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Managing EHS of PV-Related Equipment at the National Renewable Energy Laboratory

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Abstract — **Managing environment, health, and safety (EHS) risks at a national laboratory, or university, can be intimidating to a researcher who is focused on research results. Laboratory research and development (R&D) operations are often driven by scientists with limited engineering support and lack well-refined equipment development resources. To add to the burden for a researcher, there is a plethora of codes, standards, and regulations that govern the safe installation and operation of photovoltaic-related R&D equipment—especially those involving hazardous production materials. To help guide the researcher through the vast list of requirements, the EHS office at NREL has taken a variety of steps. Organizationally, the office has developed hazard-specific laboratory-level procedures to govern particular activities. These procedures are a distillation of appropriate international codes, fire agencies, SEMI standards, U.S. Department of Energy orders, and other industry standards to those necessary and sufficient to govern the safe operation of a given activity. The EHS office works proactively with researchers after a concept for a new R&D capability is conceived to help guide the safe design, acquisition, installation, and operation of the equipment. It starts with a safety assessment at the early stages such that requirements are implemented to determine the level of risk and degree of complexity presented by the activity so appropriate controls can be put in place to manage the risk. As the equipment requirements and design are refined, appropriate equipment standards are applied. Before the "to-build" specifications are finalized, a process hazard analysis is performed to ensure that no single-point failure presents an unacceptable risk. Finally, as the tool goes through construction and installation stages, reviews are performed at logical times to ensure that the requisite engineering controls and design are in place and operational. Authorization to operate is not given until adherence to these requirements is fully verified and documented. Operations continue under the conditions defined through this process and are reviewed with changing processes.**

Index Terms — **Environment, safety, and health (ESH); NREL, management, codes, standards, hazardous production materials, operations.**

I. Introduction

Managing environment, safety, and health (EHS) risks at a national laboratory, or university, can be different in many aspects than doing so at a manufacturing facility. The biggest difference is that at a national laboratory, there are many chemicals but of generally small quantities, whereas a given manufacturing facility has much fewer chemicals but in much larger quantities. A typical national laboratory (and many universities) will have chemicals in virtually all of the hazard classes—e.g., highly toxic, toxic, pyrophoric, corrosive, flammable—in both liquid and gaseous states, as well as solids with these hazards. Having a large number of chemicals invokes multiple codes and regulations that can often be complex and confusing to scientists and engineers, and therefore, makes compliance challenging.

Another difference between industrial processes and those at research laboratories is the degree to which various aspects of the process are compartmentalized. For example, in an industrial operation using hazardous gases, the gas vendor often installs cylinders and the gas-handling manifold may even be leased from the vendor. Process engineers and technicians operate the deposition equipment. The abatement system may be centralized for the facility and operated and maintained by facilities staff. In contrast, at a national laboratory, the group "owning" the experiment often is responsible for the sources, plumbing, tool, and abatement systems. The equipment itself is also quite different in terms of size and purpose. Industrial tools are often commercially fabricated, highly automated, and integrated with other tools to achieve high throughput on a continuous basis. National laboratory and university tools are often custom (or "one-off's), manually operated (or less automated than industry), and standalone to obtain answers to specific technological questions and operated on an intermittent schedule. EHS professionals need to be recruited with a broad background of experience or from industries that are similar to photovoltaics (PV). EHS professionals who come from a focused industry often find this broad range of hazards a challenge to manage.

EHS professionals who come into the PV community from the semiconductor industry also find some differences in a much less industrially mature technology. Due to decades of roadmapping and standardization [1] efforts, the semiconductor industry is the most sophisticated industry in existence [2]. Many of the processes are similar from one company to the next, although the specific application of those processes may vary. In the PV industry, processes can be quite different from one company to the next, even within the same PV technology. Each generation of semiconductor equipment is designed to move silicon wafers of the same form factor. The PV industry has many materials—glass, wafers, and foils—in a wide variety of form factors. The goal of semiconductor manufacturing is to create more circuits on smaller and smaller dies. The goal of the PV industry is to cover larger and larger areas at lower and lower cost. The available semiconductor standards and roadmaps do not necessarily apply to the PV industry. R&D endeavors have even fewer equipment standards, so it is essential to guide activities using those that are necessary and sufficient, accompanied by appropriate risk analysis.

