Time-dependent Reliability Analysis of Nuclear Hybrid Energy Systems

Askin Guler Yigitoglu
Advanced Reactor Engineering
Reactor and Nuclear Systems Division
Co-authors: M. Scott Greenwood, T. Jay Harrison

PSAM 14, Los Angeles, California
September 20, 2018

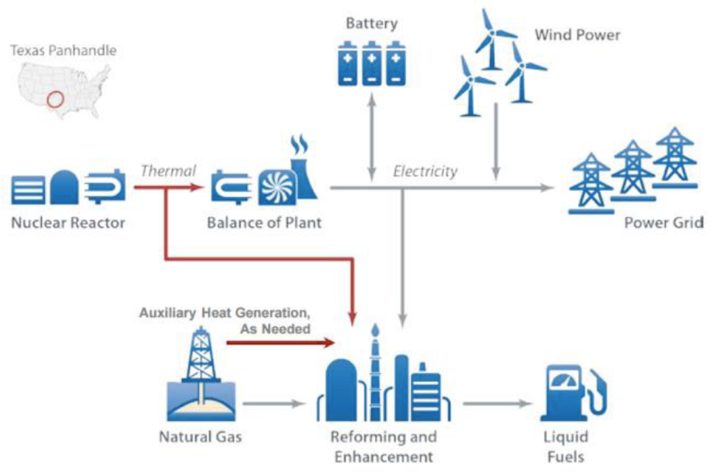
Motivation

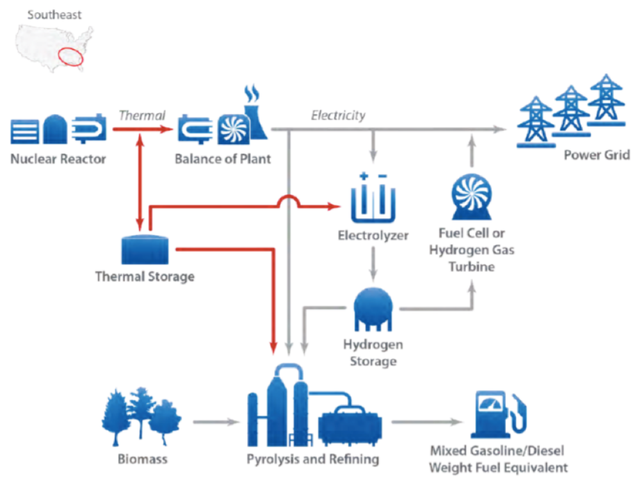
NHES design provides grid flexibility (baseload and load-following capabilities) while improving the economic performance of the overall system. Figures of merits (FOMs) were identified at the 2014 INL-NREL workshop[1]

- **Technical** (electric power frequency stability, load following response, response time and ramp-rate)
- **Economical** (net present value, internal rate of return)

The primary FOM driving the design optimization process is the **total energy cost**.

Reliability introduced as a metric at the design level to minimize reliability-related (operational and maintenance) costs over lifecycle cost by assuring reliable operation of the NHES





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Reliability as a New Figure of Merit

