Diagnostics and Prognostics: Technical Challenges

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OUTLINE

- Technical challenges
  - Degradation processed found in US nuclear plants
- General Areas for investigation
  - Components with highest degradation susceptibility
- LWR – Issue Management Tables
- Design for inspectability?
- Risk Informed ISI
- US Plant Research Needs
- NDE/ISI – new construction & advanced reactors
- PWR – possible R&D topics
- Needs, priorities and the future

Some Technical Challenges

Need: Detect, monitor, and characterize degradation severity to drive a cost effective proactive O&M

AND PREDICT REMAINING USEFUL/ECONOMIC PLANT LIFE/OPERATION.

- Smart components and structures
- Self-diagnostic systems
- Embedded Micro-Electromechanical Systems (MEMS) (and other) health monitoring sensors
- Wireless communication
- Distributed data processing and control networks
- Prognostics implementation
- Advanced NDE technologies
- Proactive operations and maintenance program

What everyone wants!

"Tricorder"

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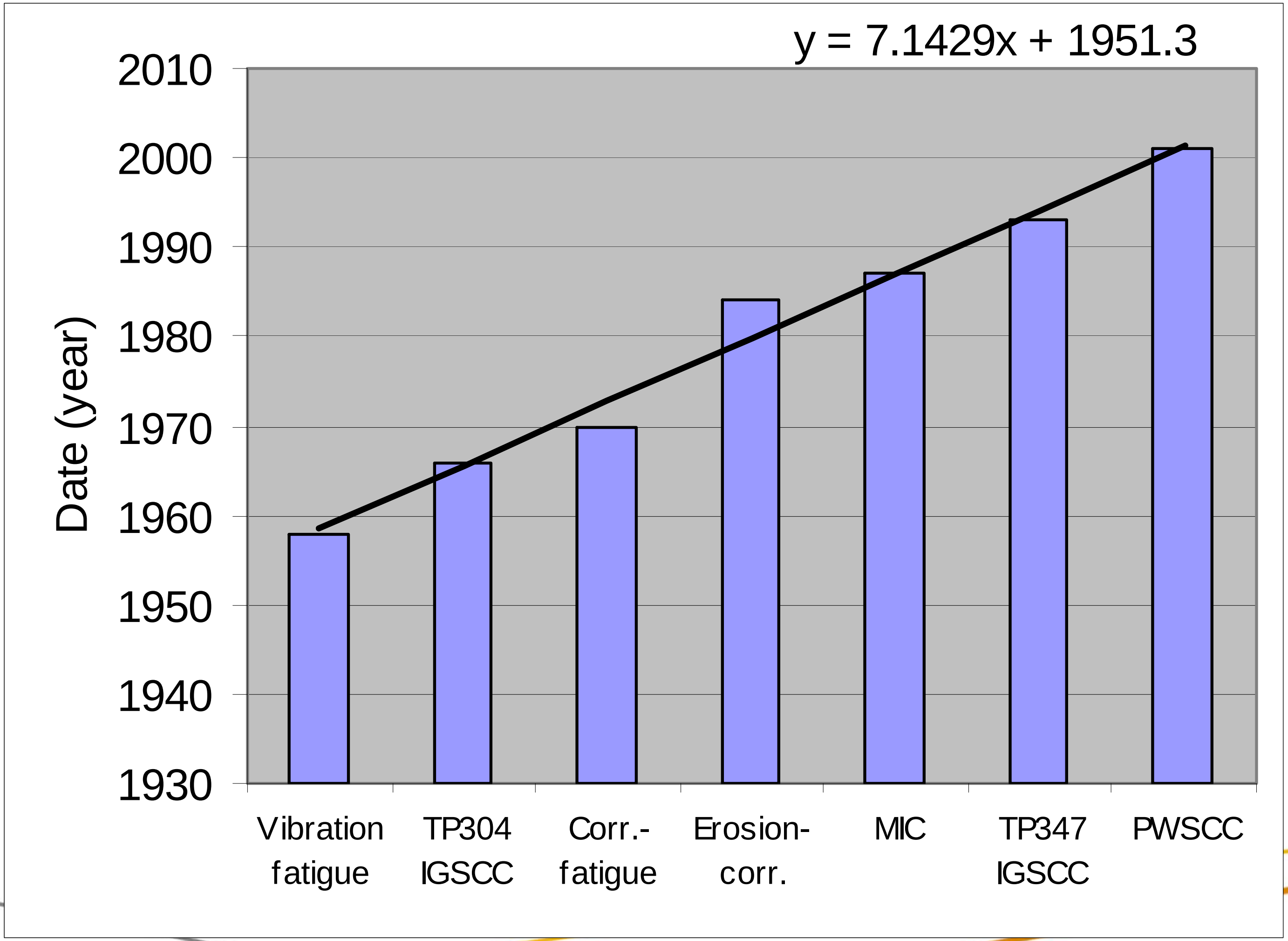
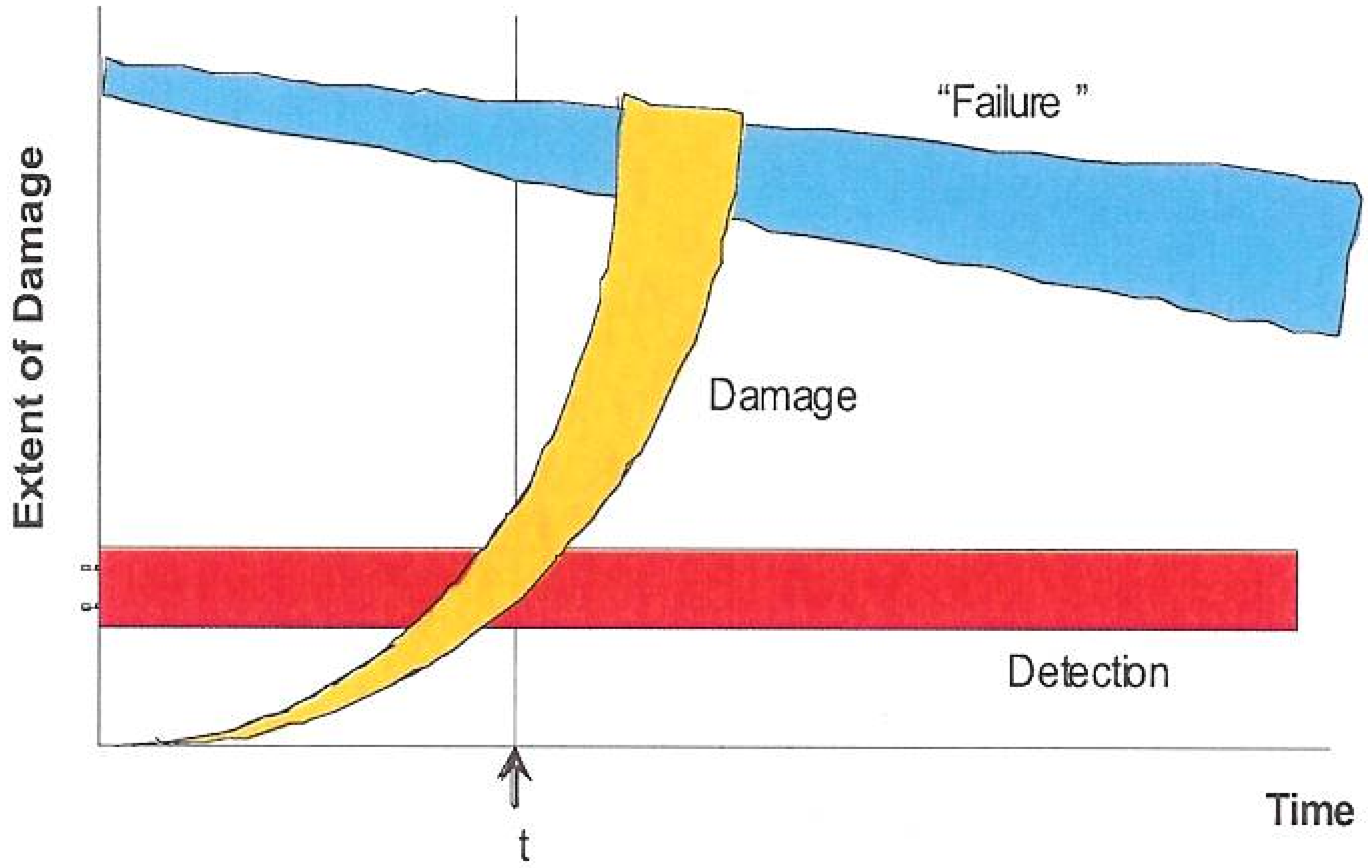
Degradation Processes Found in U.S. Nuclear Power Plants (Wilkowski 2002)



