Reliability Evaluation of PV Power Plants:
Input Data for Warranty, Bankability and Energy Estimation Models

ARIZONA STATE UNIVERSITY
PHOTOVOLTAIC RELIABILITY LABORATORY

G. TamizhMani (Mani); manit@asu.edu

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- Thanks to the SRP-R&D team and Bill Kazeta for the technical support!
- Thanks to SRP and DOE/SERIIUS for the funding support!

- This presentation material is based on two MS theses (available for free downloading at: repository.asu.edu)

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Focus of this Presentation

Bankability of solar PV projects involves a 5-step process:

1. Site Assessment (SA)
2. Design Optimization (DO)
3. Component Procurement (CP)
4. Installation & Commissioning (IC)
5. **Operation & Maintenance (O&M)**

Focus of this Presentation

From PV module perspective:

Operation ~ **degradation rate**
Maintenance ~ **Failure rate**

} Used to calculate production generation risk

Production generation risk can be calculated if **DEFINED METRICS** for the degradation and failure rates are available. The focus of this presentation is to define the metrics and apply these defined metrics on the field measured data so they **can be used for warranty insurance, bankability and energy estimation calculations**.

Presentation Outline

- Importance to stakeholders
  - Reliability evaluations in the field
- METRIC definitions (from users perspectives)
  - Safety failures, reliability failures and durability/degradation losses
- Application of definitions in field evaluation
  - Quantitative determination of safety failures, reliability failures and degradation rates of aged PV power plants
- Application of the defined metrics on data processing
  - Failure and degradation modes and rates
  - Distribution between safety failures, reliability failures and degradation rates
  - Soiling losses *(see the poster for details)*
- Conclusions

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PV Power Plant Evaluation: O&M

Project Developer Perspective:

To secure low interest loan without risk premium adders. There are three risk premium adders.

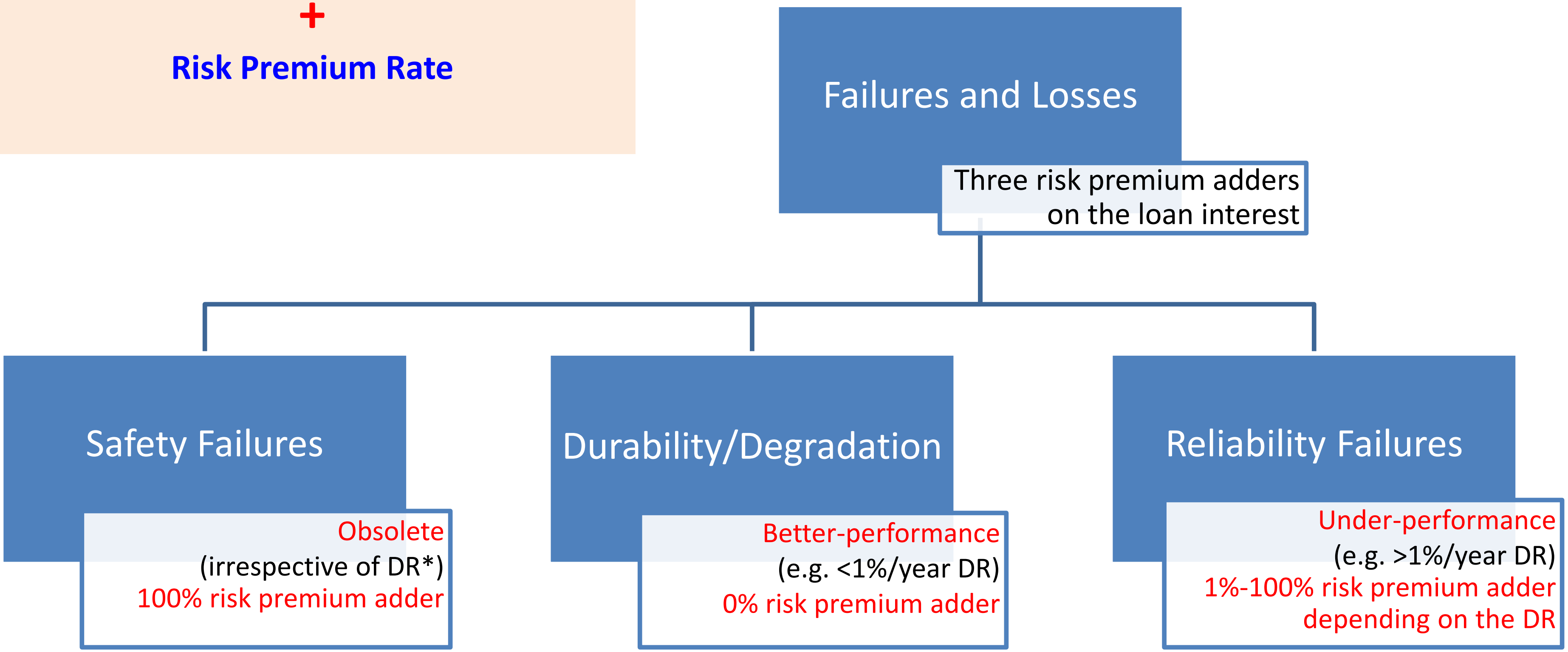
Interest Rate

=

Interest Rate @ Zero Risk

+

Risk Premium Rate



*DR = Degradation Rate

Source: ASU Photovoltaic Reliability Laboratory (ASU-PRL)

Goal: Number of modules which will have safety and reliability risks needs to be determined

PV Power Plant Evaluation: Importance to Stakeholders

Repairing or Decommissioning Decision Perspective:
To decommission the power plant when annual kWh generation declines below an acceptable level. The kWh value is dictated by three factors: safety failures over time, reliability failures over time and degradation loss over time.

kWh

is dictated by

- **Safety failures (SF) over time**
  (obsolete; qualifies for warranty returns)
- **Durability/Degradation loss (DL) over time**
  (better-performance; <1%/year degradation; does not qualify for warranty claims)
- **Reliability failures (RF) over time**
  (under-performance; >1%/year degradation; qualifies for warranty claims)

Goal: Number of modules which do not effectively contribute to kWh generation needs to be determined

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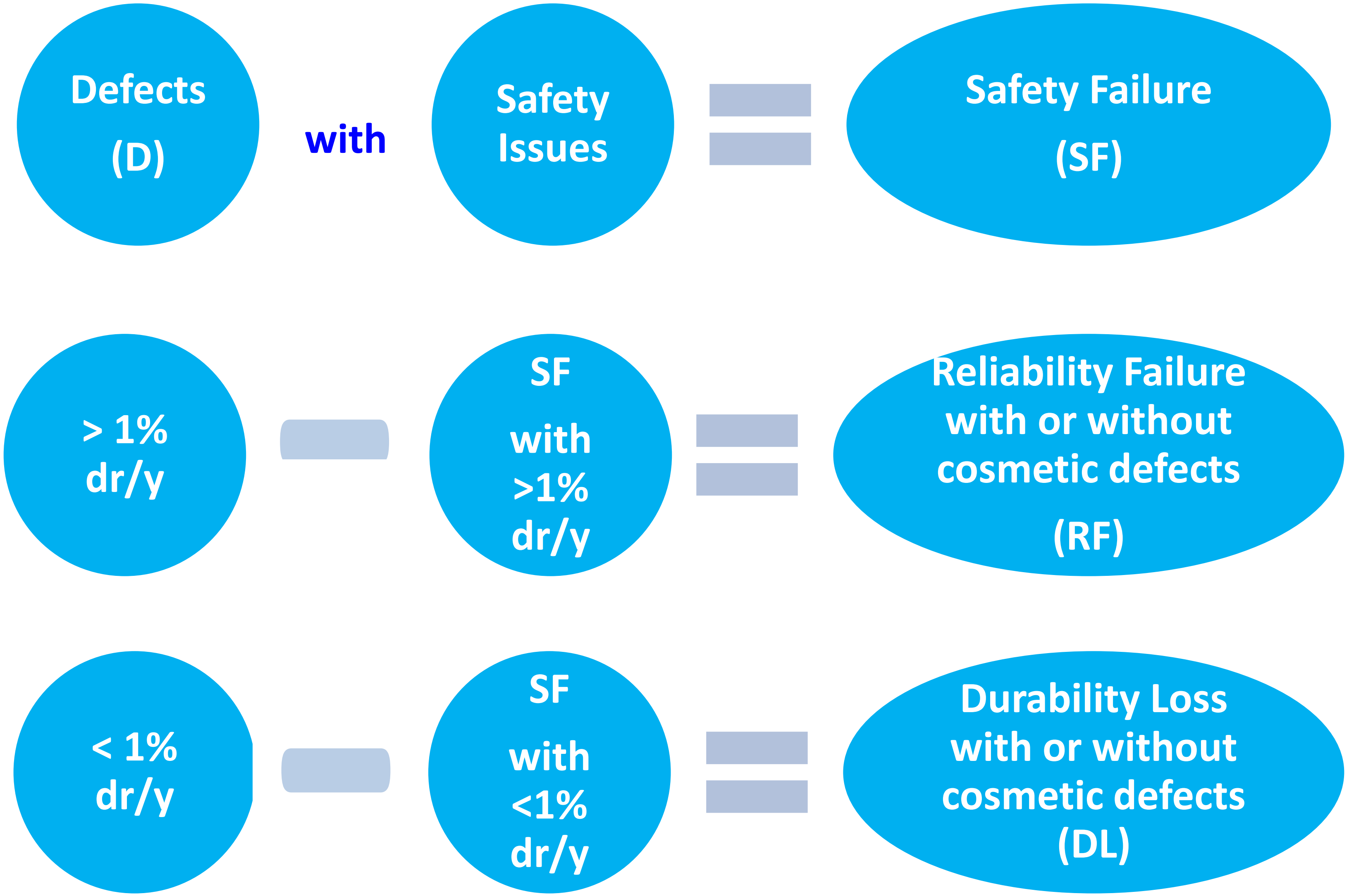
ASU-PRL's METRIC Definition of Failures and Degradation



SF = Safety Failure (Qualifies for safety returns)

RF = Reliability Failure (Qualifies for warranty claims)

DL = Durability Loss with or without Cosmetic Defects (Does not qualify for warranty claims)

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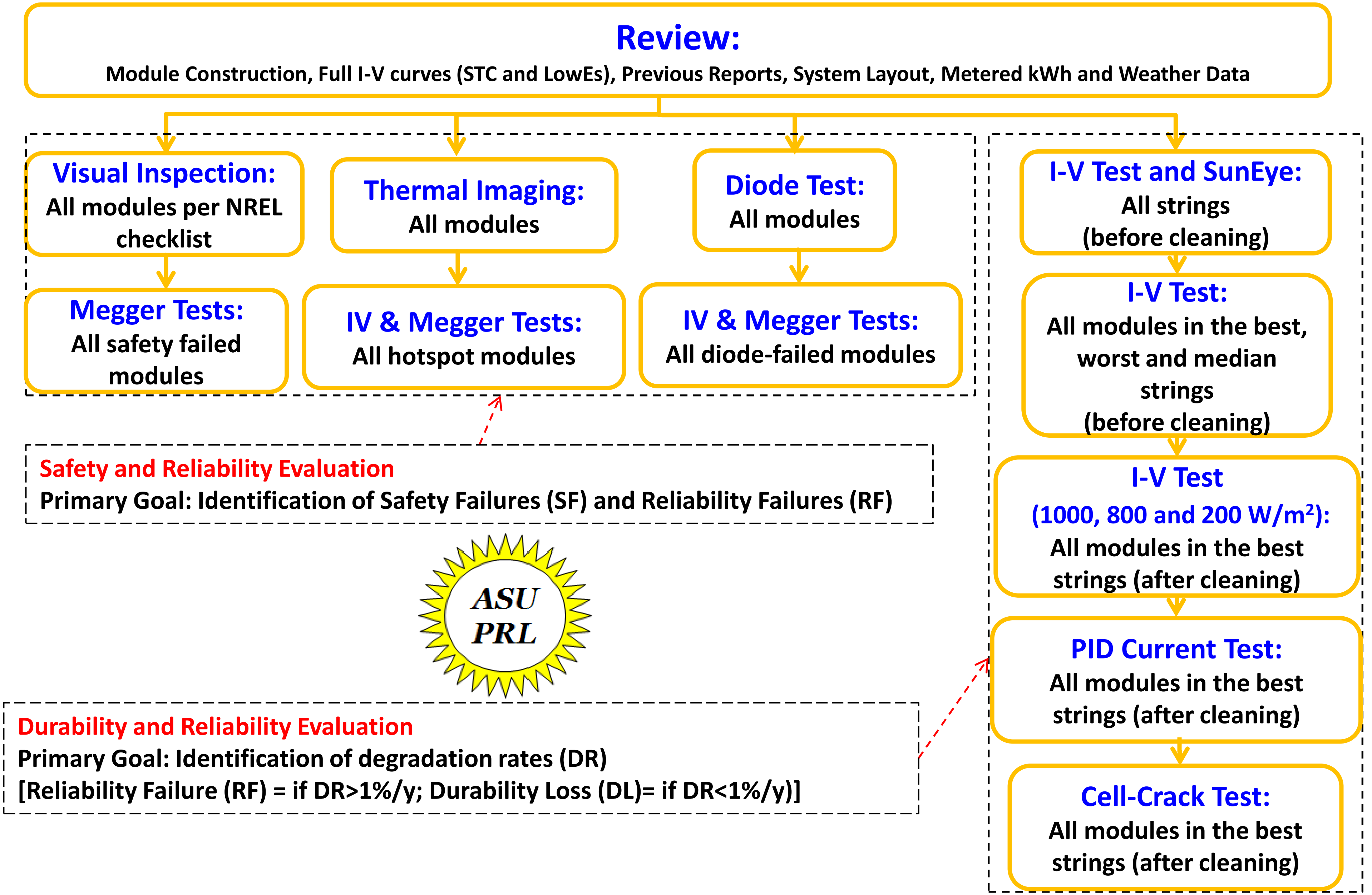
- Conclusions

Field Evaluation of PV Modules:

Application of ASU-PRL's Definitions on Field Failures and Degradation Determinations



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  - Distribution between safety failures, reliability failures and degradation rates
  - Soiling losses *(not presented here; see the poster for details)*
- Conclusions

