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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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September 16-18, 2014

Outline

- **Project Overview**
- **Technical Details**
  - Objective
  - Scope
  - Technical Approach
- **Significant Accomplishments**
- **Path Forward and Expected Outcomes**

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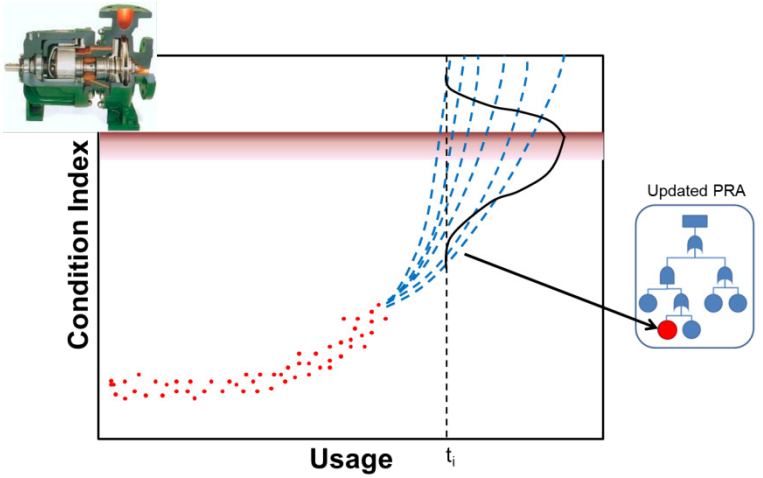
Work Package AT-15PN230105 – Enhanced Risk Monitors with Integrated Equipment Condition Assessment - PNNL

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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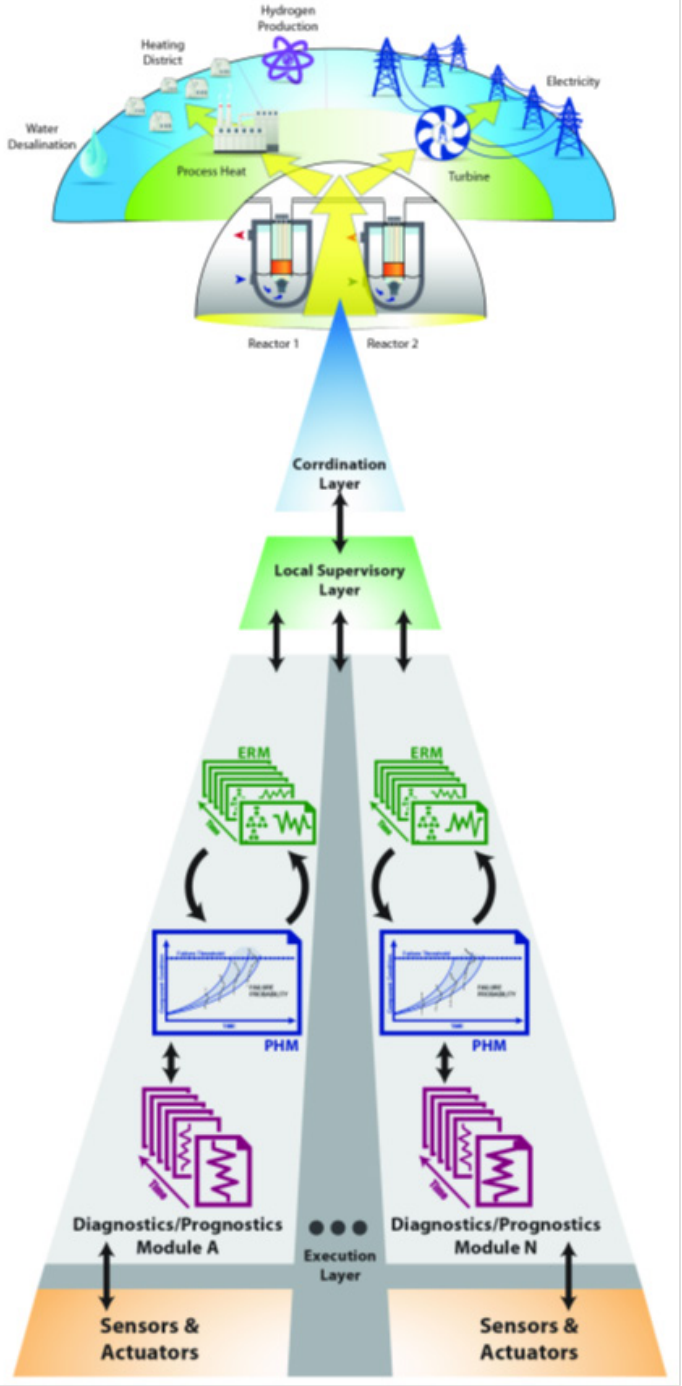
Objective

