OUTLINE

► Traditional health monitoring
  ■ Aging and life extension to prognostics

► Nuclear Industry – Past experience
  ■ Reactive to proactive – model-based diagnostics & PMMD

► Some examples of Prognostics systems
  ■ Diagnostics & Prognostics – technology maturity

► DSOM – stressor based prognostics

► Examples of PMMD & Prognostics Programs
Traditional
Health Monitoring Approaches

- Physical Redundancy
  - Multiple sensors, components, voting scheme
  - Problems: expensive, additional weight to system

- Data Driven approaches (Process history)
  - Classifiers (PCA, Statistical)
  - Neural Networks
  - Trend Analysis, Limit Checking
  - Special sensors – emulate human diagnosers
  - Problems: Dependent on operating region, require large amounts of data

Solution: Model-based methods for monitoring and diagnosis
Motivation for structural health monitoring

- Local damage detection – NDT widely used

- NDE methods have difficulty when large areas need inspection and damage below surface (e.g. CRUF’s)

- More global damage, quantifiable and automated methods needed

- Prediction – become proactive?
Related Technologies

- Non-destructive Evaluation
- Structural Health Monitoring
- Condition Monitoring
- Health and Usage Monitoring Systems
- Statistical Process Control
- Damage Prognosis (prediction of material degradation)

- Plant Optimization (Energy Efficiency)
- Energy Utilization

Predictions of Remaining System Life with Quantified Uncertainty
Aging & Life Extension to Prognostics

- Nuclear power plant life extension – developing since ~ 1972 [In USA 40-60 year license extension]
- Chemical and process industries (MTI) looking towards on-line monitoring, wireless sensors etc.
- Long-term stewardship of weapons systems (aging stockpile)
- Aging aircraft programs
- Energy efficiency and plant optimization
- Embedded diagnostics and prognostics
  - Military platforms
  - Aircraft VHM
General Description of Plant Life Management (PLiM)
The Diagnosis Problem

Wenn Autos abstürzen
ALARMSTUFE ROT

From PHM '08 Tutorial materials
State of the Art
Complex Systems

• Most complex systems are built from subsystems and components that often come with Built-in-Tests (BIT)
  – Include sensors and threshold logic
  – Generate an alarm signal when sensed value exceeds predefined thresholds

• Useful for keeping tabs on the health of individual components or subsystems
State of the Art Complex Systems

• Issues
  - System is made up of interacting subsystems
    • Alarm in one subsystem could be caused by propagating effects
  - May need more fine-grained information
    • determine effect of fault or degradation on overall system performance
  - May want to do more than just determine something is going wrong
    • Reliability of the inference
    • Fault-adaptive control
    • Predict future behavior
    • Schedule maintenance
    • Inform future design

Solution:
More comprehensive approach to health monitoring (diagnosis)
Nuclear Industry - Past Experience

- Majority of component failures
  - Active components – e.g. valve not operating
  - Passive components – service degradation
- Active components managed through maintenance program
- Passive components managed through periodic inspection

Surprises – result from new degradation mechanisms
(New programs being considered for “life-after-60”)

Benefits of diagnostics & Prognostics
Reactive – NDE/NDT and ISI

Proactive – prediction of degradation rate

NDE Resolution Limit

Structural Integrity Limit

“Now”

Time

“Damage”

Reactive

Proactive actions
Uncertainty in Prognosis – Motivation cont.

Simplified Prognosis Based on One Health Observation:
- trend a single health observation up to a failure threshold
- assumptions:
  - health observation is a perfect health indicator
  - failure density reduced to one bin
  - usage measure is not useful

Issues:
- Prognosis is inherently uncertain and its accuracy improves when all the available evidence is used appropriately
- How to integrate multiple uncertain predictions (e.g. based on more than one health observation or health and usage observations.)