Four PV Plants Evaluated

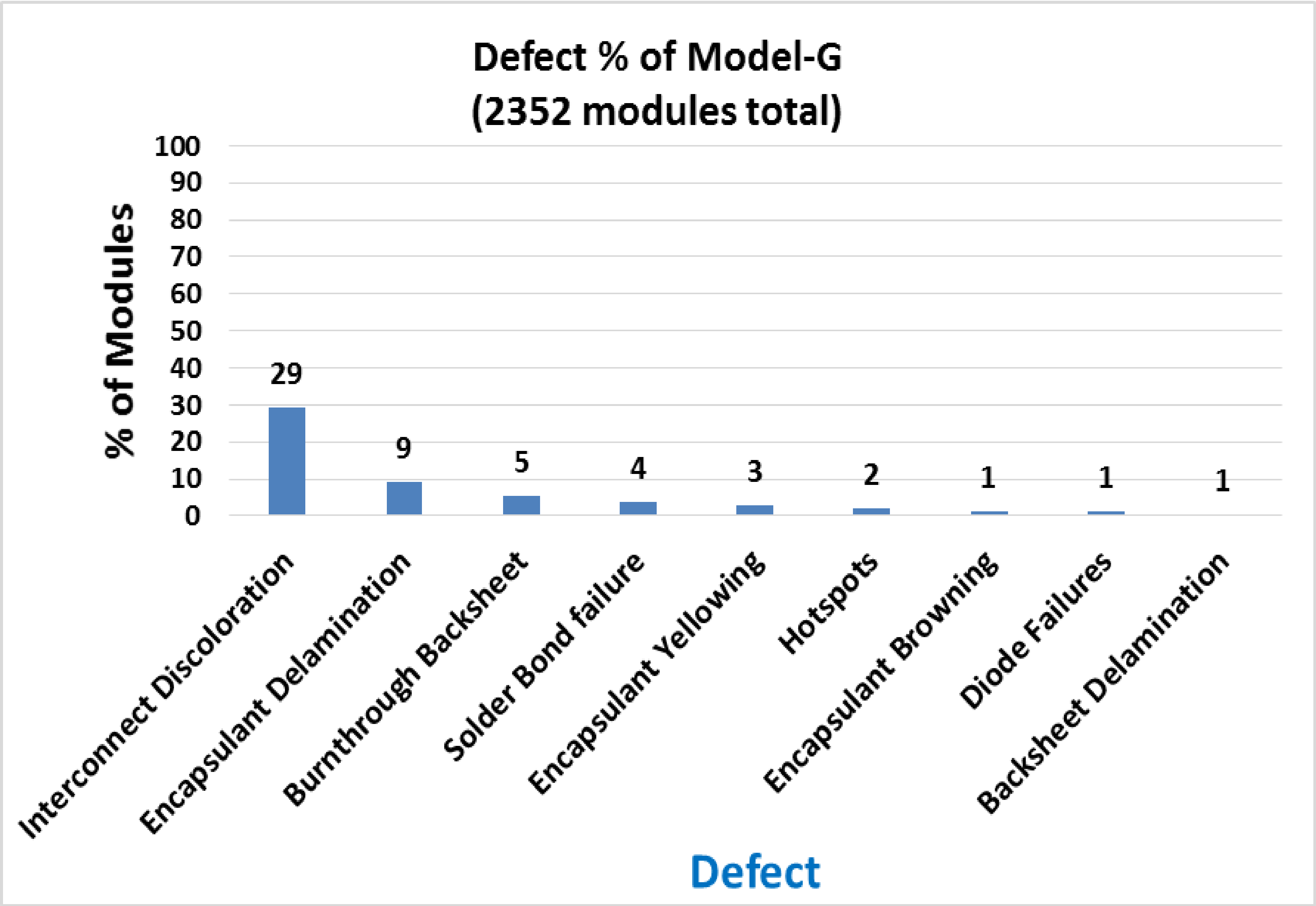
Hot-Dry Desert Climate

Four PV Power Plants Evaluated *(mono-Si; Glass/Polymer; 6656 modules)*

- **Due to time limitation, only one plant (Model G) data is presented here.**

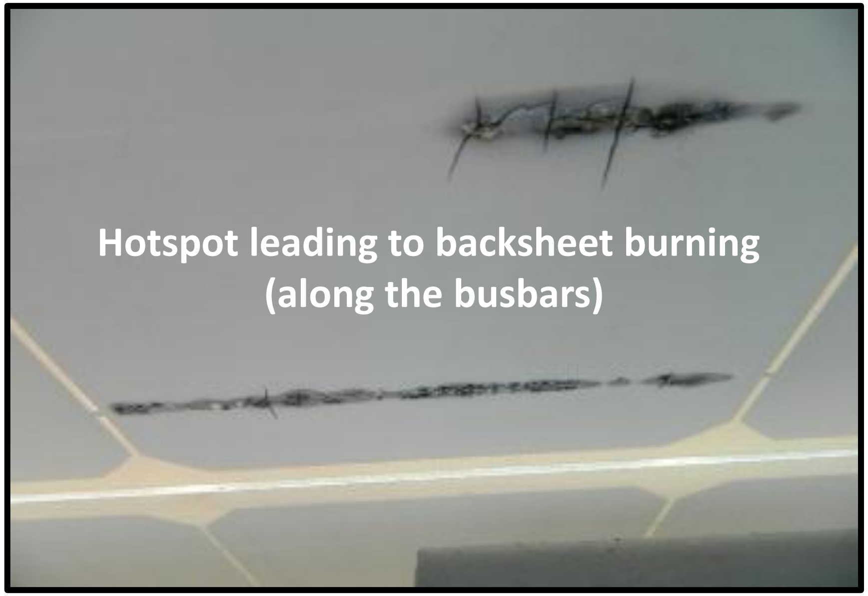
- **Data for the other three plants is made available in the appendix of this presentation.**

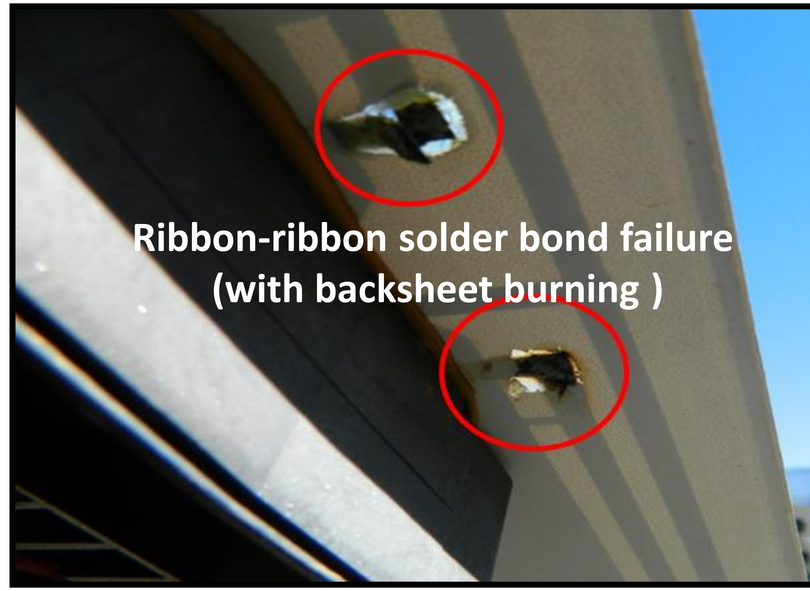
Defects Including Safety Failures (*Model G – Site 3*)

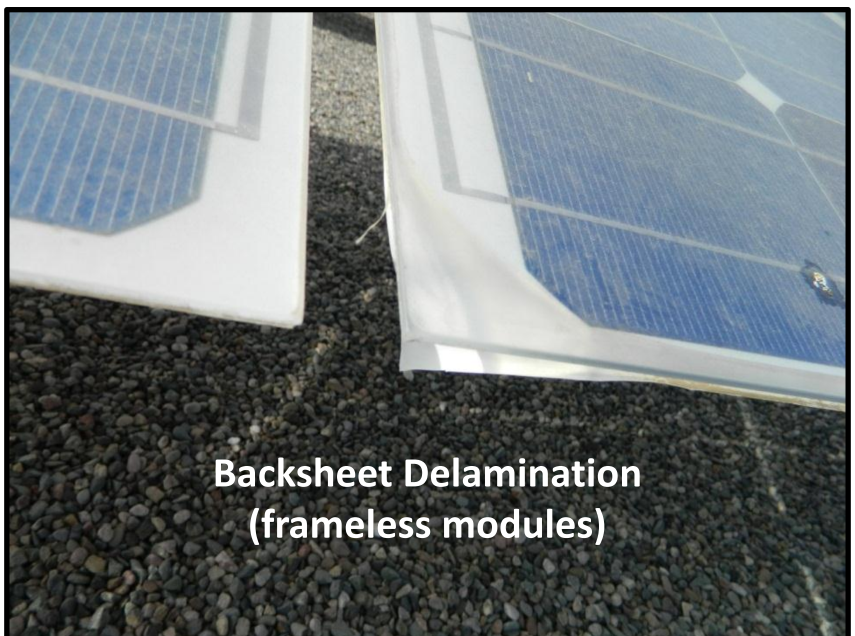


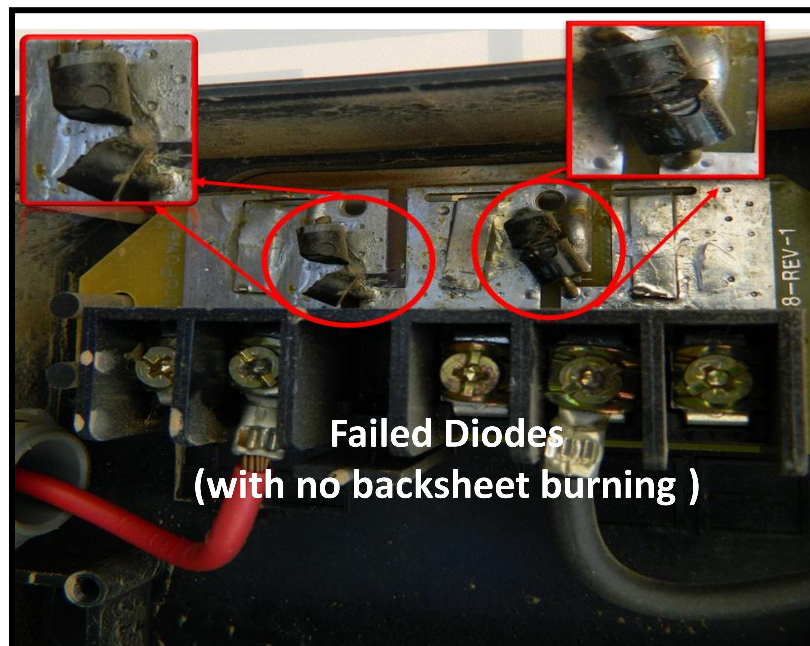
Safety Failures (*Model G – Site 3*)

12 Years – 1-axis Tracker





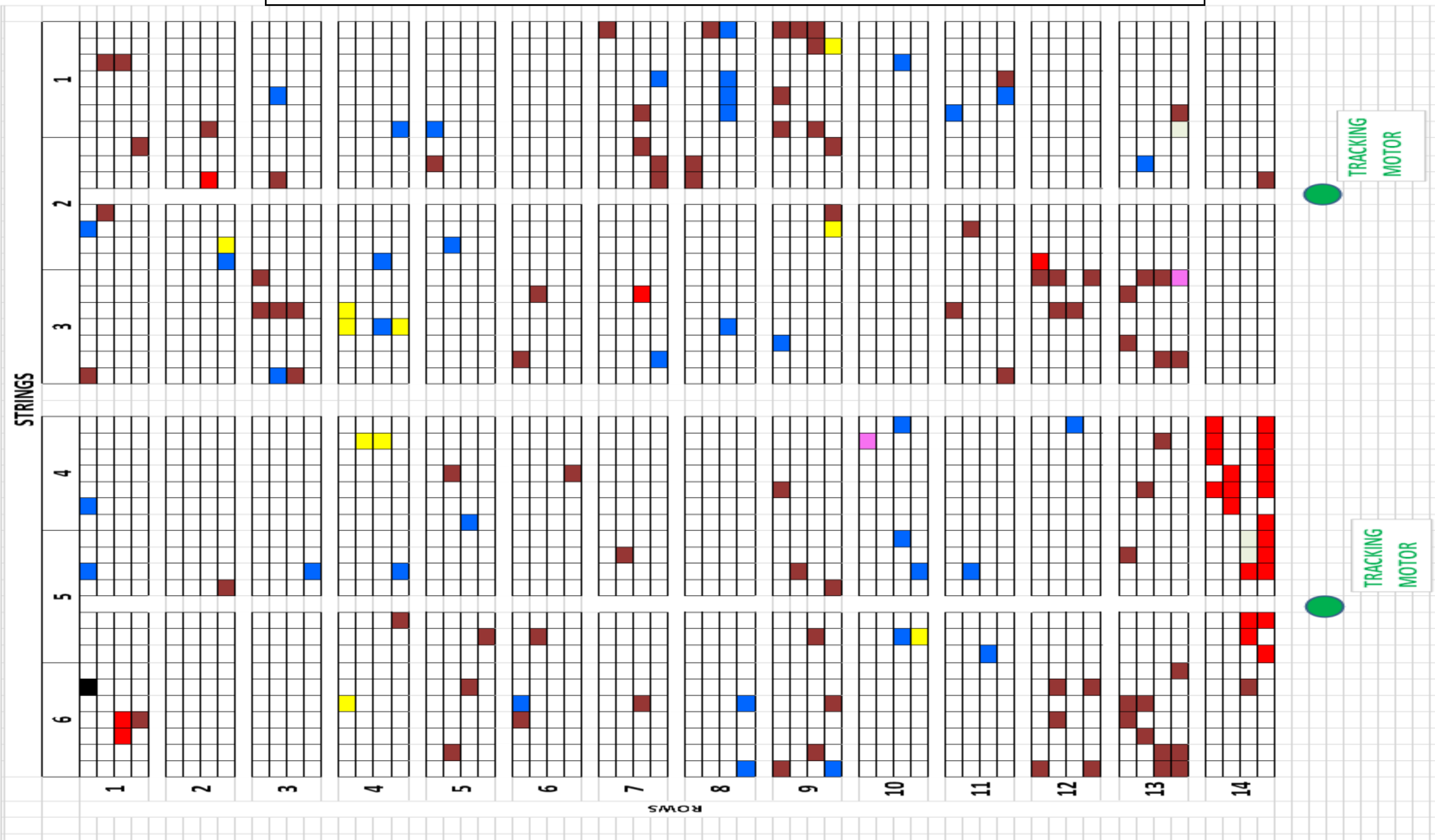




Mapping of Safety Failures (*Model G – Site 3*)