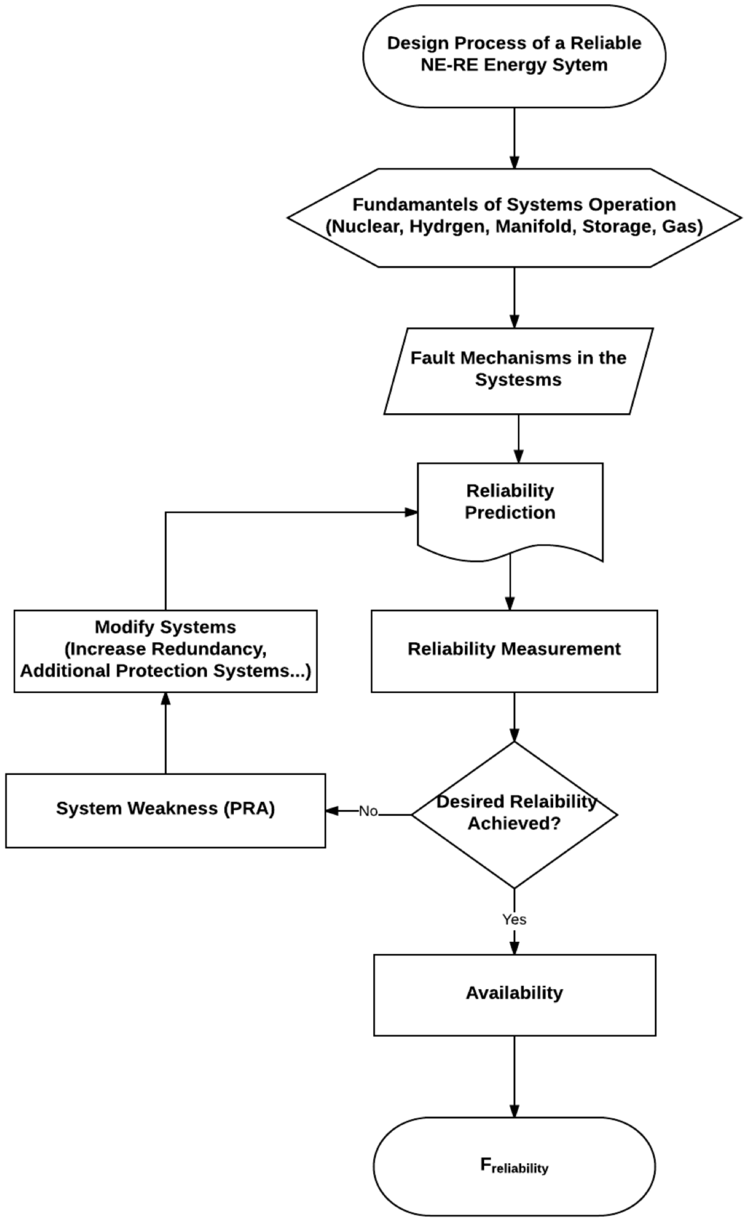
Aims to develop reliability analysis framework to track the simulated condition of a component to identify its departures from normal operation, to update the change in failure rates at each time step, and then to map this into a cost optimization model.

Three level of reliability assessment under development:

