3rd NRC – AERB NUCLEAR SAFETY PROJECTS MEETING

NRC Research Addressing Materials Degradation

February 23 – 28, 2004

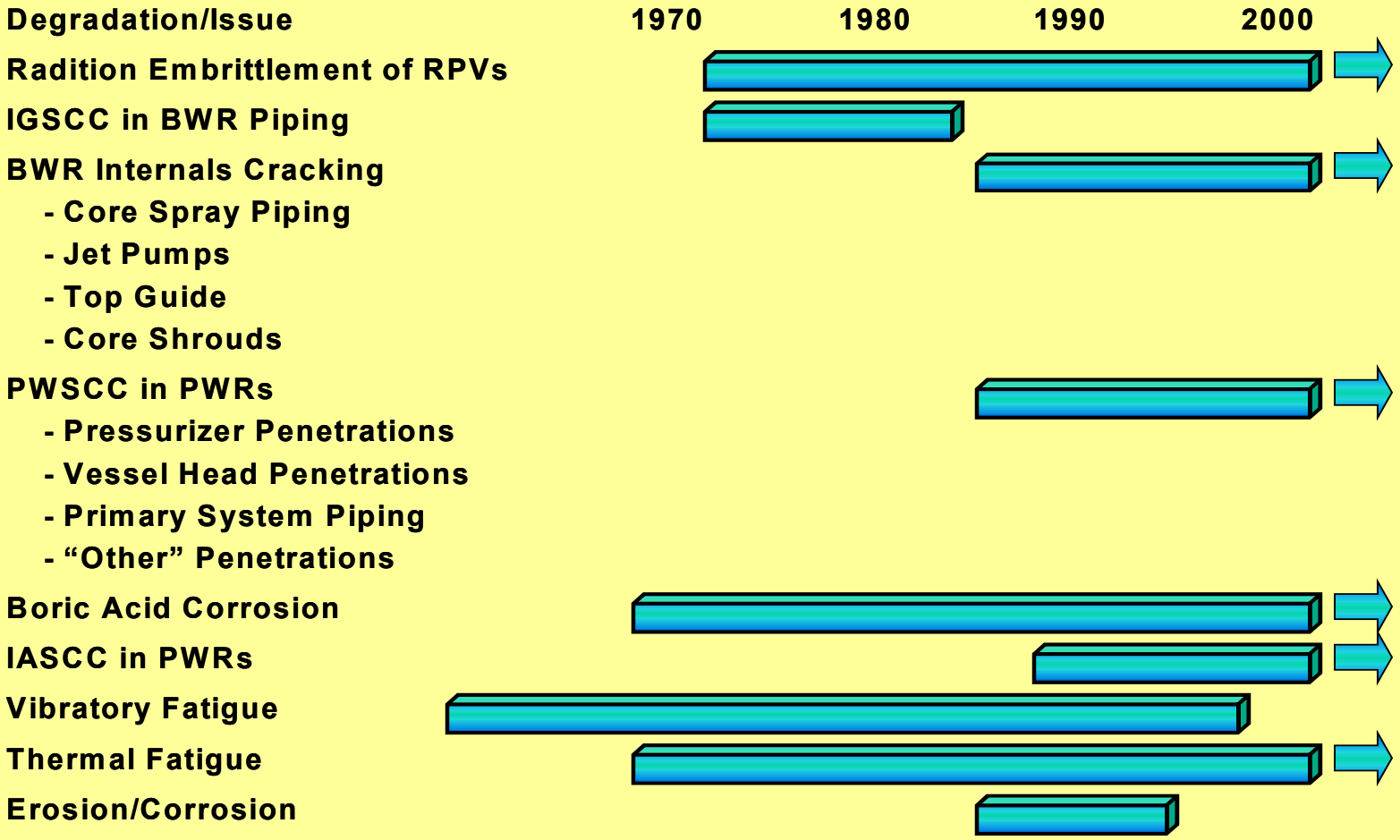
US NRC Office of Nuclear Regulatory Research
Division of Engineering Technology (DET)

M. E. Mayfield, Director
Email: mem2@nrc.gov Phone: (301) 415-5678

RES' Materials Degradation Research Programs

- EAC research an important element of RES program since 1977
- Program has been adjusted over time to respond to current degradation issues
  - IGSCC
  - IASCC
  - Fatigue Life for Piping
  - Fatigue Crack Growth in RPV and Piping
  - Steam Generator Tube Degradation
  - PWSCC
  - Boric Acid Corrosion
- Recent emphasis on proactive research

