



U.S. DEPARTMENT OF
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Office Of Nuclear Energy Sensors and Instrumentation Annual Review Meeting

Enhanced Risk Monitors with Integrated Equipment Condition Assessment

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■ Project Overview

■ Technical Details

- Objective
- Scope
- Technical Approach

■ Significant Accomplishments

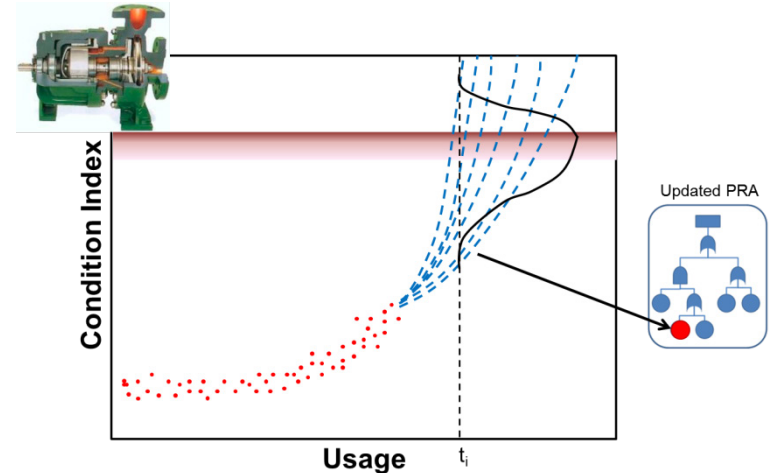
■ Path Forward and Expected Outcomes



Work Package AT-15PN230105 – Enhanced Risk Monitors with Integrated Equipment Condition Assessment - PNNL

Task Relevancy

- **Enhanced risk monitors that incorporate real-time equipment condition information help control O&M costs and improve affordability of Advanced Reactors**
 - Characterize real-time risk of operating with degraded components – optimize operation planning and maintenance scheduling
 - New risk metrics provide quantitative basis for trading off between different operational modes while maintaining safety margins
 - Offset limited advanced reactor component reliability data by providing tools for assessing risk (safety, economics, regulatory compliance) when operating with new component designs



Technical Approach, Accomplishments/Results

- **Enhanced risk monitors (ERM) methodology integrating equipment condition assessment (ECA), prognostic health management (PHM), and risk monitors**
- **Augment ERM to include uncertainty bounds and new risk metrics; validate using simulations and experimental data**
- **Accomplishments: Developed initial ERM methodology integrating ECA, PHM and risk monitors and evaluated impact of input uncertainty on predicted risk for a simplified Advanced SMR design**
- **Results indicate predicted risk metric (core damage frequency) varies with time and is affected by inspection frequency, inspection effectiveness, and maintenance effectiveness**
 - Uncertainty bounds for predicted risk impact decisions on operations and maintenance scheduling

Expected Deliverable & Schedule

- **Non-traditional risk metrics, including economic metrics and safety metrics – 9/30/2014**
- **Complete recommendations for integrating with O&M – FY2015 (April 2015)**
- **Complete prototypic ERM framework and evaluation (using available data sets) – FY2015 (September 2015)**