Framed - 12 Years – 1-axis Tracker

Safety failure rate at the plant level = 162/2352 = 7%

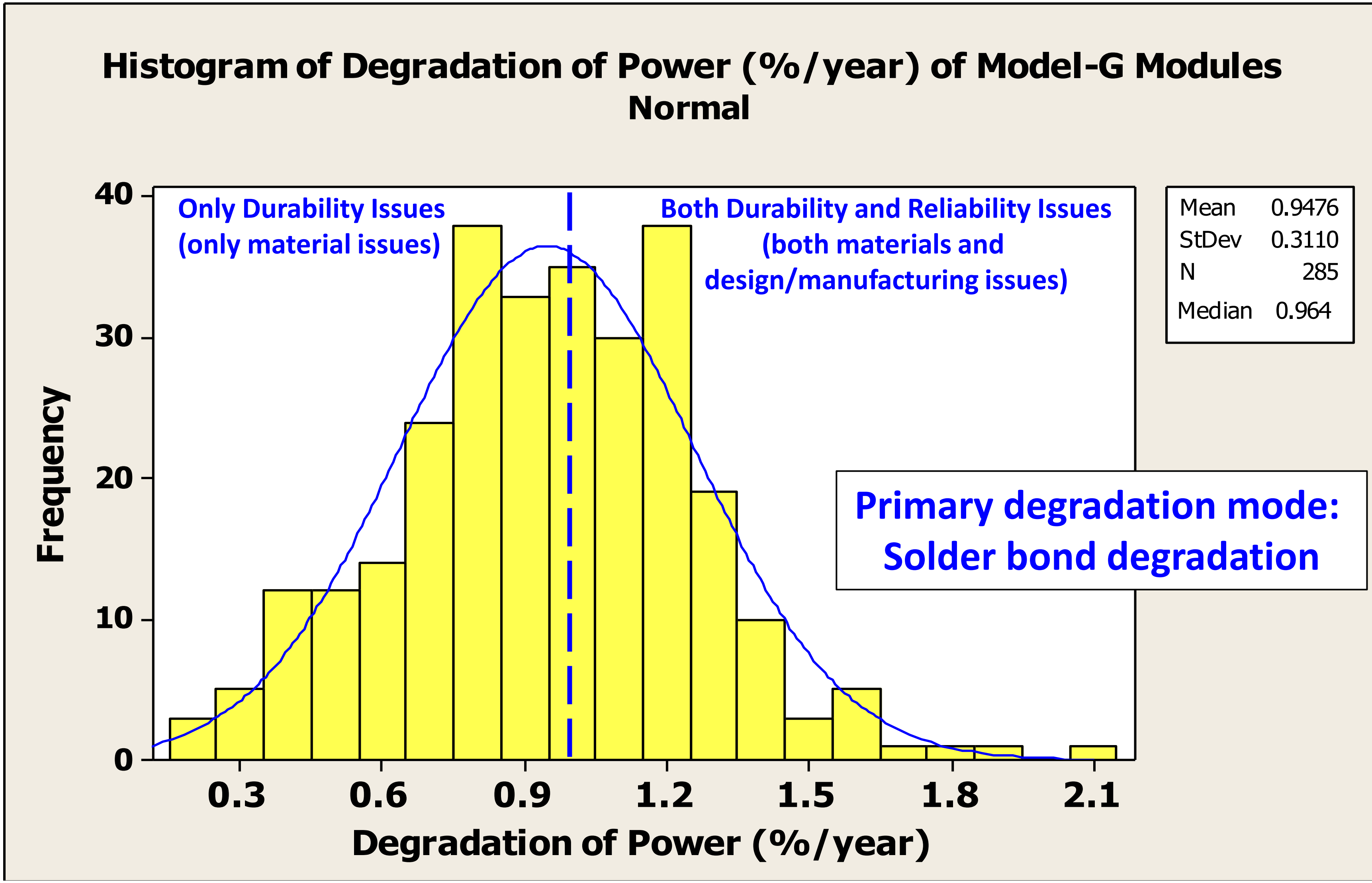


- **Hotspot issues leading to backsheet burn (37/2352)**
- **Ribbon-ribbon solder bond failure with backsheet burn (86/2352)**
- **Failed diode wih no backsheetburn (26/2352)**
- **Hotspot issues with backsheet burn + Ribbon-ribbon solder bond with backsheet burn (1/2352)**
- **Backsheet Delamination (10/2352)**
- **Backsheet Delamination + Ribbon-ribbon solder bond failure (2/2352)**

Primary failure mode:
Ribbon-ribbon solder bond failure with backskin burning

Distribution of Reliability Failures and Degradation Losses (*Model G – Site 3*)

12 Years – 1-axis Tracker



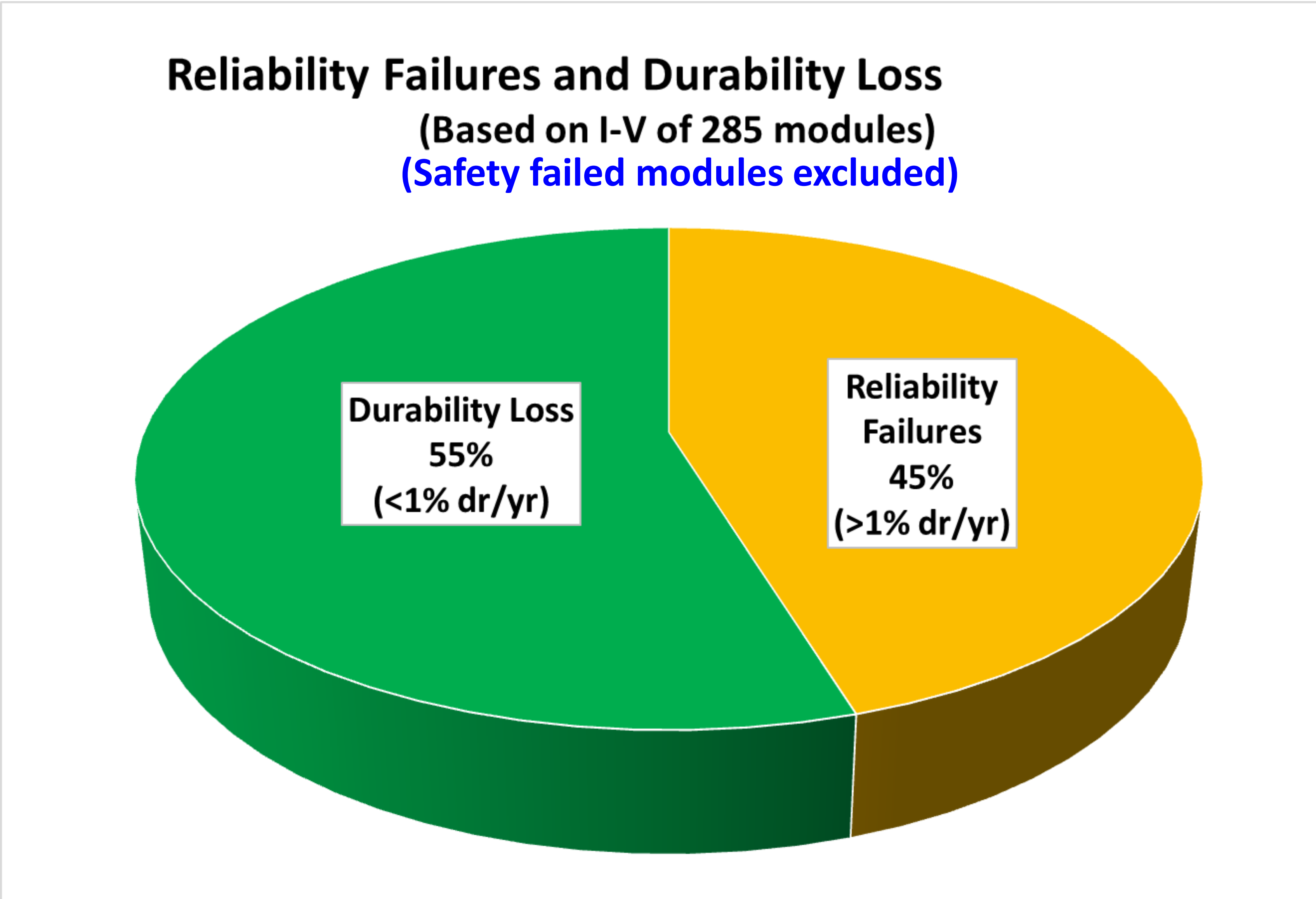
Total number of modules = 285 (safety failed modules excluded)

Mean degradation = 0.95%/year

Median degradation = 0.96%/year

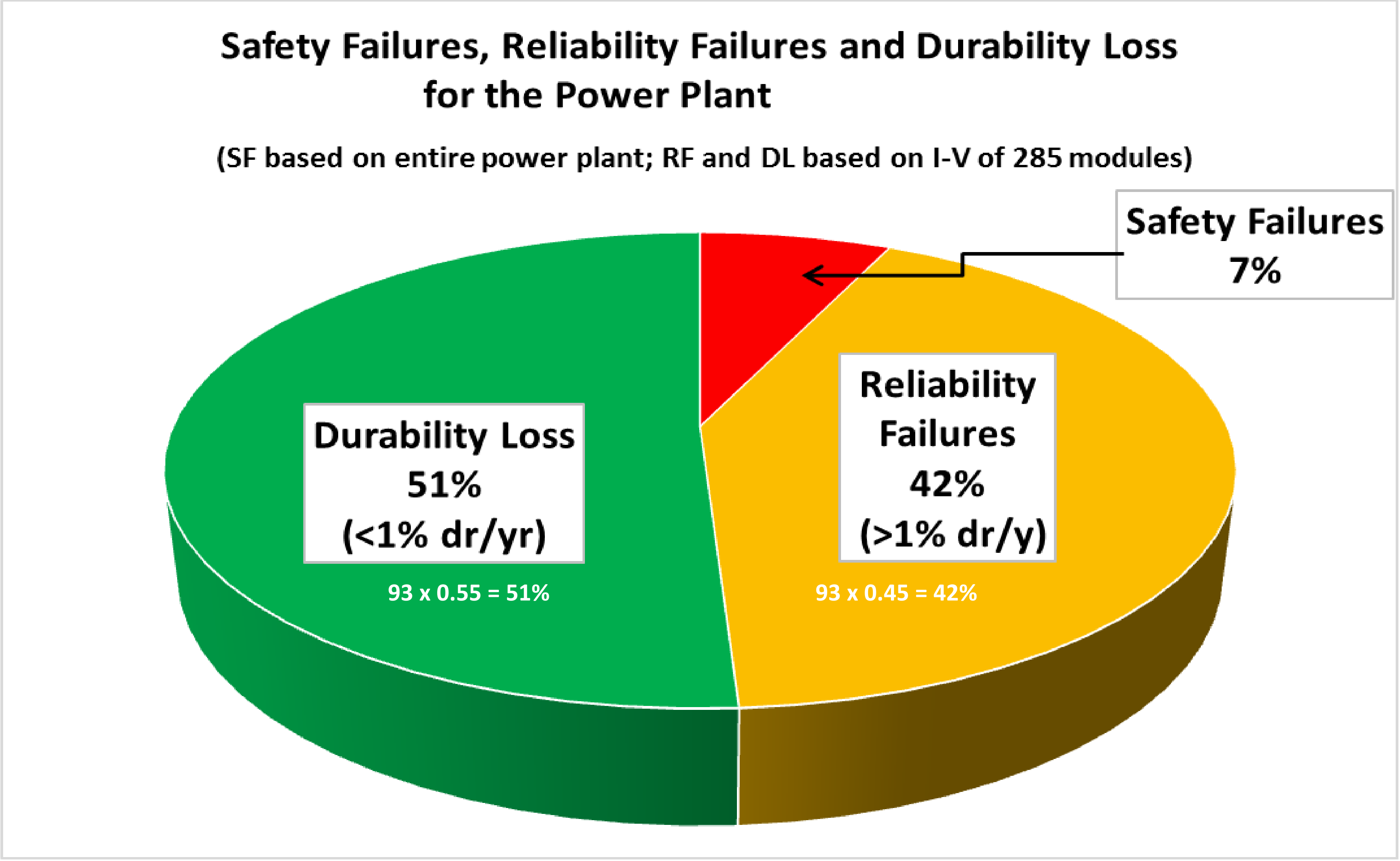
Distribution of Reliability Failures and Degradation Losses (*Model G – Site 3*)

12 Years – 1-axis Tracker

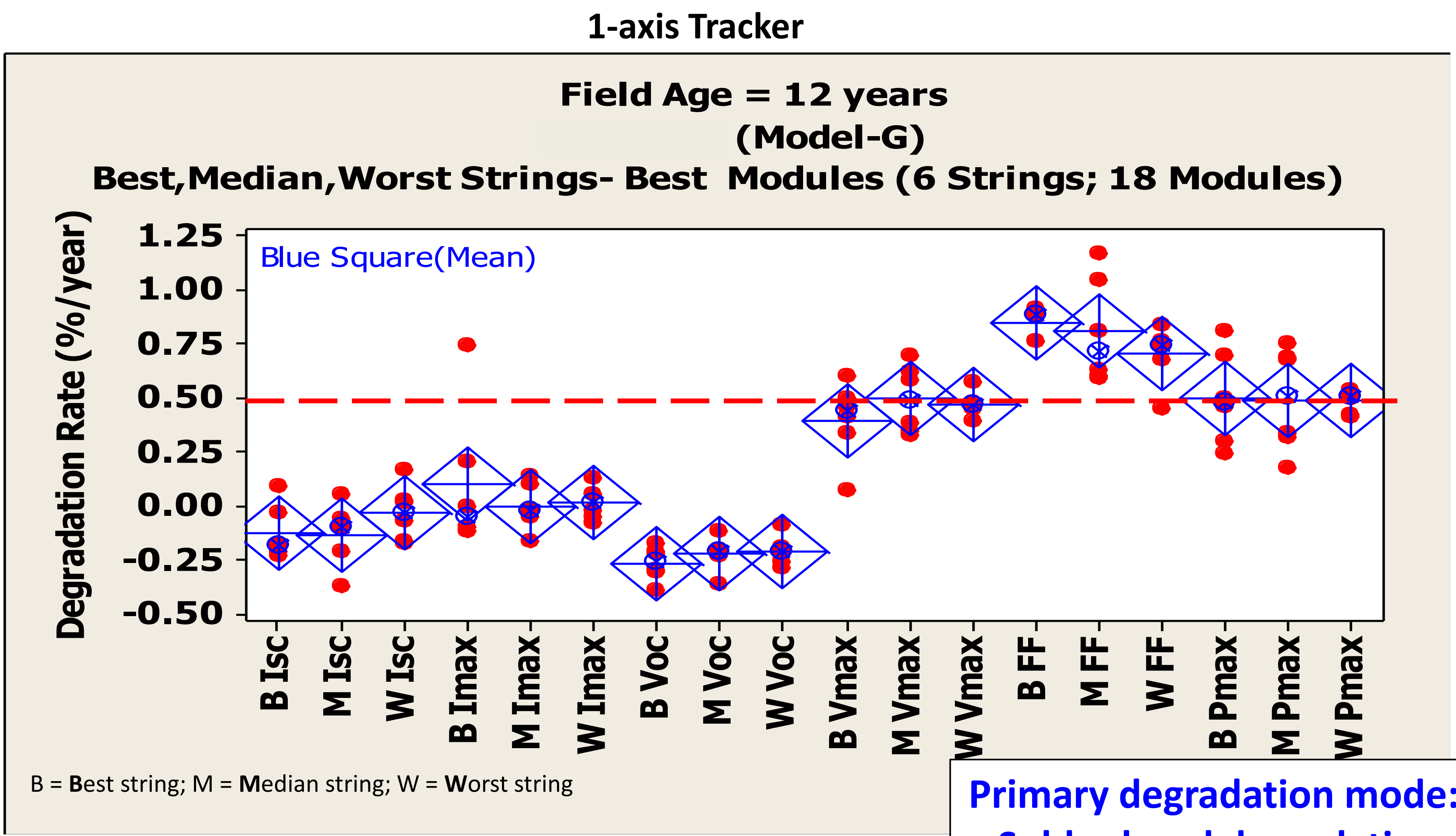


Distribution of Safety Failures, Reliability Failures and Degradation Losses (*Model G – Site 3*)

12 Years – 1-axis Tracker (combination of previous two slides)



Best Modules Experienced Only Durability Issues (*Model G – Site 3*)



