PNNL-SA-114069

U.S. DEPARTMENT OF ENERGY | Nuclear Energy

Office Of Nuclear Energy Sensors and Instrumentation Annual Review Meeting

Enhanced Risk Monitors with Integrated Equipment Condition Assessment

Pradeep Ramuhalli, Arun Veeramany, Christopher Bonebrake, William Ivans, Garill Coles, David Wootan, Evelyn Hirt, Jamie Coble*, Xiaotong Liu*
Pacific Northwest National Laboratory
* University of Tennessee

Advanced Reactor Technologies Program

October 28-29, 2015

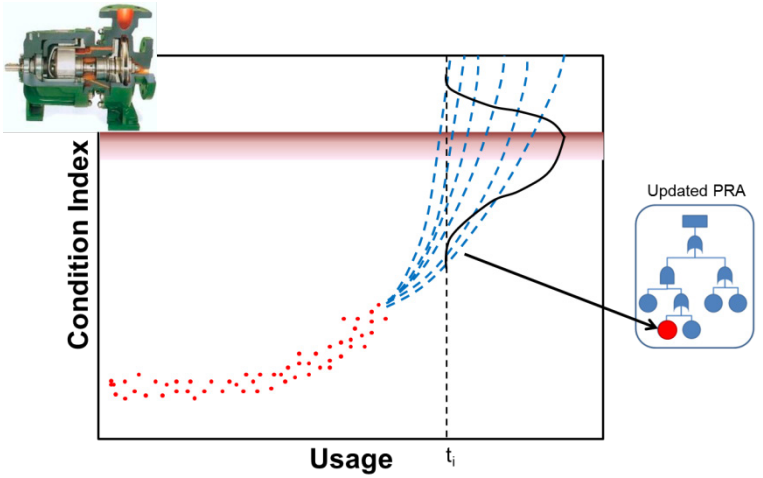
U.S. DEPARTMENT OF ENERGY

Nuclear Energy

Work Package AT-16PN230105 – 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**
  - Offset limited component reliability data by providing tools for assessing condition and risk (safety, economics) when operating with new SFR/HTR component designs
  - Characterize real-time risk of operating with degraded components over extended intervals likely typical of advanced reactors – optimize operation planning and maintenance scheduling
  - New risk metrics provide quantitative basis for trading off between different operational modes while maintaining safety margins



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**
- **Integrate ERM with supervisory control algorithm and evaluate using simulation platform**
- **Using a simplified SFR design concept, developed initial ERM methodology and evaluated impact of input uncertainty on predicted risk (safety and economic metrics)**
- **Results indicate predicted risk metric 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

- **Complete integration of ERM methodology into supervisory control framework (August 2016)**

