Status of IASCC Crack Growth Model
&
Advanced Radiation Resistant Materials (ARRM) Program

Robin Dyle, EPRI

Raj Pathania, EPRI

NRC – Industry Meeting

June 3, 2014

EPRI IASCC Data Compilation & Analysis: Objectives

- Compile crack growth rate data on irradiated stainless steels developed by EPRI, NRC, Halden and other international programs
- Convene an Expert Panel to review and screen the available CGR data on irradiated materials using appropriate screening criteria
- Develop crack growth models and disposition curves for application to BWR and PWR internals
- This work is coordinated between PSCR, BWRVIP and MRP Programs at EPRI

© 2014 Electric Power Research Institute, Inc. All rights reserved.

EPRI IASCC Expert Panel

- Industry Expert Panel Members:
    - *Peter Andresen, GE-GRC*
    - *Steve Fyfitch, AREVA*
    - *Rich Jacko, Westinghouse*
    - *Ron Horn, GE Hitachi*
    - *Torill Karlsen, IFE Halden*
    - *Pal Efsing, Vattenfall*
    - *Anders Jenssen, Studsvik*
    - *Peter Scott, Consultant*
- EPRI Participants
    - *Raj Pathania*
    - *Bob Carter*
    - *Robin Dyle*
    - *Jean Smith*
- Principal Investigator
    - *Ernie Eason, Modeling & Computing Services, LLC*

© 2014 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

EPRI IASCC Expert Panel Meeting: Screening Criteria

- Review original crack length (a) vs. time (t) curves for each specimen and test segment in the database
- For each test segment consider stress intensity (K) validity for irradiated materials vs. ASTM E 399 and alternative criteria
- Crack extension (da)
- Test segment interval (dt)
- Variation of K with crack dK/da
- Constant load or K vs. partial unloading
- Load ratio (R)
- Correlation coefficient on the linear fit to crack growth rate over a given test segment
- The consensus was that these criteria should not be applied individually without considering the entire context of the test

© 2014 Electric Power Research Institute, Inc. All rights reserved.

EPRI ELECTRIC POWER RESEARCH INSTITUTE

$\dot{a}$

Range of Selected Variables in the Low-ECP Calibration Data

Variable	Symbol	Range	Units
Crack growth rate	da/dt or	2.2×10^{-9} to 3.1×10^{-5}	mm/s
Dose	dose	0.23 to 47.5	dpa
SCC test temperature	T	275 to 340	°C
Irradiated yield stress	$\sigma_{0.2}$	257 to 1111	MPa
Stress intensity factor	K	6.5 to 32.9	MPa√m
Electrochemical potential	ECP	-359 to -894	mV_{SHE}
Dissolved H_2 concentration	$[H_2]$	0.02 to 3.29	ppm
Outlet conductivity	κ	0.06 to $\leq$ 0.3 (HWC only)	mV_{SHE}
Lithium concentration	[Li]	1.88 to 3 (PWR only)	ppm
Boron concentration	[B]	500 to 1298 (PWR only)	ppm

© 2014 Electric Power Research Institute, Inc. All rights reserved.

$\dot{a}$

Range of Selected Variables in the NWC Calibration Data

Variable	Symbol	Range	Units
Crack growth rate	da/dt or	7.7×10^{-9} to 1.4×10^{-5}	mm/s
Dose	dose	0.21 to 47.5	dpa
SCC test temperature	T	272 to 330	°C
Irradiated yield stress	$\sigma_{0.2}$	254 to 925	MPa
Stress intensity factor	K	3.85 to 28.7	MPa√m
Electrochemical potential	ECP	70 to 273	mV_{SHE}
Dissolved O_2 concentration	$[O_2]$	0.2 to 32	ppm
Outlet conductivity	κ	0.08 to 0.3	µS/cm

© 2014 Electric Power Research Institute, Inc. All rights reserved.

