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EPRI/MRP R&D Programs for PWR RCS Materials

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NRC EAC Kickoff Meeting
September 25-26, 2007
Argonne, IL

MRP Mitigation and Testing ITG: Scope

- Mitigation & Testing ITG conducts R&D for the MRP:
  - Fracture toughness and crack growth studies
  - Field specimen evaluations and reports
  - Irradiation Assisted PWSCC Testing
  - Materials testing: chemistry, crack growth on Alloy 600
  - Methods development and validation: chemical, mechanical (e.g., PWOL, peening)
  - Mitigation strategies, studies, options and evaluations for various degradation phenomena
  - Basic research and development for materials issues including chemistry effects, etc

MRP Mitigation and Testing ITG: Strategic Objectives

- Develop chemical and mechanical PWSCC mitigation strategies to delay component repair/replacement and to obtain inspection relief for RCS components
- Prepare technical bases for mitigation methods; some have been prepared or are planned over the next few years:
  - Pre-emptive weld overlay (PWOL)
  - Elevated hydrogen and zinc addition
  - Cavitation and fiber laser peening
- Conduct PWSCC testing on replacement materials to support inspection relief for RCS components
- Perform Irradiation Assisted PWSCC Testing to support RI I&E GL goals
- Support basic tactical research and development for materials issues including chemistry effects, etc
- Resolve IMT gaps (e.g. stainless steel degradation/mitigation)

Mitigation & Testing Ongoing Programs

- Boric Acid Corrosion Management Program
- SCC in Stainless Steel
  - Effect of Cold Work on SCC
  - Role of Sensitization in SCC
  - Destructive Examination of Field Samples (Braidwood)
- PWSCC Mitigation
  - PWSCC Initiation Mechanism in A82/182
  - Peening Technologies Qualification for BMNs
  - PWSCC Mitigation by PWOL
  - Qualification of H2/Zn for PWSCC Mitigation
    - PWSCC Testing
    - Safety Assessment for Elevated Hydrogen
    - Fuel Testing for Elevated Hydrogen
    - Technical Bases
- Expert Panel
- Low Temperature Crack Propagation
- IASCC Programs:
  - International IASCC Test Cofunding
  - CR-3 Baffle Bolt Retrieval and Testing
  - Boris 7 Irradiated Materials Testing
  - Crack Growth Test in Halden under PWR Environment
  - GONDOLE void swelling Irradiation and Testing
- Nickel-base Materials SCC Testing
  - Alloy 690/52/152 Crack Growth Rate Testing
  - Low K CGR Testing for Alloy 600/82/182
  - Alloy 600/690 HAZ Crack Growth Rate Testing

This presentation addresses the nickel-base materials SCC testing projects

Alloy 690/52/152 CGR Testing

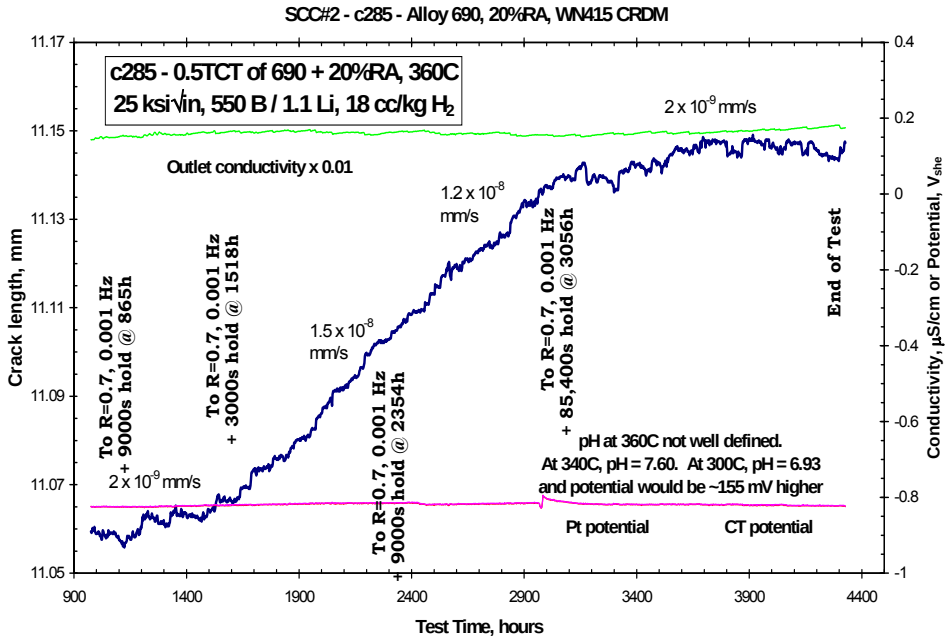
Alloy 690/52/152 CGR Testing Background and Objectives