Outline

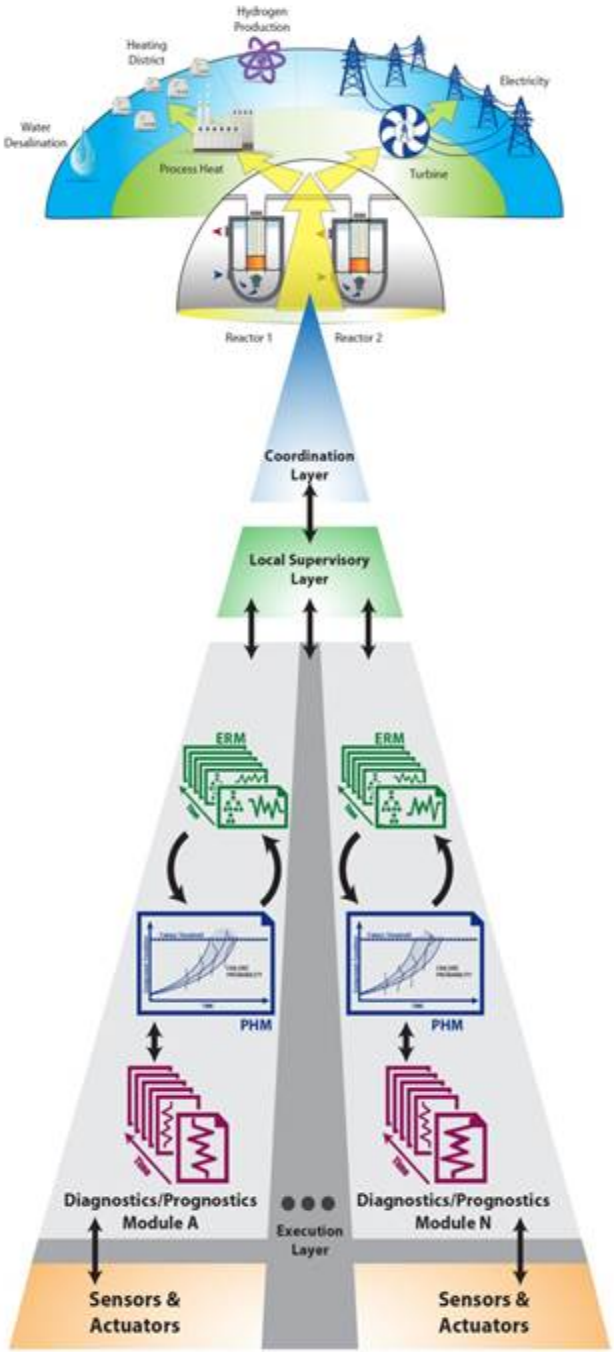
- **Project Overview**
  - Objectives
  - Background
- **Technical Details**
  - Technical Approach
  - Results
- **Significant Accomplishments**
- **Path Forward and Expected Outcomes**

U.S. DEPARTMENT OF ENERGY

Nuclear Energy

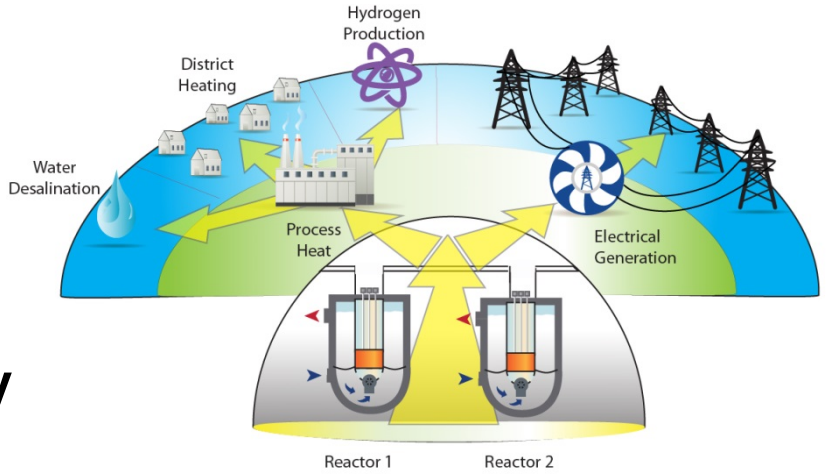
Objectives

- **Predictive risk framework for advanced reactors that integrates real-time assessments of equipment condition, predicted probabilities of failure, and risk monitors**
  - Equipment condition assessment (ECA) – real-time component health
  - Prognostic health management (PHM) – predicted probabilities of failure
  - Probabilistic risk assessment (PRA) – risk monitors
- **Enhanced risk monitor (ERM)**
  - Predictive assessment of risk based on component condition and projected failure probability over a given time horizon
  - Input to plant supervisory control system for decisions that also incorporate risk metrics



Background: Advanced Reactors

- **Non light-water coolants**
- **Higher operating temperatures**
- **New operating regimes possible**
- **Longer operating cycles between refueling and maintenance likely**
- **Consequence: components (especially in primary loop) likely to experience conditions unlike those in LWRs**
  - Will challenge ability to operate plant in a safe and economic manner



- **Ability to monitor component condition and dynamically adjust operating conditions necessary to reduce:**
  - Maintenance costs for active and passive components
  - Downtime due to unanticipated shutdown