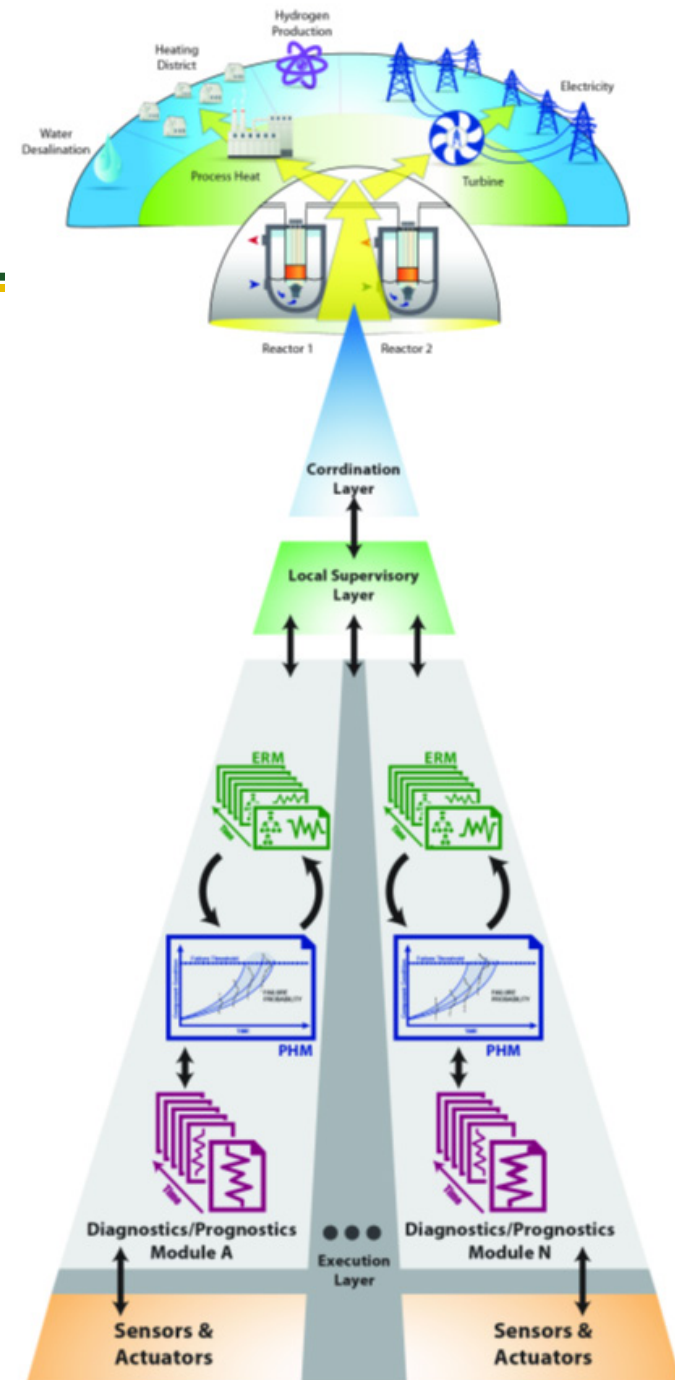


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Objective

- **Predictive risk framework for advanced reactors that integrates real-time assessments of equipment condition, predicted probabilities of failure, and risk monitors**
 - Enhanced risk monitor (ERM)
 - Equipment condition assessment – real-time component health
 - Prognostic health management – predicted probabilities of failure
 - Probabilistic risk assessment – risk monitors





Technology Impact

- **Characterize real-time risk of operating with degraded components – optimize operation planning and maintenance scheduling**
- **New risk metrics provide quantitative basis for trading off between different operational modes while maintaining safety margins**
- **Offset limited advanced reactor component reliability data by providing tools for assessing risk (safety, economics, regulatory compliance) when operating with new component designs**



PRA, Dynamic PRA, and Risk Monitors

■ Risk: Measure of the probability of some undesirable consequence

- Core damage frequency, large early release frequency, health consequences to the public

■ PRA and Dynamic PRA

- Event tree, fault tree
- Simulation-based PRA

■ Risk monitors extend PRA to reflect changing plant configuration

- Equipment unavailability

■ Current risk monitors do not take the actual condition of SSCs when evaluating risk

- Population-based event and probabilities of failure (POF) are used
- Passive component failures are largely excluded from risk monitors (except as initiating events)

EE	SGL	RVACS	SEQUENCE OUTCOM	SEQ. PROB	SEQ. NAM
External Event - Plug/Failure of RVAC	Steam Generator Louver	Reactor Vessel Auxiliary Cooling			
EE			no CD	0.00E+00	10
			no CD	0.00E+00	
			CD	0.00E+00	