Primary degradation mode: Solder bond degradation

Pmax loss → FF loss → Rs increase

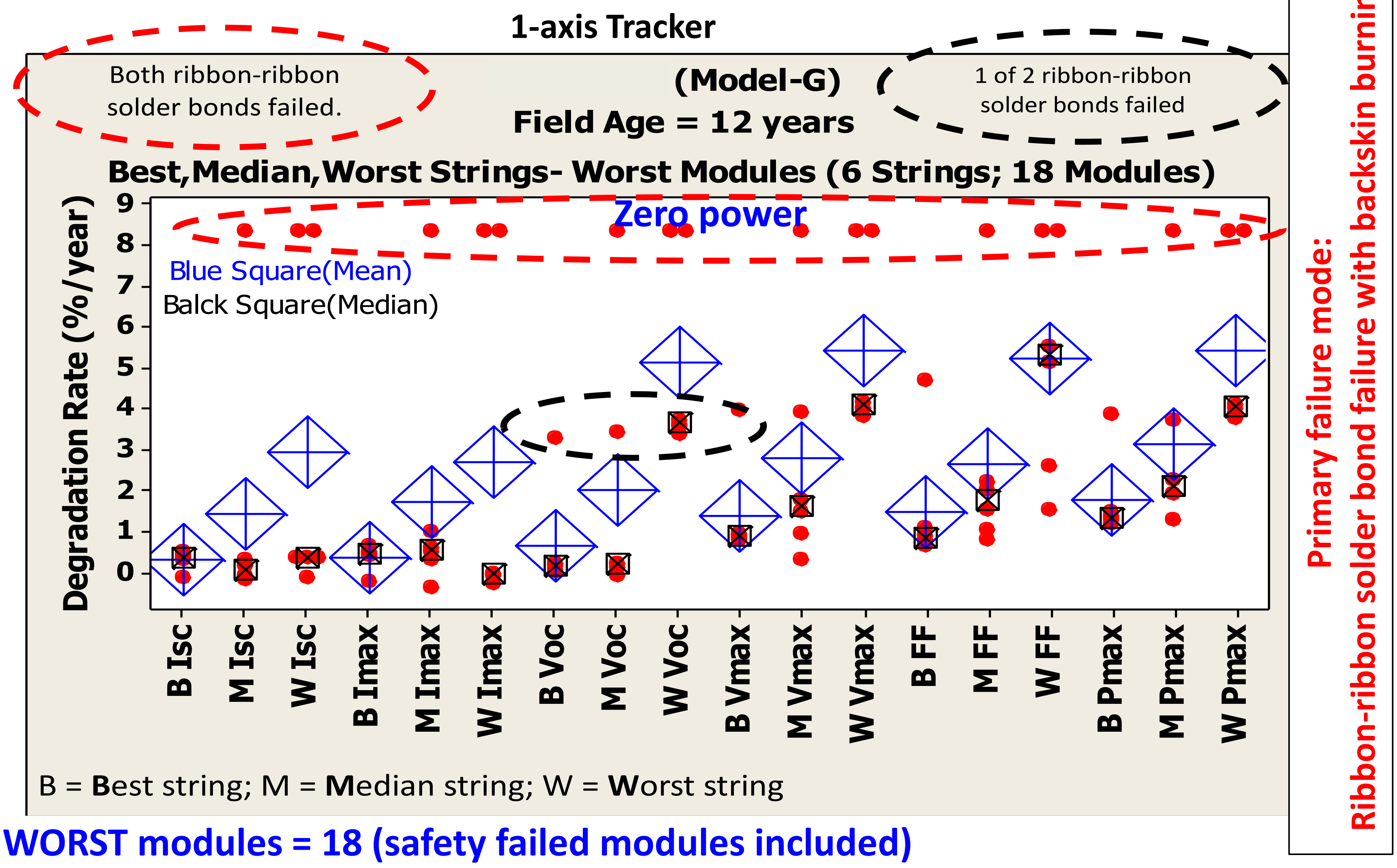
BEST modules = 18 (safety failed modules excluded)

Mean degradation = 0.5%/year

Median degradation = 0.5%/year

} *Due to only intrinsic (materials) issues contributing to real wear out mechanisms*

Worst Modules Experienced Both Reliability and Durability Issues (*Model G – Site 3*)



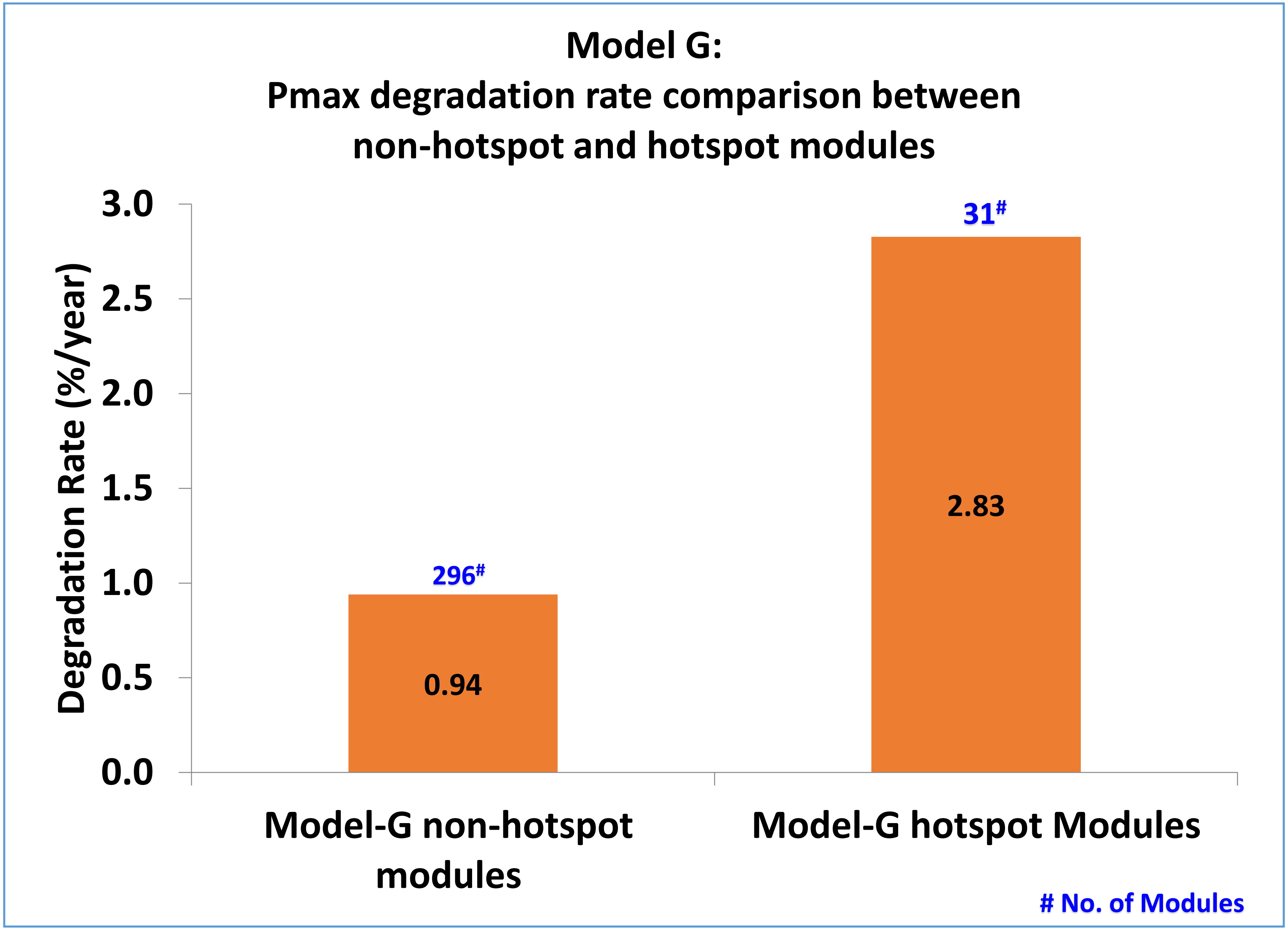
WORST modules = 18 (safety failed modules included)

Mean degradation = 1.8-5.6%/year

Median degradation = 1.4-4%/year

Due to both intrinsic (materials) and extrinsic (design/manufacturing) issues

Hotspot modules degrade at higher rates (>3 times) (*Model G – Site 3*)



Summary: Model G (Site 3) – 1-axis Tracker – 12 years

- Average degradation rate = 0.5%/year for the BEST modules and 0.95%/year for ALL the modules (excluding the safety failed modules). On an average, the modules meet the typical 20/20 warranty expectations.
- Primary safety failure mode is the ribbon-ribbon solder bond failures/cracks leading to backskin burning.
- Primary degradation mode and reliability failure mode may potentially be attributed to thermo-mechanical solder bond fatigue (cell-ribbon and ribbon-ribbon) leading to series resistance increase.
- Average soiling loss of 1-axis tracker based Model G modules is 6.9%
- 7% of the modules qualify for the safety returns under the typical 20/20 warranty terms
- 42% of the modules qualify for the warranty claims under the typical 20/20 power warranty terms
- 51% of the modules are meeting the typical 20/20 power warranty terms

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- Application of the defined metrics on data processing
  - Failure and degradation modes and rates
  - Distribution between safety failures, reliability failures and degradation rates
  - Soiling losses *(not presented here; see the poster for details)*
- Conclusions

Conclusion (Hot-Dry Desert Climate)

- **Primary degradation/failure modes & Degradation rates of the four power plants presented in this work**

- **Linking degradation and failure metric definitions withrisk premium rate calculation**

Primary degradation/failure modes & Degradation rates of the four power plants presented in this work

Average degradation rate - BEST modules:

- 0.41%/year (Model G; 12 years; 1-axis)
- 0.50%/year (Model H; 4 years; 1-axis)
- 0.85%/year (Models BRO1 & BRO2; 16 years; 1-axis and horizontal)

Average degradation rate - ALL modules:

- 0.95%/year (Model G; 1-axis)
- 1.00%/year (Model H)
- 1.1%/year (Models BRO1 & BRO2)

Primary safety failure modes:

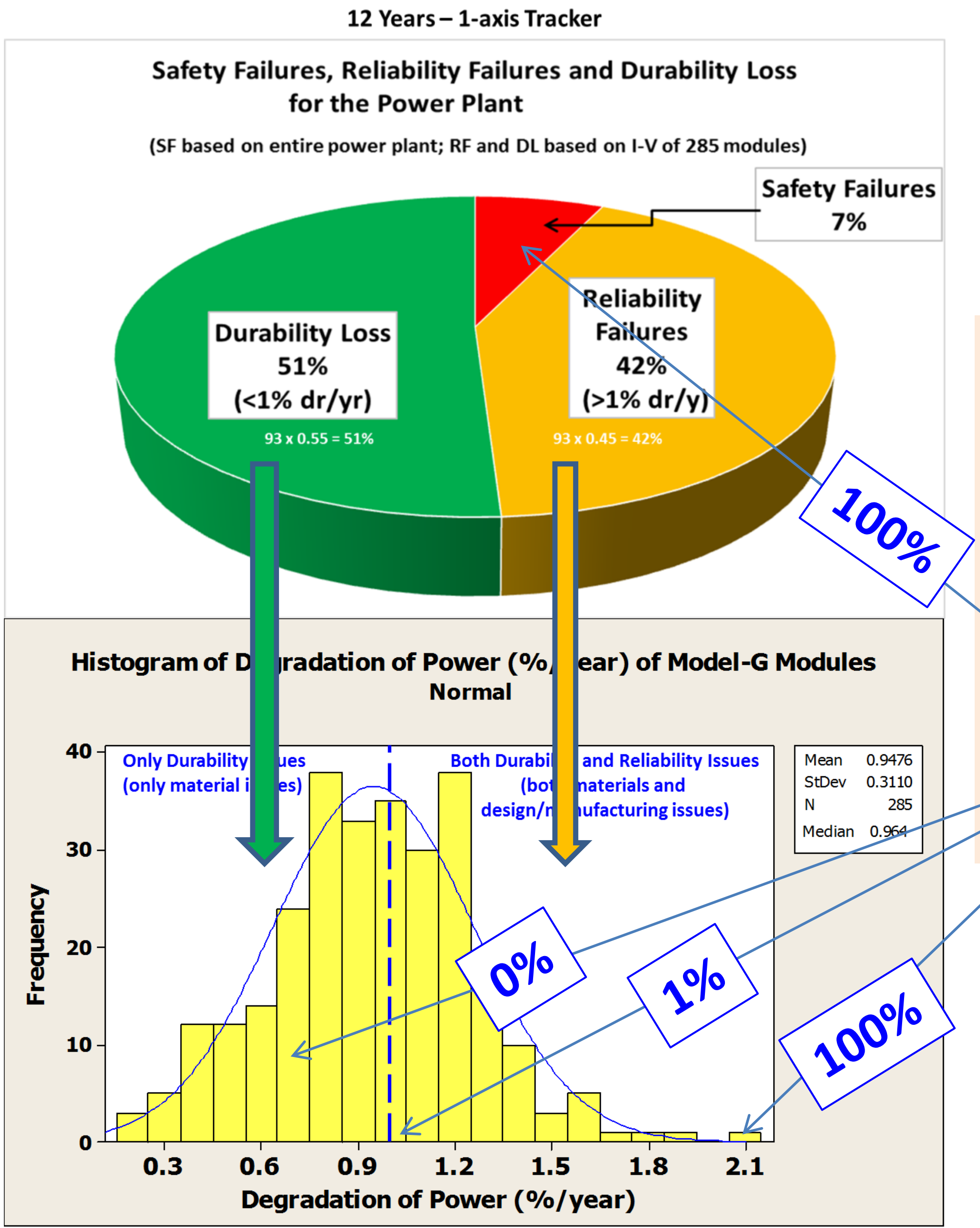
- **Backsheet delamination** (frameless modules; Models BRO1 & BRO2, and Model G)
- **Backsheet burning** (only Model G) and none (Model H)

Primary degradation mode and reliability failure modes:

- Encapsulant **browning** leading to transmittance/current loss (only Models BRO1 & BRO2)
- Thermo-mechanical **solder bond fatigue** leading to series resistance increase (all models: G, BRO1, BRO2 & H).