From PHM ’08 Tutorial materials
Techniques for Making Predictions

- **Physics-based modeling**
  - Dynamic stochastic equations
  - Lumped-parameter models
  - Functional models

- **Data-driven techniques**
  - Least-Squares Regression
  - Gaussian Process Regression
  - Neural Nets
  - Relevance Vector Regression

- **Statistical/lifting models**
  - Weibull Models

- **Hybrid Techniques**
  - Particle Filters

From PHM '08 Tutorial materials
Condition Monitoring (CM)

The application of the appropriate sensors (data), analysis (knowledge), and reasoning (context) to estimate the health and track the degradation of equipment.

Condition-Based Maintenance (CBM)

A philosophy of maintaining equipment based on an estimation of its condition and maintenance logistics. Enhanced application of CBM is through the prediction (prognosis) of the equipment remaining useful life or time to service need.

Prognostics & Health Management (PHM)

A health management approach to reduce/eliminate inspections and time-based maintenance through accurate monitoring, incipient fault detection, and prediction of impending faults. Coupled with Autonomic Logistics for greater responsiveness, cost effectiveness, and mission availability.
Detection through Prognosis

Detection
Monitored parameter(s) has departed its normal operating envelope

Diagnosis
Identify, localize, and determine severity of an evolving (incipient fault through functional failure) condition

Prognosis
Reliably and accurately forecast remaining operational time to end of useful life, future condition, or risk to complete mission

From PHM '08 Tutorial materials
Select and Develop PHM Algorithms

Applicability

- Generic, Signal Processing-Based Algorithms
- Pattern Recognition/Fuzzy Logic - Evolutionary/Estimation Models
- Physical Model

Increasing Cost & Accuracy

Algorithms

- Signal-Based Anomaly Detection
- Evolutionary or Data-Driven Models
- Reduced-Order or Estimation Models

From PHM ‘08 Tutorial materials
Motivation: On-board Diagnosis

Permanent multiple faults
- Fault 1
- Fault 2

Intermittent multiple faults
- Faults 1, 2, 83
- Fault 3
- Fault 2

How to detect and isolate multiple faults (permanent or intermittent) occurring over time?

Fault 1
- Throttle / pedal position sensor / malfunction

Unreliable sensors

Engine coolant temperature circuit malfunction

From PHM ‘08 Tutorial materials
Reliability to Prognostics: Evolution

Measure → Monitoring → Residual Analysis

Model Predicted → Fault Progression

Fault Detection Threshold → Projected Path

Feature Space → Prognosis

Reliability/Usage Models → Bayesian Updates → Prognosis

Trending

Operational/Mission

From PHM '08 Tutorial materials
Closed-Loop PHM Cycle

1. Monitoring
   - FirstCheck™
   - HealthCheck™
   - Initiated: BIT
   - Startup: BIT
   - Background: BIT
   - BITE
   - SW Applications
   - BIT Events

2. Fault Detection and Status
   - Status
   - Operational Health
   - Thresholding
   - FAST™

3. Fault Isolation & Prognostics
   - REASONPRO™
   - PHM Design™

4. Maintenance Reasoning
   - PBMS™
   - AIMSS™

5. Maintenance Feedback & Q-Learning™

From PHM '08 Tutorial materials
Benefits of Model-based Diagnosis

- Covers entire system
- Unforeseen faults
- Fault models not necessary
- Multiple faults
- Intermittent faults
- Connection faults
- Proposes new information gathering actions and repairs
- Probabilistic
- Maximum expected utility

Needs/Costs:
- Models

From PHM '08 Tutorial materials
Diagnostics/prognostics Processes

- **Plant Data**
  - Calculations
  - Rule-Based Logic
  - Modeling Neural Nets
  - Stressor Measurement & Correlation

- **Efficiency**
  - Process Efficiency
    - Plant Configuration
    - Operating Limits
    - System Faults
    - Operating Condition
    - Specific Faults
    - Degradation Rate
    - Time to Failure