Sample of Significant Materials Degradation Issues in U.S. Nuclear Power Plants (Excluding Steam Generators)



RES' Materials Degradation Research Programs

- **Major Activities**
  - Environmentally-assisted Cracking in Light-Water Reactors
    - IGSCC in BWR piping
    - BWR internals cracking
    - PWSCC in PWRs
    - IASCC in PWRs
    - Fatigue
    - Erosion Corrosion
  - Corrosion of Pressure Boundary Materials in Concentrated Boric Acid Solutions
  - Examination of North Anna 2 Nozzles & J-Welds
    - PWSCC in PWRs
  - Proactive Materials Degradation Initiative

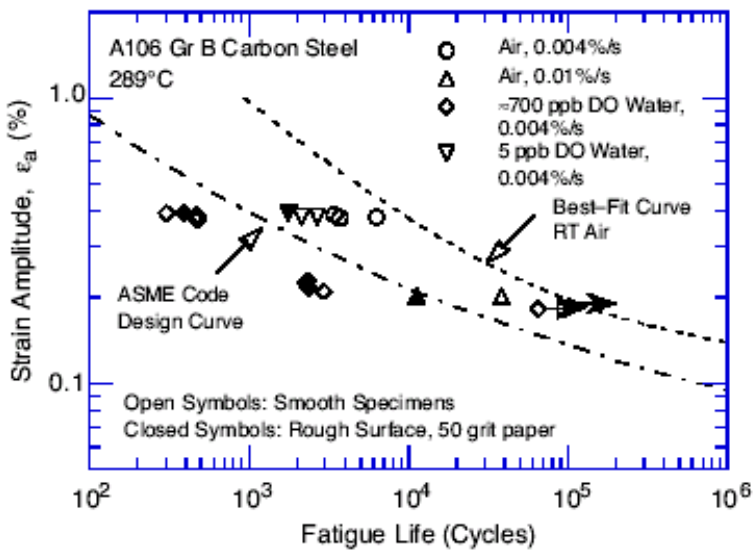
RES' Materials Degradation Research Programs

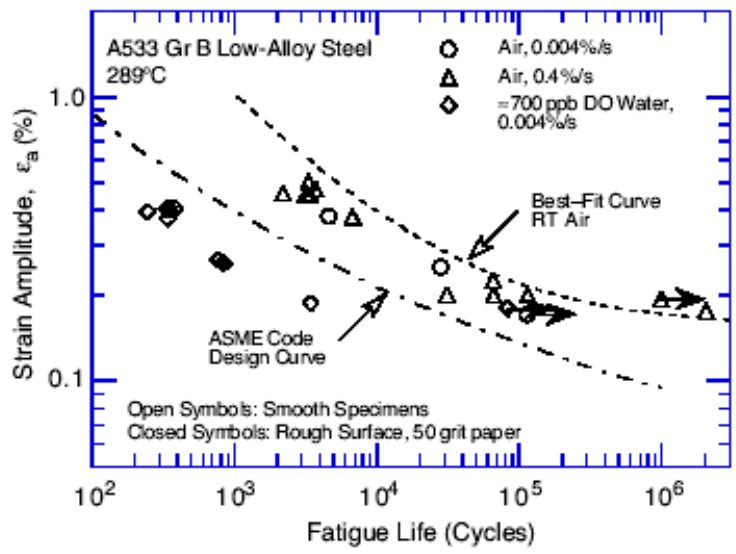
- Other Tasks
  - Vessel Penetration Conference – Sept. 29 – Oct. 2, 2003
    - Crack growth rates
    - Structural and fracture mechanics analyses
    - Risk
    - Inspection technology
    - Mitigation techniques
    - Continued plant operation
  - Alloy 600 experts Task Group
    - PWSCC in PWRs
  - Formation of Int'l Coop Group on PWSCC and NDE