Linking Failure and Durability Definitions with Risk Premium Rate Calculation

A Conceptual Representation



Interest Rate

=

Interest Rate @ Zero Risk

+

Risk Premium Rate

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Appendix

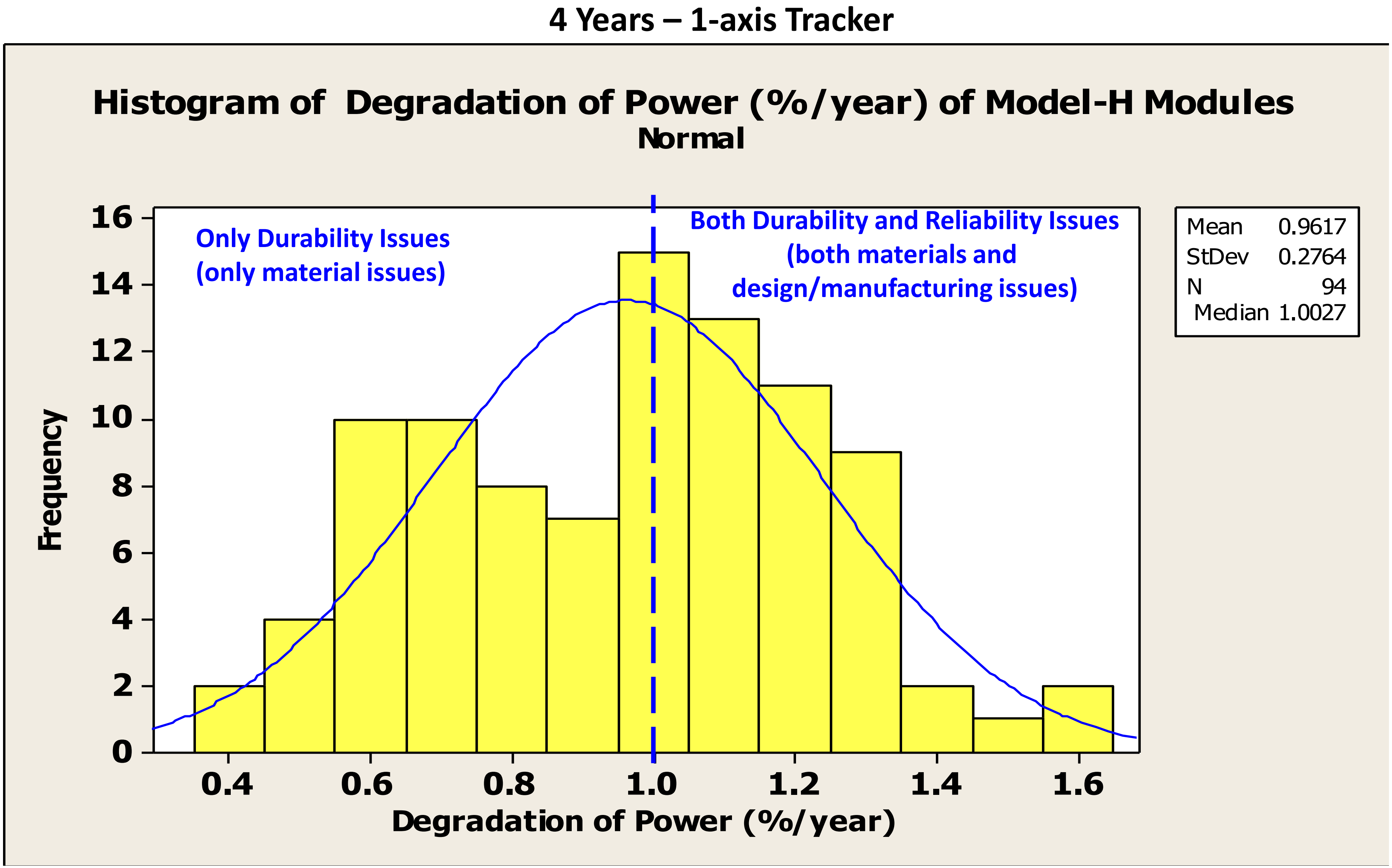
Model H

(Site 4C)

Mapping of Safety Failures (*Model H – Site 4C*) **Framed - 4 Years – 1-axis Tracker**

Safety failure rate at the plant level = 0/1280 = 0%

Distribution of Reliability Failures and Degradation Losses (*Model H – Site 4C*)

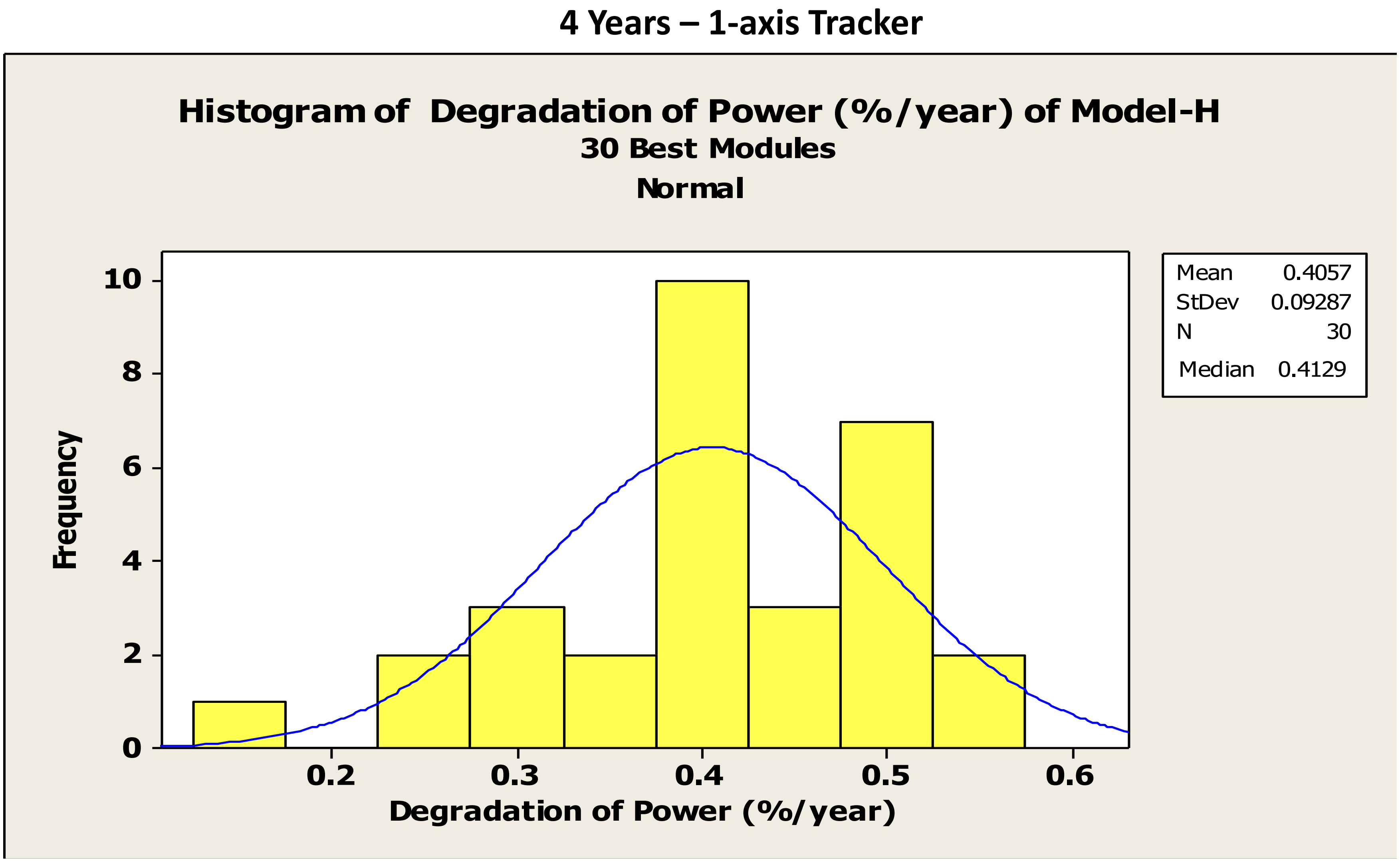


Total number of modules = 94 (safety failed modules excluded)

Mean degradation = 0.96%/year

Median degradation = 1.00%/year

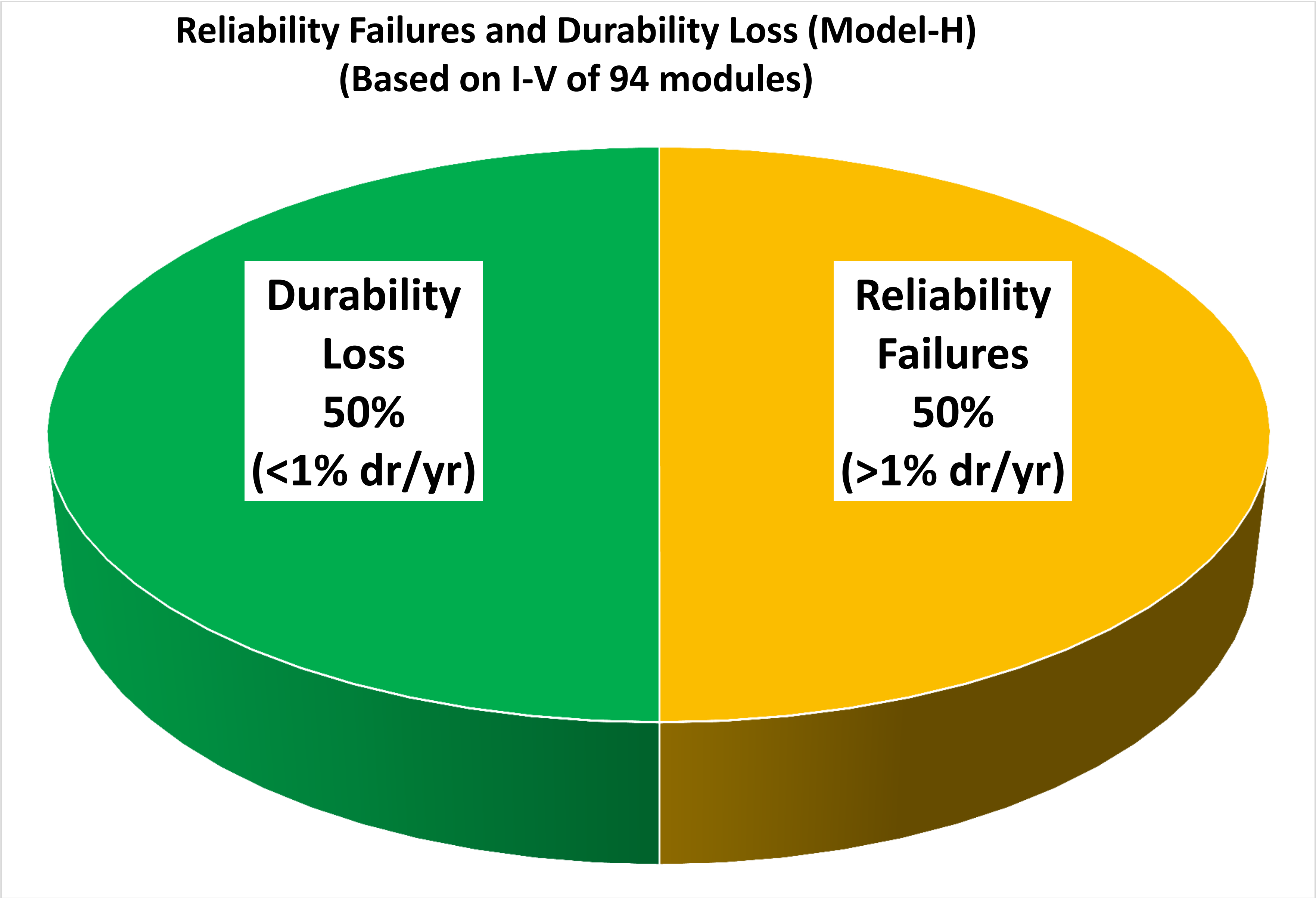
Degradation Distribution of Best Modules (*Model H – Site 4C*)



Total number of BEST modules = 30 (safety failed modules excluded)
Mean degradation = 0.41%/year
Median degradation = 0.41%/year

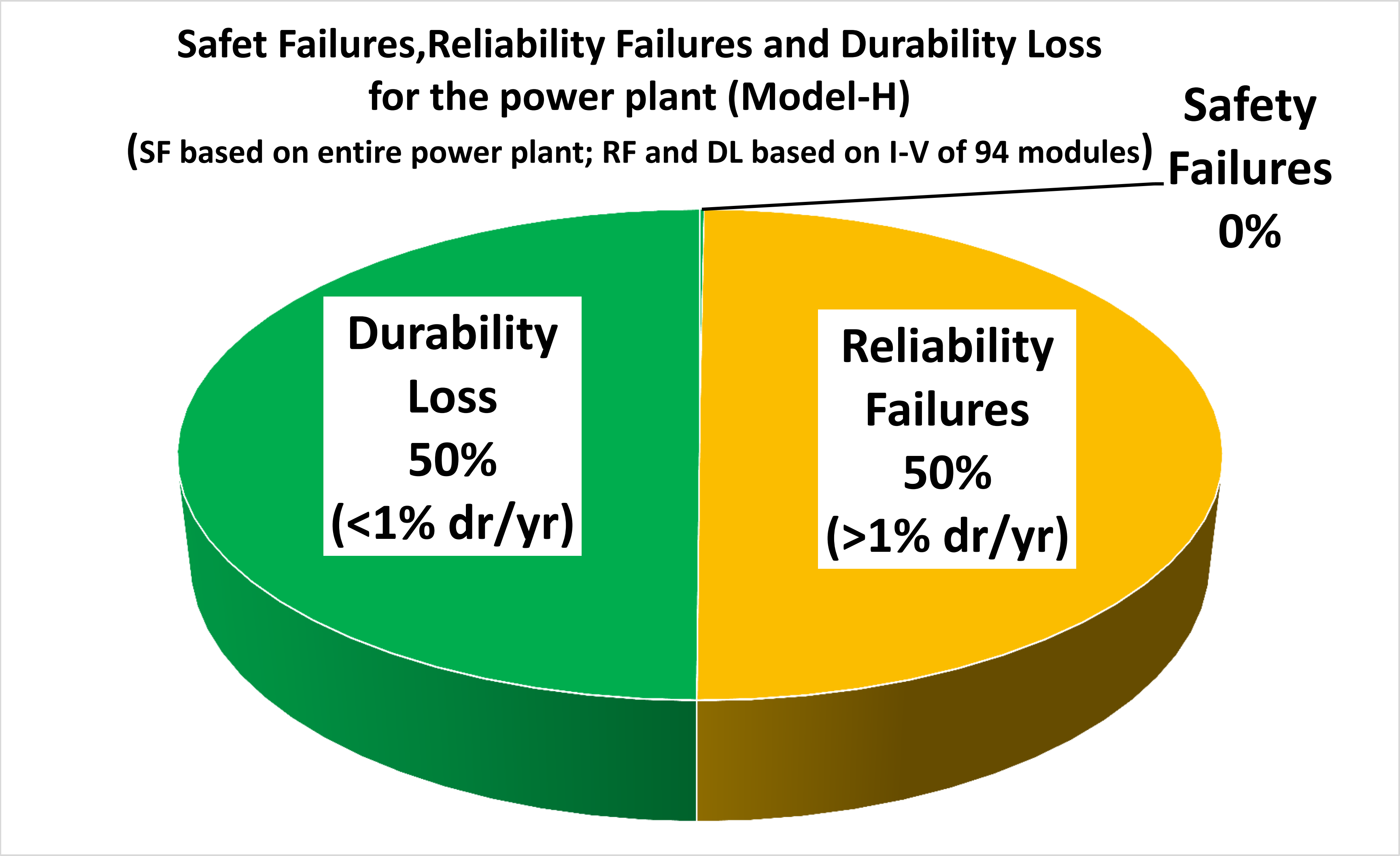
Distribution of Reliability Failures and Degradation Losses (*Model H – Site 4C*)