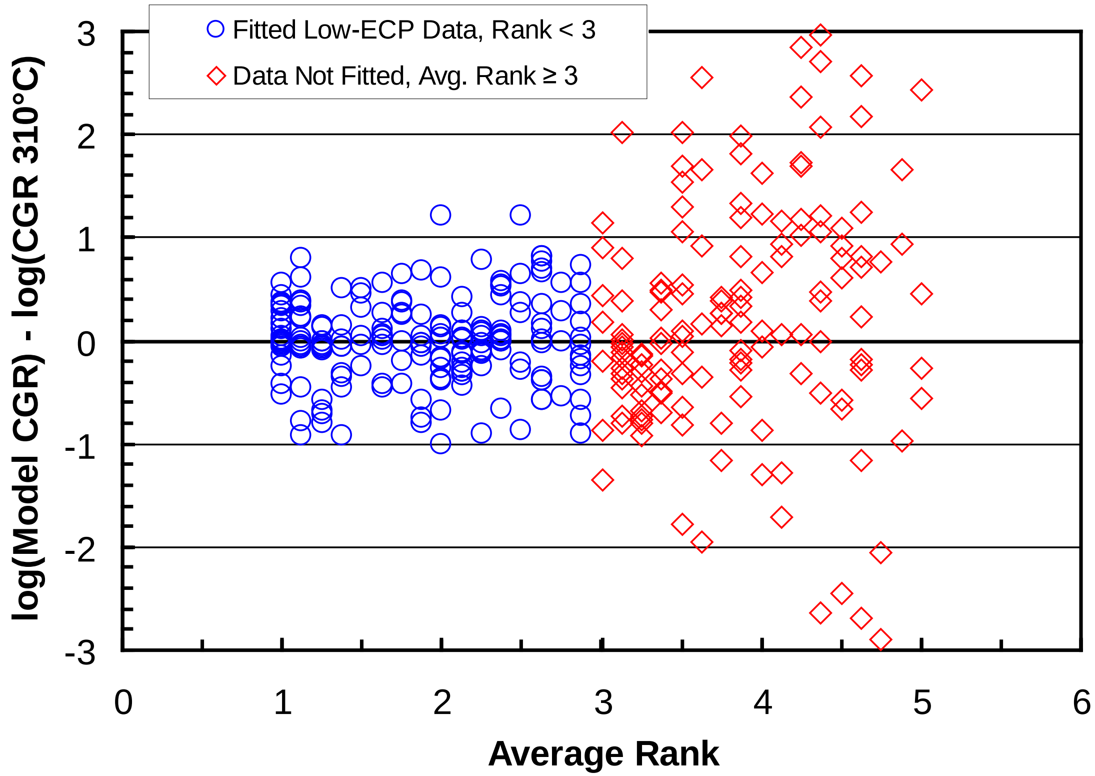
EPRI ELECTRIC POWER RESEARCH INSTITUTE

EPRI IASCC Expert Panel Status

- The database includes more than 1600 test segments including those under cyclic loading
- For IASCC crack growth rates only test segments under constant load or periodic partial unloading were considered
- The reviewers ranked the test segments on a scale of 1 (best) to 5 (unsuitable) after examining the raw data from crack length vs. time plots
- Data with average ranks from 1 to 3 was considered suitable for development for IASCC crack growth models for BWR NWC, HWC and PWR environments

© 2014 Electric Power Research Institute, Inc. All rights reserved.