- **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
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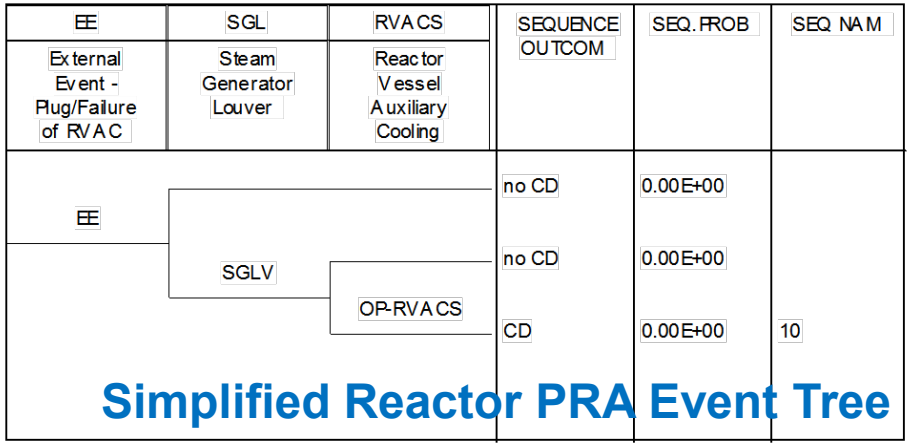
PRA, Dynamic PRA, and Risk Monitors

- **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)