4 Years – 1-axis Tracker



Distribution of Safety Failures, Reliability Failures and Degradation Losses (*Model H – Site 4C*)

12 Years – 1-axis Tracker



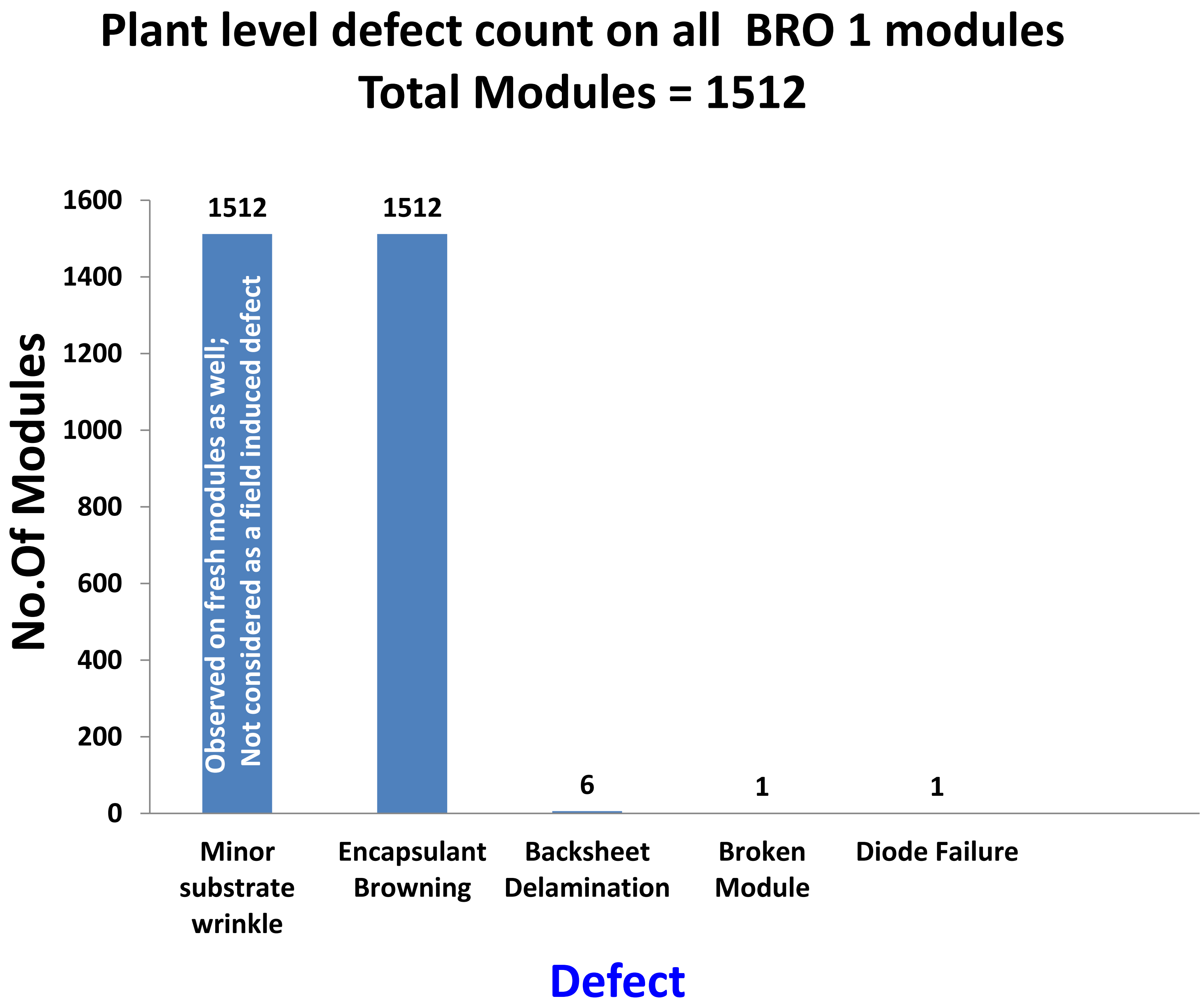
Summary: Model H (Site 4C) – 1-axis Tracker

- Average degradation rate = 0.41%/year for the BEST modules and 1.00%/year for ALL the modules (excluding the safety failed modules). On an average, the modules meet the typical 20/20 warranty expectations.
- Practically, no safety failures have been detected.
- Primary degradation mode and reliability failure mode may potentially be attributed to thermo-mechanical solder bond fatigue (cell-ribbon and ribbon-ribbon) leading to series resistance increase.
- Average soiling loss of 1-axis tracker based model H modules is 5.5%
- 0% of the modules qualify for the safety returns under the typical 20/20 warranty terms
- 50% of the modules qualify for the warranty claims under the typical 20/20 power warranty terms
- 50% of the modules are meeting the typical 20/20 power warranty terms

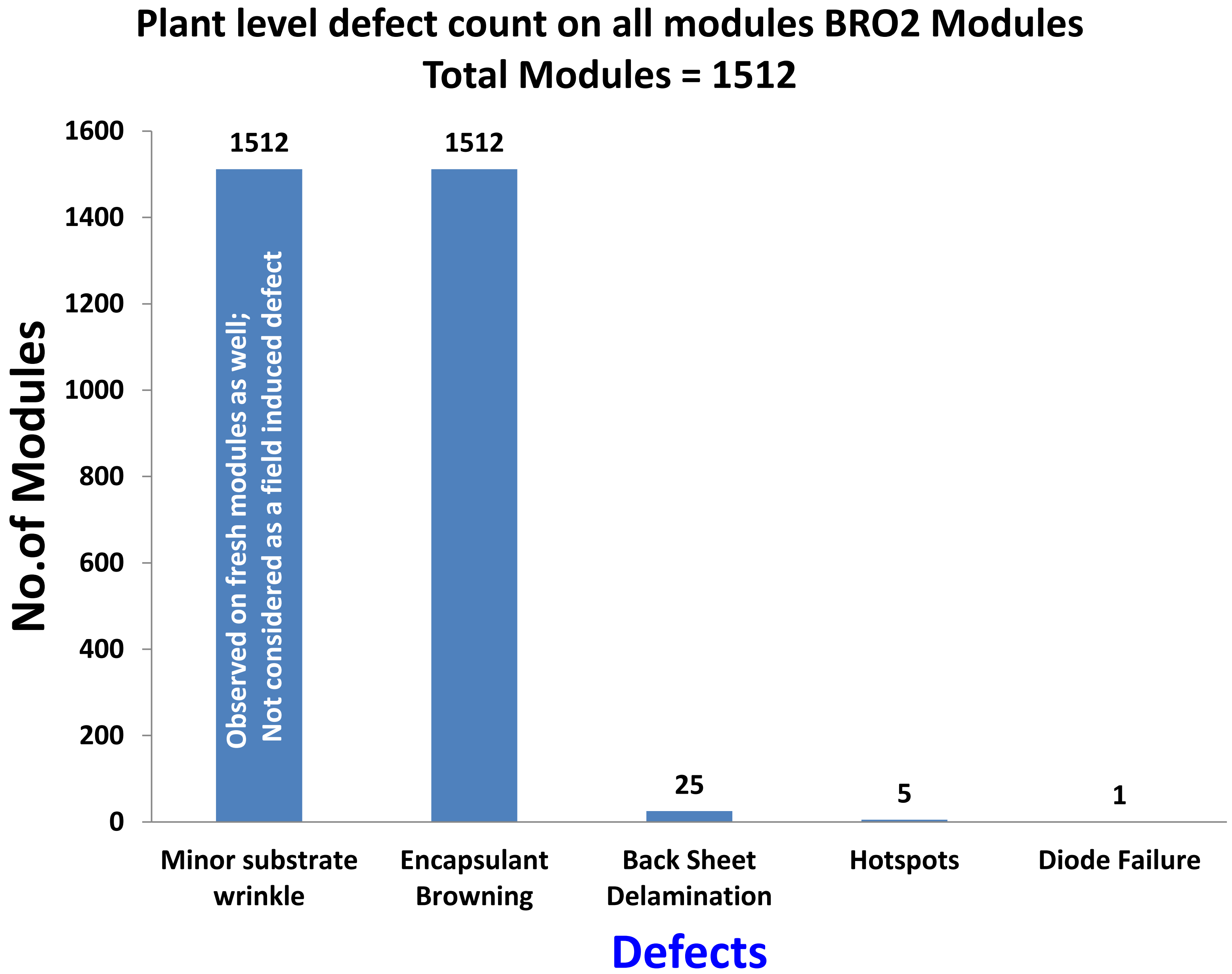
Model BRO1 & BRO2

(Site 4A & 4B)

Defects Including Safety Failures (*Model BRO1 – Site 3*)



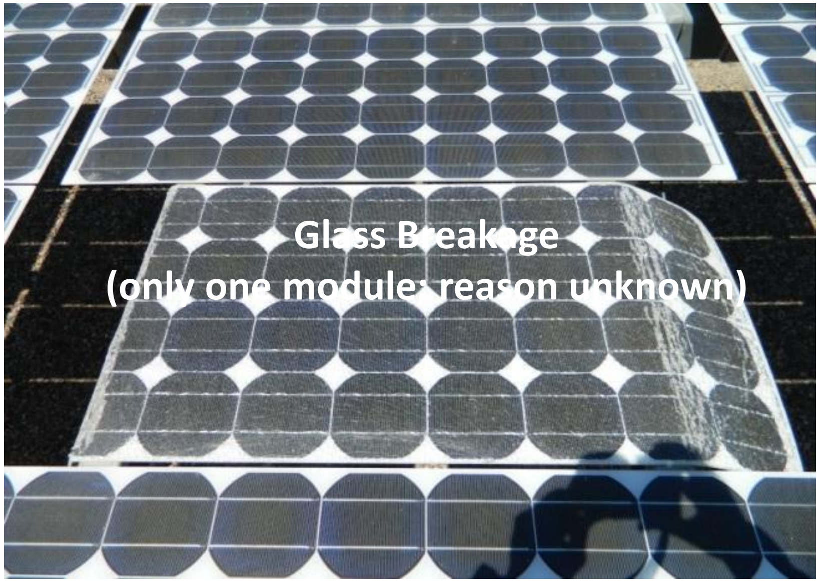
Defects Including Safety Failures (*Model BRO2 – Site 3*)



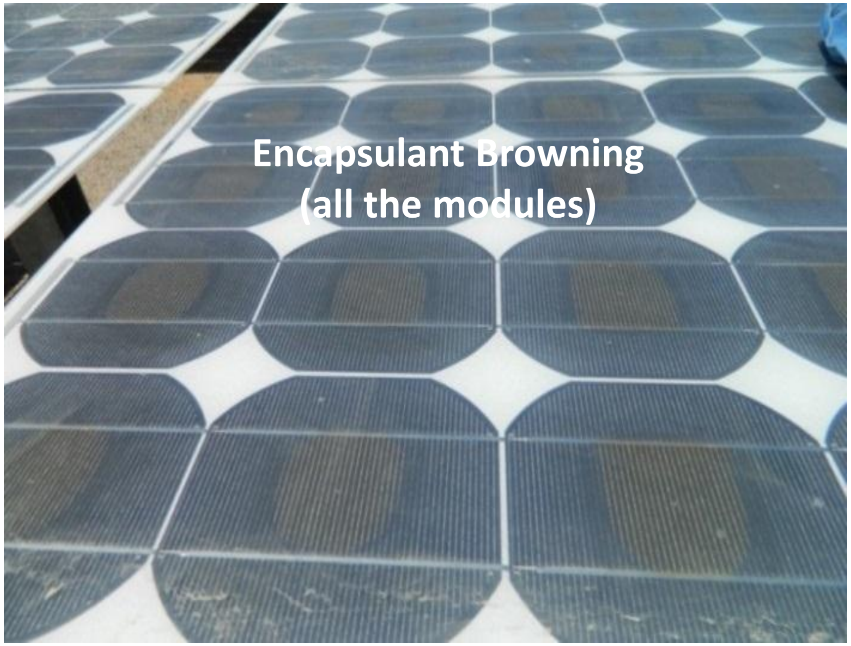
Safety Failures and Reliability Failures (*Models BRO1 & BRO2– Site 4A & 4B*)

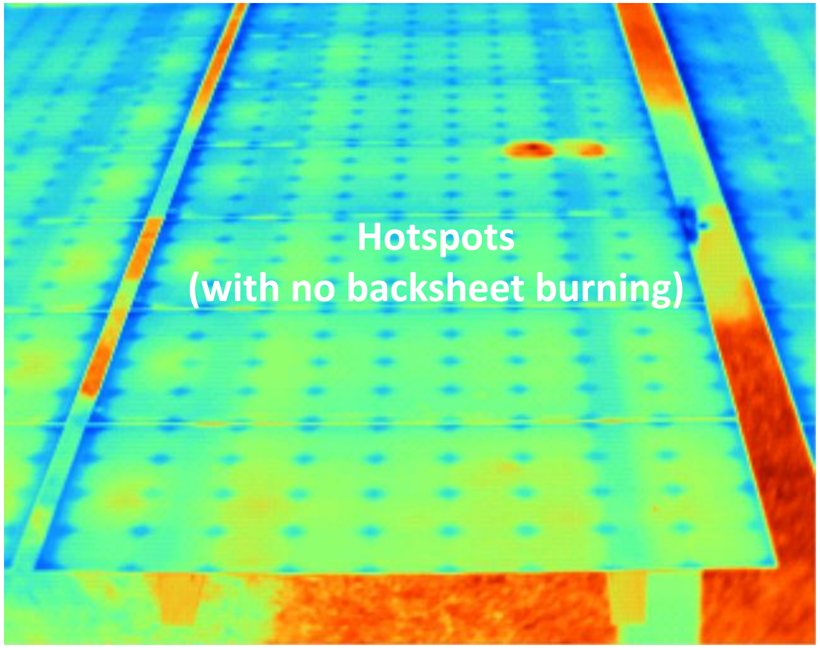
16 Years (7 years – 1-axis; 9 years – horizontal tilt)