Low-ECP Residuals vs. Average Rank

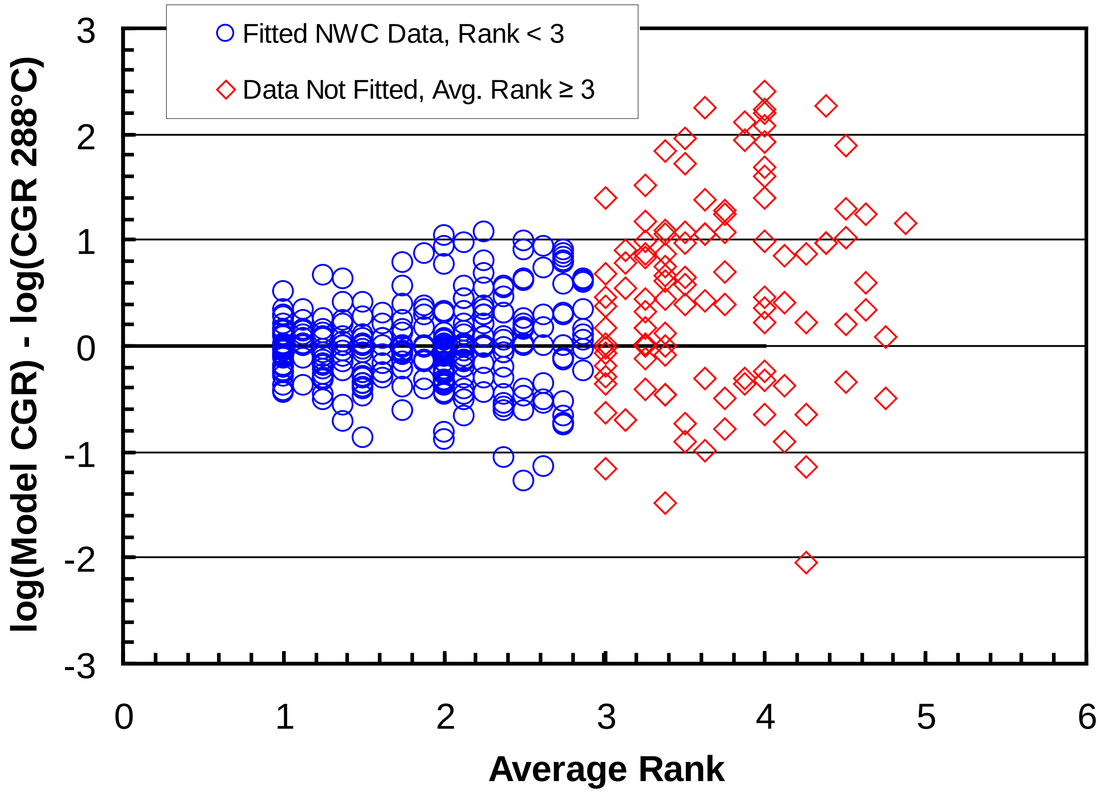


- *187 CGR observations in proposed model (73 in HWC &114 in PWR primary water)*
- *22 heats*
- *52 specimens*
- *Tested in 6 laboratories*

© 2014 Electric Power Research Institute, Inc. All rights reserved.

EPRI | ELECTRIC POWER RESEARCH INSTITUTE

NWC Residuals vs. Average Rank



- *283 CGR Observations in proposed model*
- *22 Heats*
- *56 Specimens*
- *Tested in 5 laboratories*

© 2014 Electric Power Research Institute, Inc. All rights reserved.

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Alternative Yield Stress Term

- Dose and irradiated yield stress are strongly correlated, as shown in the next slide
- Yield stress is known to strongly affect SCC CGR, in both unirradiated and irradiated conditions
- Irradiated yield stress can be measured or estimated from the correlation with dose (MRP-135 Rev1)
- For the above reasons, yield stress based models were developed as an alternative to the dose models

© 2014 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

High and Low ECP Models

- Overall form:

$$\frac{da}{dt} = C_i \cdot f(PPU) \cdot \sigma_{0.2}^{v} \cdot \exp\left[-\frac{Q}{R}\left(\frac{1}{T} - \frac{1}{T_{ref}} \right) \right] \cdot K^{u}$$