1. Component Reliability (Bayesian-Weibull Model)

2. Subsystem Reliability (includes subsystems interactions) via stochastic petri nets models

3. NHES System Reliability using PRA (fault tree/event tree)



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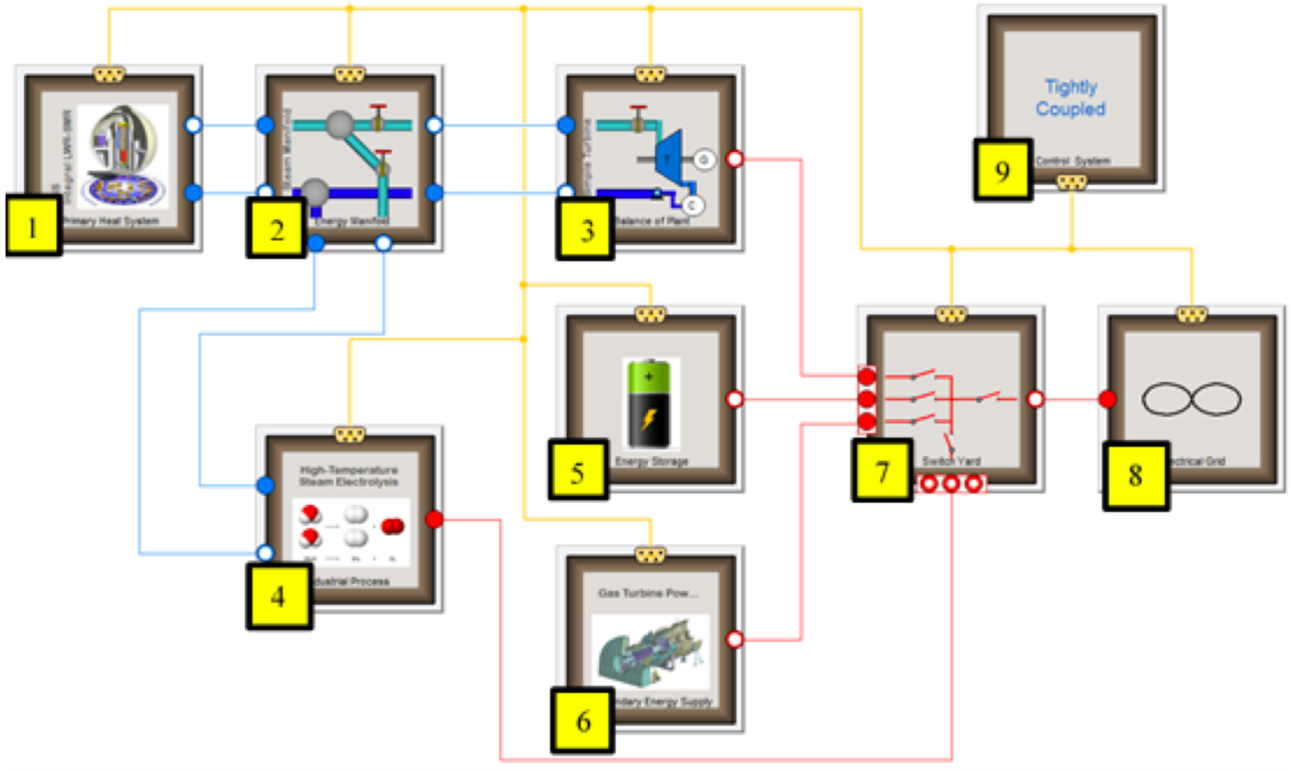
Nuclear Hybrid Energy System Configuration

The Modelica simulation of the NHES captures the typical dynamic characteristics of the selected component and the model used to predict system performance.



1 Primary heat system
2 Energy manifold
3 Balance of plant
4 Industrial process
5 Energy storage
6 Secondary energy supply
7 Switchyard
8 Electrical grid
9 Control system center

Fluid

Electricity

Sensor/control signal

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Component Reliability Model

The procedure of the component reliability analysis method is including four main steps:

1. Create synthetic operational time series data or gather from Modelica

2. Fit the data set to the Weibull distribution and determine scale and shape parameter

$$f(t|\beta,\eta) = \frac{\beta}{\eta^{\beta}} t^{(\beta-1)}\, exp\left\{-\left(\frac{t}{\eta}\right)^{\beta}\right\}, \eta > 0, \text{and } \beta > 0$$

3. Model accuracy tests on the distribution to determine the acceptance of the statistical model

4. Calculate MTBF, reliability and availability metrics

$$R(t) = 1 - P(T \leq t) = 1 - F(t|\beta,\eta) = exp\left\{-\left(\frac{t}{\eta}\right)^{\beta}\right\}$$