Simplified Reactor PRA Event Tree



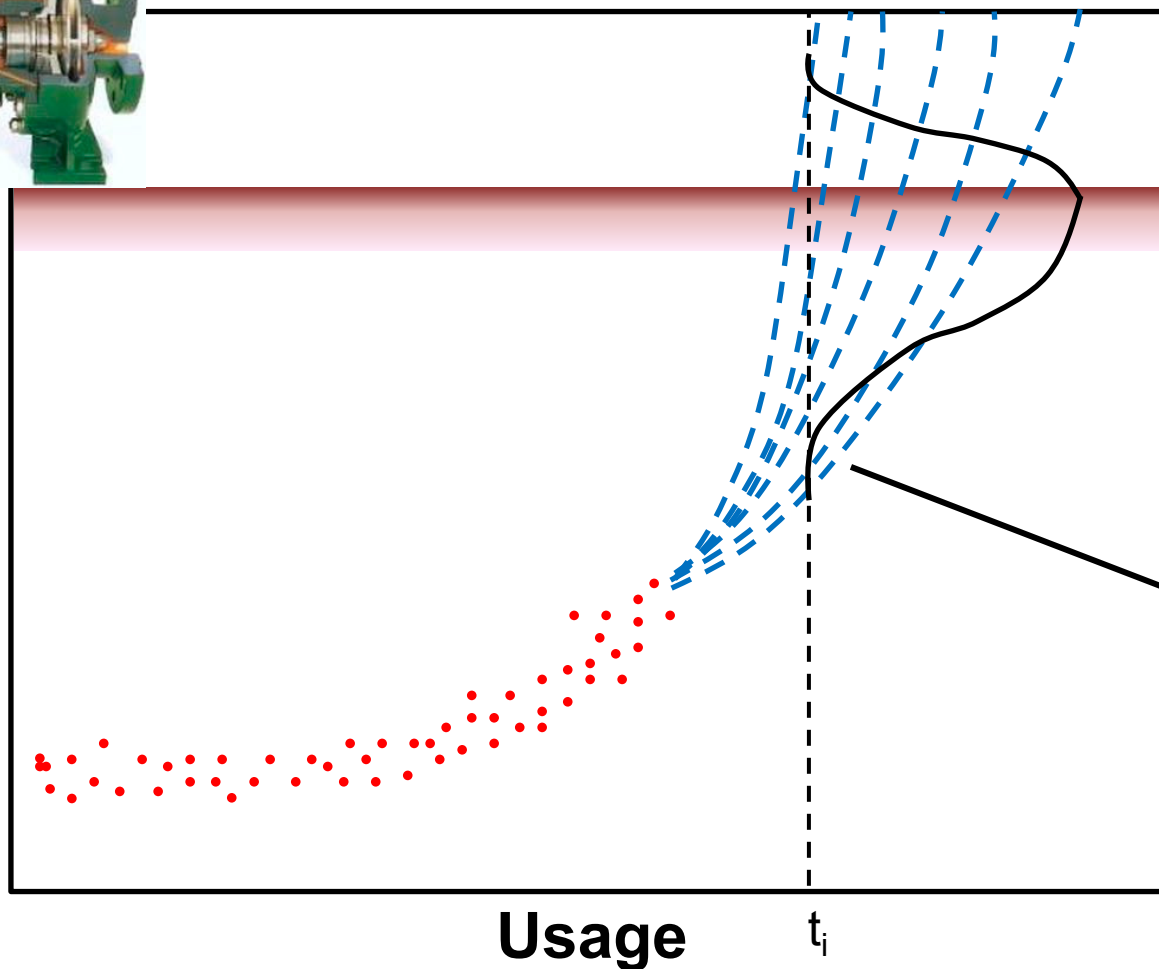
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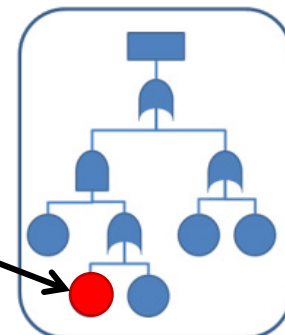
Enhanced Risk Monitors Use Predicted POF using Actual Component Condition and are Updated in Real-time