  - *da/dt* is crack growth rate (mm/s)
  - C_i is a material/environment coefficient calibrated to each specimen or heat
  - *f* (PPU) partial periodic unloading constant = CGR_{PPU}/CGR_{CL}
  - $\sigma_{0.2}$ is the irradiated yield stress at the temperature and dose of the IASCC test specimen (MPa)
  - *Q* is the activation energy (kJ/mol)
  - *R* is the universal gas constant 8.314 J/(mol-K)
  - *T* is the SCC test or model application temperature
  - T_{ref} is a reference temperature at which the model is calibrated
    - T_{ref} = 583.15 kelvin (310°C) for low-ECP data
    - T_{ref} = 561.15 kelvin (288°C) for NWC data
  - *K* is the stress intensity factor, (MPa√m)
  - *v* and *u* are fitted exponents

© 2014 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

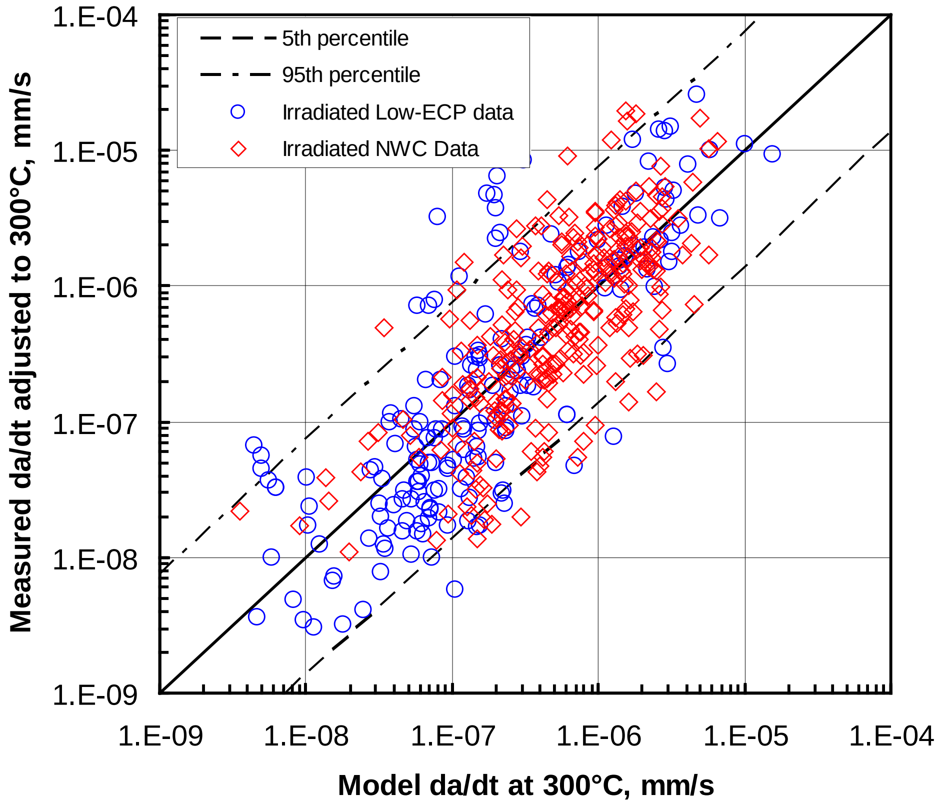
EPRI IASCC Expert Panel: Draft Low and High ECP Models

- The models account for effects of dose, stress intensity K, ECP, temperature, type of loading (constant load vs. PPU)
- The CGRs under PPU were approximately 2X higher than under constant load
- After accounting for above parameters there is still a significant heat to heat (or specimen to specimen variability) reflected in coefficient C*i*
- A similar heat to heat variability has been observed in Ni-base alloys (MRP-55 and MRP-115)
- There was no significant difference in the CGRs between BOR 60 and LWR irradiated materials after accounting for the above factors
- Analysis showed that a common model can be used for BWR-HWC and PWR environments with a temperature term to account for higher PWR temperatures
- The ratio between NWC CGR and low-ECP CGR, is a factor of ~6 for mean coefficients and a factor of ~4.5 for 75% coefficients

© 2014 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

Overall fit of proposed model



Based on Heat Coefficients

© 2014 Electric Power Research Institute, Inc. All rights reserved.