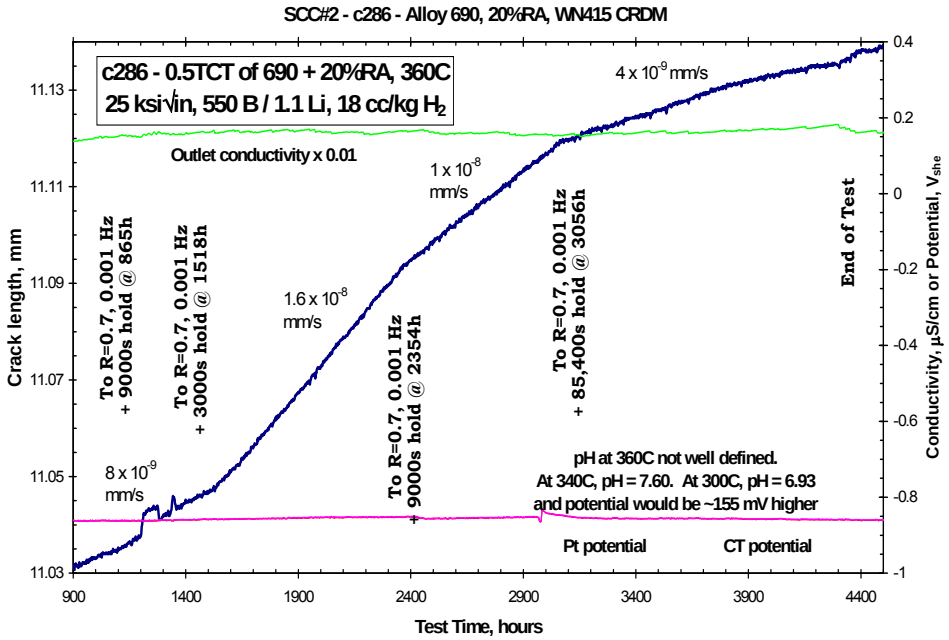
- MRP-111 (published in March 2004) documented what was then known about the PWSCC resistance of the Alloy 600 replacement materials
- Although generally positive, this report identified a number of gaps in knowledge concerning the behavior of thick-section Alloy 690 material (as opposed to SG tubing)
- E.g., very little information was found on the PWSCC behavior of the weld metals (Alloys 52 and 152)
- Objective is ***quantification of margins of improvement*** and documentation in a revision to MRP-111

Alloy 690/52/152 CGR Testing

- EPRI Testing:
  - MRP CGR testing at 340-360ºC underway at GE GRC (CT specimens at 360ºC primary water)
  - MRP CGR testing completed at Westinghouse (CT specimens at 385ºC supercritical water)
  - PSCR program at *AREVA uses a "metallurgical transition" approach*
- NRC CGR testing underway at 340-360ºC at ANL and PNNL
- Significant CGR data provided by the NR labs
- UNESA plans CGR testing at CIEMAT
- Other organizations are showing interest in CGR testing
- A Japanese consortium has recently provided its long-term PWSCC initiation data

Alloy 690/52/152 PWSCC Testing at GE-GRC: Example of CGR data obtained on duplicate CTs





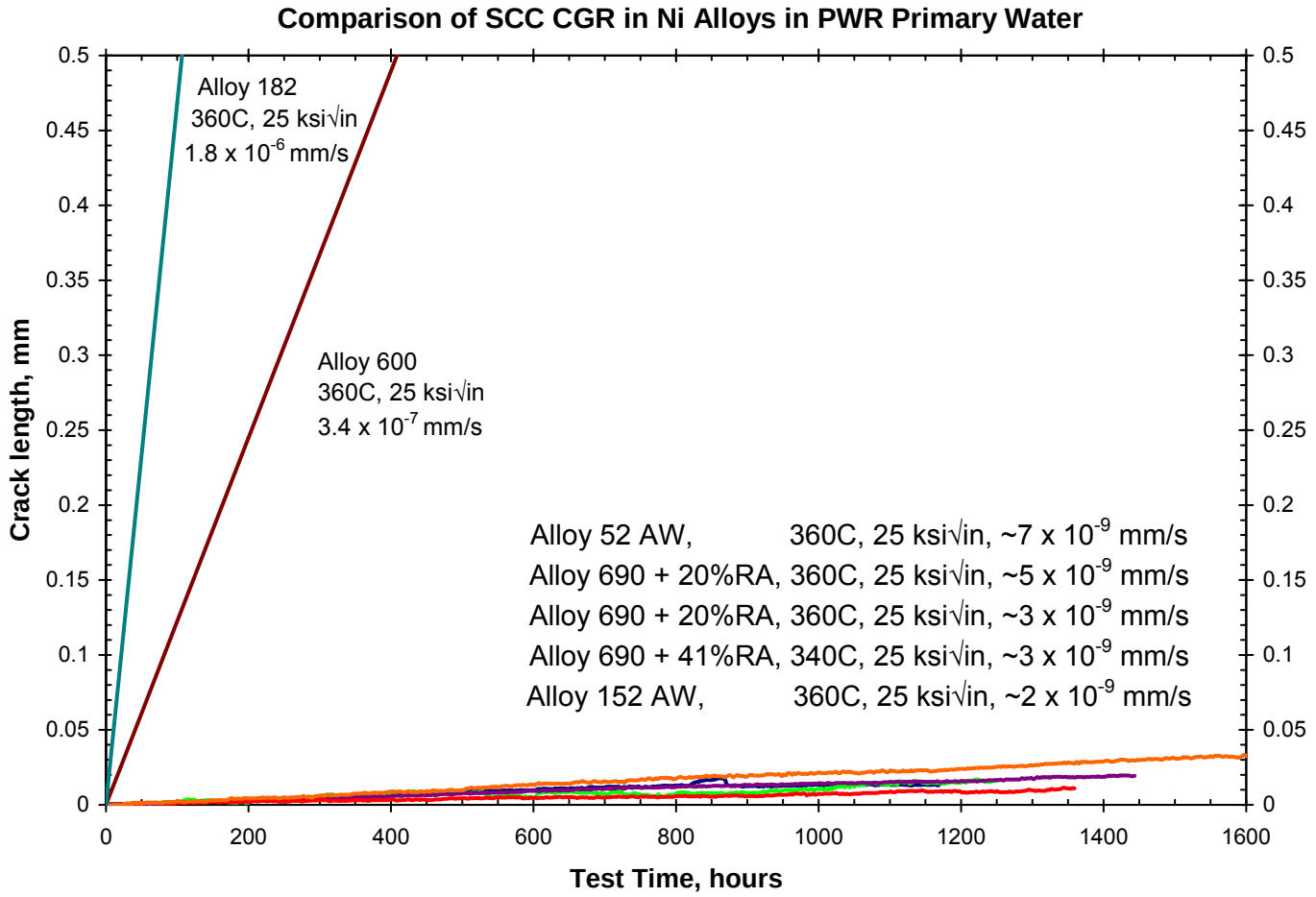
EPRI Program on 20%CW 690 CRDM at const. K_{max}