- **Diagnostics**
  - Component Health

- **Prognostics**
Component Health Prognostics

Stressor Measurement

6 months to live
Condition Based Maintenance

- Mitigation and Repair
- Fix What Broke
- Preventive Maintenance Zone
- Predictive Maintenance Zone
- Degradation Zone
- Time =>
- Stressor Applied
- Recognition
- Proactive Operations and Maintenance Zone
- Prediction and Planning
- Mitigation and Repair
- Fix What Broke
Prognostics

- Move from diagnosis to prediction of remaining life and structural health monitoring/management

- Prognostics (for machinery) is the prediction of a remaining safe or service life, based on an analysis of the system or material condition, stressors and degradation phenomena
Proactive Management of Materials Degradation (PMMD)

Know

Predict

Gains In Regulatory Efficiency

Numerous Large Reports
Distilled and Integrated via Information Tool
Help Identify Research Program Priorities
Degradation Time Line
Knowledge Improved
Army: M1-Abrams Tank

- Turbine Engine Diagnostics using Neural Networks
- Uses onboard electronics, sensors and added electronics, sensors and microprocessor
- Aim to facilitate condition based maintenance

TEDANN: Sensors to Prognostics

- Sensor Data
  - Sensors provide data to monitor power pack operation
- Diagnostics
  - On-board diagnostic derived based on sensor data.
- Data Trending
  - Data trended to predict time to next required maintenance.
- Prognostics
  - Specific prognostics can be made at component level.
  - Reduced maintenance costs Greater force readiness

PNNL (1998)
NDE to Prognostics

- Evaluation/analysis
- Health Sensors/NDE/NDI
- Aging/damage models
- Probabilistic analysis
- Cost of ownership
- Probabilistic risk assessment
- Developing in other industries
Northrop Grumman AEW/EW Bethpage
Prognostics for Aerospace Systems

Multi-Scale Analytic Models (Cornell Univ.)
- centimeters
- millimeters
- micrometers
- nanometers

Sensor Systems & Web
(Analatom, NGC-Others)
- Fatigue
- Corrosion
- Etc.

Signal Processing

Current Programs
- Predictive Failures & Advanced Diagnostics - AFRL
  - Applying Diagnostics & Prognostics to Legacy Aircraft,
- Joint Strike Fighter Prognostics & Health Management - LM
  - Lead for Mission Systems FHM Design and Algorithm Development,
    Supporting Vehicle Systems FHM and Systems Integration
- 2nd Generation Reusable Launch Vehicle - NASA
  - Technology Area 5, Integrated Vehicle Health Management
- Software Enabled Control - DARPA
  - Health Management for Multiple Autonomous Vehicles, Flight Critical Systems
- Unmanned Combat Air Vehicle - Navy
  - IVHM Technology and Architecture Definition, Phase 1B, Phase 2
    Autonomous Support Technology Demo
- E-2C Advanced Hawkeye - Navy
  - Integrated Diagnostics for E-2C Upgrade, Health & Usage Monitoring System (HUMS) Upgrade for UK RFI

Potential Systems Applications (mission/vehicle)
- Broad Area Maritime Surveillance (BAMS)/Global Hawk
- Unmanned Combat/Naval UCAV
- Homeland Security/Swissair

Prognostics
- Adaptive Modeling
- Model-Based Reasoning
- Neural Networks
- Fuzzy Systems
- Probabilistic Reasoning

Uncertainty Management

Intelligent Management of Assets

From DARPA web site
Reduces Ships-Crew by virtual Presence - ATD
Diagnostics and prognostics: technology base maturity matrix

<table>
<thead>
<tr>
<th>Diagnostic/Prognostic Technology For:</th>
<th>AP</th>
<th>A</th>
<th>I</th>
<th>NO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic Machinery (motors, pumps, generators, etc.)</td>
<td>D</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Complex Machinery (Helicopter Gearboxes, etc.)</td>
<td>D</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metal Structures</td>
<td>D</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Composite Structures</td>
<td>D</td>
<td>P</td>
<td>D&amp;P</td>
<td></td>
</tr>
<tr>
<td>Electronic Power Supplies (Low Power)</td>
<td>D</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Avionics and Controls Electronics</td>
<td>D</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium Power Electronics (Radar, etc.)</td>
<td>D</td>
<td>P</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High Power Electronics (Electric Propulsion, etc)</td>
<td>D</td>
<td>P</td>
<td>D&amp;P</td>
<td></td>
</tr>
</tbody>
</table>