Technology Impact

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

U.S. DEPARTMENT OF ENERGY
Nuclear Energy

Technical Approach

- **Extension of risk monitors to support integration of equipment condition information**
  - Multiple, interdependent modules
  - Common mode failures across modules
  - Accident scenarios applicable to advanced reactors
  - *Variable plant loads, which may affect success criteria*
- **Propagation of uncertainty through the ERM calculations**
- **Non-safety risk measures (e.g., economic risk)**
- **Requirements for integrating ERM into plant control and O&M practices**
- ***Condition assessment methods for active components (e.g., EM pumps)***

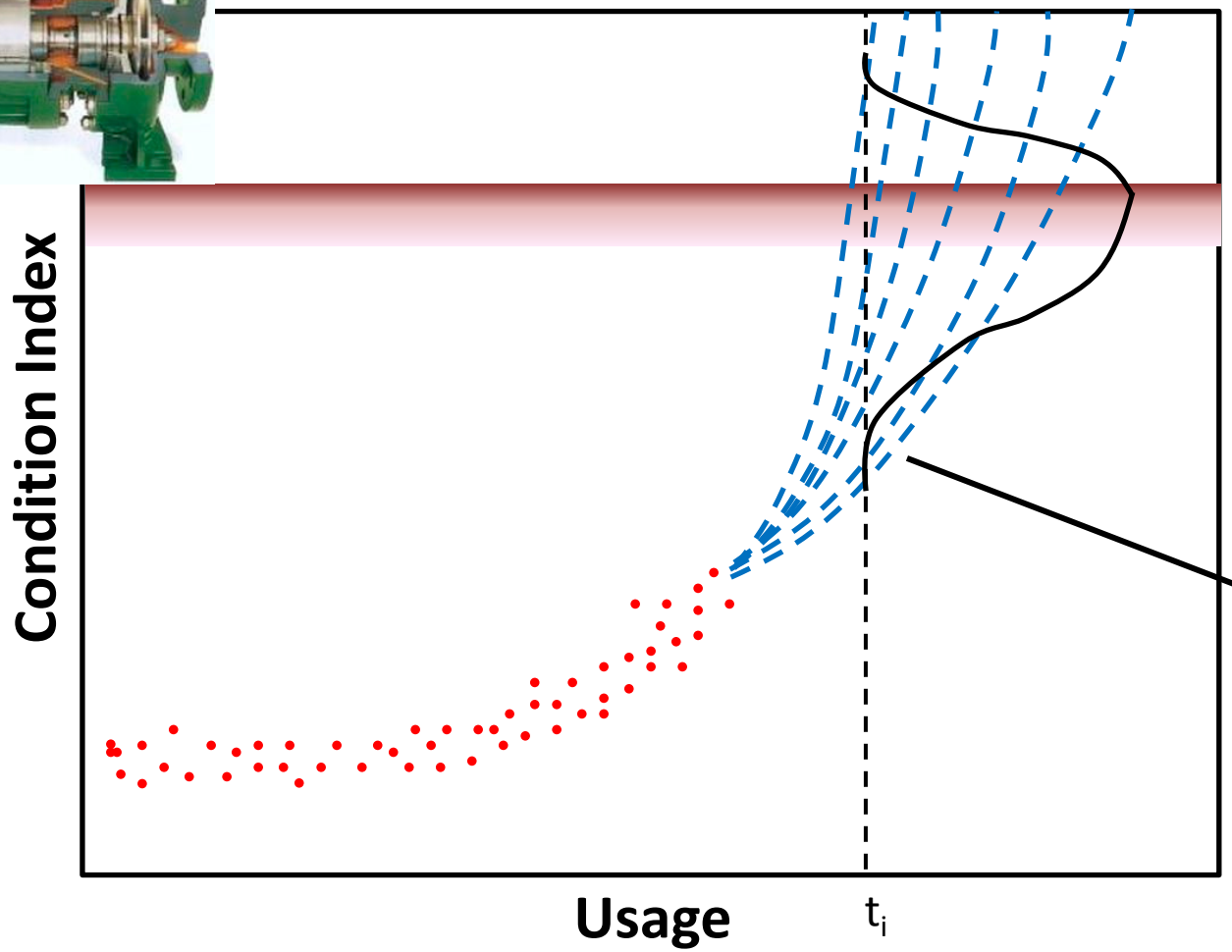
U.S. DEPARTMENT OF ENERGY
Nuclear Energy