Safety Issues



Durability and Reliability Issues



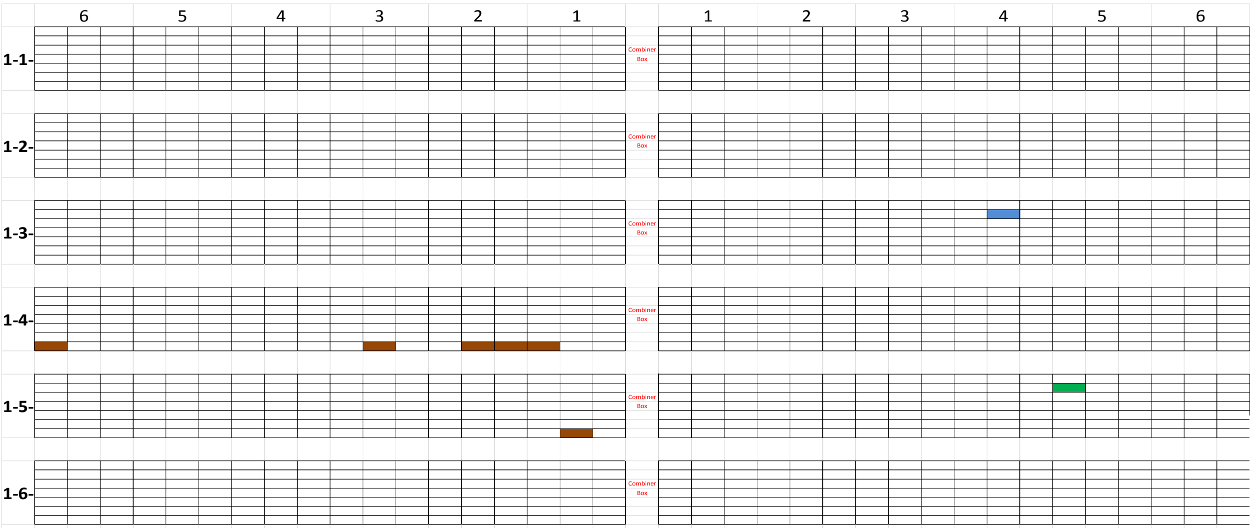


Mapping of Safety Failures (*Models BRO1 & BRO2 – Site 4A & 4B*)

Framed - 16 Years

(7 years 1- axis; 9 years horizontal)

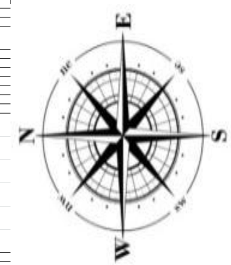
BRO1: Safety failure rate at the plant level = 8/1512 = 0.5%



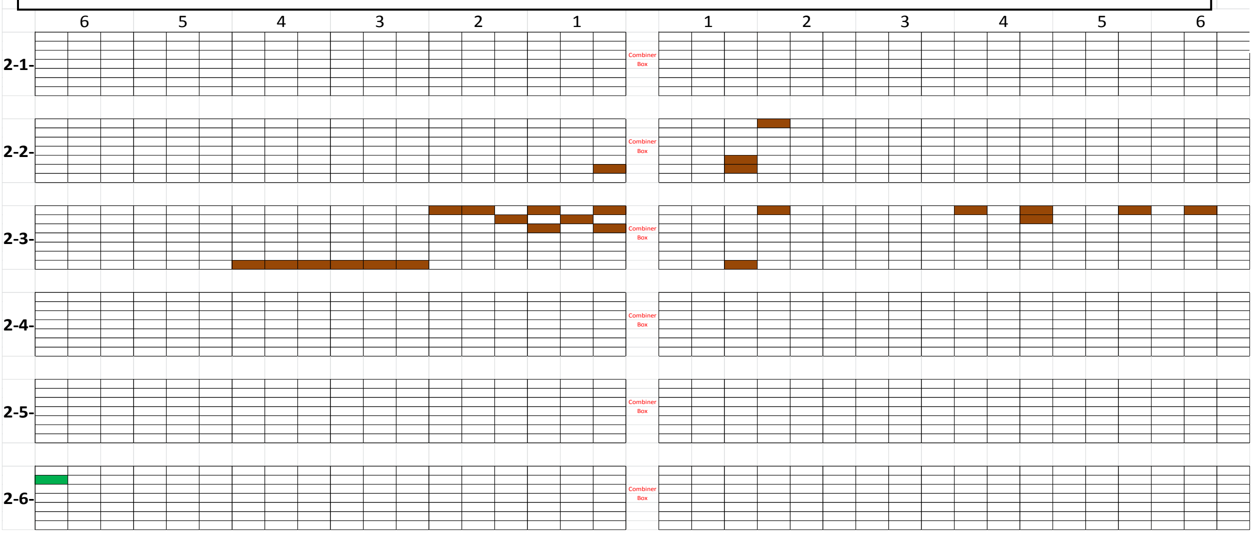
Backsheet Delamination

Broken Module

Diode Failure

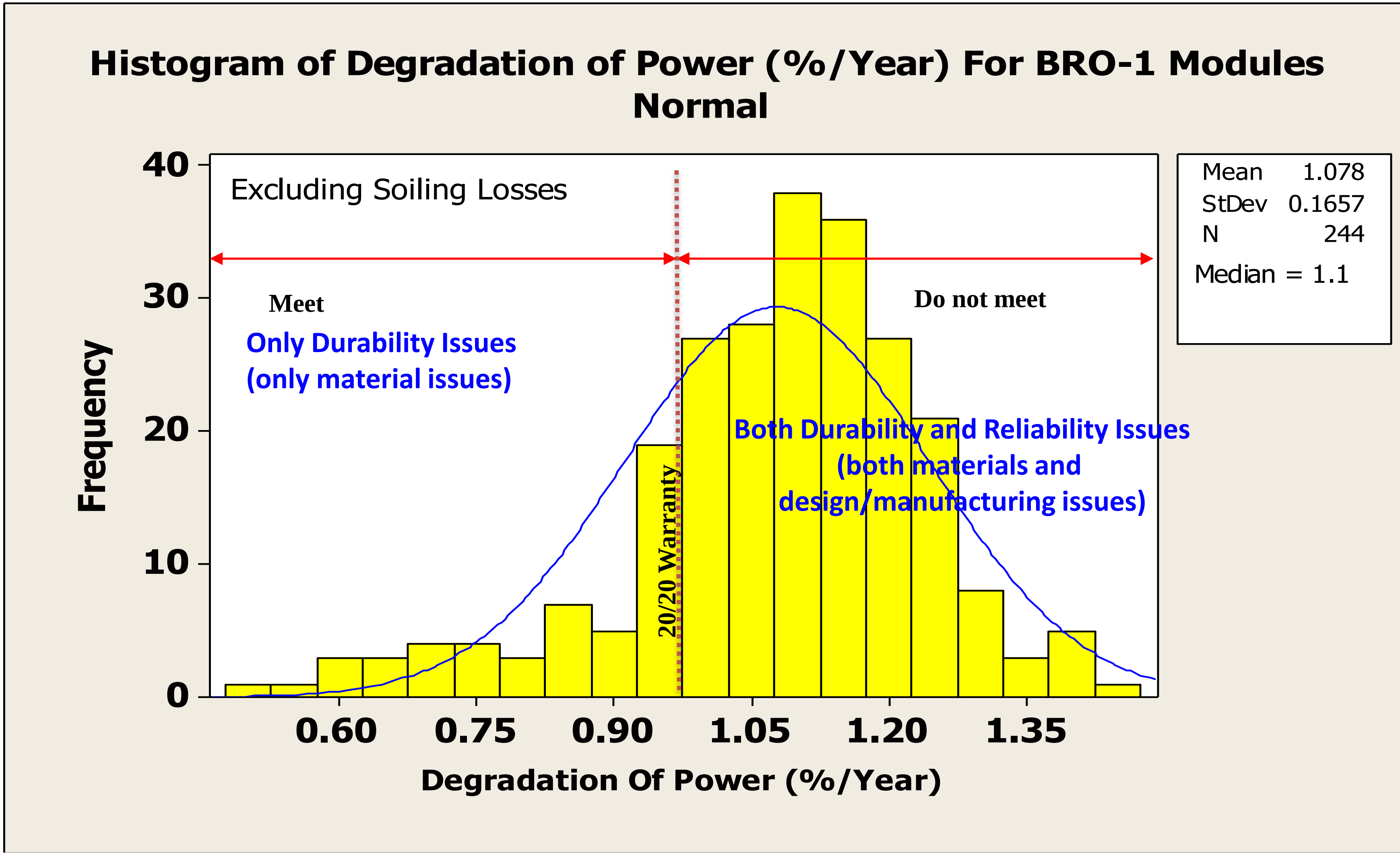


BRO2: Safety failure rate at the plant level = 26/1512 = 1.7%



Distribution of Reliability Failures and Degradation Losses (*Model BRO1 – Site 4A*)

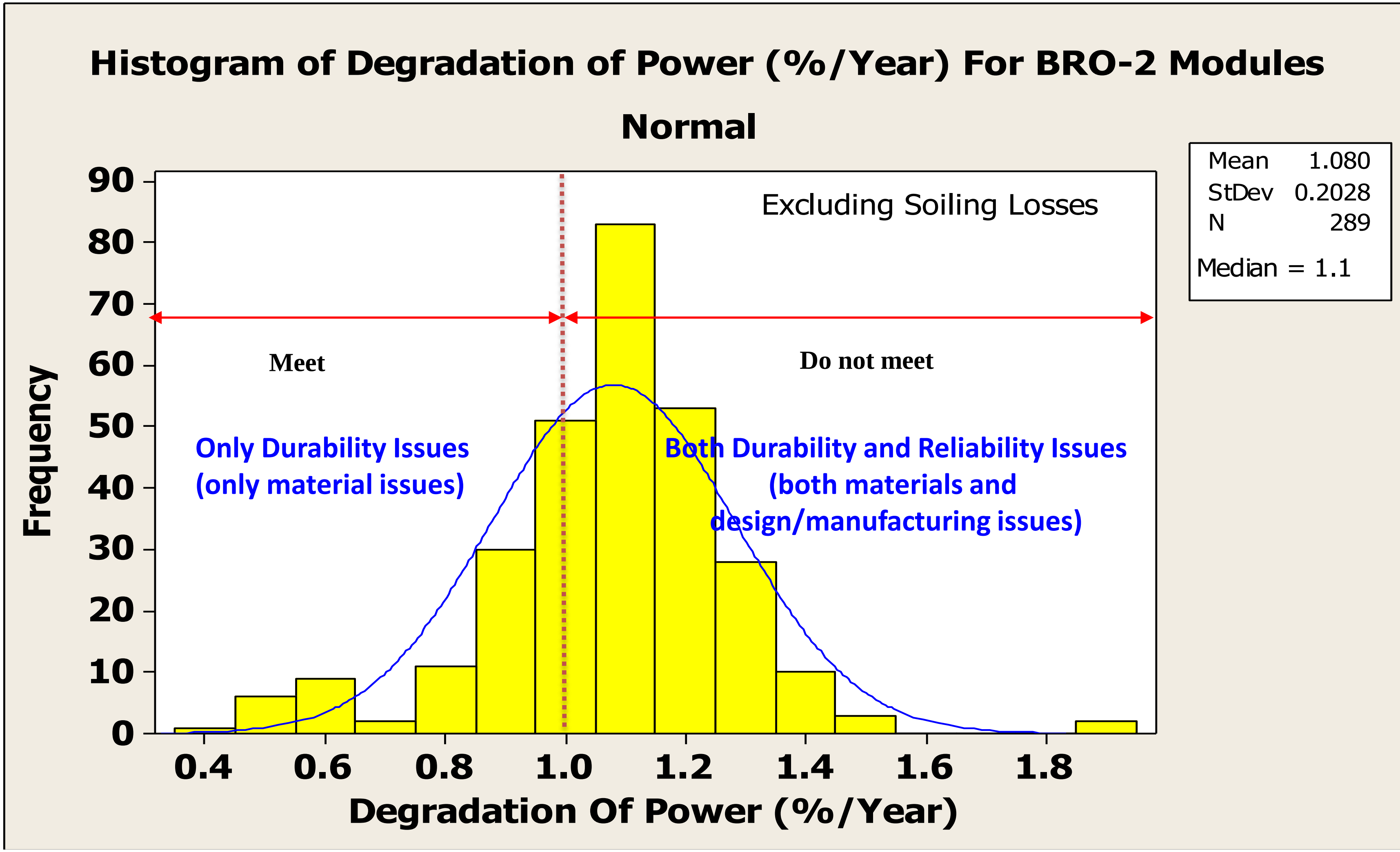
16 Years – 1-axis tracker for first 7 years and horizontal tilt for 9 years



Total number of modules = 244 (safety failed modules excluded)
Mean degradation = 1.1%/year
Median degradation = 1.1%/year

Distribution of Reliability Failures and Degradation Losses (*Model BRO2 – Site 4B*)

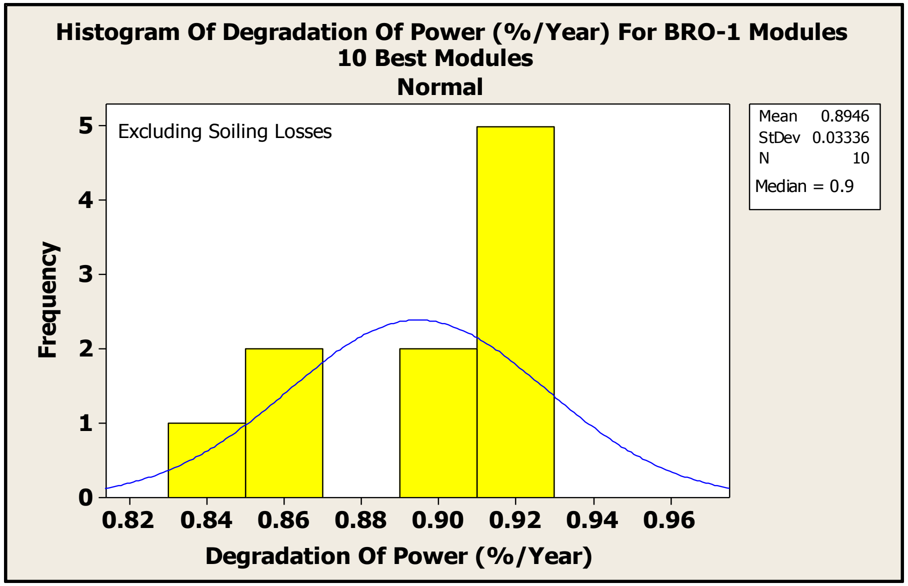
16 Years – 1-axis tracker for first 7 years and horizontal tilt for 9 years

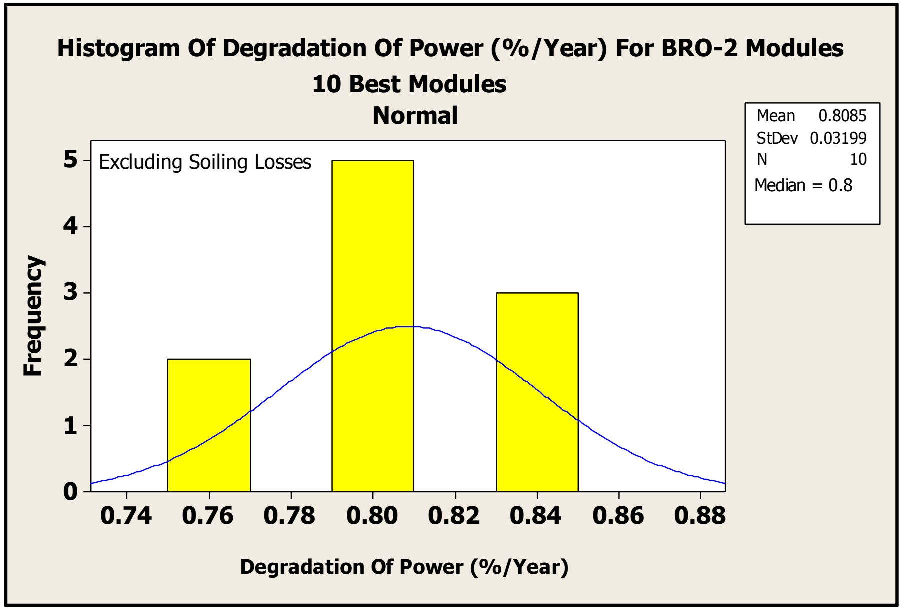


Total number of modules = 289 (safety failed modules excluded)
Mean degradation = 1.1%/year
Median degradation = 1.1%/year