D – Diagnostics:  P - Prognostics

- AP – technology currently available and proven effective
- A - technology currently available, but V&V not completed
- I – technology in process, but not completely ready for V&V
- NO – No significant technology development in place

[Howard (2005)]
Olkiluoto, Finland

- Areva - building the world's first next generation PWR, Olkiluoto plant
- 265 Channel – on-line monitoring
- Advanced diagnostics
Scope for Prognostics?

- Concrete
- Cables
- Core Internals
- Structural metals
- Passive components
- Active Components
- Materials degradation
- Mitigation & repair
- Advanced ISI/on-line monitoring
- Probabilistic risk assessment (PRA)
Examples of PMMD & Prognostics Programs

- Europe – Safelife to NULIFE
- Japan – NISA
- Korea – PMDM/PMMD
- USA
- International
  - IAEA -- CRP’s: PLiM (Meeting Series): TECHDOCS
  - OECD-NEA: committees + Reports
SAFELIFE (EU Program)  
(http://SAFELITE.JRC.EC.EUROPA.UE/)
Planned Organization and Evolution of the EU NULIFE Program 2006–2011

- Key integration indicators

- Integration plan
  - Viable expert groups
  - Coherent structure
  - Communication methods

- Preparation of business plan
  - Business plan, Updated structure
  - Links with national programmes
  - Approaches to training, knowledge and communication

- Consolidation of integration plan
  - Launching of new RTD projects
  - Development and application of procedures and best practices

- Creation of Virtual Institute
  - Structure with permanent entity features
  - Joint use of facilities
  - Investment policy

- Transition plan for permanent entity
  - Permanent management structure
  - Long term business plan
  - Acknowledged solution provider

- Beyond 5 years

- Past Networking activities
Create a single organisation structure, capable of providing harmonised R&D at European level to the nuclear power industry and the related safety authorities in the area of lifetime evaluation methods for CSS.

Vision is to create a **Virtual Institute** with
- **Integrated RTD platform**
  - Made of European stakeholders
  - Completely new structure with improved and efficient use of public and private RTD funding
- **Sustainable forum for realizing harmonized technical procedures**
  - Impact for Nuclear energy industry, National regulators and European Regulatory Working Groups
- **Service provider**
  - Sustainable source of qualified expertise for all customers in Nuclear energy field
  - Innovator and executor of R&D projects

- **Time schedule** 10.2006 - 9.2011, 5 years
- **Total budget** 8.4 million euro
- **EC funding** 5 million euro
- **VTT coordinator**

- **11 Core contract members and 26 other members representing**
  - National research institutes
  - Industrial research centres
  - Vendors, plant providers
  - Service providers
  - Power companies
NULIFE Work Packages and leading organisations

Strategy
End User Group
RA-2 EDF (EKK)

Business and integration plan
IA-7 VTT

Advanced PLIM methodologies

Harmonisation
IA-5 JRC

Links to regulators
SA-5 CEA

R&D projects
Proposal evaluation and planning
RA-1 BE

Pilot projects
- SCC RA-3 SCK•CEN (EDF)
- TF RA-4 CEA (EDF)
- I&C (feasibility) RA-5 FKA
- DMW (feasibility) RA-6 ANP-G

R&D projects

Resources
Knowledge management and communication
IA-3 NRI

Expert Groups
- Materials IA-2-1 SCK•CEN (EDF)
- Integrity IA-2-2 ANP-G (SERCO)
- Lifetime IA-2-3 SERCO (EKK)
- Safety & risk IA-2-4 FKA (VTT)

Competences and facilities
IA-1 CEA
Japanese – NISA Project

The NISA Project as a whole

- **Project objective**
  - Improve the technical information infrastructure in order to utilize knowledge as well as information related to ageing management and maintenance of nuclear power plants.

