Design Feature: The vent pipes from the House Hydrogen System pressure relief devices are raised vertically to release any hydrogen above people / property.	EP	C341 - HPTC

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Risk ID Number	Accident Type	Scenario	System, Laboratory or Activity	Credited Controls (Control Types: EP - Engineered Passive, EA - Engineered Active, AC - Administrative Control)	Control Type	Applicable Location
170-5	Explosion - blast overpressure	Backflow of hydrogen from storage (outside the building) to ESIL (where hydrogen is generated/compressed) causing over pressure of piping or equipment with release.	House Hydrogen System	Work Control Documents for the House Hydrogen System require isolation valves to the pressure relief devices to be in the open position.	AC	C341 - HPTC
170-6	Explosion - blast overpressure	Backflow of hydrogen from storage (outside the building) to ESIL (where hydrogen is generated/compressed) causing over pressure of piping or equipment with release.	House Hydrogen System	Work Control Documents for the House Hydrogen System specify pressure relief device calibration frequencies and these requirements are incorporated in the preventive maintenance requirements for the system.	AC	C341 - HPTC
210-1	Fire	Hydrogen fire during vehicle filling because connection is not leak-tight	House Hydrogen System	Work Control Documents for the House Hydrogen System define requirements for the control of ignition sources in accordance with classification of the hydrogen station (C1D2 Group B).	AC	ESOTA
210-2	Fire	Hydrogen fire during vehicle filling because connection is not leak-tight	House Hydrogen System	Design Feature: EPA/NFPA safety standards for hydrogen refilling stations are incorporated into the hydrogen filling station design.	EA	ESOTA
210-3	Fire	Hydrogen fire during vehicle filling because connection is not leak-tight	House Hydrogen System	Design Feature: The hydrogen filling station is designed according to NFPA guidelines including the installation of pressure relief devices.	EA	ESOTA

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Risk ID Number	Accident Type	Scenario	System, Laboratory or Activity	Credited Controls (Control Types: EP - Engineered Passive, EA - Engineered Active, AC - Administrative Control)	Control Type	Applicable Location
210-4	Fire	Hydrogen fire during vehicle filling because connection is not leak-tight	House Hydrogen System	Work Control Documents for the House Hydrogen System specify pressure relief device calibration frequencies and these requirements are incorporated in the preventive maintenance requirements for the system.	AC	ESOTA
210-5	Fire	Hydrogen fire during vehicle filling because connection is not leak-tight	House Hydrogen System	Design Feature: The hydrogen filling station is located outside to allow ventilation and dispersion of any released hydrogen.	EP	ESOTA
210-6	Fire	Hydrogen fire during vehicle filling because connection is not leak-tight	House Hydrogen System	Design feature: A UV/IR camera is provided that covers the hydrogen dispensing area and will activate a shutoff valve if a hydrogen fire is detected.	EA	ESOTA
210-7	Fire	Hydrogen fire during vehicle filling because connection is not leak-tight	House Hydrogen System	Work Control Documents for the House Hydrogen System specify preventive maintenance requirements for the UV/IR camera and shut off valve.	AC	ESOTA
240-1	Fire Explosion - fire Exposure to high temperature	Grass fire heats hydrogen storage vessels, compressor, components, causing pressure relief valve to vent H_2 gas	House Hydrogen System	Work Control Documents for the House Hydrogen System define the requirements for the control of combustible materials around the vessel storage area.	AC	ESOTA