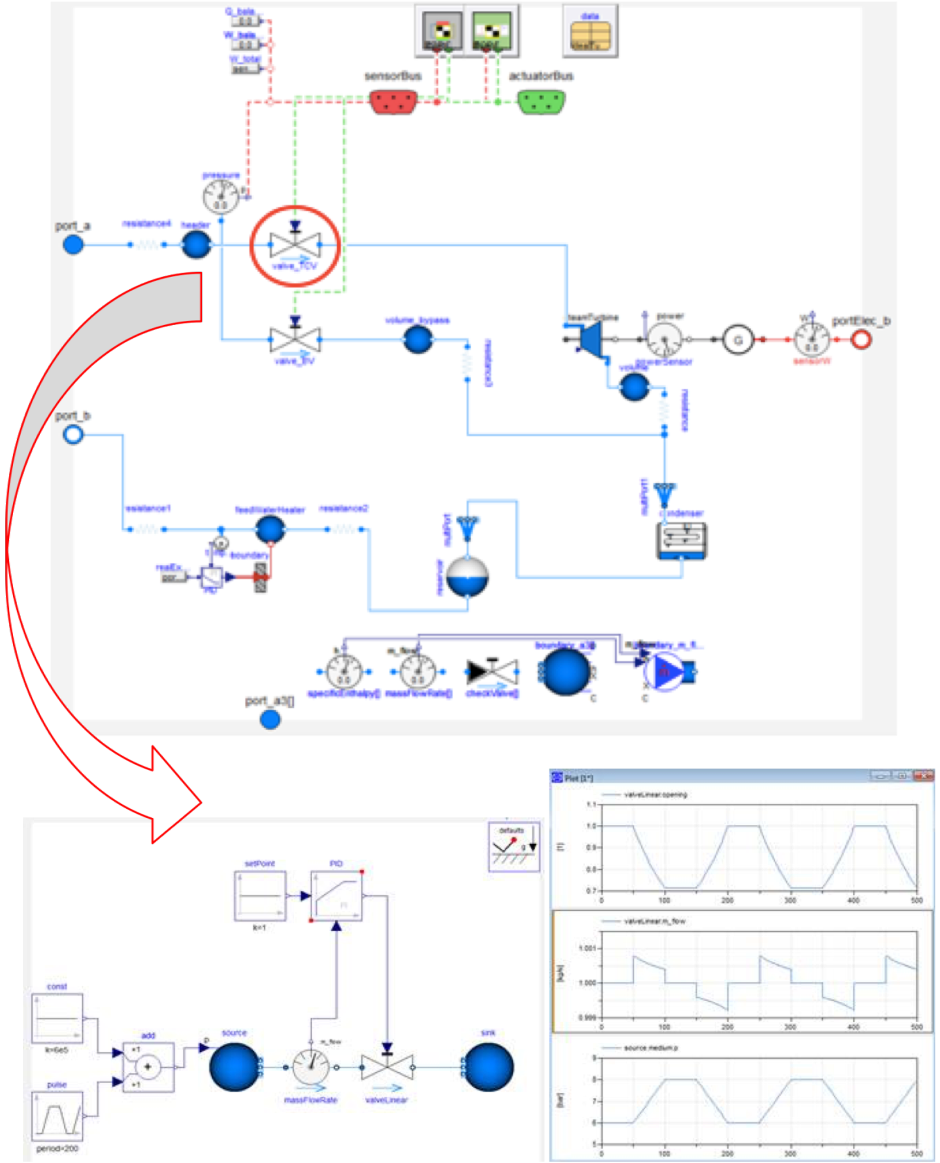
Demonstration Case

Dynamic characterization of turbine control valve (TCV) reliability performance measurements are calculated and updated

Input: Time-Dependent Load & Component Operational Data

- The maximum and minimum values for the valve positioning and minimum amount of occurrences for each period are considered, stated percentage of the maximum frequency at the histogram.
- The TCV valve has a time requirement of 0.3s and this defines functional thresholds for failure state.