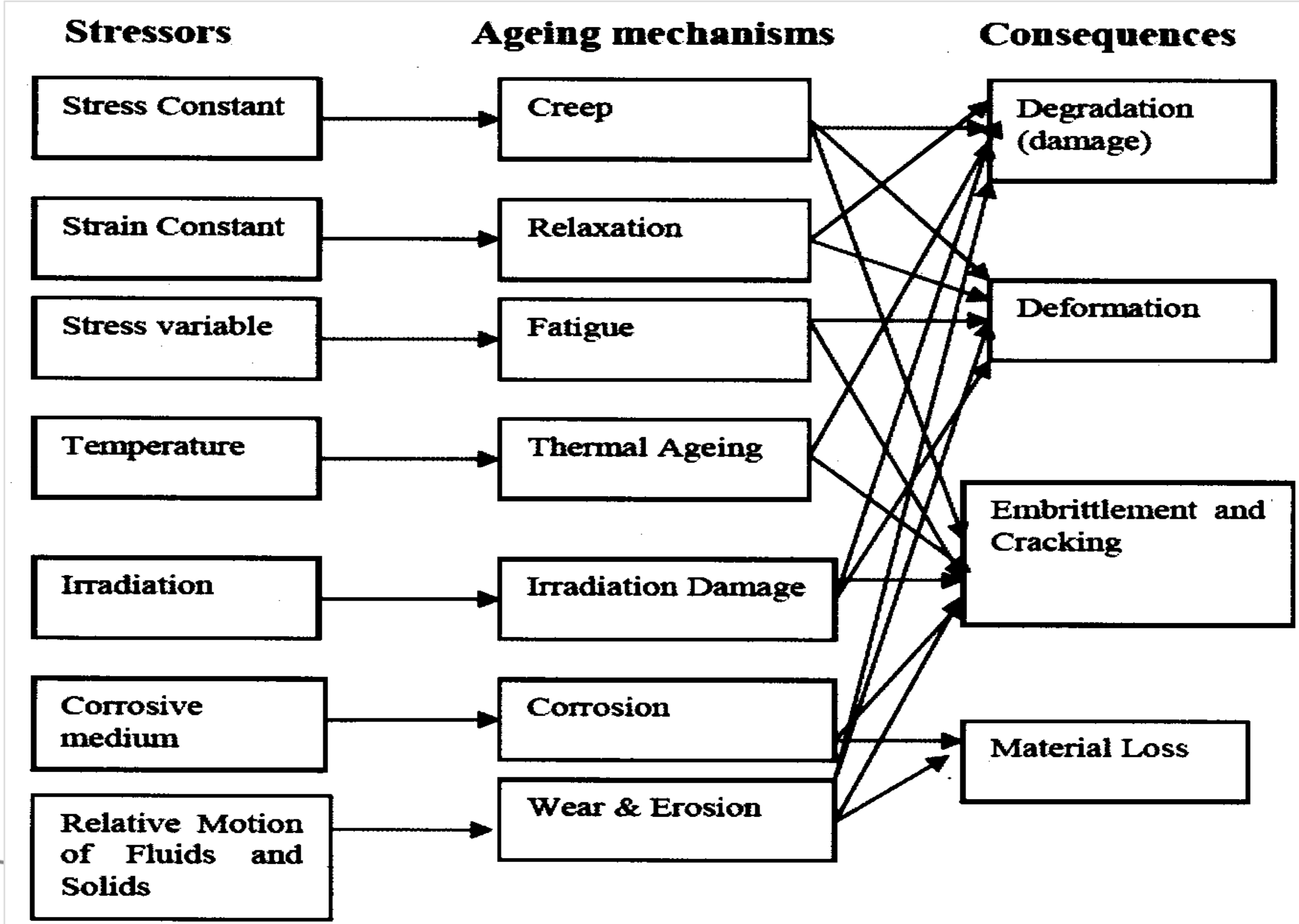
What is next?