- **Project period and scale**
  - Started in FY2006 and implemented for 5 years.
  - FY2006: ¥770 million  FY2007: ¥1.32 billion  FY2008: ¥1.4 billion

- **Feature of the project process**
  - Cluster system adopted: Tohoku, East Japan, Ibaraki, Fukui
  - Promote researches reflecting the characteristics of each district by utilizing its facilities and human resources.
  - Promote information sharing, coordination, and cooperation for similar theme researches.
  - Build the industry-government-academia coordination system in line with “Strategy Map for ageing management”.
Structure of Roadmaps for Aging Management

R&D Roadmaps for Ageing Management and Safe Long Term Operation
developed by Atomic Energy Society of Japan in 2004-2005

To Keep Safety and Reliability of Nuclear Power Plants for Long Term Operation

1. Establishment of Information Basis
   - Database for Degradation of Materials
     - Systematic Ageing Management Program
     - Database on Regulation Procedures in Other Countries

2. Technical Development
   - Evaluation Technology for Degradation of Components
     - IASCC
     - RPV Radiation Embrittlement

3. Codes and Standards
   - Standardization of Ageing Management Procedures
     - Schemes to Apply New Techniques
     - Performance Index

4. Systematic Maintenance
   - Optimization of Maintenance
     - Risk-based Maintenance
     - Human Resources

(Sekimura 2007)
**Example of Technology Issues**

### Maps for Technical Issues

#### 1. Safety Research to Solve Ageing Issues

<table>
<thead>
<tr>
<th>Aging phenomenon</th>
<th>Current Status</th>
<th>40th to 50th year</th>
<th>Long-life, next-generation reactor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irradiation embrittlement</td>
<td>* Countermeasures are being taken by rule of thumb based on plant data.</td>
<td>* Prediction methods and monitoring technology will be upgraded.</td>
<td>* Advanced designs will be developed based on past operating experience.</td>
</tr>
<tr>
<td>Stress corrosion crack</td>
<td>* Countermeasures suited to materials in use are being taken.</td>
<td>* Use of SCC-resistant materials will be ensured.</td>
<td>* Simulation methods will be established.</td>
</tr>
<tr>
<td></td>
<td>* Calculation is being performed.</td>
<td>* Database will be established.</td>
<td>* All technology will be upgraded.</td>
</tr>
<tr>
<td>Fatigue</td>
<td>* Countermeasures suited to materials in use or environment are being taken,</td>
<td>* Countermeasures suited to materials in use or environment will be taken, and database will be constructed</td>
<td>* Monitoring technology will be established.</td>
</tr>
<tr>
<td></td>
<td>and database is being constructed.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wall thinning</td>
<td>* Countermeasures suited to materials in use are being taken, and database</td>
<td>* Mechanism-based prediction methods will be established.</td>
<td>* Monitoring technology will be upgraded.</td>
</tr>
<tr>
<td></td>
<td>is being constructed.</td>
<td>* Risk-based maintenance methods will be established.</td>
<td></td>
</tr>
<tr>
<td>Deteriorated cable</td>
<td>* Countermeasures suited to materials in use are being taken, and database is</td>
<td>* Deterioration diagnosis technology will be upgraded.</td>
<td>* Monitoring technology will be upgraded.</td>
</tr>
<tr>
<td>insulation</td>
<td>being constructed.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decreased strength of</td>
<td>* Insufficient study in aging made on actual some fields.</td>
<td>The reliability of integrity evaluation methods will be improved or enhanced.</td>
<td>* Plant records of performance will be reflected in maintenance technology and reliability designs for new plants,</td>
</tr>
<tr>
<td>concrete</td>
<td></td>
<td>* CCV integrity evaluation methods will be established.</td>
<td>* Recycling methods will be established for replaced structures and materials.</td>
</tr>
</tbody>
</table>