Degradation Distribution of Best Modules (*Models BRO1 &BRO2 – Site 4A & 4B*)

16 Years – 1-axis Tracker for 7 years and horizontal tilt for 9 years

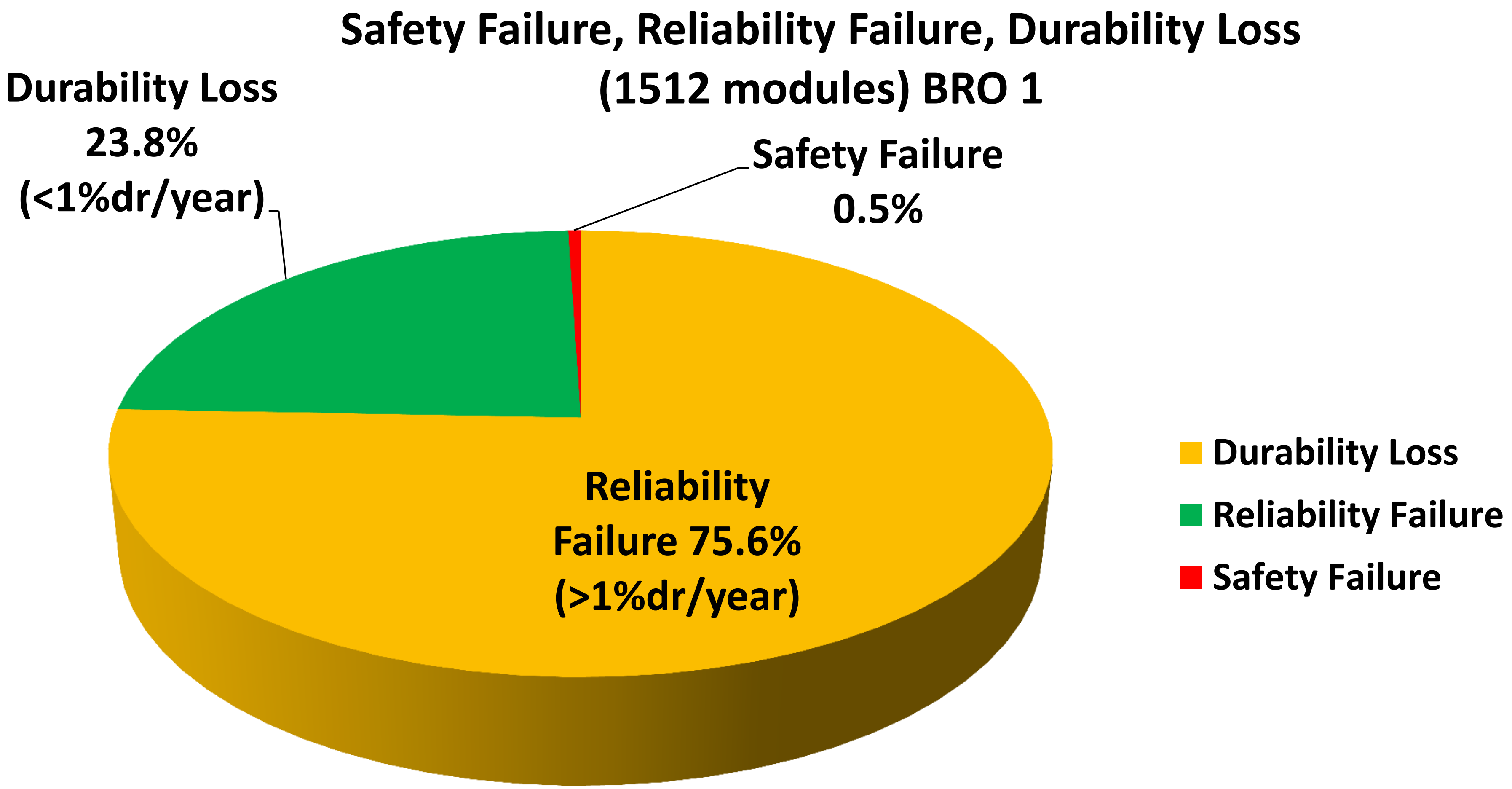




Total number of BEST modules = 20 (safety failed modules excluded)
Mean degradation = 0.8-0.9%/year
Median degradation = 0.8-0.9%/year

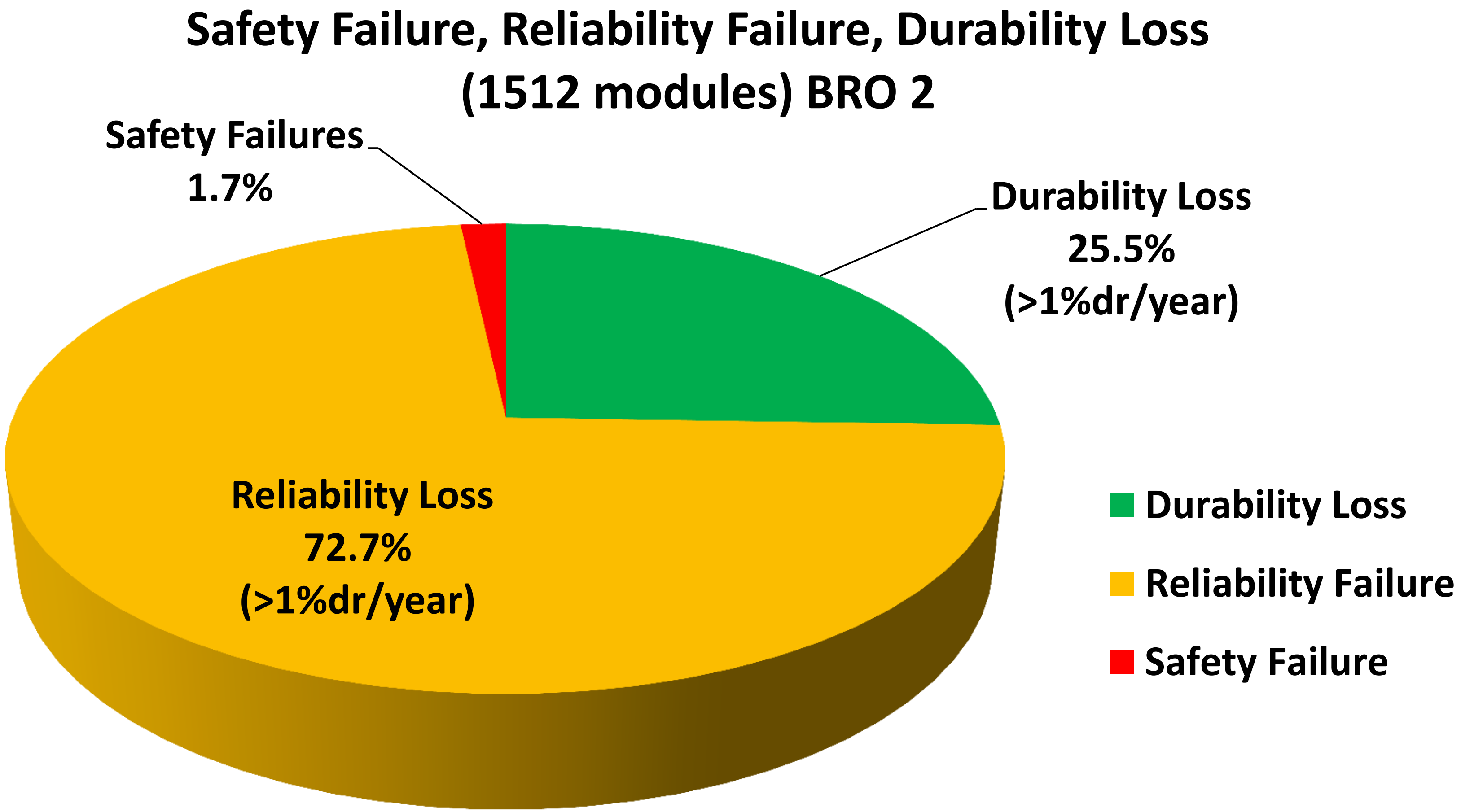
Distribution of Reliability Failures and Degradation Losses (*Model BRO1 – Site 4A*)

16 Years – 1-axis Tracker for 7 years and horizontal tilt for 9 years

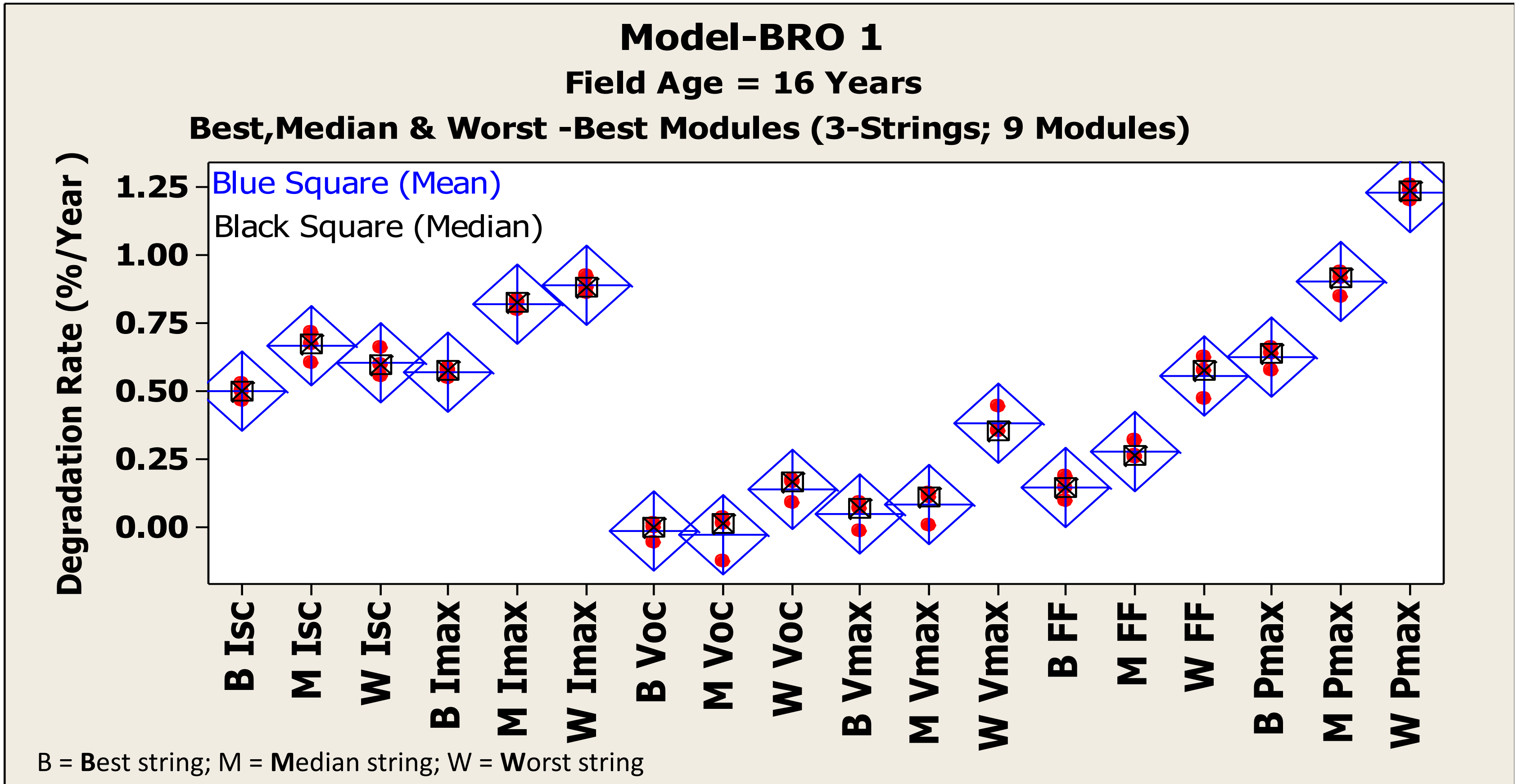


Distribution of Reliability Failures and Degradation Losses (*Model BRO1 – Site 4A*)

16 Years – 1-axis Tracker for 7 years and horizontal tilt for 9 years



Best Modules Experienced Only Durability Issues (*Model BRO1*)



Primary degradation modes:
Encapsulant browning & solder bond degradation

Pmax loss ➡ Isc loss (encapsulant browning) & FF loss (solder bond degradation)

BEST modules = 9 (safety failed modules excluded)
Mean degradation = 0.85%/year

Summary: Models BRO1 & BRO2 (Sites 4A and 4B) – 16 years (7 years on 1-axis tracker and 9 years horizontal tilt)

- Average degradation rate = 0.85%/year for the BEST modules and 1.1%/year for ALL the modules (excluding the safety failed modules). On an average, the modules do not meet the typical 20/20 warranty expectations (due to two degradation modes: solder bonds and browning).

- Primary safety failure mode is the backsheet delamination though it is small (less than 1.7%)

- Primary degradation mode and reliability failure mode may potentially be attributed to encapsulant browning leading to transmittance/current loss and thermo-mechanical solder bond fatigue (cell-ribbon and ribbon-ribbon) leading to series resistance increase.

- Average soiling loss of horizontal tilt based modules is 11.1% (nearly double vs. 1-axis)

- 0.5-1.7% of the modules qualify for the safety returns under the typical 20/20 warranty terms

- 73-76% of the modules qualify for the warranty claims under the typical 20/20 power warranty terms

- 24-26% of the modules are meeting the typical 20/20 power warranty terms

Overall Conclusions

(for all four power plants)

Overall Conclusions for All the Modules – Hot Dry Desert Climates

- Metric definitions for safety failures, reliability failures and degradation rates are provided
- Metric definitions were applied on the power plant evaluations
- Metric results obtained in this work can be used to perform bankability calculations
- Degradation rate - BEST modules: Average Degradation = 0.41%/year (Model G; 12 years; 1-axis), 0.50%/year (Model H; 4 years; 1-axis) and 0.85%/year (Models BRO1 & BRO2; 16 years; 1-axis and horizontal)
- Degradation rate - ALL modules: Average Degradation = 0.95%/year (Model G), 1.00%/year (Model H) and 1.1%/year (Models BRO1 & BRO2)
- Safety failure modes: Primary modes are backsheet delamination (frameless modules; Models BRO1 & BRO2, and Model G), backsheet burning (only Model G) and none (Model H)
- Degradation mode and reliability failure modes: Primary modes are encapsulant browning leading to transmittance/current loss (only Models BRO1 & BRO2) and thermo-mechanical solder bond fatigue leading to series resistance increase (all models: G, BRO1, BRO2 & H).
- Soiling loss: Average soiling loss is 5.5% (Model H; 1-axis; urban surrounding), 6.9% (Model G; 1-axis; rural surrounding) and 11.1% (Models BRO1 & BRO2; horizontal; urban surrounding)