Condition Index



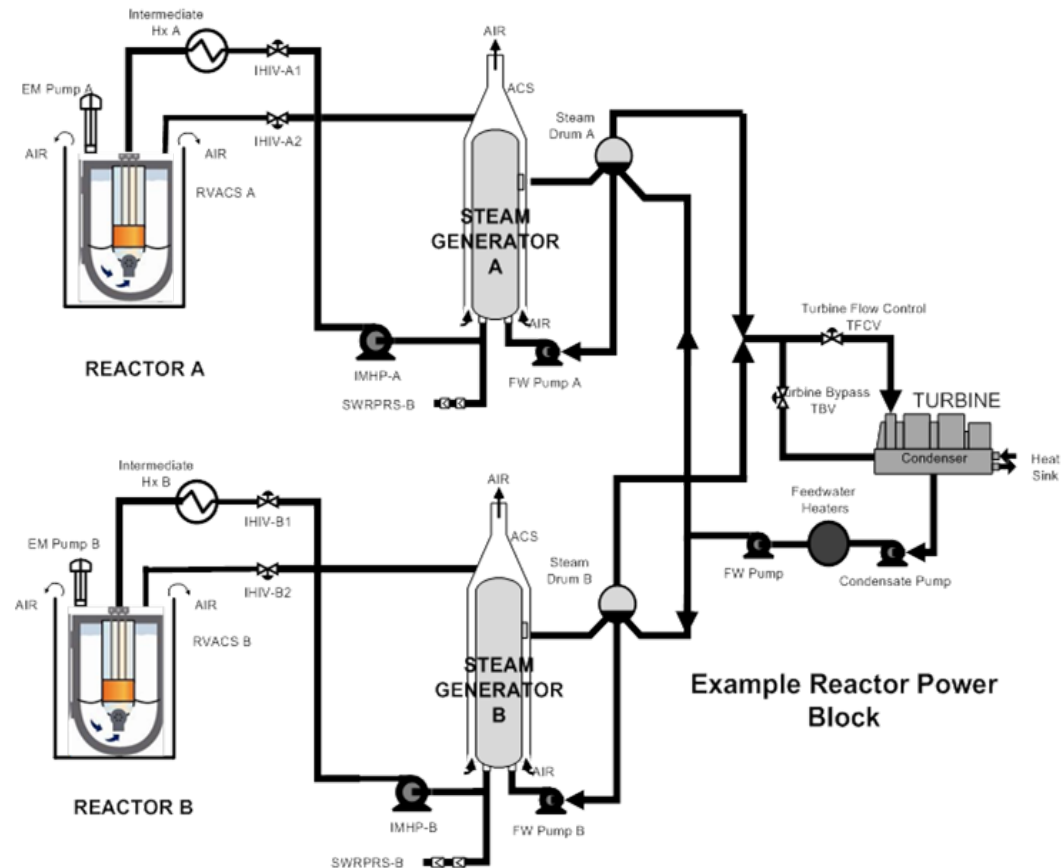
Updated PRA





Case Study of ERM Applied to a Simplified AdvSMR Design

- Each reactor module is connected to a dedicated steam generator
 - Liquid metal reactor modules
- Two reactor module/steam generators are connected to a common balance of plant
- Focus of project on active component failures
 - Basic methodology may be extended to include passive component failures





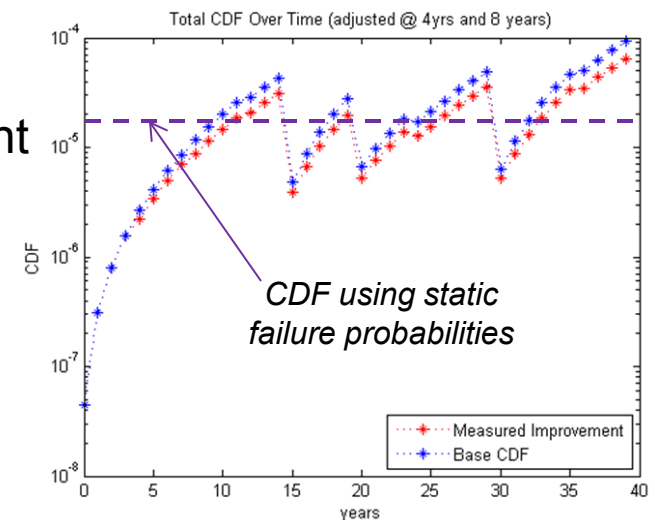
Initial PRA Model Consisted of a Number of Cutsets that Lead to Core Damage