Damage as a function of time – relationship to detection and failure



After NUREG/CR 6923

Aging factors, mechanisms and possible consequences



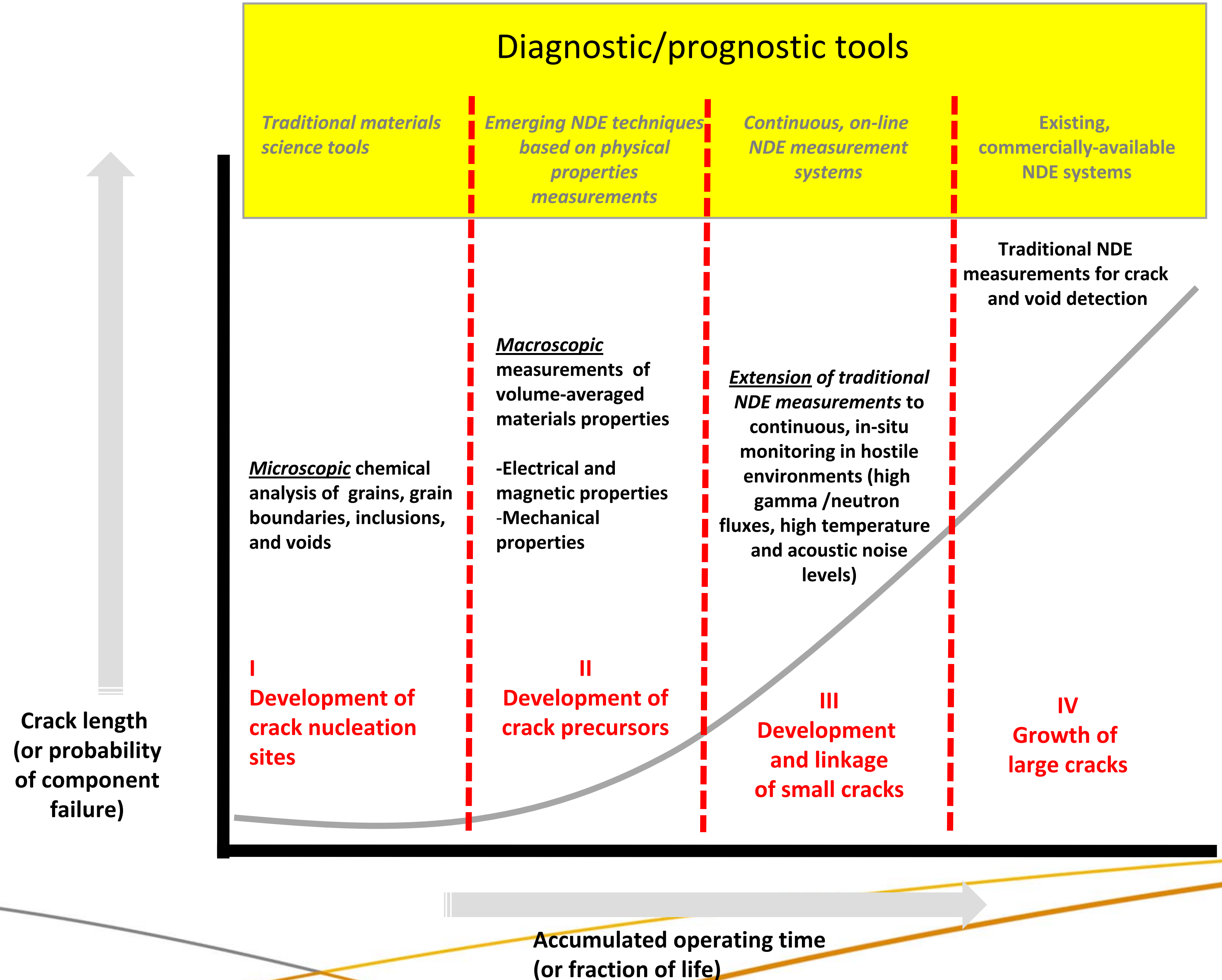


Figure 1 – Strategy for development of a PMMD system

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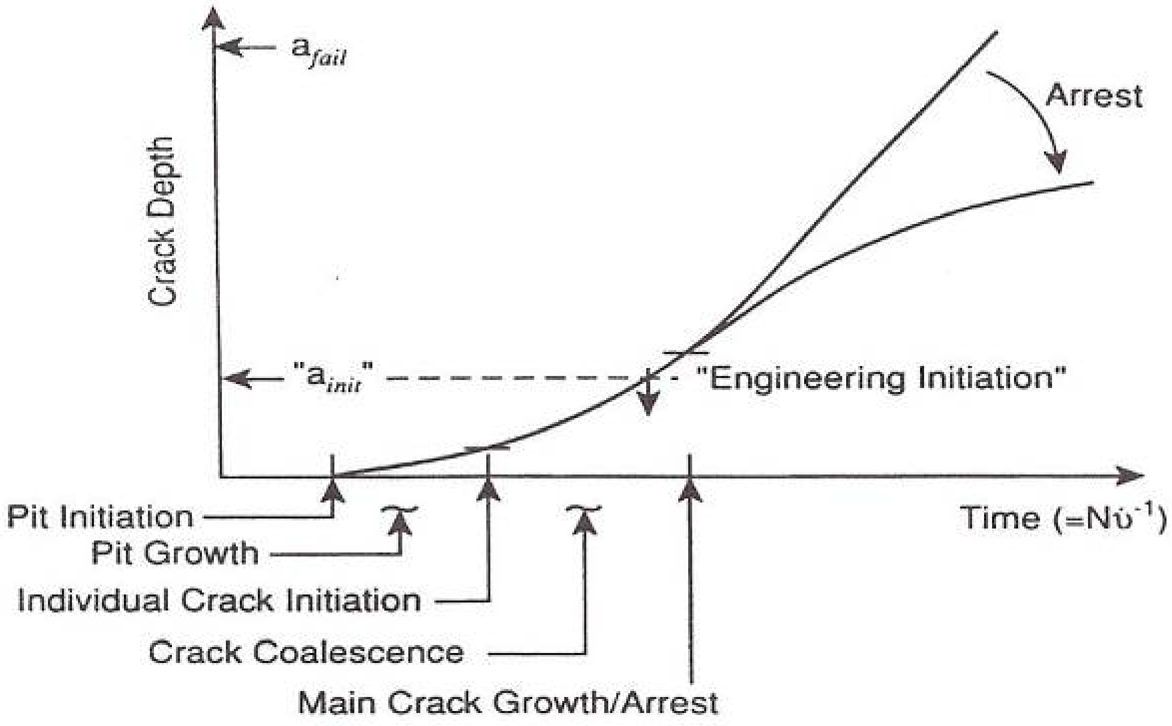
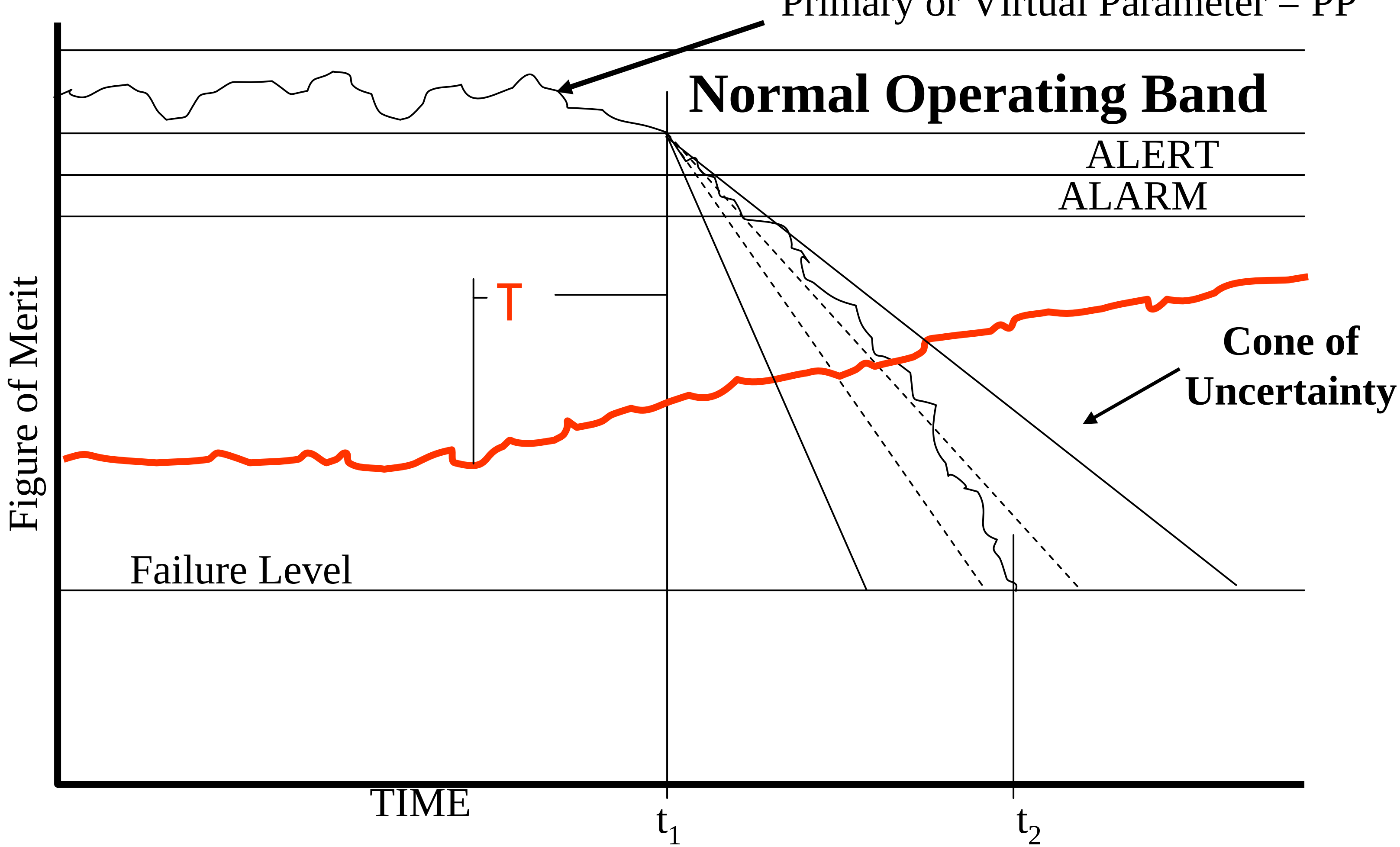
Crack initiation, coalescence and growth during sub-critical cracking (aqueous environment)