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Risk ID Number	Accident Type	Scenario	System, Laboratory or Activity	Credited Controls (Control Types: EP - Engineered Passive, EA - Engineered Active, AC - Administrative Control)	Control Type	Applicable Location
240-2	Fire Explosion - fire Exposure to high temperature	Grass fire heats hydrogen storage vessels, compressor, components, causing pressure relief valve to vent H_2 gas	House Hydrogen System	Design Feature: The hydrogen storage pad design is concrete to prevent a fire directly under a tank.	EP	ESOTA
240-3	Fire Explosion - fire Exposure to high temperature	Grass fire heats hydrogen storage vessels, compressor, components, causing pressure relief valve to vent H_2 gas	House Hydrogen System	Design Feature: Pressure relief devices are provided on the hydrogen storage vessels, piping, and other equipment.	EA	ESOTA
240-4	Fire Explosion - fire Exposure to high temperature	Grass fire heats hydrogen storage vessels, compressor, components, causing pressure relief valve to vent H_2 gas	House Hydrogen System	Design Feature: The vent pipes from the House Hydrogen System pressure relief devices are raised vertically to release any hydrogen above people / property.	EA	ESOTA
287-1	Equipment damage	Pressure or flow required by compressor is not provided resulting in compressor damage and/or release of hydrogen (closed valves, obstruction, failed pressure transmitter, etc.).	House Hydrogen System	Design Feature: The hydrogen control system has feedback on automated valves to alert the system of a failure (i.e., valve failing to open).	EA	ESOTA

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Risk ID Number	Accident Type	Scenario	System, Laboratory or Activity	Credited Controls (Control Types: EP - Engineered Passive, EA - Engineered Active, AC - Administrative Control)	Control Type	Applicable Location
287-2	Equipment damage	Pressure or flow required by compressor is not provided resulting in compressor damage and/or release of hydrogen (closed valves, obstruction, failed pressure transmitter, etc.).	House Hydrogen System	Work Control Documents for the House Hydrogen System specify preventive maintenance requirements for the automated valves and these requirements are incorporated in the preventive maintenance requirements for the system.	AC	ESOTA
287-3	Equipment damage	Pressure or flow required by compressor is not provided resulting in compressor damage and/or release of hydrogen (closed valves, obstruction, failed pressure transmitter, etc.).	House Hydrogen System	Design feature: the House Hydrogen System includes pressure transmitters that monitor and shutoff the hydrogen compressor.	EA	ESOTA
287-4	Equipment damage	Pressure or flow required by compressor is not provided resulting in compressor damage and/or release of hydrogen (closed valves, obstruction, failed pressure transmitter, etc.).	House Hydrogen System	Design Feature: The hydrogen compressor's supply pressure switch low cut off is interlocked with the compressor.	EA	ESOTA
294-1	Explosion - fire	Accidentally connect air or O_2 cylinder to H_2 system	House Hydrogen System	Design Feature: The standard design for gas bottles requires fittings for oxygen bottles and air bottles that are incompatible with hydrogen system connections.	EP	ESOTA

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Risk ID Number	Accident Type	Scenario	System, Laboratory or Activity	Credited Controls (Control Types: EP - Engineered Passive, EA - Engineered Active, AC - Administrative Control)	Control Type	Applicable Location
294-2	Explosion - fire	Accidentally connect air or O_2 cylinder to H_2 system	House Hydrogen System	Work Control Documents for the House Hydrogen System define the requirements and procedure for attaching gas bottles to the House Hydrogen System if on-site generated hydrogen is not used.	AC	ESOTA
189-1	Release	Spill, leak or open liquid nitrogen dewar	Nitrogen (House) System/ FCDTL	Design Feature: The oxygen detectors will alarm prior to achieving an oxygen deficient atmosphere.	EA	C323 - FCDTL
189-2	Release	Spill, leak or open liquid nitrogen dewar	Nitrogen (House) System/ FCDTL	Work Control Documents include PPE requirements in accordance with the Chemical Safety Program to protect workers from exposure due to spills or leaks.	AC	C323 - FCDTL
189-3	Release	Spill, leak or open liquid nitrogen dewar	Nitrogen (House) System/ FCDTL	Work Control Documents include requirements and procedures for correct handling to prevent spills, and procedures for cleaning up spills.	AC	C323 - FCDTL
189-4	Release	Spill, leak or open liquid nitrogen dewar	Nitrogen (House) System/ FCDTL/ Laboratory Supply Ventilation and Laboratory Exhaust Ventilation Systems	Design Feature: The Lab Ventilation Supply and Exhaust Systems provide adequate air change rate to remove released inert gas.	EA	C323 - FCDTL