Simplified Reactor PRA Event Tree

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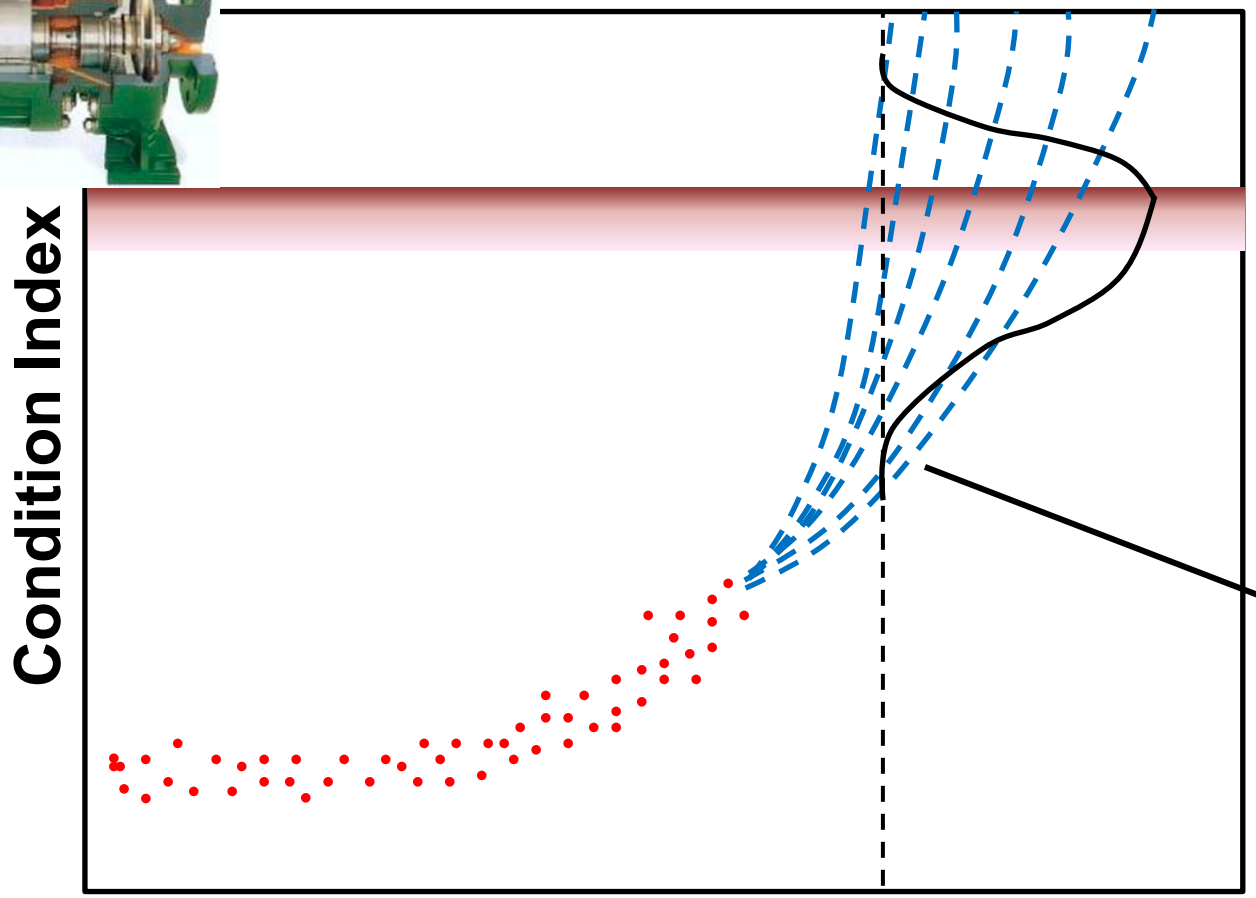
Enhanced Risk Monitors Use Predicted POF using Actual Component