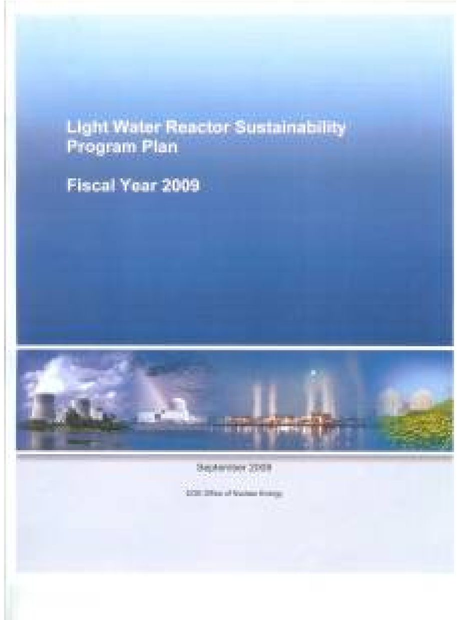
Stressor Intensity Measurement Provides Prognostic Information BEFORE Degradation can be Detected

Stressor Amplitude Approach



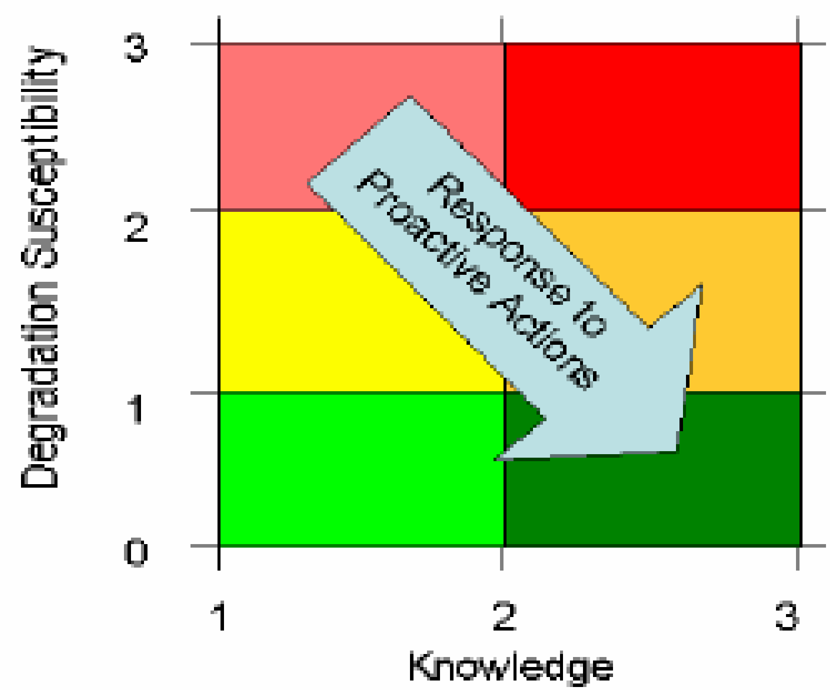
General Areas for investigation:

- Concrete
- Cables
- Structural Metals
  - Pressure vessel
  - Core Internals
- Active Components
- Passive Components
- Material degradation
- ISI/on-line monitoring
- Risk and Prognostics



Identification of Components with Highest Susceptibility to Degradation

- Materials degradation is highly likely, with limited knowledge for mitigation (pink zone)
  - 21 scenarios for PWRs
  - 1 scenario for BWRs
- Materials degradation is highly likely, but knowledge exists for mitigation (red zone)
  - 24 scenarios for PWRs
  - 62 scenarios for BWRs