Difficulty in sustaining growth at longer hold times

Alloy 690/52/152 PWSCC Testing: GE-GRC Status - Summary

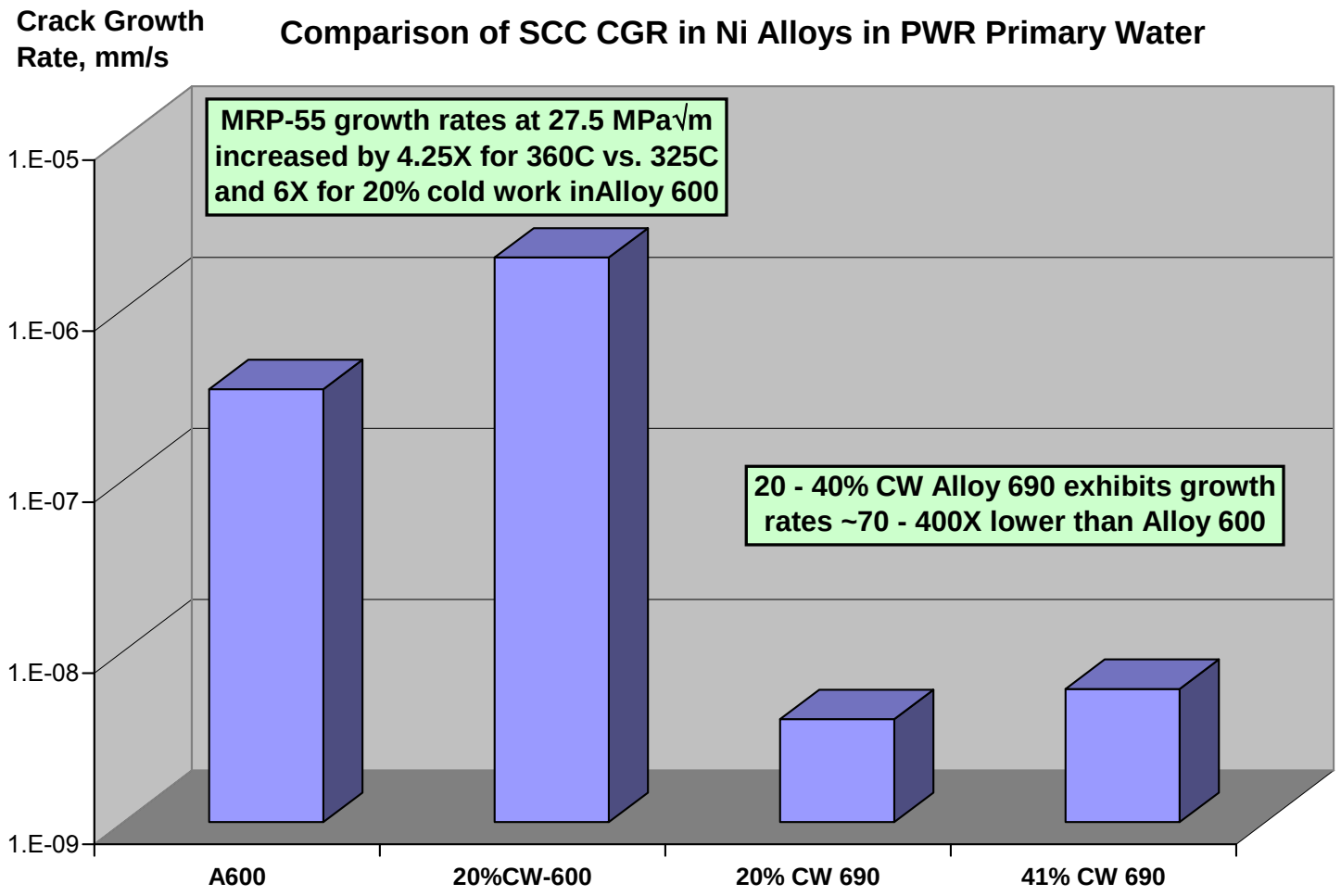
- Phase 1 of GE test program was successfully completed mid 2006
- Data generation was slow (due primarily to the need for very long autoclave exposure times to measure steady-state values of CGR)
- Results show that neither Alloy 690 nor its weld metals are immune to ***crack growth*** through SCC in PWR primary water of nominal composition
- Growth rates are low, however, and almost certainly of ***little or no engineering significance***
- Crack morphology in base metal is predominantly intergranular
- Weld metal fracture surfaces are highly unusual, with the SCC region very flat and featureless
- Comparisons with Alloy 600/82/182 data to determine factors of improvement are shown next