Output: Time Dependent Failure Probability on Demand & Economical Value

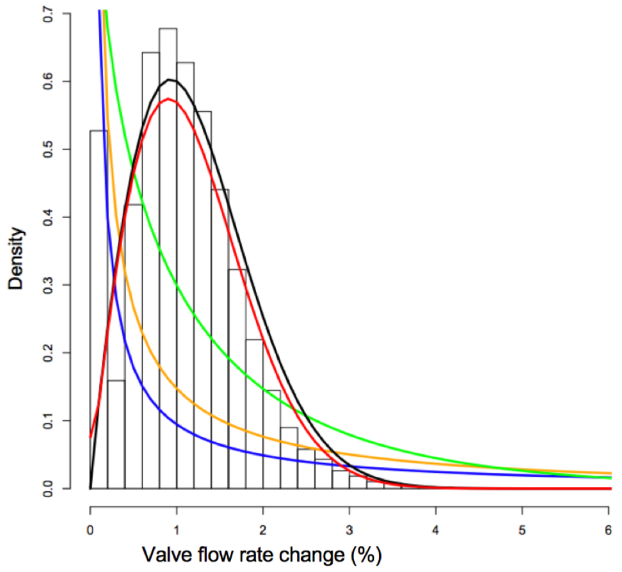


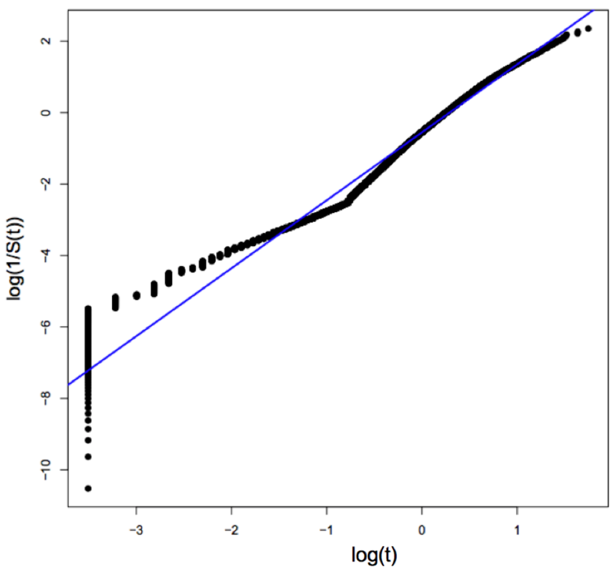
TCV Reliability Results

Weibull Parameters and Reliability Estimations

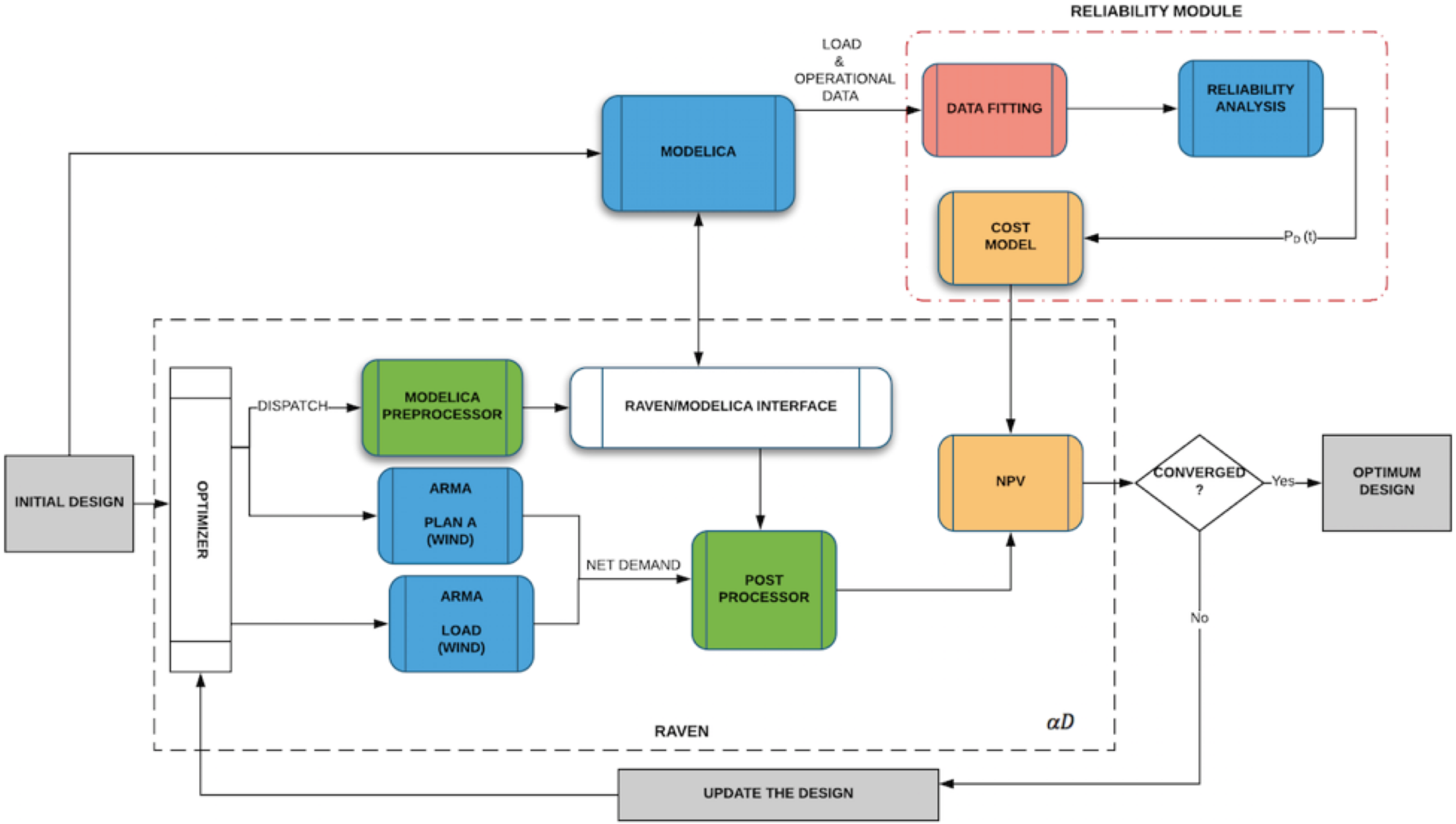
Time Interval	Beta (β)	Eta (η) hours	R (%)
Period #1	1.358	90,129	76.63
Period #2	1.372	79,797	69.26
Period #3	1.383	68,854	63.71