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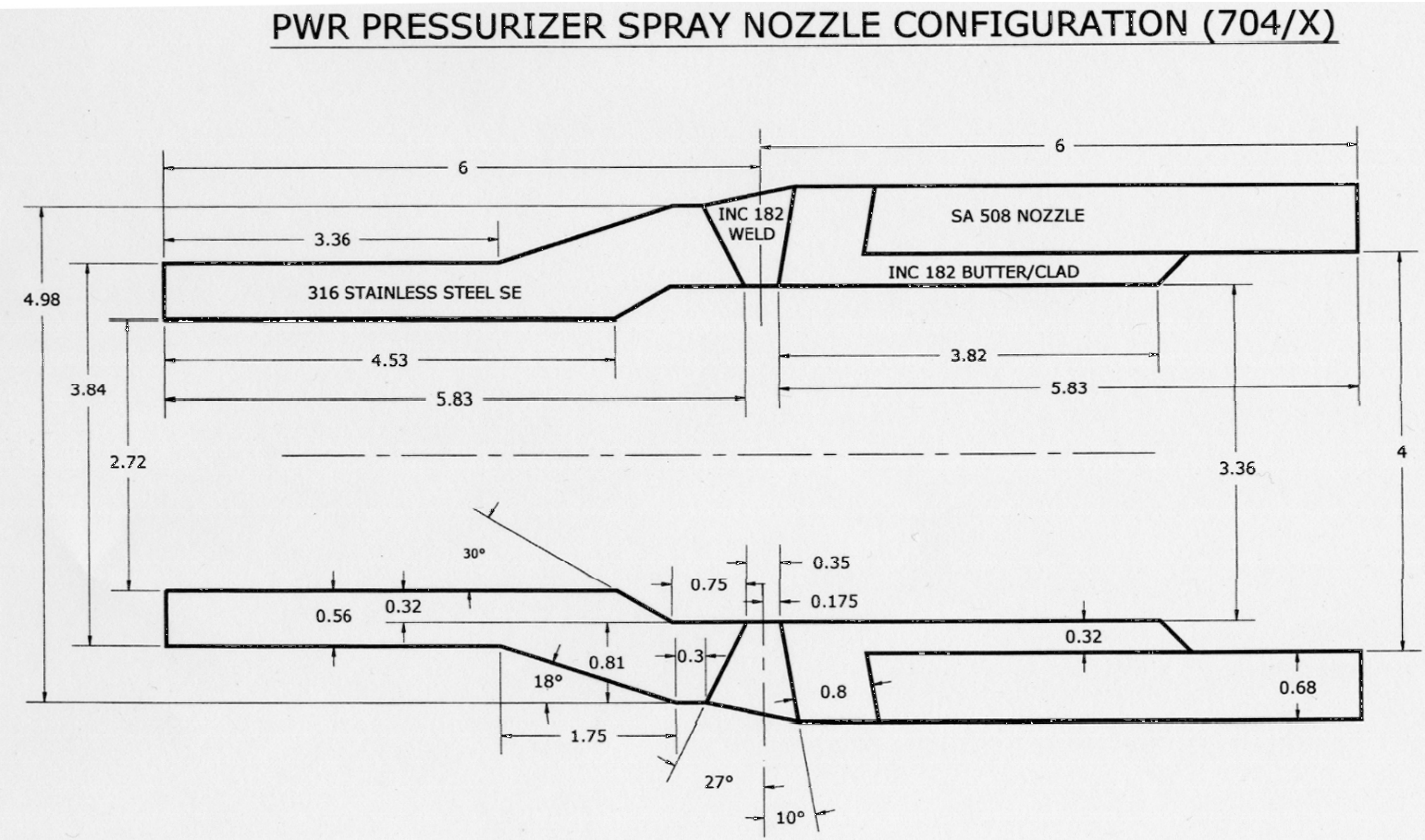
Work on Internals Testing Supported by Analyses of PMDA Results – high degradation susceptibility with limited knowledge for mitigation

System	Subgroup (Structure and/or Component)	Location on Structure and/or Component	Material	Environment	Aging Mechanism	LWR Type	Susceptibility
RCS	12.11 (reactor vessel internals)	Cold-worked austenitic reactor vessel internals	Type 316 austenitic SS	PWR primary water, >0.5 dpa (high fluence); 556°F to 620°F, 2250 psia	Irradiation creep (IC)	PWR	Pink
RCS	12.11 (reactor vessel internals)	Cold-worked austenitic reactor vessel internals	Type 316 austenitic SS	PWR primary water, >0.5 dpa (high fluence); 556°F to 620°F, 2250 psia	SCC	PWR	Pink
RCS	12.11 (reactor vessel internals)	Cold-worked austenitic reactor vessel internals	Type 316 austenitic SS	PWR primary water, >0.5 dpa (high fluence); 556°F to 620°F, 2250 psia	Swelling	PWR	Pink

LWR Issue Management Tables

- "Bottom-up Approach" based on Materials Degradation Matrix (MDM)
  - Complementary to "Top-Down Approach" used in component-level Proactive materials degradation assessment based on phenomenon identification & ranking tables (PMDA/PIRT analyses)
  - MDM and issue management tables (IMTs) to be maintained as living documents
- IMT focus on degradation of long-lived passive components
- Post-PMDA planning meetings addressed R&D on topics such as:
  - Materials and degradation mechanisms
  - Mitigation, repair and replacement
  - Nondestructive examination and continuous monitoring
- Common high priority R&D "gaps" identified from both PMDA and IMT evaluations
  - Inspection & evaluation (I&E) guidelines of reactor internals
  - Environmental fatigue of pressure boundary components
  - PWSCC management: Ni alloy reactor internals