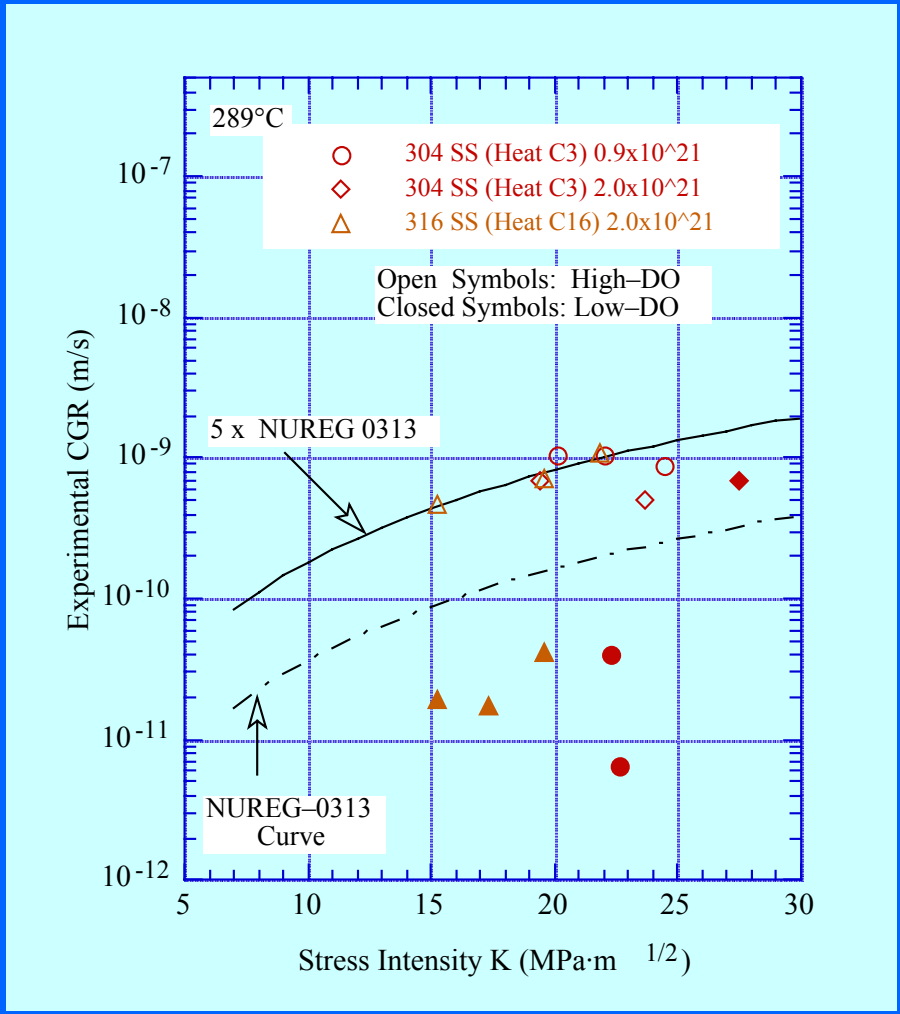
Elements of EAC in LWR Program at Argonne

- Fatigue Life Evaluation – PWR & BWR Environments
  - Carbon and Low-Alloy Steels (NUREG/CR-6583)
  - Stainless Steels (NUREG/CR-5704, CR-6787)
- IASCC for Stainless Steels in BWR & PWR Coolant Environments
- CGRs in Nickel-Base Materials
  - Alloys 600, 182, 690, 152
    - Samples taken from former Davis-Besse Head
- Code Committee/Rule Making Involvement