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Risk ID Number	Accident Type	Scenario	System, Laboratory or Activity	Credited Controls (Control Types: EP - Engineered Passive, EA - Engineered Active, AC - Administrative Control)	Control Type	Applicable Location
189-5	Release	Spill, leak or open liquid nitrogen dewar	Nitrogen (House) System/ FCDTL	Design Feature: The size of the laboratories creates a large volume that will not be easily replaced with inert nitrogen in the event of a bottle spill.	EP	C323 - FCDTL
189-6	Release	Spill, leak or open liquid nitrogen dewar	Nitrogen (House) System/ FCDTL	Design Feature: Dewars are designed so that they will not tip over causing a spill. The material of construction for dewars prevents leaks.	EP	C323 - FCDTL
168-1	Equipment damage with injuries	Rupture of component in High Pressure Test Cell, media can be Water, Oil, Helium, Hydrogen or Nitrogen gas	High Pressure Test Cell	Design Features: The high pressure test bays are constructed with blowout panels to relieve pressure in the laboratories caused by an overpressure event or explosion. Areas in front of the panels are fenced for restricted access. The panels are located at an elevation to prevent introducing additional hazards to personnel in the area and are tethered to prevent them from going beyond the fenced area.	EP	C341 - HPTC C342 - HPTC
168-2	Equipment damage with injuries	Rupture of component in High Pressure Test Cell, media can be Water, Oil, Helium, Hydrogen or Nitrogen gas	High Pressure Test Cell	Design Feature: Shutoff valves and control components are located outside the high pressure test cells to prevent damage to these components during an event and to assure that hazards can be removed at the end of a test.	EP	C341 - HPTC C342 - HPTC
168-3	Equipment damage with injuries	Rupture of component in High Pressure Test Cell, media can be Water, Oil, Helium, Hydrogen or Nitrogen gas	High Pressure Test Cell/ Laboratory Exhaust Ventilation System	Design Feature: Duct work inside of the high pressure test cells is designed to handle expected pressures generated by a release. Additional exhaust duct work provides an additional means of venting to relieve pressure.	EP	C341 - HPTC C342 - HPTC

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Risk ID Number	Accident Type	Scenario	System, Laboratory or Activity	Credited Controls (Control Types: EP - Engineered Passive, EA - Engineered Active, AC - Administrative Control)	Control Type	Applicable Location
168-4	Equipment damage with injuries	Rupture of component in High Pressure Test Cell, media can be Water, Oil, Helium, Hydrogen or Nitrogen gas	High Pressure Test Cell	Design Feature: Ignition sources inside the high pressure test cells are controlled (designed, installed, and maintained) in accordance with the hazard classification of the test bays.	EP	C341 - HPTC C342 - HPTC
168-5	Equipment damage with injuries	Rupture of component in High Pressure Test Cell, media can be Water, Oil, Helium, Hydrogen or Nitrogen gas	High Pressure Test Cell/Gas Detection System/House Hydrogen	Design Feature: Hydrogen gas detection is provided inside the high pressure test cells.	EA	C341 - HPTC C342 - HPTC
168-6	Equipment damage with injuries	Rupture of component in High Pressure Test Cell, media can be Water, Oil, Helium, Hydrogen or Nitrogen gas	High Pressure Test Cell/Gas Detection System/House Hydrogen	Work Control Documents address the following test design requirements: experiments that require continuous hydrogen supply gas require design and installation of an automated valve that will shutoff of hydrogen supply to the test cells if hydrogen is detected.	AC	C341 - HPTC C342 - HPTC
168-7	Equipment damage with injuries	Rupture of component in High Pressure Test Cell, media can be Water, Oil, Helium, Hydrogen or Nitrogen gas	High Pressure Test Cell/Gas Detection System/ SCADA	Work Control Documents for the Gas Detection System in the high pressure test cells require an operable SCADA System or define compensatory measures if the SCADA System is not operable. (The high pressure test cells have hydrogen and oxygen detection reported via the SCADA so that personnel can confirm that the space has returned to acceptable conditions prior to entering the space. The SCADA System is only credited as an administrative control as design does not include any provisions beyond monitoring and remote operation requests.)	AC	C341 - HPTC C342 - HPTC