Alloy 690/52/152 PWSCC Testing: GE-GRC Status – Phase 1 results (MRP-196)



Note that "test time" refers only to the parts of the data curves actually evaluated – times on load in the autoclave were very much longer, as shown earlier

Alloy 690/52/152 PWSCC Testing: GE-GRC Status – Phase 1 results (MRP-196)



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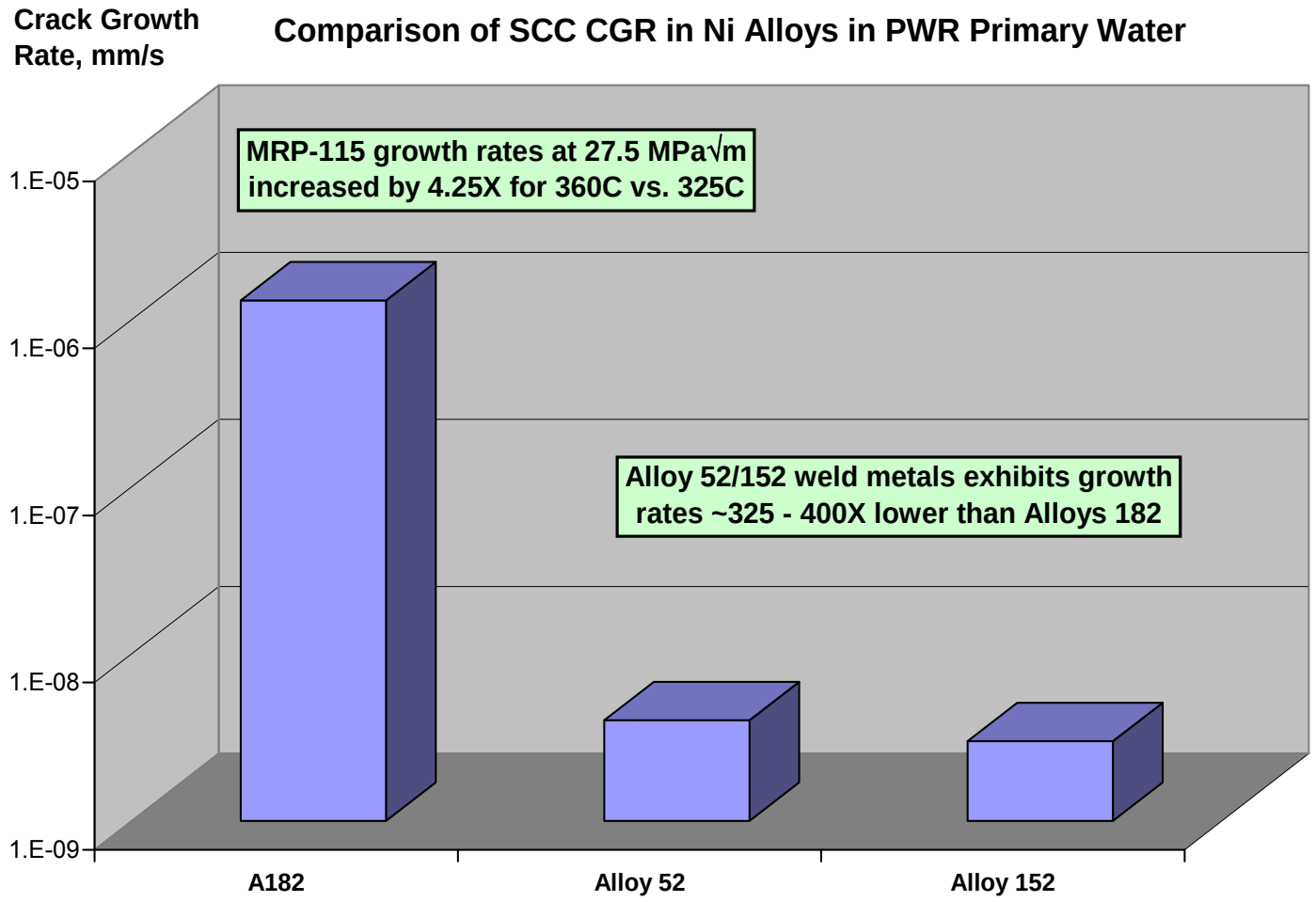