II. SAFE HPM EQUIPMENT FUNCTIONALIZATION

To guide researchers through the vast array of codes and standards, the EHS office at NREL works proactively with the researchers to safely bring new capabilities on line, as summarized in Table 1. Once a new research need is defined, and a general idea of the equipment needed to perform that work is mapped out, the EHS office works with the researcher to define the specific EHS controls necessary to perform that work safely. Depending on the hazards presented by the operation, the controls can range from following a procedure in an equipment manual to writing a process-specific safe operating procedure to documenting that the equipment is in compliance with existing hazard-specific laboratory-level procedures (a process called a readiness verification) to a very detailed operational readiness review (ORR). Operations using hazardous production materials (HPMs) [3] require the most stringent shepherding through the various stages to bring the equipment on line.

Table 1. Stages of HPM Equipment Development

Researchers	Vendor	EHS Support
Define research need		
Concept specifications	Consult on possibilities	Hazard analysis
Design revisions	Budgetary quotations	Equipment standards
Purchasing process	Provide bid	
"To-build" specifications	Finalize contract	Process hazard analysis
Site facilitation	Equipment fabrication	
	Vendor acceptance	Tool-specific ORR inspection
	Delivery to site	
Hook up utilities		Stage 1 ORR
Test with power and inert gases		Stage 2 ORR
Observed operation		Stage 3 ORR
Fully operate		

The equipment design revision stage involves bringing all appropriate parties to the table to minimize roadblocks further down the development cycle. In addition to researcher technical reviews, potential vendors might be consulted to offer input into what capabilities are possible, site operations personnel are consulted to ensure facility capacity, contracts and business services are made aware of what is coming to give tips on how various acquisitions can best be put through the contractual system, and the legal office may be consulted, especially if intellectual property is involved. It is at this point that the EHS office helps with providing EHS-specific equipment standards to ensure that the equipment will be properly designed from the beginning. Most research laboratories do not get SEMI-S2 [1] fully compliant equipment for two main reasons: cost, and because R&D equipment tends to be unique and making the first version of a piece of equipment fully S2-compliant is exceedingly difficult, resulting in significant delays. These equipment specifications are constantly evolving to ensure that those that are necessary and sufficient are required, while best practices are recommended based on the risk and cost-benefit considerations. It is advisable to separate EHS requirements into what is required by the vendor and what is required to be in place in the laboratory so that the vendor has clarity on responsibility. The specifications are closely coupled to the ORR requirements, as described below, to ensure that reviewers and those constructing and installing equipment are focused on the same elements. The equipment design revision stage is usually an iterative process because researchers typically begin with a very large scope and reduce the scope as available budgets are evaluated relative to early budgetary quotations that are usually larger than expected.

Once a final set of specifications is achieved, the purchasing process begins, which ultimately, if not painfully, leads to a contract with an equipment supplier. Because the potential vendors cannot invest enough time into the bid process to look at every detail of the equipment fabrication, it is typical that a phase of clarification occurs, leading to an agreement between the researcher and the vendor on the final "to-build" specifications and drawings. The EHS office works proactively with the researcher to ensure that the equipment will safely perform as requested.. At this stage, a process hazard analysis (PHA) is performed to ensure that no single-point component failure causes an unacceptable risk. It is best that the PHA occurs before equipment is assembled to avoid costly change orders.

The next two stages are parallel activities. The equipment vendor starts fabrication. Once enough is known about the specific facility requirements of the equipment, the researcher—along with site operations (facilities) and EHS consultation—starts readying the facility for the equipment installation so that everything is ready to hook up to the equipment upon its arrival. The researchers, along with other appropriate parties, monitor the equipment fabrication to ensure that it is constructed to the specifications. This is done through frequent emails, phone calls, and teleconferences to exchange documents and pictures, ensuring that the research needs are being implemented by the vendor. Researchers who dedicate significant effort to managing this communication get a better product in the end. Those who just place an order and trust that the vendor can understand all the technical nuances of their needs as they construct the tool can be surprised with non-compliance issues at later stages.