■ Each cutset leads to core damage in one of the two reactor modules

- Probability of damage in both modules from a single initiation event is assumed to be small enough to ignore
- Cutsets are repeated for each module

■ Total core damage frequency (CDF) predicted over time

- Base case: Information at plant start-up, with are shown for time-dependent (linear) failure probabilities for each component
- Staggered periodic maintenance activities assumed to return equipment to like-new condition
- Condition assessment of SG louver at 4 and 8 years changes predicted risk

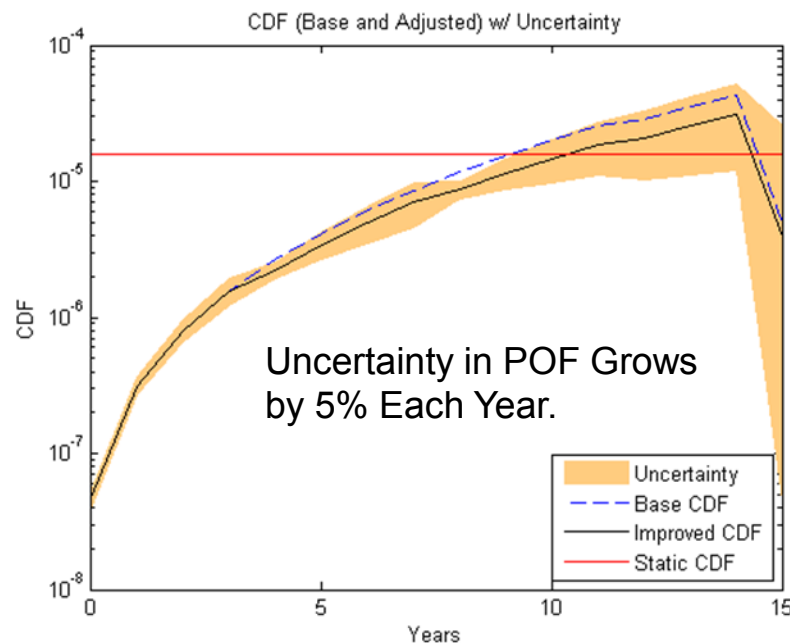
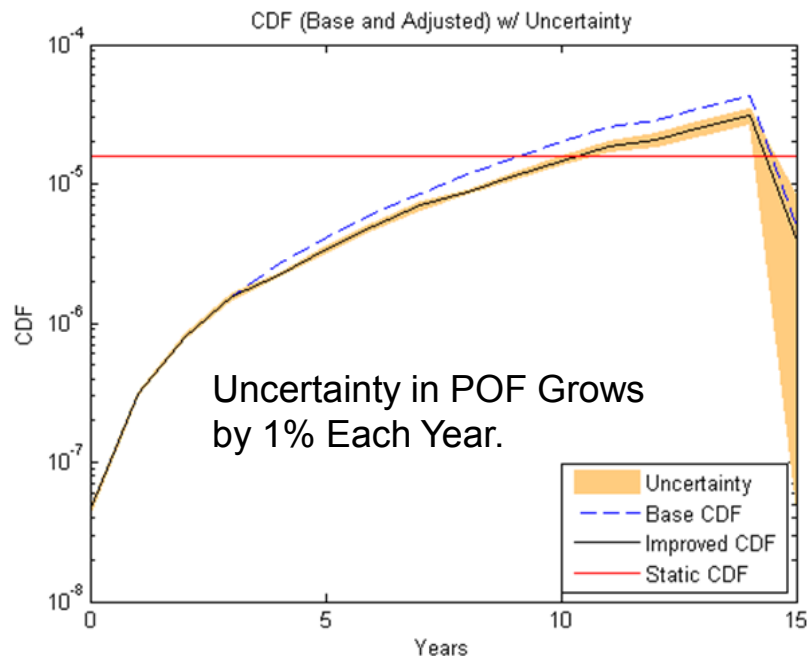




ERM Provides Mechanism for Dynamically Updating Total Risk and Computing Safety Margins

■ Uncertainties in condition estimates impact predicted failure probabilities, and predicted risk