Alloy 690/52/152 PWSCC Testing at GE-GRC: Follow-on Program (Phase 2)

- Designed to address:
  - other heats of alloy 690 & 152/52 weld metals
  - off-microstructure & alternate cold work orientations
  - reproduce vulnerabilities identified in NR program
- Several tests planned at 360°C, each with 2 CTs in series
- This involves additional welds:
  - MHI/NMC 152 weld and GENE 52 weld
- Further possible test materials have also been identified (exchange of materials with NRC RES contractors)
- Additional processing for 690 awaits study of NR data

Alloy 690/52/152 PWSCC SC Water Testing

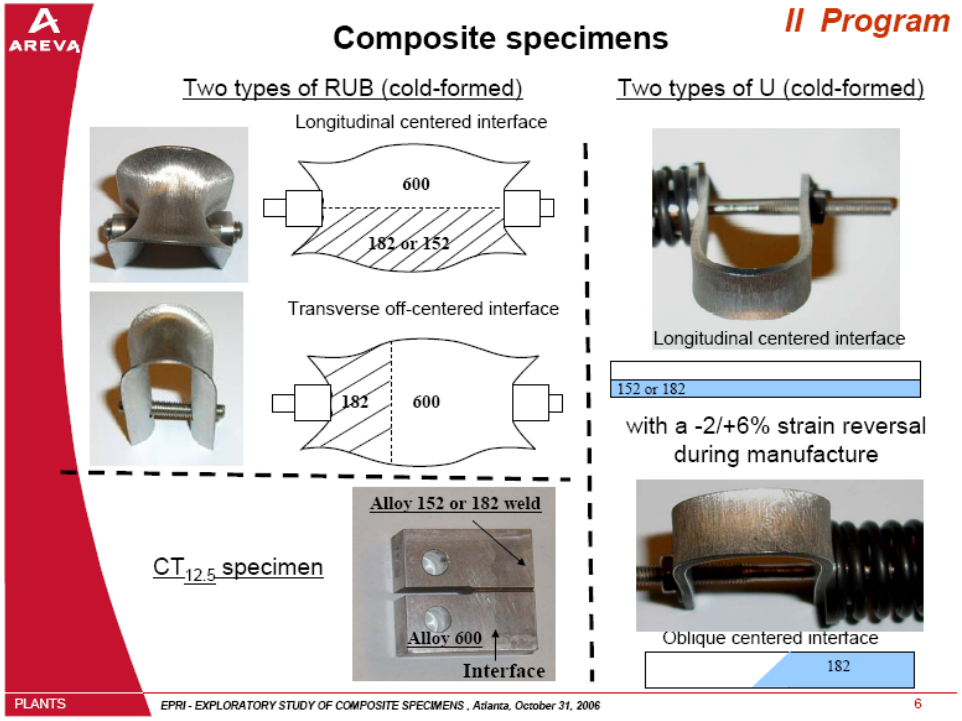
- The Westinghouse program in supercritical Li/B water at 385ºC was designed to provide thermal acceleration of SCC
- The project has been well-executed, but the data obtained have been surprising with regard to the extent of PWSCC seen in Alloys 690/52M and the limited cracking in Alloys 600/182
- To recap:
  - Conditions were expected to lead to rapid cracking in Alloys 600/182 and “80-day” test was supposed to establish the factor of acceleration wrt. subcritical water
  - “200-day” test was designed to study Alloy 690/52M material variables and was started before the results of the 80-day test became available
- Raw data from the 80-day test showed only relatively small differences in CGR between 600 & 690; Similar small difference between 182 & 52M were noted
- Alloy 600/182 result from the 80-day test suggests that the degree of thermal acceleration originally expected was not obtained

Alloy 690/52/152 PWSCC SC Water Testing (cont'd.)

- 200-day test showed much less cracking in Alloy 690 than expected from 80-day test, perhaps because of increased time spent at nearly constant load, and/or because of lower K
- Unfortunately, however, no Alloy 600 had been planned for inclusion in this test, so direct comparisons to establish factors of improvement are impossible
- There is presently no established basis for extrapolating the measured CGRs down to subcritical temperatures in order to make comparisons with the MRP databases for 600/182/82; this is currently being explored
- The test did not differentiate between the heats of Alloy 690 and showed only a relatively small effect of (~10%) cold work
- The draft final report is currently under review

Alloy 690/152 PWSCC Testing (PSCR Program): AREVA Composite Specimen Feasibility Study

- Goal: *Induce rapid PWSCC in a susceptible Alloy 600 material by exposure of miniature RUB and 0.5" CT specimens to hydrogenated steam at 400 C and examine behavior of crack as it reaches the interface with the more resistant alloy to assess the viability of this novel testing method*
- Test conditions: *Exposure for ~ 6 weeks in a static autoclave to pure, hydrogenated (0.7 bar H_2) steam at 400 C; (CT specimens at 40 MPa $\sqrt{m}$)*
- Result: *Cracks appear to arrest in the Alloy 600 HAZ (where Cr has diffused in to a level of about 20 to 22%) and do not enter the more resistant Alloy 690 or 152 materials*