Characteristic life time of the component for different time histories calculated as 10.29, 9.11 and 7.86 years.





Reliability Module Integration into Optimization



Reliability Related Cost

Glasser's optimum replacement equation:

$$O_r = \frac{C_p * e^{-(t/\eta)^\beta} + C_{up} * \left(1 - e^{-(t/\eta)^\beta}\right)}{\int_0^t e^{-(t/\eta)^\beta}\, dx}$$

For the computation of the NPV, a weighted average cost of capital (WACC) of 5% has been assumed. The reference for this cash flow is a 1100MWe plant that has yearly fixed O&M cost of $93.5 million.

$$NPV_c = \lambda_c CF - \sum_i \left[\frac{(t_i+t_0)^{\beta_c}}{(1+DR)^i} - \frac{(t_{i-1}+t_0)^{\beta_c}}{(1+DR)^i}\right]$$

Planned and Unplanned Cost Estimation and NPV Changes

	Planned Replacement Cost ($) C_p	Unplanned Replacement Cost ($) C_{up}	Optimum Interval (Years)	NPV change
Period #1	250,000	400,000	5.83	-3,484%
Period #2	250,000	400,000	5.21	-4,171%
Period #3	250,000	400,000	3.73	-4,633%

Week-long Modelica Run

Weibull parameters and failure rate estimations with Bayesian estimation

Time Interval	β	η hours	λ	E[λ|z] with Uniform ($\beta = 1.35, 1.4$)
Period #1	1.358	90,129	1.109E-05	**1.491E-05**
Period #2	1.372	79,797	1.253E-05	**1.543E-05**
Period #3	1.383	68,854	1.452E-05	**1.652E-05**

Weibull parameter and failure rates with Bayesian estimation for week-long data

Time Interval	η hours	E[λ|z] with Uniform ($\beta = 1.35, 1.4$)	P-Value
Period #1	69.67	**1.74E-05**	**0.69**
Period #2	81.22	**9.87E-06**	**0.51**
Period #3	150.38	**3.15E-07**	**0.99**
Period #4	117.63	**6.29E-07**	**0.82**
Period #5	125.74	**4.97E-07**	**0.54**
Period #6	121,85	**5.24E-07**	**0.68**
Period #7	76.94	**6.52E-06**	**0.51**

Acknowledgement

Additional laboratory participation:

- C. Rabiti, A. Epiney, P. Talbot, J. S. Kim, S. Bragg-Sitton, A. Alfonsi (INL)
- R. Ponciroli, R. Vilim, G. Maronati, F. Ganda (ANL)

This project was funded by the US Department of Energy's Office of Nuclear Energy under the Office of Advanced Reactor Deployment.

Questions?

Contact me at **yigitoglua@ornl.gov**