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Risk ID Number	Accident Type	Scenario	System, Laboratory or Activity	Credited Controls (Control Types: EP - Engineered Passive, EA - Engineered Active, AC - Administrative Control)	Control Type	Applicable Location
168-8	Equipment damage with injuries	Rupture of component in High Pressure Test Cell, media can be Water, Oil, Helium, Hydrogen or Nitrogen gas	High Pressure Test Cell	Design Feature: The walls of the high pressure test cells are designed to contain the pressure from the expansive gas and shrapnel from a failed component.	EP	C341 - HPTC C342 - HPTC
168-9	Equipment damage with injuries	Rupture of component in High Pressure Test Cell, media can be Water, Oil, Helium, Hydrogen or Nitrogen gas	High Pressure Test Cell	Work Control Documents for the high pressure test cells include requirements for inspection after a rupture event to assure that the strength of the walls has not been compromised.	AC	C341 - HPTC C342 - HPTC
168-10	Equipment damage with injuries	Rupture of component in High Pressure Test Cell, media can be Water, Oil, Helium, Hydrogen or Nitrogen gas	High Pressure Test Cell	Fencing and general security controls restrict access so that only trained personnel are allowed access into the area.	AC	C341 - HPTC C342 - HPTC
168-11	Equipment damage with injuries	Rupture of component in High Pressure Test Cell, media can be Water, Oil, Helium, Hydrogen or Nitrogen gas	High Pressure Test Cell	Work Control Documents for the high pressure test cells include setting limits for the testing media volume at 3.5L @15,000 psi.	AC	C341 - HPTC C342 - HPTC
168-12	Equipment damage with injuries	Rupture of component in High Pressure Test Cell, media can be Water, Oil, Helium, Hydrogen or Nitrogen gas	High Pressure Test Cell/ Laboratory Supply Ventilation and Laboratory Exhaust Ventilation Systems	Design Feature: The Laboratory Ventilation and Exhaust Systems provide an adequate air change rate to remove released gases.	EA	C341 - HPTC C342 - HPTC

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Risk ID Number	Accident Type	Scenario	System, Laboratory or Activity	Credited Controls (Control Types: EP - Engineered Passive, EA - Engineered Active, AC - Administrative Control)	Control Type	Applicable Location
247-1	Fire	Failure of power electronics board could causes fire and/or damage to laboratory fuel supply lines, resulting in a sustained fire	Electrical Characteriz-ation Laboratory	Design Feature: Code-compliant low resistance grounding of the test article reduces the heat generated during an event.	EP	C316, C317 - ECL
247-2	Fire	Failure of power electronics board could cause fire and/or damage to laboratory fuel supply lines resulting in a sustained fire	Electrical Characteriz-ation Laboratory	Work Control Documents define the process for elimination of residual flammable gases in fuel lines during testing.	AC	C316, C317 - ECL
247-3	Fire	Failure of power electronics board could cause fire and/or damage to laboratory fuel supply lines resulting in a sustained fire	Electrical Characteriz-ation Laboratory	Design Feature: Fuel shut-off valves are located outside laboratories that contain fuel lines.	EA	C316, C317 - ECL
247-4	Fire	Failure of power electronics board could cause fire and/or damage to laboratory fuel supply lines resulting in a sustained fire	Electrical Characteriz-ation Laboratory	Work control documents address the following test design requirement: Power electronics must be in a robust enclosure when being surge tested.	EP	C316, C317 - ECL