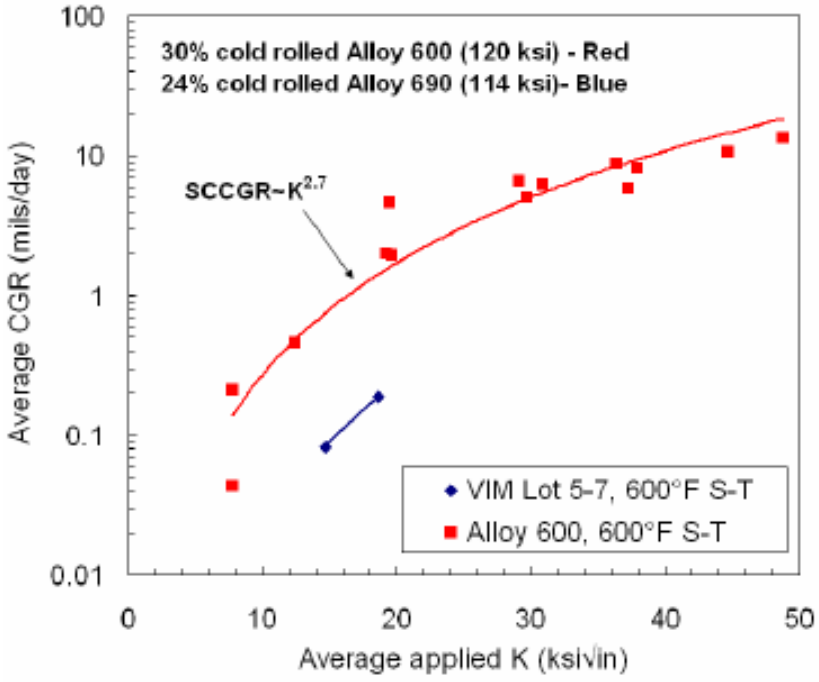


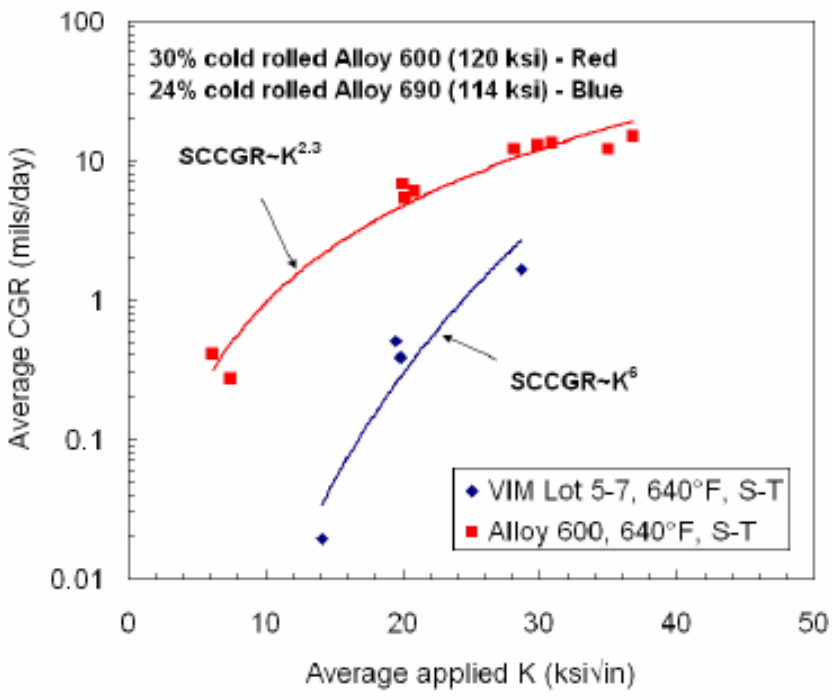
Status of Alloy 690/52/152 CGR Testing Project: CGR Data from NR Contractor (Bettis)

- The wealth of A690 data released in November 2006 by NR at the Atlanta Expert Panel meeting deserves intensive study
- The following 3 slides give a some impressions and indicate that surprisingly high CGRs were often measured
- ***However***, it is likely that the material processing used here is not directly relevant to commercial reactor components
- This is being addressed by DEI taking into account possible unplanned fabrication steps, repairs, weld-induced strain etc.
- The role of material texture (and thus specimen orientation) is clearly also very important for base metal, not just welds

Status of Alloy 690/52/152 CGR Testing Project: Example of recently released Bettis data