Challenging Configuration to Reliably Inspect



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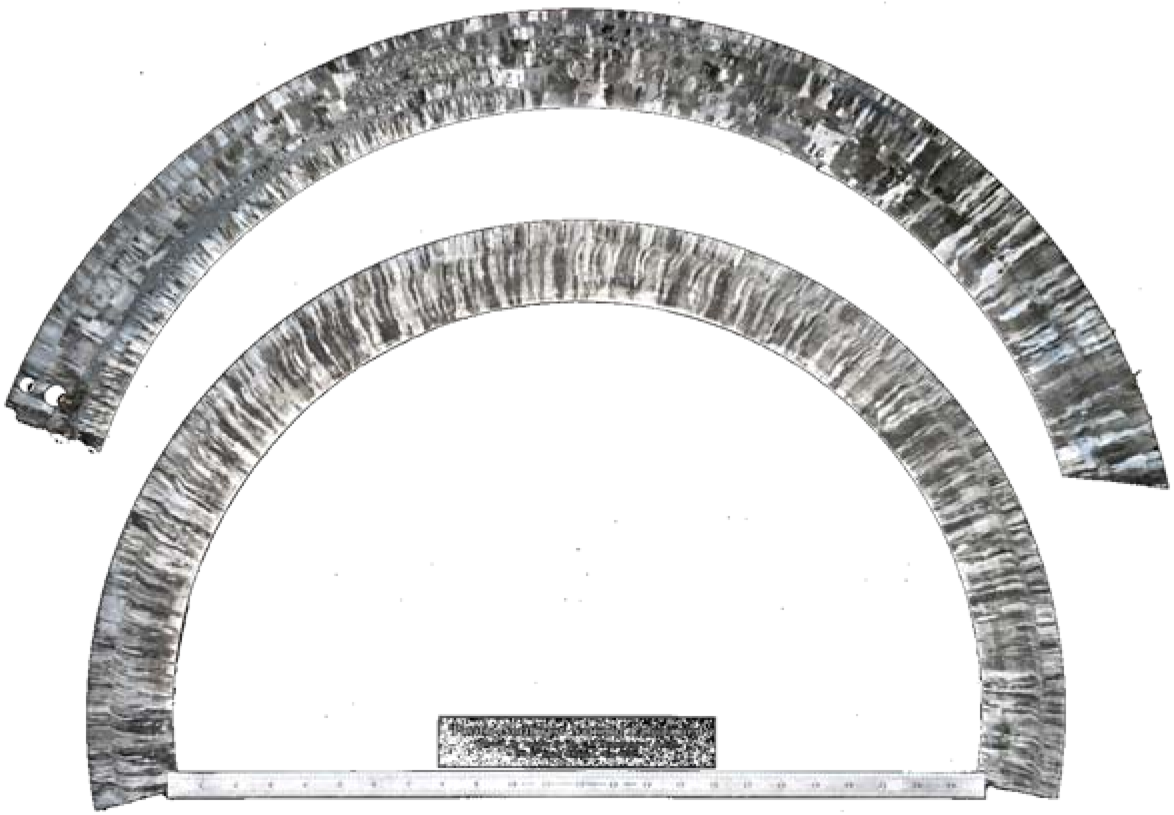
Risk Informed ISI

- The ASME Code uses risk informed strategy
- Unfortunately, the implementation of the RI/ISI has led to a **significant reduction in the number of components being periodically inspected**
- Although risk (of core damage) is being managed, the problem is that this strategy will lead to more cases of failure because fewer components are being inspected – **gives the appearance of not managing degradation**
- If surprises are to be eliminated in the future then a more comprehensive program is needed – **detect the unexpected**

Research Needs for Operating Fleet of U. S. Nuclear Power Plants

- **Modeling of NDE** – although the use of **performance demonstration provides confidence** that the unexpected will be detected, this is **empirically based** and validation through modeling would be beneficial and assist expansion to other components, degradation processes and modifications to NDE methods
- Many inspections on nuclear power plants can not be conducted effectively and new or improved solutions are needed
  - Cast stainless steels
  - ID and OD surface conditions of weldments
  - Proximity of other welds or access constraints
  - Tapers
- Nondestructive material property measurements – **NDE Holy Grail**

Performance Demonstration Vintage Cast Stainless Steel



- All supplements in ASME B&PV Code **Appendix VIII** are implemented except for **Supplement 9** on **centrifugally cast austenitic stainless steel piping** welds

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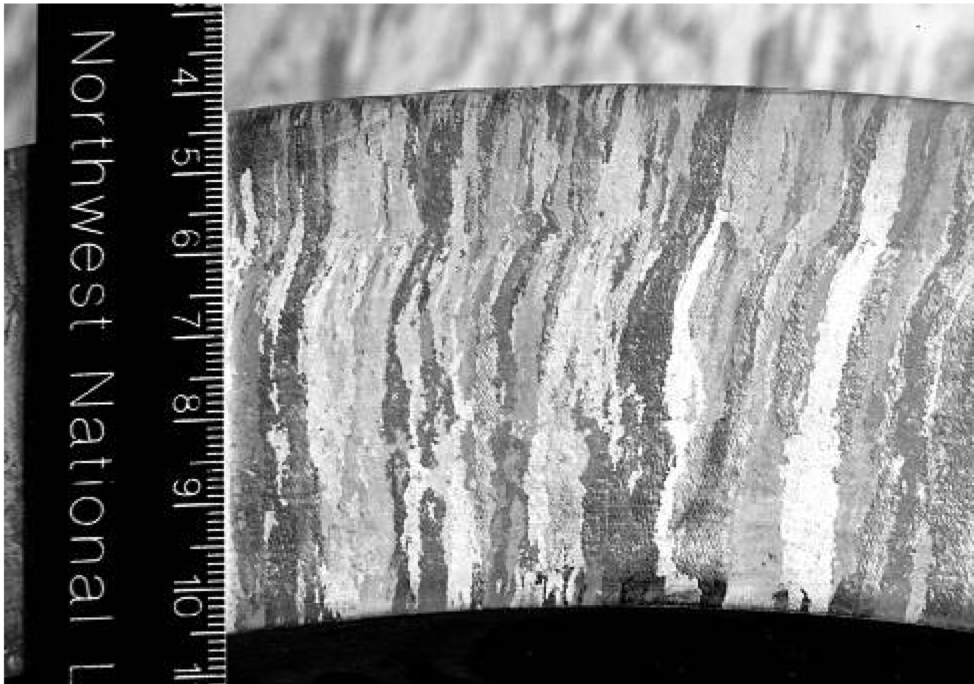
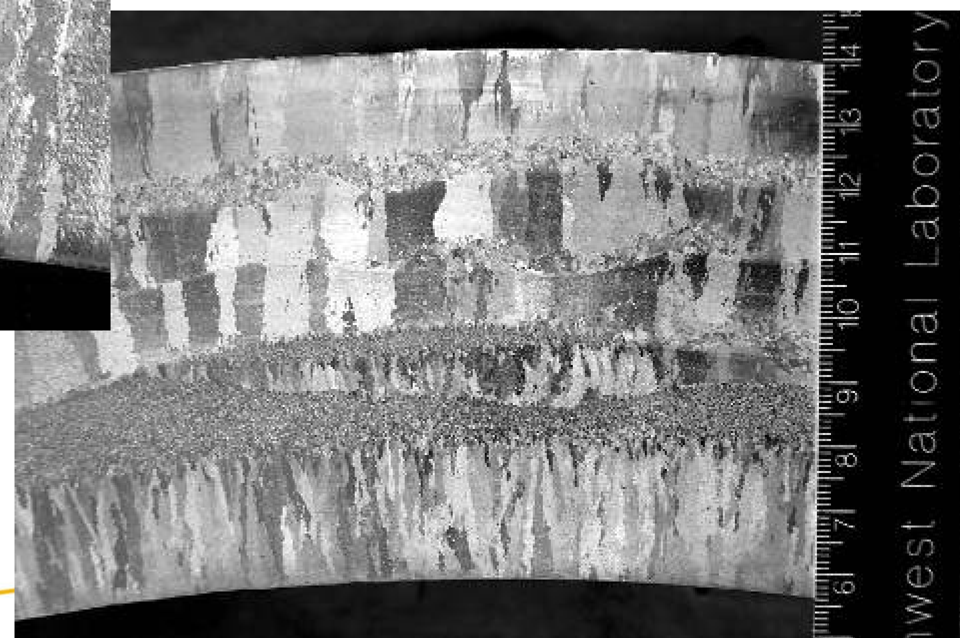
Performance Demonstration
Vintage Cast Stainless Steel