Risk Monitors Evaluate Point-in-time Risk of Operating in Different Plant Configurations

- **Risk is a measure of the probability of some undesirable consequence**
  - Traditional nuclear power plant (NPP) risk measures: core damage frequency, large early release frequency, health consequences to the public
  - Non-safety risk measures: availability, productivity, ability to meet demand, probability of mission completion
- **Risk monitors extend PRA to reflect the dynamically changing plant configuration**
  - Equipment availability
  - Operating regime
  - Environmental conditions
- **Current risk monitors do not take the actual condition of systems, structures and components (SSCs) when evaluating risk**
  - Population-based event and failure probabilities are used
  - Passive component failures are largely excluded from risk monitors (except as initiating events)

U.S. DEPARTMENT OF ENERGY
Nuclear Energy

ERM incorporates real-time condition assessment to estimate risk



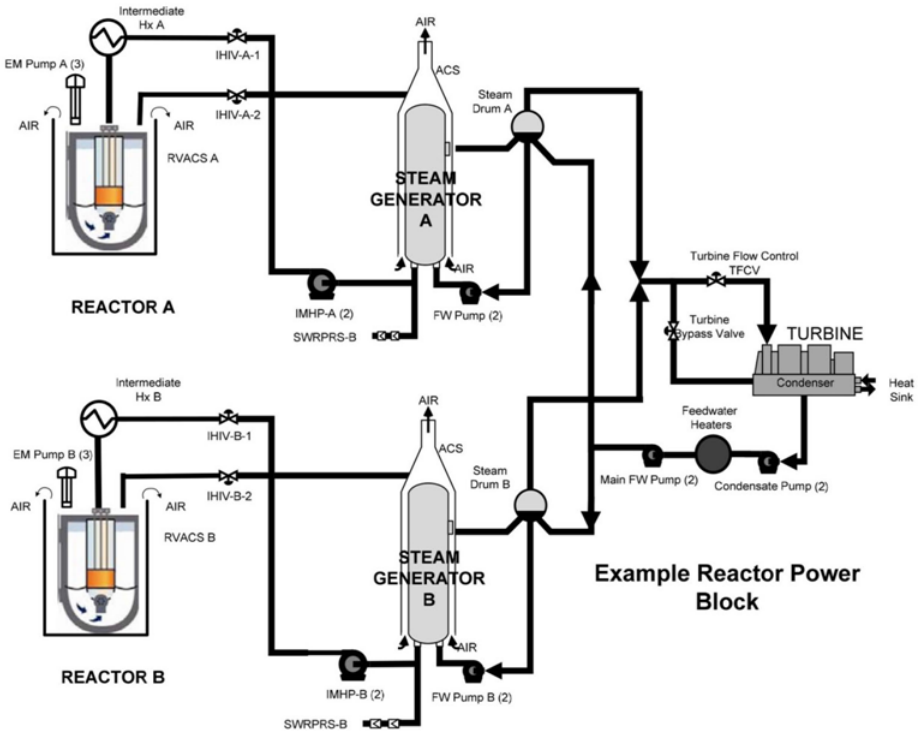
Types of Uncertainty in ERM

- **Uncertainty in component history**
  - Variability in materials and manufacturing
  - Variability in operational stresses
- **Uncertainty in calculations**
  - Estimated probabilities of failure
- **Uncertainty in measurements**
  - Calibration drift of measurement equipment
  - Accuracy of measurement method
  - Precision of measurement equipment
  - Noise (electrical, mechanical, etc.)
- **Human Error**