Alloy 690 vs. Alloy 600

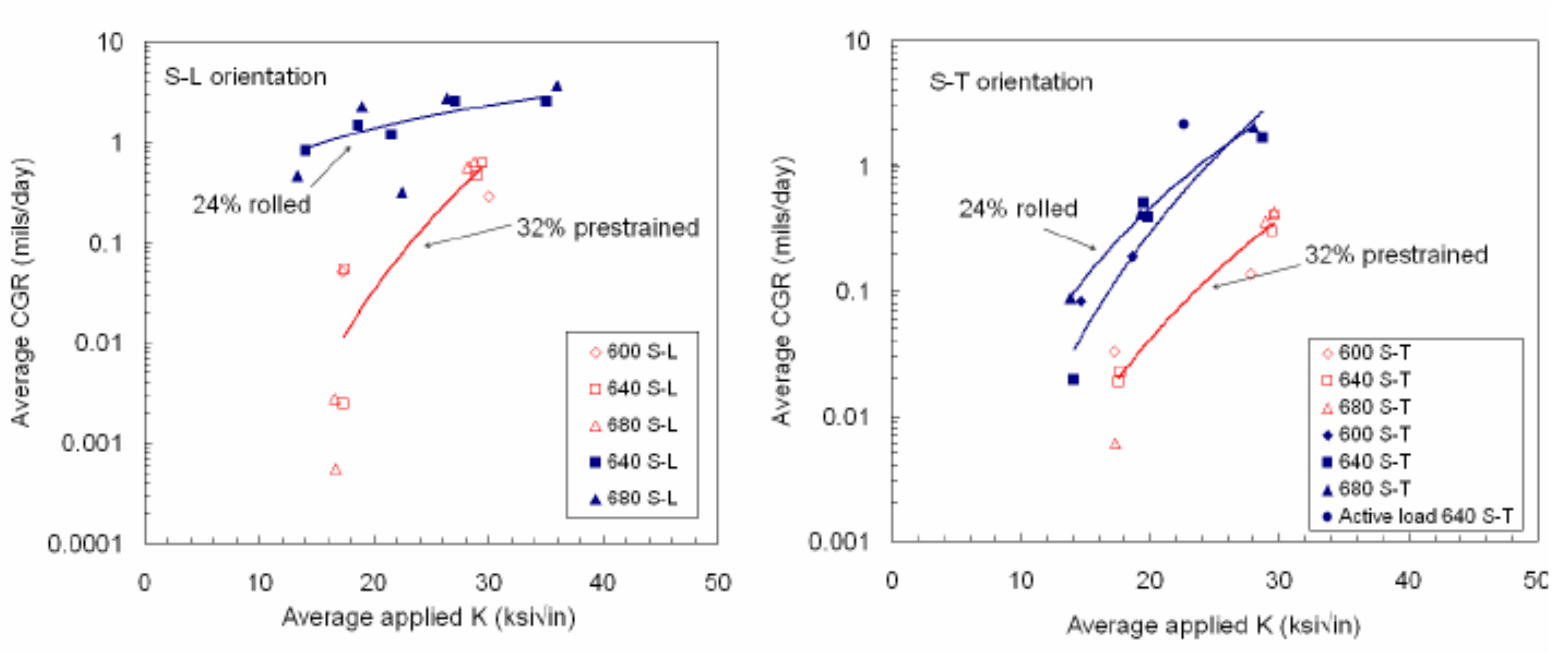




- Overall, Alloy 690 Rates a Factor of 5 to 10 lower than Alloy 600 for similar YS

Status of Alloy 690/52/152 CGR Testing Project: Example of recently released Bettis data