It is best that at least two vendor site visits are scheduled, with the first when things are far enough along that the equipment can be inspected to ensure things are headed in the right direction to meet specifications. This includes looking at the general footprint, how the tool will interface with building and specialty utilities (to help ready the facility for eventual arrival), quality of components, and discuss technical detail of final construction face-to-face. Once the equipment is able to be tested at the vendor location, a vendor site acceptance test occurs. This is where the researcher ensures that the equipment performs the desired technical functions and the

equipment is evaluated to ensure the EHS requirements are in place. It is recommended that at least two people make this trip to divide up the responsibility for areas of inspection (e.g., one looking at performance items and the other looking at EHS items). It is prudent to make this a formal and strict process. The vendor has a much stronger incentive to fix deficiencies while it is on their site (because they want to get the equipment out of their plant) than they do once it ships to the final location. Once the equipment is performing technically and safely at the vendor location, it is shipped to NREL.

Because these systems are complicated and often require being hooked up to a variety of utilities (e.g., cooling water, power, house gases, specialty gases, ventilation, monitoring equipment), the ORR process is phased over three equipment installation stages.

The first ORR stage is to ensure that the tool can be safely hooked up to the non-HPM utilities and then properly installed. HPM utilities (e.g., toxic, pyrophoric, flammable delivery systems) can be installed, but no HPM sources can be installed. Once these hook-ups are complete, the ORR process documents that the requirements to do equipment testing are in place. The next stage is putting the equipment through operational testing with power and inert gases. This is where many bugs and loose ends are resolved. The ORR process documents that the requirements to admit HPMs into the equipment are in place and that there is nothing outstanding that presents an undo risk. Complex equipment, or operations intended for multiple shifts, are required to start up under closely observed conditions and demonstrate safe operation before being allowed to fully operate. The entire ORR usually consists of two to three dozen checklists of requirements (see Table 2), depending on the complexity of the process, where requirements are matched commensurately to the hazard present. These checklists are closely matched to equipment design standards.

Any non-conforming items receive a risk analysis [4], as summarized in Figure 1. The risk of nonconformity is related to both the probability a particular event (failure) occurring and the consequences of that event occurring. NREL only accepts operations that present low or routine risks.

The intersection of the probability of occurrence and the consequences provides the level of risk. In other words, something with a relatively large consequence could have a low level of risk if the probability of occurrence is low due to adequate and redundant engineering controls. Research laboratories tend to have lower event consequences than manufacturing facilities due to having lower quantities of materials. However, they also tend to have a larger number of chemicals, so the probability of occurrence may increase due to the statistics of large numbers. Engineering controls (e.g., exhausted enclosures) help reduce the risk by lowering the event consequences and administrative controls (e.g., chemical reduction programs) help reduce the risk by lowering the probability of occurrence.

A generalized approach is used to assign values to both the probability of occurrence and the consequences of an event because specific data for formal fault-tree analysis is often difficult to obtain. Sometimes there is a conflict between protecting the safety of workers and protecting the environment. A similar methodology is used to strike the proper balance of risk between these cases.

Table 2. Checklists in the NREL ORR Documentation

Code	Requirement Checklist
1.a	HPM Gas Distribution Systems
1.b	General Gas Requirements
2.a	Pyrophoric Liquids and Solids Distribution
2.b	Highly Toxic Liquid and Solid Distribution
2.c	Cryogenic Liquid Distribution
3.a	Reaction Vessels and/or Chambers
3.b	Guarding
3.c	Electrical Design
3.d	Safety Interlocks
3.e	Fire Protection
3.f	Mechanical Design
3.g	Automated Material Handlers (robotics)
3.h	Lasers
4.a	Effluent Removal Systems
5.a	Safe Operating Procedures
5.b	Required Documentation
5.c	Warning Signs and Labels
5.d	Emergency Shutdown
5.e	Hazardous Energy Isolation
6.a	Exhaust Systems
6.b	Gas Cylinder Cabinets
6.c	General Lab Readiness Issues
7.a	Monitoring Room & Interlocks
7.b	Hydride Gas Monitor
7.c	Hydrogen Monitoring
7.d	Corrosive Gas Monitoring
8.a	Environmental Protection
9.a	Operator Training
9.b	General Ergonomics
9.c	Seated Workstation Ergonomics
9.d	Standing Workstation Ergonomics
9.e	System Specific Requirements

III. SUMMARY

This process, although seemingly confining, has proven to be effective at brining HPM operations on line in a manner that reduces change orders and redesigns late in development and ensures the safe installation, operation, and disposal of HPMs.