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Risk ID Number	Accident Type	Scenario	System, Laboratory or Activity	Credited Controls (Control Types: EP - Engineered Passive, EA - Engineered Active, AC - Administrative Control)	Control Type	Applicable Location
247-5	Fire	Failure of power electronics board could cause fire and/or damage to laboratory fuel supply lines resulting in a sustained fire	Electrical Characteriz-ation Laboratory	Work control documents require that articles being tested, that have the potential to produce shrapnel, have a restricted access zone around them.	AC	C316, C317 - ECL
247-6	Fire	Failure of power electronics board could cause fire and/or damage to laboratory fuel supply lines resulting in a sustained fire	Electrical Characteriz-ation Laboratory	Articles being tested, that have the potential to produce shrapnel, are required to have physical barriers to protect piping from shrapnel.	EP	C316, C317 - ECL
238-1	Spill	Spill of fuel collects in below grade trenches	Low Voltage Outdoor Test Area	Work Control Documents require inspection of fuel tanks and inspection and tagging of electrical equipment before use.	AC	LVOTA
238-2	Spill	Spill of fuel collects in below grade trenches	Low Voltage Outdoor Test Area	Work Control Documents define the spill prevention measures required when refueling equipment in the LVOTA.	AC	LVOTA
238-3	Spill	Spill of fuel collects in below grade trenches	Low Voltage Outdoor Test Area	Work Control Documents require that a spill cart be provided at the LVOTA.	AC	LVOTA
238-4	Spill	Spill of fuel collects in below grade trenches	Low Voltage Outdoor Test Area	Only Department of Transportation (DOT)-approved fuel tanks, 50 gallon maximum capacity, are to be supplied with equipment.	EP	LVOTA

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Risk ID Number	Accident Type	Scenario	System, Laboratory or Activity	Credited Controls (Control Types: EP - Engineered Passive, EA - Engineered Active, AC - Administrative Control)	Control Type	Applicable Location
235-1	Release with exposure	Exposure to toxic gas	Laboratory Supply Ventilation and Laboratory Exhaust Ventilation Systems	Design Feature: The Laboratory Supply and Exhaust Ventilation Systems provide an adequate air exchange rate to remove toxic gases.	EA	C221 - PSIL
235-2	Release with exposure	Exposure to toxic gas	Gas Detection System	Design Feature: Toxic gas monitoring equipment is provided in laboratories used to test combustion engines. The equipment will alarm to alert personnel of a potential release.	EA	C221 - PSIL
235-3	Release with exposure	Exposure to toxic gas	Laboratory Exhaust Ventilation System	Design Feature: The Laboratory Exhaust Ventilation System provides the capability to connect to vehicle/DUT exhaust.	EA	C221 - PSIL
235-4	Release with exposure	Exposure to toxic gas	Laboratory Exhaust Ventilation System	Design Feature: The design of laboratories provides a large space relative to the exhaust rate. (This reduces the likelihood that toxic gas levels can be reached due to a leak, failure of vent system, or failure to connect the vent to the exhaust.)	EP	C221 - PSIL
213-1	Exposure to high temperature Fire - small local fire in work area	Burns from exposure to release of heat transfer and small local fire	Thermal Storage Process Components Laboratory	Heat transfer fluid boilers must be supplied with a pressure relief device and an enclosure (i.e., spray shield) that would minimize the spray of the heated fluid from failed components.	EA	C332 - TSPCL

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Risk ID Number	Accident Type	Scenario	System, Laboratory or Activity	Credited Controls (Control Types: EP - Engineered Passive, EA - Engineered Active, AC - Administrative Control)	Control Type	Applicable Location
213-2	Exposure to high temperature Fire - small local fire in work area	Burns from exposure to release of heat transfer and small local fire	Thermal Storage Process Components Laboratory	Work Control Documents address the use of appropriate materials that can withstand high temperature testing of corrosive materials.	AC	C332 - TSPCL
213-3	Exposure to high temperature Fire - small local fire in work area	Burns from exposure to release of heat transfer and small local fire	Thermal Storage Process Components Laboratory	Work Control Documents define the PPE requirements when working with thermal testing equipment.	AC	C332 - TSPCL
213-4	Exposure to high temperature Fire - small local fire in work area	Burns from exposure to release of heat transfer and small local fire	Thermal Storage Process Components Laboratory/ Fire Detection System	Design Feature: The Fire Detection System will detect a significant release and alarm, alerting personnel to evacuate.	EA	C332 - TSPCL
213-5	Exposure to high temperature Fire - small local fire in work area	Burns from exposure to release of heat transfer and small local fire	Thermal Storage Process Components Laboratory/ Fire Suppression System	Design Feature: Hot vapors or fire will activate the Fire Suppression System and alarm, alerting personnel to evacuate.	EA	C332 - TSPCL