Condition and are Updated in Real-time



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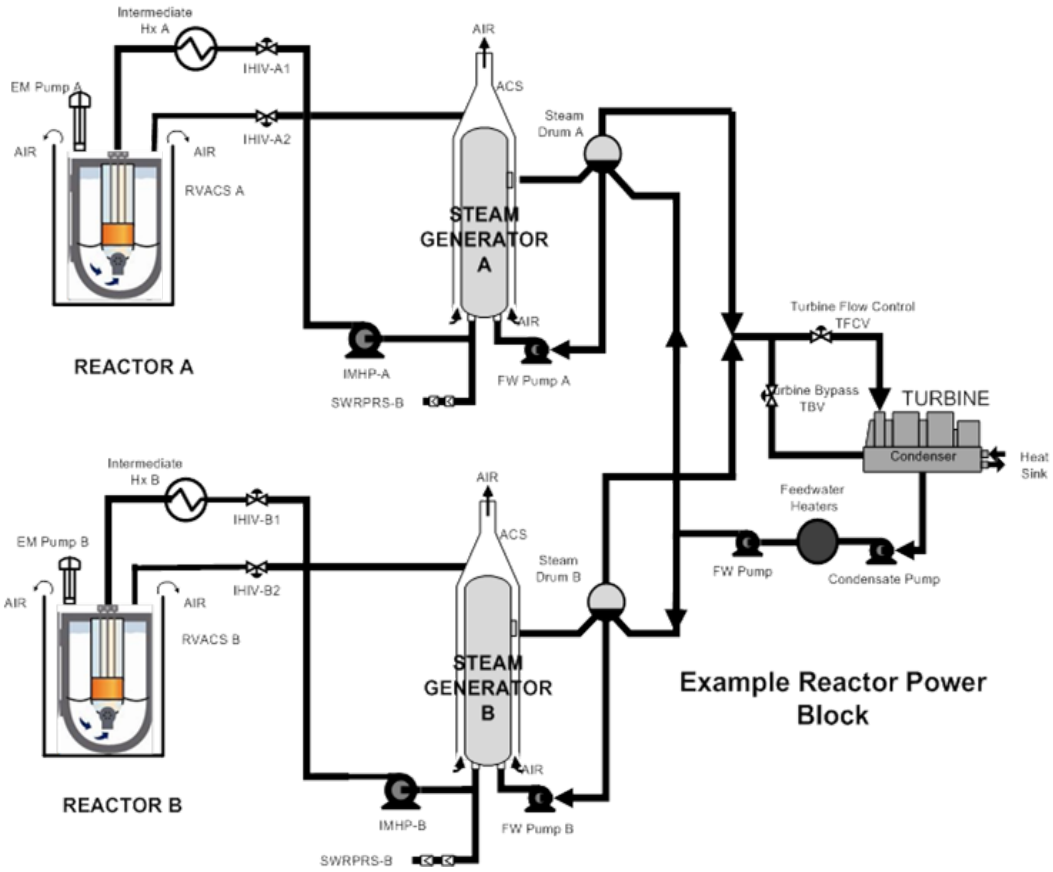
Case Study of ERM Applied to a Simplified AdvSMR Design