Degradation of Fatigue Life Due to Surface Roughness and Coolant Environment





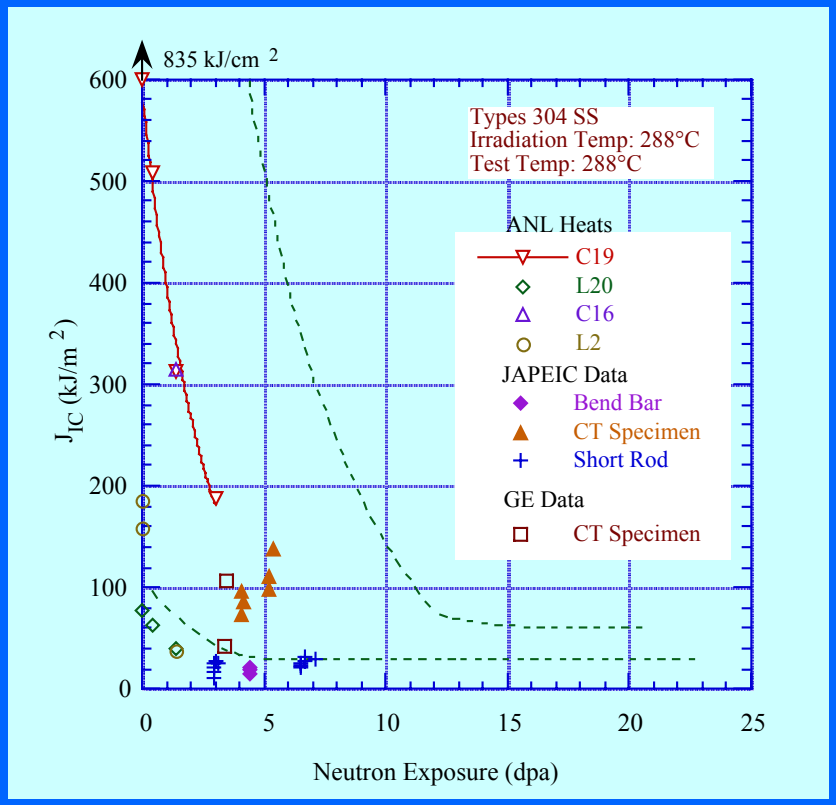


- In NWC BWR environment, CGRs from present study are a factor of "5 higher than NUREG 0313 curve for austenitic SSs
- CGRs decreased by more than an order of magnitude in low–DO water
- Decrease in DO appears to have no effect on CGRs of Heat C3 Irradiated to 2.0 x 10^{21} n/cm^2

Summary of IASCC Effects for Stainless Steels (BWR Coolants)

- CGR data have been obtained under gentle cycling and constant load in simulated BWR environments for Type 304 & 316 SS irradiated up to 2.0 x 10^{21} n/cm^2 (3.0 dpa) at 288°C
- In NWC BWR environment, CGRs of irradiated steels are a factor of "5 higher than NUREG 0313 curve for non-irradiated austenitic SSs
- In low–DO BWR environments, CGRs of irradiated steels are decreased by more than an order of magnitude; beneficial effect of decreased DO level not observed for Type 304 SS Heat C3 irradiated to 2.0 x 10^{21} n/cm^2

Degradation of Fracture Toughness of Stainless Steels Due to Irradiation Damage



- *Fracture toughness J–R curve data obtained on several heats of austenitic SSs irradiated to "0.3, 0.9, and 2.0 x 1021 n/cm2 (0.45, 1.35, & 3.0 dpa) at 288°C*
- *Neutron irradiation at 288°C decreased the toughness of all steels*
  - *commercial steels exhibit superior fracture toughness*
  - *poor toughness of laboratory heats reflected in their fracture behavior*
- *The results for commercial heats falls within the scatter band for data obtained from higher temp irradiations*

Planned Research on IASCC Effects for Stainless Steels (PWR Coolants)

- Irradiations to 4 dose levels: 5, 10, 20 & 40 dpa
  - In BOR-60 reactor, at ~300°C (5 & 10 dpa doses completed)
- Examination of C, S & O effects in commercial and model 304, 316, 347, 348 & cast stainless steel
- SCC, tensile, shear-punch tests
- Microstructural characterization (precipitates, RIS, grain boundary chemistry)
  - Characterization of crack tip chemistry
- Development of quantitative modeling and IASCC projections for PWR coolant environments

Sept. ’03 Conference on CRDM and related Issues

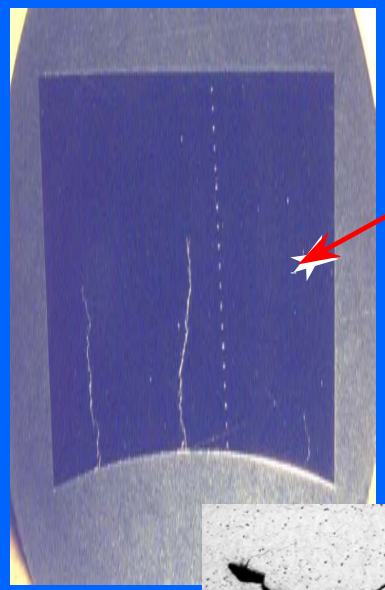
- Five main session topics
  - Structural Analysis and Fracture Mechanics Issues
  - Inspection technologies, disposition & sizing of flaws, new developments
  - Crack growth rates for relevant nickel-base alloys & welds
  - Mitigation & Foreign Experience
  - Continued Plant Operation
- Sept. 29 – Oct. 2 at Gaithersburg-Marriott
- 220 attendees (11 countries) & participants
- Proceedings to be issued as CD and NUREG/CP in 4/04