(Sekimura 2007)
Japanese Strategy Map Revision Process

Continuous Revision of Strategy Maps for Ageing Management by All the Stakeholders

Safety Research Sub-Committee in the Coordinating Committee on Ageing Management

Strategy Maps for Ageing Management

1. Introduction Scenario
   - Needs
   - Targets
   - Milestones

2. Maps of Technical Issues

3. Roadmaps
   - 
   - 
   - 

Periodic Revision through Latest Knowledge

- R&D projects
- Information Basis

- Hardware Resources
- Human Resources

Publicity

- Budgetary Actions for Research and Infrastructure
- Regulation Systems with Codes and Standards

Publication

Comments & Participation

2006 -

Nuclear Safety Regulatory Standard Committee in NISA

(Sekimura 2007)
Roles in Japanese Ageing Management Program

Major Roles of Industries, Government and Academia for Ageing Management

**Academia**
- Responsibility to contribute to safety research activities
  - to accumulate and expand fundamental knowledge
  - to keep human resources through the safety research

**Government**
- Responsibility to establish and improve safety regulations
  - by conducting safety researches,
  - by keeping infrastructure
  - Responsibility to promote nuclear energy for national energy security

**Industries**
- Primary responsibility to keep safe operation of power plants
  - research and development, and development of the infrastructure for safety and public interests

**Academic Societies**
- To develop, review strategy maps periodically and build a consensus with experts from industries, government and academia
  by identifying important issues to be solved
  by discussing roles of stakeholders for rational and efficient implementation of research
- To develop and improve codes and standards based on safety research outcome

(Sekimura 2007)
Some Glimpses from ISaG  (Japan – July 2008)
Schematic Showing PLiM Process for Korean Kori Unit 1

**Life Assess . Generic Tech.**
- Generic Integrated plant assessment method
- SCs life eval. meth. & req. mts
- Technical procedures

**Kori 1 Life Assessment**
- Kori 1 SCs life assessment
- RPV archive material test

**Monitoring System**
- System perf. monitoring
- RCS VV leak detection
- Ex-vessel dosimeter

**Field Aging Test & Diag.**
- Concrete/buried struc./cables
- PZR surge line therm. Strain
- Generator Degradation
- Main steam/feed water pipe

**Kori 1 PLIMDB**

**Kori 1 Aging Management Plan**
- Design-life evaluation report
- Current aging management practices
- Aging mgmt. plan for the latter life of Kori 1

(Kim et al. 1999)
PMMMD Approach in Korea

Proactive Research and Innovative Materials Aging Network, established in 2007

Network of Expert Group: PRIMA-NET

- Inspection
  - Method & timing
  - Inspection reliability
- Mechanism
  - Physico-chemical parameters
  - Remedial measures
- Mitigation & Repair
  - Applicability
  - Procedure qualification
- Materials Integrity
  - Flaw Tolerance
  - Growth

PRIMA-NET

Proactive Research and Innovative Materials Aging Network (PRIMA-NET) was established in 2007 in Korea to promote research and innovative materials aging networks. This network focuses on various aspects such as inspection methods, reliability, mechanism, mitigation and repair, materials integrity, and growth. The network aims to enhance the reliability and longevity of materials through comprehensive research and innovative approaches.
Korean PMMD Program

- **PRIMA NET Organizations:**
  - Regulation : KINS
  - National Labs : KAERI, KEPRI
  - Utility : KHNP & NETEC
  - Design & Fabrication : KOPEC, DHIC
  - Maintenance : KPS
  - Academia : SNU, KAIST

- **Expectations**
  - Korean PMMD Framework
  - Review of Focused Efforts
  - Planning and Prioritization for Focused Efforts
  - International Co-operation
Proactive Management of Materials Degradation (PMMD) – (previously PMDM)

► Philosophy
  ■ Become “proactive” ---- prediction of remaining life
    ■ Avoid surprises – maintain safe operation

► Methodology
  ■ Adopt new methods e.g. on-line monitoring (go beyond CBM)
  ■ Leverage migration to digital I&C
  ■ Stressor – based prognostics (?)