U.S. DEPARTMENT OF ENERGY
Nuclear Energy

Generic Nuclear Plant Model Used for Developing and Evaluating ERM

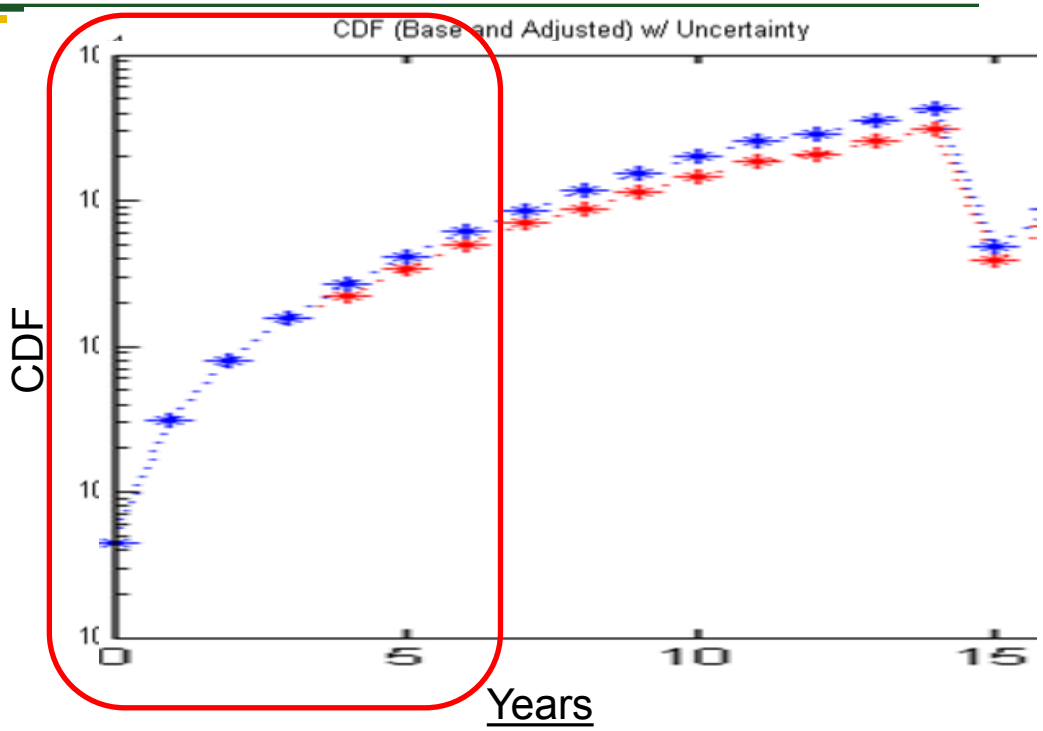
- Simple model consisting of two small reactor cores that are identical and one turbine generator
- Incorporates basic equipment and operational characteristics found in a typical plant
- Industry documented failure data was used as a starting point to define baseline initiating event and component failure probabilities



U.S. DEPARTMENT OF ENERGY
Nuclear Energy

Example: PRA Model with Cutsets Leading to Core Damage

- **Total core damage frequency (CDF) predicted over time**
  - Base case: Information at plant start-up with time-dependent 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



- **Uncertainties in condition assessment impact predicted risk uncertainty**
  - Impact to safety margin, O&M decision making

U.S. DEPARTMENT OF ENERGY
Nuclear Energy

Decision Making Using Alternate Risk Metrics

- **Motivation: Alternate metrics (such as economic risk metrics) can help**
  - Avoid unplanned outages (i.e., those outside of normal refueling operations)
  - Prioritize maintenance operations based on real-time system status, forecasted status and acceptable risk
  - Minimize the impact of maintenance operations on outage length
  - Identify those operation and maintenance strategies that not only meet safety goals but also established economic guidelines

- **Initial focus on an economic risk metric to help avoid unplanned outages**

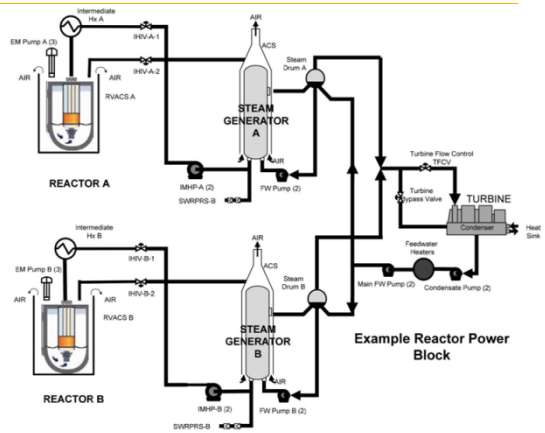
Economic Risk Metric

Approach

- Focus on combinations of equipment, the failure of which would lead to an unplanned outage