Harvesting of RPV Head for Additional Research

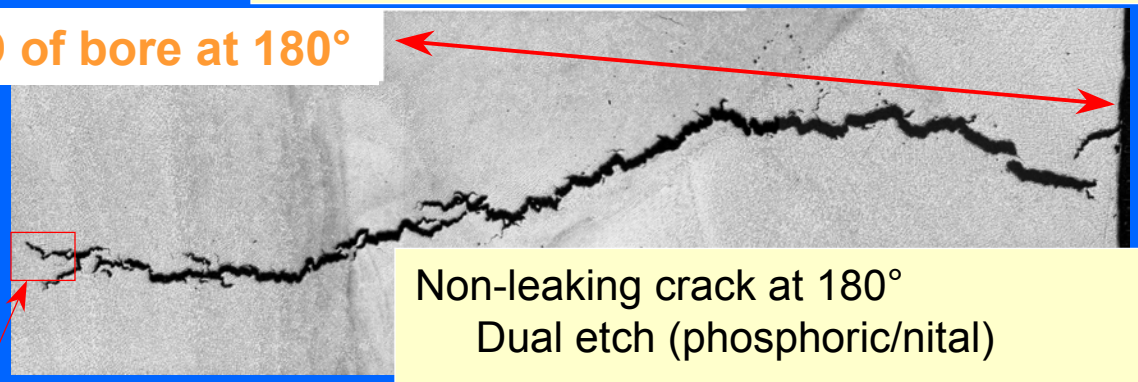
- Nozzle #3 and surrounding low-alloy steel at BWXT-Lynchburg
  - Optical & SEM Microscopy of Cavity Surface
  - Cladding Properties, Microstructure, etc.
- Nozzles #2 and #46 - removed in June
  - Sent to PNNL for exam of cavity and research on “anomalous” UT indications
  - Additional nozzles for crack growth rate testing
- Crack Growth Rate Testing of Alloy 600 (Nozzle #3) and Alloy 182 (J-weld, from Nozzle #11) underway
- North Anna Unit 2 Head Being Harvested by Industry
  - NRC/Industry Coordination of NA2 Research
  - Program combines NDE, stress analysis and SCC studies

Character of PWSCC cracks in J-weld of Nozzle #3

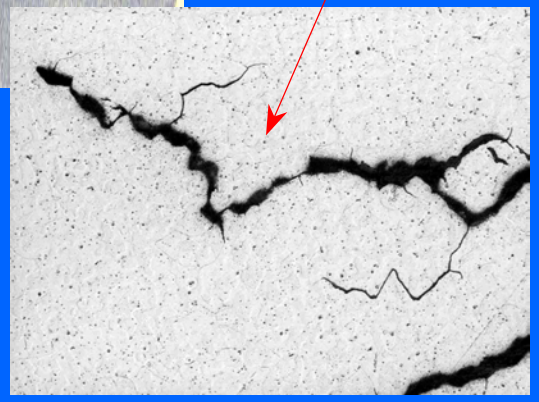
Optical image (left) and metallographs (below) are mirror images of each other.

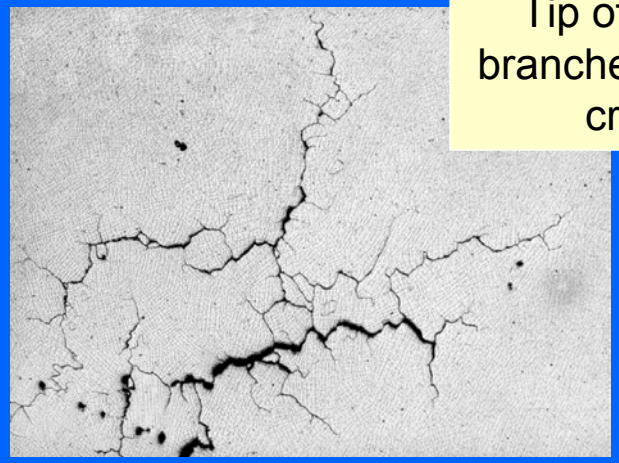


ID of bore at 180°



Non-leaking crack at 180°
Dual etch (phosphoric/nital)