► Technology
  ■ New sensors
  ■ New Communication systems (wireless?)
  ■ New data processing and prediction methods
Proactive Management of Materials Degradation

Develop information
- Materials behavior
- Mitigation or repair
- Inspection or monitoring

Proactively address potential future degradation
- Avoid failures
- Maintain integrity and safety

Increase cooperation
- Prioritize PMMD research with industry
- Pursue additional international collaborations

Evaluate existing inspection and monitoring requirements
- Integrity of susceptible components
- Inspection techniques, inspection intervals and monitoring regulations

Avoid Surprises e.g. V.C. Summer And Davis-Besse
Example of Part of the Materials Degradation Matrix Developed by EPRI (Crane 2004)

**Materials Degradation Matrix**

**Level 1**

<table>
<thead>
<tr>
<th>PWR Reactor Pressure Vessel</th>
<th>PWR Pressurizer</th>
<th>PWR SG Shell</th>
<th>PWR Reactor Internals</th>
<th>PWR Piping</th>
<th>PWR SG Tubes &amp; Internals</th>
<th>BWR Pressure Vessel</th>
<th>BWR Reactor Internals</th>
<th>BWR Piping</th>
</tr>
</thead>
</table>

**Level 2**

<table>
<thead>
<tr>
<th>PWR Component</th>
<th>Material</th>
<th>SCC</th>
<th>SCC</th>
<th>Corrosion/Wear C &amp; W</th>
<th>Fatigue Fat.</th>
<th>Reduction in Toughness</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWR Reactor Pressure Vessel</td>
<td>C&amp;LAS</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>PWR Pressurizer</td>
<td>C&amp;LAS</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>(Including Shell, Surge and Spray Nozzles, Heater Sleeves and Sheaths, Instrument Penetrations)</td>
<td>Wrought SS</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>SS Welds &amp; Clad</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>Wrought Ni Alloys</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>Ni-base Welds &amp; Clad</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
</tbody>
</table>

**Level 3**

- e030 Corrosion-assisted fatigue is a known phenomenon on secondary side (e.g., in the vicinity of girth welds in steam generator shells and in the region of feedwater nozzles) and is not like environmental fatigue described in other areas of this DM. Environmental fatigue research relevant to this specific phenomenon is not ongoing within MRP Fatigue ITG, and is a potential gap.
Integrated Structural & Materials Reliability Program

Prepared by: S.R. Gosselin and F.A. Simonen
Pacific Northwest National Laboratory
Phases in degradation - early intervention saves money

I
Development of Crack Nucleation Sites

II
Development of Crack Precursors

III
Development and Linkage of Small Cracks

IV
Growth of Large Cracks

Detection Limit

Units of Time (or Fraction of Life)

Cost

Corrosion Research

Issue Programs

Crack Length

Detection Limit

Phases in degradation - early intervention saves money

Issue Programs
Linear dimensions of microstructure and defects

After Dobmann et al (1997)
Operations

Decision Support for Operations & Maintenance - Information Tailored to User

Operations

Maintenance

Engineering

Administration

M
Maintenance

O
Operations

T
Training

E
Engineering Support

A
Administration

Administration

Operations

Maintenance

Engineering

Decision Support for Operations & Maintenance - Information Tailored to User

Operations

Maintenance

Engineering

Administration
Stressor Intensity Measurement Provides Prognostic Information BEFORE Degradation can be Detected

Stressor Amplitude Approach

Primary or Virtual Parameter = PP

Normal Operating Band

ALERT
ALARM

Cone of Uncertainty

Figure of Merit

Failure Level

TIME

\( t_1 \)