Scenario

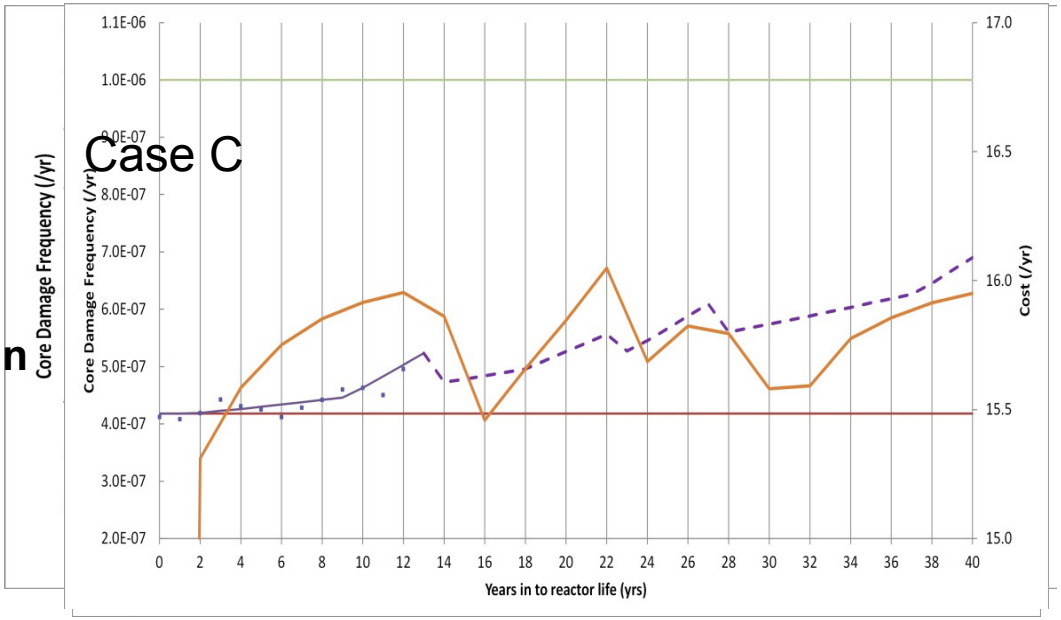
- Based on generic two-unit LMR described earlier
- Multiple active components with all possible combinations of failure
  - Example: Three pumps, of which two are required to support a particular function that supports continued operation
  - Two pumps are normally running and one is in standby
  - Failure combinations include:
    - Pump 1 fails to run and then Pump 2 fails thereafter
    - Pump 2 fails to run and then Pump 3 cannot be started thereafter