This paper focused on acquiring new equipment through a rigorous process that ensures performance and safety without undue delays. However, there are additional EHS issues that arise from aging equipment and facilities. Quarterly safety inspections are performed to “put eyes on the equipment” to ensure systems and practices put into place at tool installation are still in place. New risk analysis is performed in some cases as aging equipment raises the probability of failure. One area we are currently evaluating is necessary requirements for

replacing specific HPM distribution components that have been in service for more than 10 years.

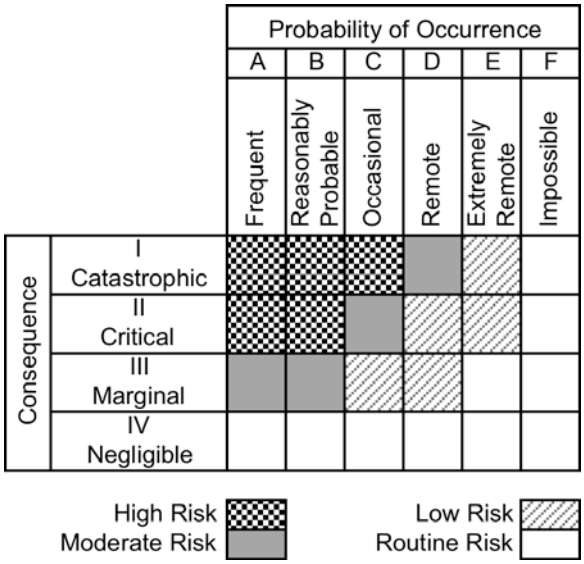

Fig. 1. Risk Assessment Matrix: Operations must receive engineering controls so they present Low or Moderate Risk.

Table 3. Event Probability Classification Table: Probability the event will occur in a given year.

Level	Annual Probability	Description of the Probability Level
A	Frequent (> 1.0)	Likely to occur many times during the life cycle of the system (test/activity/operation)
B	Reasonably probable (0.1 to 1.0)	Likely to occur several times during the life cycle of the system
C	Occasional (0.01 to 0.1)	Likely to occur sometime during the life cycle of the system
D	Remote (10^{-4} to 10^{-2})	Not likely to occur in the life cycle of the system, but possible
E	Extremely remote (10^{-6} to 10^{-4})	Probability of occurrence cannot be distinguished from zero
F	Improbable (< 10^{-6})	Physically impossible to occur

Table 4. Hazard Consequence Classification Table

Category	Description (Est. $ Lost)	Potential Consequences
I	Catastrophic (equipment loss > $1,000,000)	May cause death or system loss
II	Critical ($100,000 to $1,000,000)	May cause severe injury or occupational illness, or minor system damage
III	Marginal ($10,000 to $100,000)	May cause minor injury or occupational illness, or minor system damage
IV	Negligible (< $10,000)	Will not result in injury, occupational illness, or system damage

ACKNOWLEDGEMENT

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REFERENCES

[1] SEMI Standards can be obtained from http://www.semi.org/en/store/P001204

[2] Editors, "The top ten most significant advances in materials science over the last 50 years," *Materials Today*, Oxford, UK, December 18, 2007

[3] HPMs are defined as a solid, liquid, or gas that has a degree-of-hazard rating in health, flammability, or reactivity of Class 3 or 4 and that is used directly in research, laboratory, or production processes with nonhazardous end products.

[4] Moskowitz, P.D.; Fthenakis, V.M.; Crandall, R.S.; Nelson, B.P., "Analyzing risks associated with hazardous production materials," *Solid State Technology*. **37**(7), July 1994; pp. 121–129. Acc No. 15942.