\( t_2 \)
Effect of First-Principles Prognostics on Reactor Operational Risk – PRA Impact

### Present Risk Monitor Practice

**Scheduled Maintenance and Testing**

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<th>January</th>
<th>February</th>
<th>March</th>
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<tbody>
<tr>
<td>Maintenance</td>
<td>SW1 PMP</td>
<td>ECS1</td>
<td></td>
<td>SW2 PMP</td>
</tr>
<tr>
<td>Testing</td>
<td>MOV1</td>
<td>MOV2</td>
<td>MOV3</td>
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<td>Diesel Gen</td>
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**Unscheduled Events (failures)**

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<tr>
<td>Repair/replacement due to failure</td>
<td>ECS2 PMP</td>
<td></td>
<td>SW1 Pmp</td>
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**Risk (Core Damage Frequency)**

- 1.00E-03
- 1.00E-04
- 1.00E-05
Effect of First-Principles Prognostics on Reactor Operational Risk – PRA impact

RISK MONITORING WITH SDMS
Scheduled Maintenance, Testing and Failures

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Risk (Core Damage Frequency)

1.00E-03
1.00E-04
1.00E-05
Relationship of Maintenance and License Renewal Rules

(from Gregor and Chockie 2006)
US (nuclear) Program(s)…..

► EPRI

► DOE-NE
  ■ Legacy LWR Sustainability
  ■ I&C-HMI Advanced NPP

► NRC – PMMD
  ■ LWR sustainability

► Standards
  ■ IEC
  ■ IEEE
Organizational Structure of the Committee on the Safety of Nuclear Installations within the OECD/NEA
Technical community for advanced diagnostics and prognostics

During Cold War military systems replaced due to obsolescence – NOT due to reaching end of service life.

LIFE EXTENSION IS NOW REQUIRED for many military systems

Pan American Advanced Study Institute on Damage Prognosis: October 2003

DARPA Prognostics Program (2002) – Aero engines

The Material Society Meeting – September ’04
  3-day Damage Prognostics workshop

MFPT Meetings:
  E.g. April 2005: Essential Technologies for Successful Prognostics
Some recent meetings

- **Japan**
  - Int. Symp. Aging Management NPP – Tokyo (July 24-25 -08)
  - Hokkaido Cluster – NISA Project (Oct 29-31 – 08)

- **Korea Int. Workshop (PMMD)**
  - September 26, 08

- **France – Materials Aging Inst**
  - (November 08)

- **Prognostics and Health Management PHM-08** (Denver, CO, Oct 2008)
Summary & Conclusions

Advanced diagnostics & prognostics is being developed and deployed in increasingly complex systems

- Applications in cars & aero-space

Nuclear community recognizing the potential benefits (and challenges) for prognostics and extended life.

Major (research) programs developing in Asia, Europe and USA

International coordination through IAEA & OECD-NEA

Advanced diagnostics and CBM systems being developed to leverage transition to digital I&C systems
Need: Detect, monitor, and characterize degradation severity to drive a cost effective proactive O&M AND PREDICT REMAINING USEFUL/ECONOMIC PLAN LIFE/OPERATION.

Program…. Requirements: What everyone wants!!!!
- Robust
- Reliable
- Low-cost
- User-friendly
- Effective for wide area coverage
- Near Real-time
- Provides a record of inspection
- Predict remaining life AND MORE!!!!!

“Tricorder”
Acknowledgements

Further details and full citation references for some materials are to be found in:

- Proactive Management of Materials Degradation – A review of principles and programs

Selected materials are reproduced for educational purposes from the “Tutorials” given at the IEEE Reliability Society, PHM ‘08(Prognostics and Health Management) Conference – Denver Colorado, October 6-9, 2008. Additional information in 175+ meeting papers in meeting proceedings.

Materials providing program details in Korea, Japan and the EU are gratefully acknowledged. Full details at program web sites and recent program meeting proceedings: ISaG – 2008 (Japan): PRIMA-NET (Seoul National University – Korea)

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