EPRI IASCC Crack Growth Report–Status

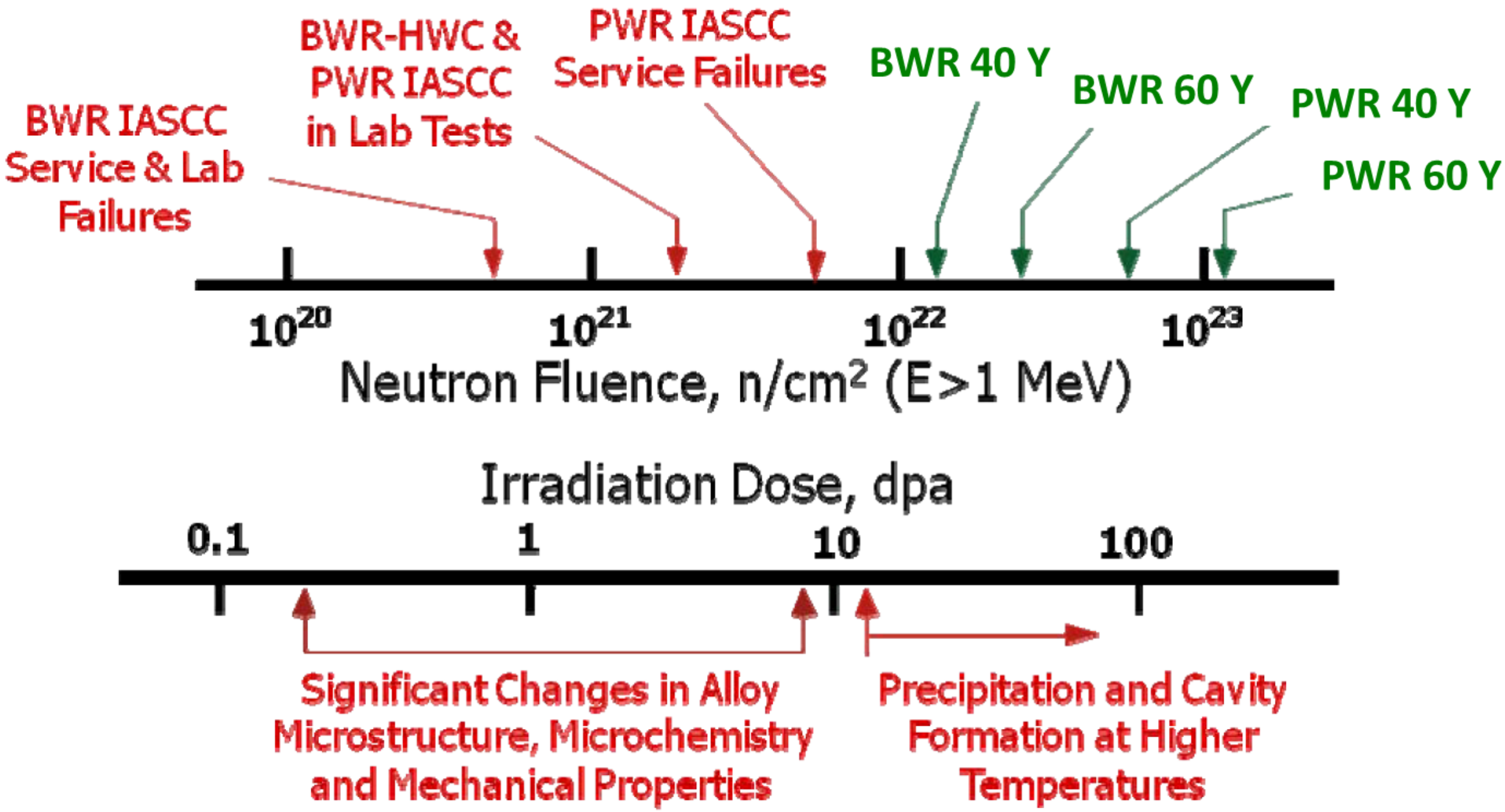
- Prepare a draft report on the IASCC database and low ECP (PWR and HWC) and high ECP (NWC) IASCC models for Expert Panel /EPRI review-*completed*
- Expert panel conference call to discuss and resolve comments-*completed*
- Address expert panel comments, revise report and send to PSCR, MRP and BWRVIP committees for review: *July-August 2014*
- Resolve industry comments, revise report and publish by end of 2014
- The report will provide the technical basis for crack growth disposition curves for irradiated BWR and PWR stainless steel internals
- Expect to provide report to NRC for review in 2015