- Impact to safety margin, O&M decision-making





Accomplishments

■ Developed initial ERM methodology for predictive risk estimates

- Actual component condition used to predict component failure probabilities over given time horizon
- Methodology for incorporating predicted component failure probabilities into risk monitors – enables predictive risk calculations over given time horizon
- Uncertainty propagation in risk estimates
- Non-traditional risk metrics

■ Research to date documented in:

- Technical Report PNNL-22377 R0 (SMR/ICHMI/PNNL/TR-2013/02)
- Technical Report PNNL-22752 R0 (SMR/ICHMI/PNNL/TR-2013/05)
- Technical Report PNNL-23478 R0 (SMR/ICHMI/PNNL/TR-2014/01)



SMR/ICHMI/PNNL/TR-2014/01



Accomplishments – Publications and Presentations

- Coble JB, GA Coles, RM Meyer, and P Ramuhalli, "Incorporating Equipment Condition Assessment in Risk Monitors for Advanced Small Modular Reactors," In *Chemical Engineering Transactions*, vol. 33, pp. 913-918, 2013. doi:10.3303/CET1333153.
- Coble JB, GA Coles, RM Meyer, and P Ramuhalli, "Enhanced Risk Monitors With Integrated Online Equipment Condition Monitoring for Improved Risk Management," Presented at *ANS Utility Working Conference*, Hollywood, FL, August 13, 2013.
- JB Coble (Univ. of TN), GA Coles, RM Meyer, P Ramuhalli, "On Enhancing Risk Monitors for Advanced Small Modular Reactors," Presented at *ANS Winter Meeting 2013*, Washington DC, 2013.
- P Ramuhalli, GA Coles, EH Hirt, RM Mayer, JB Coble, R Wood, "Controlling O&M Costs of Advanced SMRs using Prognostics and Enhanced Risk Monitoring" *Nuclear Plant Journal*, Vol. 32 No.1, pp 42-44, Jan-Feb, 2014.
- Ramuhalli P, CA Bonebrake, WJ Ivans, Jr, EH Hirt, and GA Coles, "Enhanced Risk Monitoring - Potential Application to Surveillance Test Interval Extension," Presented at *Nuclear Energy Institute (NEI) Working Group (WG)* meeting on NRC Initiative 5b, Online WG meeting, on April 15, 2014.
- WJ Ivans, "Introduction to Predictive Risk Estimation: Methods and Applications," Tutorial Presented at *IEEE Int'l. Conf. on Prognostics Health Management 2014*, Cheney WA, June 2014.
- DW Wootan, P Ramuhalli, GA Coles, EH Hirt, MF Brass, "Fast Flux Test Facility Experience Relevant to AdvSMR Enhanced Risk Monitoring," Abstract accepted for *ANS NPIC-HMIT 2015*.
- CA Bonebrake, P Ramuhalli, WJ Ivans, GA Coles, EH Hirt, "Addressing Uncertainty in Predictive Estimates of Risk," Abstract accepted for *ANS NPIC-HMIT 2015*.
- CA Bonebrake, P. Ramuhalli, WJ Ivans, GA Coles, EH Hirt, "Evaluation of Enhanced Risk Monitors for use on Advanced Small Modular Reactors," To be Submitted to *IEEE Transactions on Reliability*.



■ FY2014:

- Assessment of ERM framework incorporating online condition assessment for key components
- Uncertainty quantification for risk measures
- Investigation of alternative risk measures

■ FY2015:

- Complete prototypic ERM framework development and evaluation
 - Uncertainty quantification for measurement noise, model errors, unknown future load, POF distributions, etc.
 - Incorporate dynamic success criteria that may result from AdvSMR concepts of operation
 - Leverage developments in prognostics for passive components, and potentially include some passive components in full ERM analysis
- Define requirements for integrating with O&M tools



Conclusion

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- **Research focused on addressing high-impact technical gaps to developing real-time predictive risk monitors for advanced reactors**
 - Enhanced risk monitors for active components in advanced reactors (AR) designs by integrating real-time information about equipment condition and predicted failure rates.
 - **Outcomes enable**
 - Real-time assessment of advanced reactor operational risk based on component degradation condition.
 - Tools for quantifying changes in risk and trading off between different operational modes while maintaining overall safety margins
 - **Outcomes support**
 - Improved reliability and economics for advanced reactors