Tip of one of many branches of the leaking crack at 10°

Content of New Boric Acid Corrosion Research Program

- 1. Crack Growth Rates of Alloys 600 & 182 from Davis-Besse Head
  - Specimens Fabricated, Supporting Tests underway, complete by 4/04
- 2. Computational Model, Probabilistic Assessment of:
  - Statistics of Initiation, Probability of Detection & Accuracy of Sizing
  - Crack Growth Rate Variations, Stress Intensity Factor Gradients
  - Electrochemical Potential and Polarization Measurements of Low-Alloy Steel, Alloys 600 & 182 in Concentrated Boric Acid Solutions
- Measure E_{cp} and wastage rates for range of solution compositions, temperatures & pressure boundary materials
  - Tests completed, report due 4/04

Status of North Anna 2 Discarded Head Exams

- Part of NRC/Industry Collaboration on Alloy 600 Issues
- Seven nozzles removed in late June, shipped to PNNL
- Decontamination completed 11/03
- Several NDE teams will re-examine nozzles
  - Laboratory confirmation of indications – compare to field results
  - NDE exams by industry teams to be completed by 3/15/04
  - Independent exam by NRC contractor to be completed by 12/04
  - Silastic molding of nozzles completed by 2/29/04
- Destructive exams to follow
  - Confirmation of defects, types of cracking
    - PWSCC, TGSCC, fatigue (?), how initiated
    - Leak paths (or absence thereof !)
    - Materials for crack growth studies, residual stress analysis

Salvaging of nozzles from North Anna 2's Discarded Reactor Head

Nozzle #31

Nozzle #59

Materials Degradation Management

- Management of Identified Degradation
- Evaluation of New Materials, Inspection Procedures and Techniques, New Degradation Mechanisms
- Evaluation of Repair and Mitigation Strategies

Proactive Materials Degradation Initiative

Motivation

- Reactive approaches to dealing with materials degradation problems have been inefficient
  - Increased financial and manpower burden
  - Compromise regulatory effectiveness and efficiency
  - Potential to erode public confidence
- NRC/RES decided to take a proactive approach to materials degradation assessment
  - Develop a foundation for appropriate actions to keep materials degradation from adversely impacting safety

Proactive Materials Degradation Initiative

Approach

- First step is to identify materials and locations where degradation can reasonably be expected in the future
- Next step is to develop and implement a research program for the components and degradation of interest that will review, evaluate, and develop as needed:
  - Inservice inspection and continuous monitoring techniques for the detection, characterization, and evaluation of degradation
  - Techniques to ameliorate stressors for mitigation or prevention of expected degradation
  - Materials for repair or replacement
  - Repair and replacement techniques
  - Post-repair and fabrication inspection techniques
- Research program will consider ongoing international research and address gaining a better understanding of current and potentially new degradation mechanisms

Proactive Materials Degradation Initiative
Identify Components of Interest

- To accomplish the first step, use a PIRT-like process
  - Has been used extensively by NRC
  - Have evaluated its potential use for proactive materials degradation assessment
  - Structured expert elicitation
  - 7-member (or larger) international expert panel: Materials/corrosion, systems, operational experience
  - 8 meetings over one year to initiate in Summer 2004
  - Provide background information to panel on materials, stressors, function of components
  - Develop list/report of PWR and BWR components with associated degradation phenomena including ranking and the bases for the findings
  - International peer review

Proactive Materials Degradation Initiative
International Cooperative Research Group

- To accomplish the second step, an international group will be assembled/sponsored by NRC and EPRI
- Technical experts and sponsoring organizations
- Together develop a broad-based research program plan
  - Materials and degradation mechanisms
  - Mitigation
  - Repair and replacement
  - Nondestructive evaluation
- Through cooperative agreement, sponsor, implement and share research results
- Meetings to develop program plan and cooperative agreement:
  - April 2004 in Japan in conjunction with the ICG/EAC meeting
  - Summer 2004 in USA
  - Fall 2004 in Europe
- Initiate research and cooperation 2005