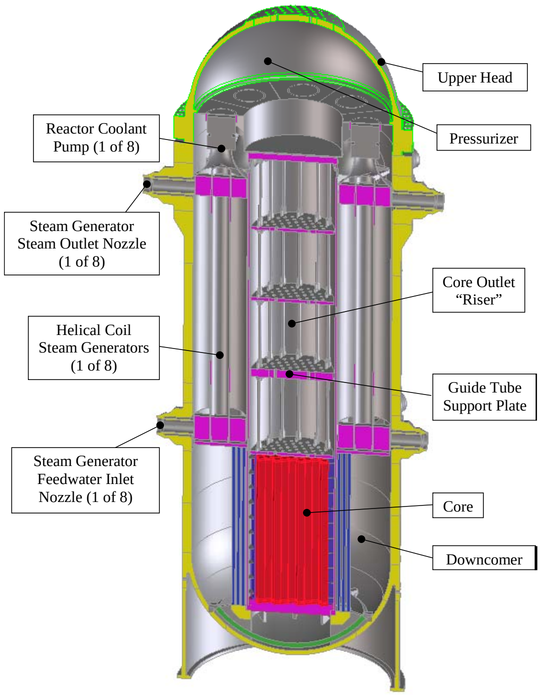


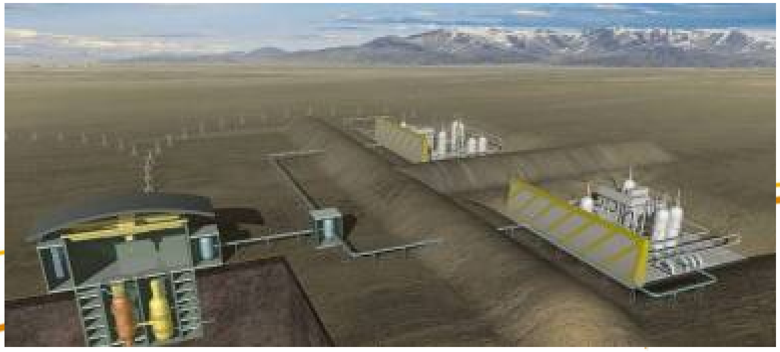
NDE/ISI – for New Construction

- Do not repeat the problems that exist with current generation plants
- **Minimize** the number of **welds**
- Select **more degradation resistant materials**
- **Prepare the ID and OD surfaces** to optimize NDE
- Provide **good access** regarding surrounding constraints
- Select **materials** based in part on the **ability to reliably inspect**
- **Select NDE** based on all materials and potential degradation processes
- **Design welds** that permit optimum inspections
- **Do not use NDE as a workmanship standard (look at fitness for purpose)**
- Consider using **continuous on-line monitoring** for detecting flaws and tracking their growth
- Build **smart systems**
- **Require performance demonstration for all NDE during construction, preservice and inservice**

Prognostics can provide

- Condition-based maintenance
- Life maximization/operational optimization
- Asset management, economic and life safety advantage
- Enhanced situation awareness
- Operational readiness & more informed decision making
- Enhanced system security





Needs for Advanced Reactor Designs and Past Experience

- New advanced gas reactors and Generation IV nuclear power plants (NPP)

- Expected to operate with high capacity factor (90%+)
- Longer refueling cycles (4–6 years)
- Gen IV NPP will operate at higher temperatures (potentially 510°C to 850-900°C (possibly 1000°C).
- Necessary inspections and maintenance performed during shorter outages.
- One challenge is limited knowledge of material performance for next-generation designs, including balance of plant and secondary units for process heat or hydrogen production.

PWR – possible R&D Topics (Compiled by Peter Scott – 2008)

PWR Generic R&D Topics (1)

- General corrosion, localized corrosion and corrosion product release
  - Oxide composition, structure, ion transport properties, modelling oxidation and cation release from first principles, changes of metal substrate composition below the oxide film
  - Flow assisted corrosion, reliability of current predictive models
  - Fouling, modelling of flow effects
  - Boric acid corrosion, leak modelling
  - Compendium of good practice for protecting tertiary cooling systems from internal and external corrosion, microbiological corrosion
  - Steel corrosion in contact with concrete, crevice effects

PWR – possible R&D Topics (Compiled by Peter Scott – 2008)

PWR Generic R&D Topics (2)

Stress corrosion cracking:

- Initiation of SCC in austenitic alloys, stochastic features, heat to heat variability
- Crack growth mechanisms, narrow crack tips, load/unload & ripple loading, dK/da effects, crack coalescence
- Weld metals, hot cracks , HAZs and dilution zones, residual stresses and their measurement, strain localization
- Water chemistry, pH_2, Zn, water chemistry transients, particularly oxygen
- Effects of long exposure periods (definition of initial condition and precursors), plant upgrades
- Effects of cold work and deformation path, CW and compositional banding
- Pb SCC and scaling of Alloy 690, reduced S SCC of Alloy 690
- External surface SCC due to surface chloride contamination, effect of modern SS compositions, influence of choice of thermal insulation
- Creep, hydrogen effects, strain aging and impurity effects on SICC of LAS & C steels

More topics….

PWR Generic R&D Topics (3)

Effects of irradiation on stainless steel core support structures:

- IASCC initiation criteria as a function of dose, stress, time and dynamic loading
- Neutron spectrum effects, high neutron doses, late blooming phases, transmutation gas products/bubbles
- Swelling & irradiation creep, non-destructive detection of degradation

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More topics….