- **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



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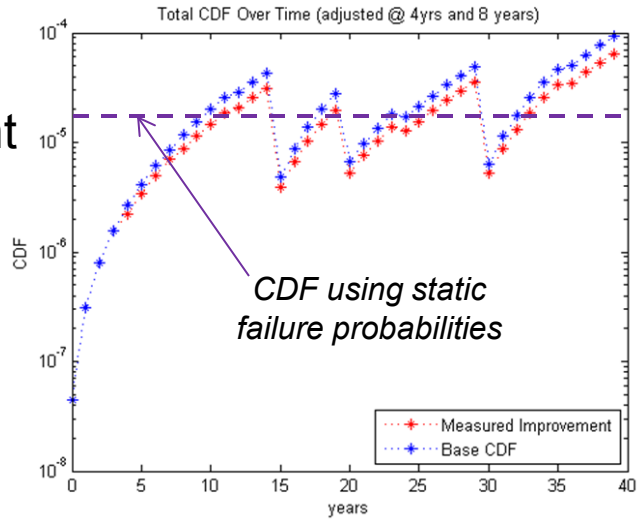
Initial PRA Model Consisted of a Number of Cutsets that Lead to Core Damage

- **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



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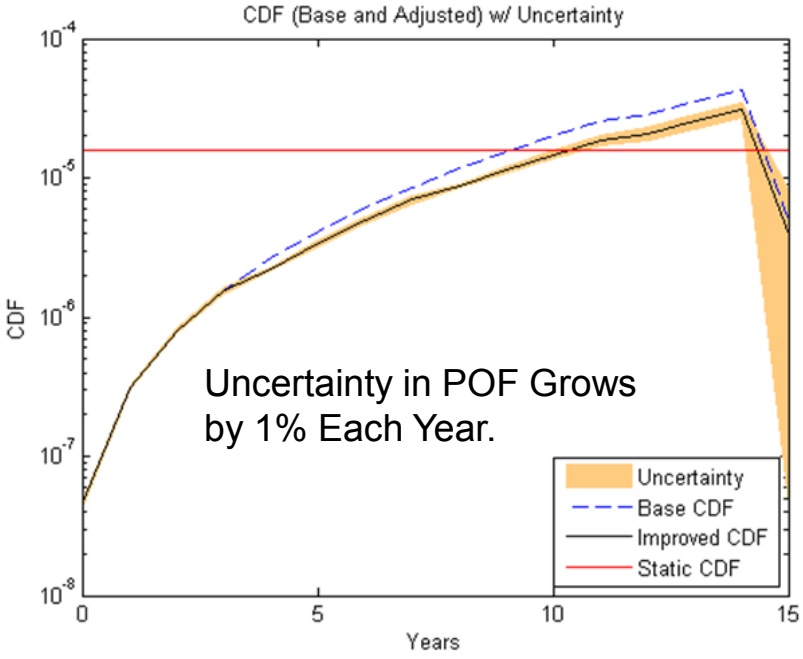
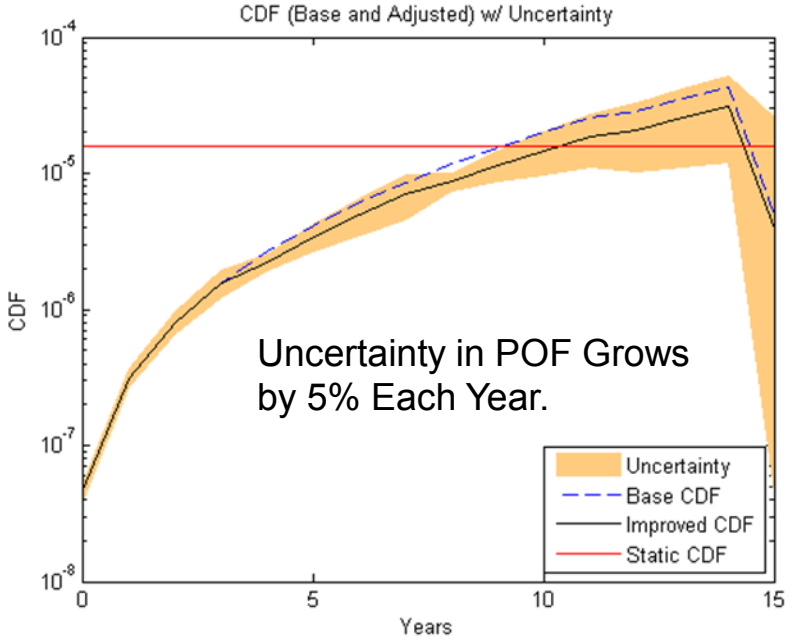
ERM Provides Mechanism for Dynamically Updating Total Risk and Computing Safety Margins

- **Uncertainties in condition estimates impact predicted failure probabilities, and predicted risk**
  - Impact to safety margin, O&M decision-making





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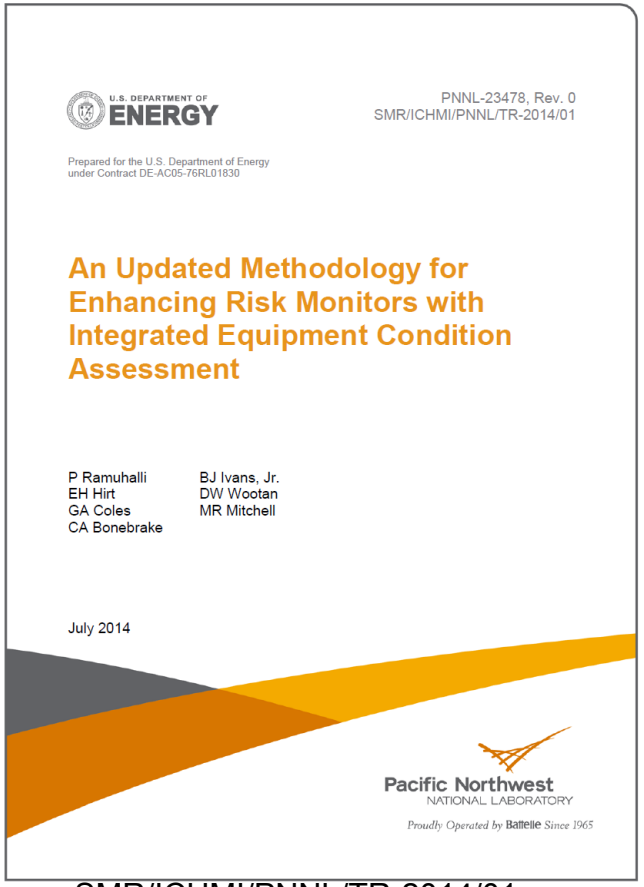
Accomplishments

- **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

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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*.

Path Forward

- **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

- **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