© 2014 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

Advanced Radiation Resistant Materials (ARRM) Program

Irradiation Induced Degradation of Austenitic Stainless Steels



© 2014 Electric Power Research Institute, Inc. All rights reserved.

Objectives of ARRM Program

- EPRI and the U.S. Department of Energy (DOE) are initiating a global, collaborative research effort to develop the next generation of materials for in-core structural components and fasteners.
- The two primary research goals are:
  - By 2022, to develop and test a degradation-resistant alloy that is within current commercial alloy specifications
  - By 2024, to develop and test a new advanced alloy with superior degradation resistance

© 2014 Electric Power Research Institute, Inc. All rights reserved.

ARRM Critical Issues Report and Roadmap

- EPRI and DOE have published “Critical Issues Report and Roadmap for Advanced Radiation Resistant Materials Program”, (EPRI Report 1026482, December, 2012)
- Objectives:
  - Identify candidate materials for use in structural applications in LWR reactor internals that have increased resistance to irradiation-induced degradation compared to currently used materials
  - Develop a systematic test program for further evaluation of these candidate materials in a phased manner, including irradiation out to high neutron doses

© 2014 Electric Power Research Institute, Inc. All rights reserved.

Commercial Alloys for Further Development

Low Strength Applications

- Hastelloy C22
- Alloy 690
- Alloy 625 (solution-annealed, not precipitation-hardened)
- Alloys 800/800H/825
- Alloys 309/310
- 12Cr F-M alloys (Optimized HT9)
- 9Cr F-M alloys (NF616)
- Zr-2.5Nb

High Strength Applications

- Alloy 625 Plus (precipitation-hardened condition)
- Alloy 725/718

© 2014 Electric Power Research Institute, Inc. All rights reserved.

Advanced Alloys for Further Development

<u>Low Strength Applications</u>

- Ti Alloys (Grade 26 + 0.1Ru)
- Higher Cr (>14Cr) F/M alloys (Type 439)
- ODS alloys (8-14Cr and Higher Cr with Al) (14YWT)
- High Cr, High Al ODS Alloys (?)

<u>High Strength Applications</u>

- ODS alloys (8-14Cr and Higher Cr with Al) (14YWT)

Advanced alloys will need ASME code qualification

© 2014 Electric Power Research Institute, Inc. All rights reserved.

Key Deliverables

- Critical Issues Report and Roadmap for the Advanced Radiation-Resistant Materials Program (Report 1026482, December 2012).
- Interim report documenting the results of microstructural, mechanical and stress corrosion cracking studies on proton irradiated alloys to identify promising alloys for further evaluation (December 2015).
- Final report recommending alloys for further evaluation under irradiation (December 2017).
- Interim report documenting microstructural, mechanical and stress corrosion cracking studies on neutron irradiated alloys (December 2019).
- Final report on qualification of radiation resistant commercial alloys for LWR internals (December 2022)

© 2014 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

ELECTRIC POWER RESEARCH INSTITUTE

Together…Shaping the Future of Electricity