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Risk ID Number	Accident Type	Scenario	System, Laboratory or Activity	Credited Controls (Control Types: EP - Engineered Passive, EA - Engineered Active, AC - Administrative Control)	Control Type	Applicable Location
205-1	Electric shock or arc flash	AC Ground Faults (phase to ground or phase to phase) due to insulation breakdown, mis-wiring, physical damage or equipment failure	REDB System	Design Feature: REDB breakers provide industry standard overcurrent protection.	EA	MVOTA C213 - SPL C220 - OCL C221 - PSIL C2243, C225 - REDB Rooms C316, C317 - ECL C323 - FCDTL C325 - ESL C336, C337, C338, C339 - ESIL LVOTA RTA
205-2	Electric shock or arc flash	AC Ground Faults (phase to ground or phase to phase) due to insulation breakdown, mis-wiring, physical damage or equipment failure	REDB System	Design Feature: Design and installation of the REDB is per the NEC.	EP	MVOTA C213 - SPL C220 - OCL C221 - PSIL C2243, C225 - REDB Rooms C316, C317 - ECL C323 - FCDTL C325 - ESL C336, C337, C338, C339 - ESIL LVOTA RTA

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Risk ID Number	Accident Type	Scenario	System, Laboratory or Activity	Credited Controls (Control Types: EP - Engineered Passive, EA - Engineered Active, AC - Administrative Control)	Control Type	Applicable Location
205-4	Electric shock or arc flash	AC Ground Faults (phase to ground or phase to phase) due to insulation breakdown, mis-wiring, physical damage or equipment failure	REDB/SCADA System	Design Feature: SCADA provides remote indication and operation of critical components. (SCADA is only credited as an administrative control for this area as design does not include any provisions beyond component status and remote operation requests.)	EA	MVOTA C213 - SPL C220 - OCL C221 - PSIL C2243, C225 - REDB Rooms C316, C317 - ECL C323 - FCDTL C325 - ESL C336, C337, C338, C339 - ESIL LVOTA RTA

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Policies and Laboratory-Level Procedures

The following policies and laboratory-level procedures are referenced in this *Hazard Analysis Review*. The most current versions are available at http://thesource.nrel.gov/rm/procedures.html.

- 2-3.1, Quality Management Program
- 2-3.2, Nonconforming Items including Suspect and Counterfeit
- 2-3.10, Assessments
- 3-5, Records Management
- 3-5.2, Management of Active and Inactive Records
- 4-8, Conduct of Research and Analysis
- 6-1, Integrated Safety Management and Environmental Management
- 6-1.4, Environmental, Health, and Safety Training
- 6-1.5, Integrated Safety Management and Environmental Management Systems
- 6-1.36, Fire Protection
- 6-1.46, Chemical Safety
- 6-1.47, Compressed Gas Safety
- 6-1.48, Local Exhaust Ventilation
- 6-1.54, Electrical Safety
- 6-1.55, Lockout/Tagout
- 6-1.56, Hoisting and Rigging
- 6-1.62, Pressure Safety
- 6-6.2, Hazard Identification and Control
- 6-6.5, Safe Work Permits
- 8-3, Configuration Management
- 8-6.1, Safe Conduct of Operations
- 8-11, Site Maintenance
- 8-11.3, Site Maintenance Program
- 10-1.2, Purchase Requests

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