PWR Generic R&D Topics (4)

Fracture resistance

- Effects of environment including LTCP
- Irradiation embrittlement, high fluence, large forgings, predictive models
- Thermal embrittlement of LAS at pressurizer temperatures, predictive models
- Thermal embrittlement of CASS and weld metals and possible degradation of SCC resistance, non destructive detection of embrittlement
- Hot cracking, causes, discriminating hot cracks from SCC
- Properties of weld dilution and heat affected zones, residual stresses and their measurement, strain localisation
- Strain aging of LAS and carbon steels

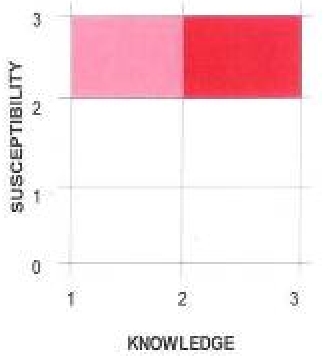
PWR Generic R&D Topics (5)

- Thermal fatigue crack initiation and propagation in austenitic stainless steels
  - Surface condition, environmental effects, transient waveform effects
- Vibration fatigue – small amplitude very high cycle fatigue

US PMMD – Compiled from NUREG/CR – 6923

"High susceptibility/likelihood" scores for PWR

- SCC of Alloy 182/82 weldments in PWR primary system
- SCC of cold worked Alloy 600MA and 600 TT components
- Irradiation induced creep & stress relaxation of high strength bolts at >0.5 dpa
- SCC of austenitic stainless steel >0.5 dpa
- Swelling of austenitic st.st. at higher temperatures and doses
- Corrosion of low alloy steels in boric acid concentrate (in, for example, CRDM annuli)
- Fatigue due to unanticipated vibration and thermal fluctuations (e.g. socket welds, primary circuit dead legs, baffle bolts with stress relaxation)
- Environmental effects on fatigue of austenitic stainless steel at low corrosion potentials
- Flow assisted corrosion of, for example, carbon steel tube support sheets
- Wear of SG tubes on secondary side



US – PMMD – Longer range concerns (NUREG/CR 6923 Panel)

- SCC and fabricability of Alloys 690,52,152 with concerns associated with the weld metal, HAZ, etc.
- SCC of severely (i.e.>20%) cold worked stainless steel in PWR primary water
- Ripple loading in primary circuit due to increasing use of low leakage cores leading to SCC increase
- Secondary side degradation of SG tubes due, for example, to lead and low valency sulfur ions
- Potential concerns during end of fuel cycle chemistry if B content reduced below minimum guidelines during cycle stretch-out (in boiling crevices of the pressurizer)

Some technical challenges

- Sensing: what to measure and how to measure
- Data interrogation, communication and integration
- Predictive models (e.g. damage evolution)
- System integration and deployment on real-world hardware
- *Quantification of uncertainty* – (ill-posed problems)
- Integration of prognostics into plant operation and O&M approach

Needs, Priorities and the Future

Future systems will have the ability to integrate off-line NDE inspection information with intelligent self-diagnostic capabilities that will alert operators and initiate remediation strategies…..

AND OPTIMIZE UTILIZATION & OPERATION

- Smart components and structures
- Self-diagnostic systems
- Embedded Micro-Electromechanical Systems (MEMS) (and other) health monitoring sensors
- Wireless communication
- Distributed data processing and control networks
- Prognostics implementation
- Advanced NDE technologies
- Proactive operations and maintenance program
- Optimized Plant of the Future

Areas for action…..

- Much can be learned by **looking back** at the history of degradation in nuclear power plants and the evolution of NDE/ISI to manage it
- If we want to **achieve high public confidence** in nuclear power then we must control surprises and **convincingly demonstrate** that **degradation is being managed**
- **Over the past 30 years Performance Demonstration** has been the **single biggest factor in improving UT/ISI reliability**
- For the future, much work is needed to **expand performance demonstration** to
  - other NDE methods,
  - other reactor components,
  - new construction including Generation IV designs with many new degradation processes and materials to consider
- Continue research to **develop advanced ISI/NDE technologies** and quantify their reliability
- Look to learn from other industries AND consider where on-line monitoring and utilization of enhanced functionality of digital I&C can make plant operators smarter – and enhance plant life management (PLiM)

Potential Economic Impact

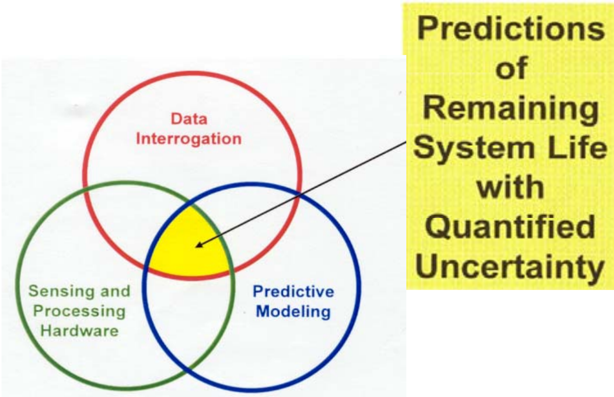
- **Nuclear – 104 US legacy systems – Potential savings for the Industry estimated at over $1 B / year (applicable risk significant equipment). (Bond et al (2002)**
  - **Increase in plant availability**
  - **Reduce radiation exposure to plant personnel**
  - **Reduction in plant O&M costs**
  - **Increase in plant shutdown safety margins**

- **New US nuclear plants – significant but yet not quantified**

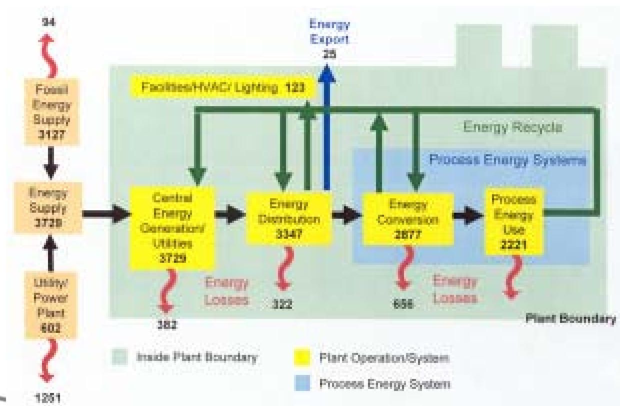
- In US - "**More than $1 Trillion is spent each year replacing perfectly good equipment** …"[McLean et al (2002)]

INTEGRATED "Prognostics +" VISION of BENEFITS

Condition Assessment/Damage Prognosis



Optimized and Integrated Energy and Process Control



Power plant, Factory (or Process Plant) of the Future

- Process Control
- Process Optimization
- Advanced Energy Management
- Condition Based Maintenance
- Advanced Data Visualization and Management Tools
- Optimize plant staffing
- Optimize cost of Ownership and Operation

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Conclusions

- There are many programs (e.g. DARPA, Navy, AF, NASA etc) looking at system health monitoring/prognostics and potential for impact being recognized
- Many researchers working on Structural Health Monitoring / condition-based maintenance and prognostics
- In most cases Structural Health Monitoring and Prognostics have not transitioned from research to engineering practice
- Few are bringing ALL the requisite technologies together and then advancing these in a synergistic manner
- Prognostics is a "Grand Challenge" for the engineering community to address in the 21st century – that is VITAL for optimization of operation of both legacy and next generation (nuclear) energy and process plant systems

Acknowledgements

- Further details and full citation references for some materials are to be found in:
- Bond L.J. et al (PNNL Report # 17779 – August 2008)
  - Proactive Management of Materials Degradation – A review of principles and programs

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