U.S. DEPARTMENT OF ENERGY
Nuclear Energy

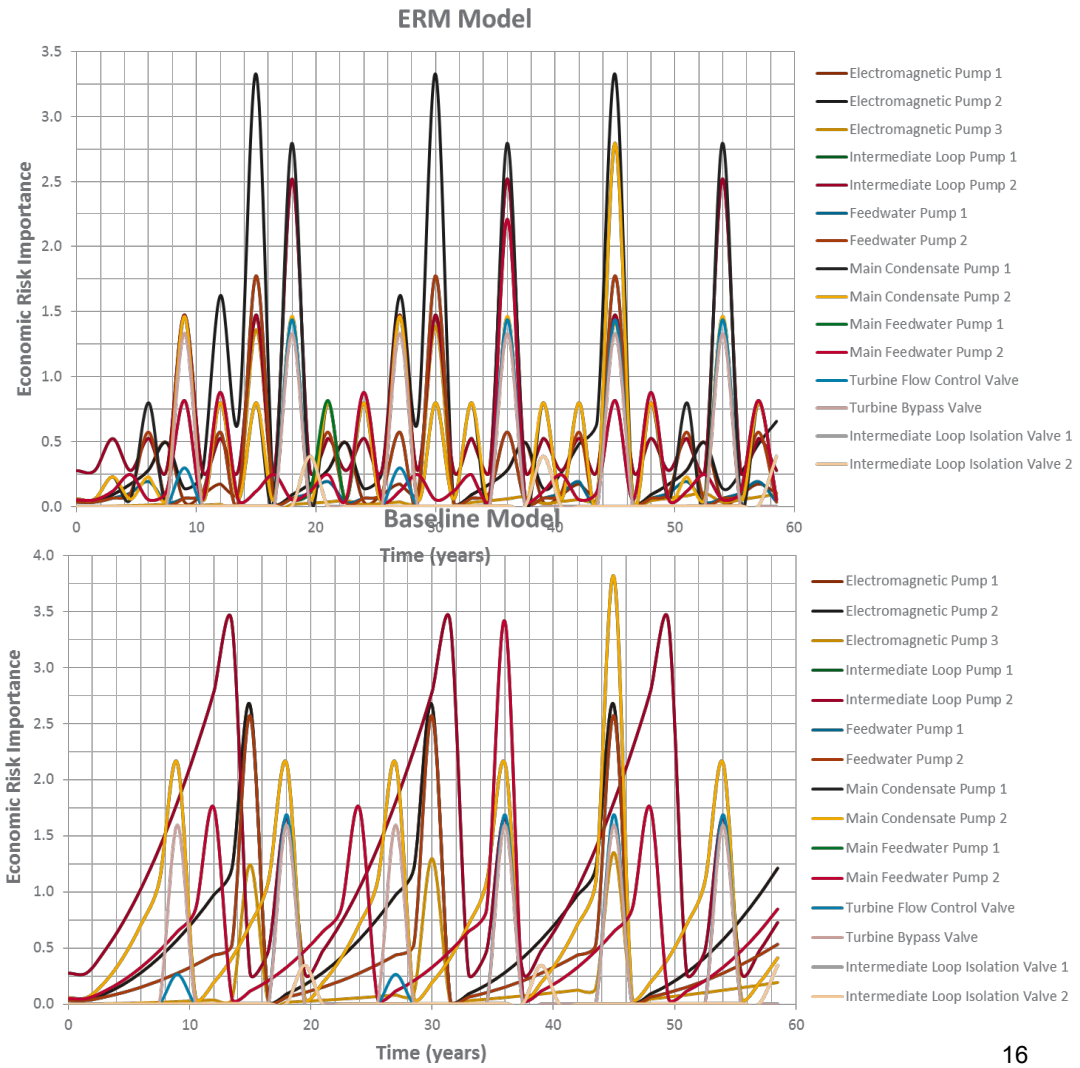
Case Studies and Results

- **Case A: Replace the components that have reached their end-of-service-life during a subsequent planned outage.**
- **Case B: Utilize ECA/ERM to perform equipment replacement just prior to failure.**
- **Case C: ERM to Avoid Unplanned Outages. Use condition monitoring regime to predict unplanned outages. In combination with preventive maintenance, schedule any necessary predictive maintenance to avoid unplanned outages.**



Importance Measures

- **CDF**
  - Fussell-Vesely importance measure
- **Economic risk**
  - Based on cutset probability leading to unplanned outages



U.S. DEPARTMENT OF ENERGY
Nuclear Energy

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," Presented at *ANS NPIC-HMIT 2015*.
- P. Ramuhalli, A. Veeramany et al , "Methodology for Risk-informed Operations and Maintenance Decision-Making in Nuclear Power Plants," Submitted to *ICONE24*, 2016.
- A. Veeramany, P. Ramuhalli, CA Bonebrake, WJ Ivans, GA Coles, EH Hirt, "Evaluation of Enhanced Risk Monitors for use on Advanced Reactors," To be Submitted to *IEEE Transactions on Reliability*.

Path Forward

- **FY2016:**
  - Integrate ERM methodology with supervisory control framework (ORNL)

Conclusions

- **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