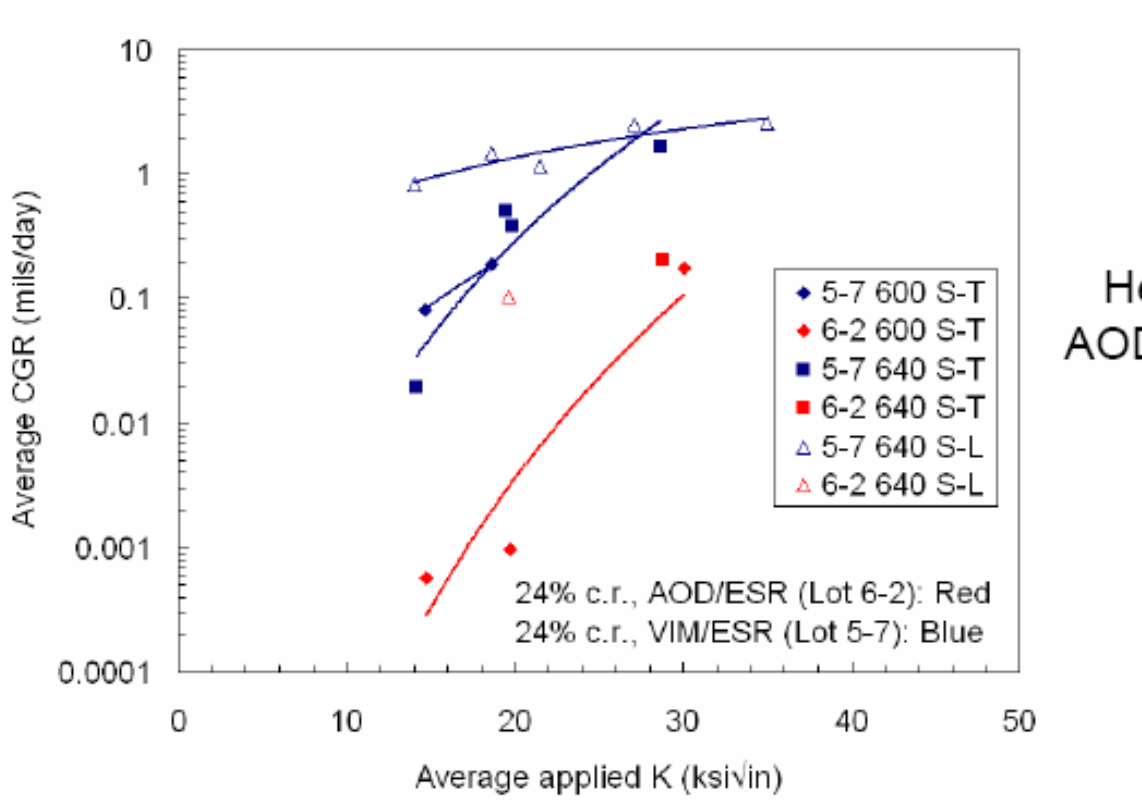
Rolled vs. Tensile Prestrained



- Yield Strengths: 125 ksi (tp) vs. 114 ksi (cr)
- Tensile Prestrained Rates Consistently Lower Than Rolled Rates
- Possible Influence Of Texture At High Strain Levels

Status of Alloy 690/52/152 CGR Testing Project: Example of recently released Bettis data

Melt Practice Effects



HTA1+TT
Heat Treatment
AOD and VIM heats

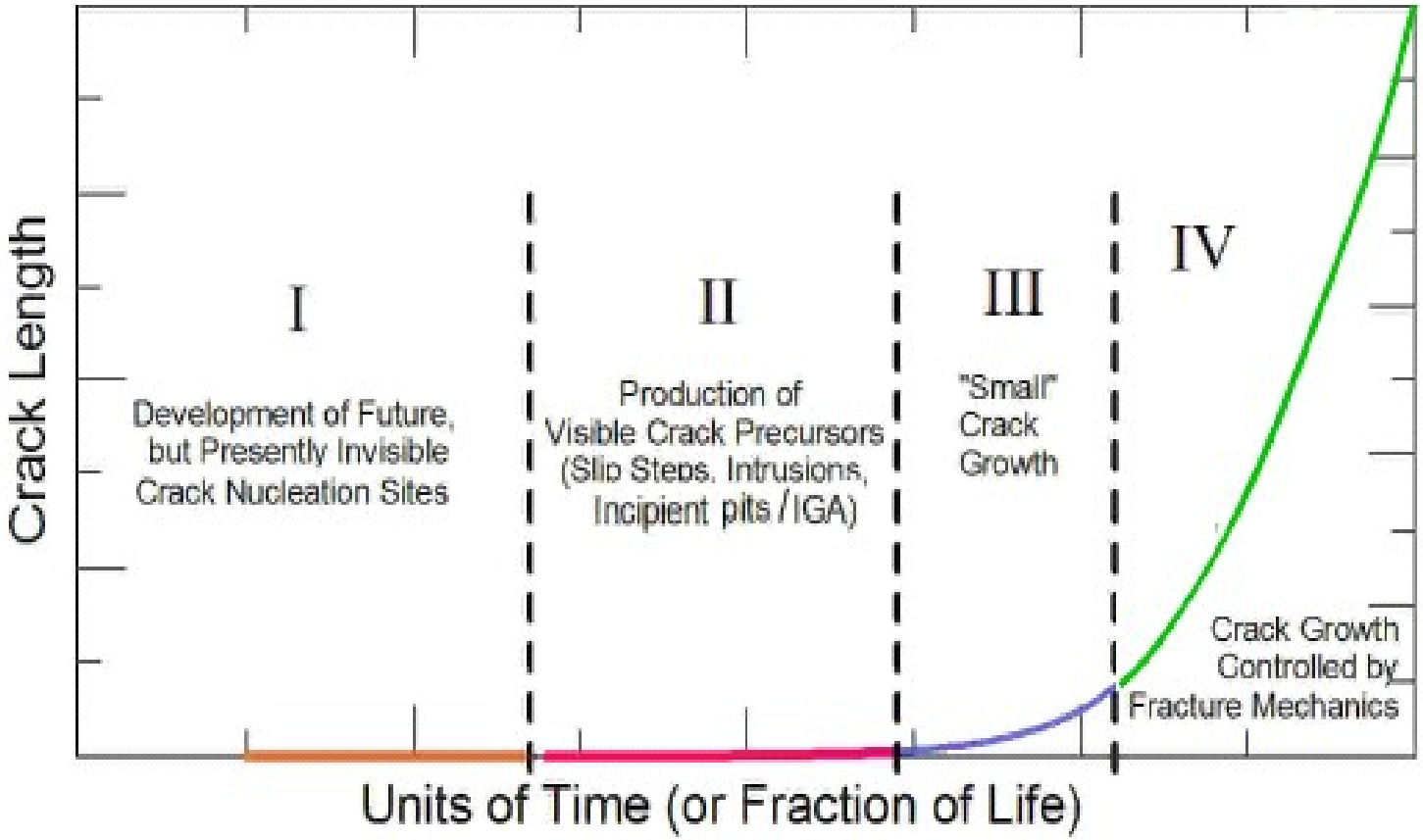
- AOD Heat Appears To Have Greater SCC Resistance
- Little To No SCC In Heat AOD-1, Lot 6-1 (12% Rolled) For Any Orientation

A690/52/152 Expert Panel Meeting

- A large body of sometime inconsistent CGR data exists that is being evaluated and summarized in a white paper
- Many variables may need to be evaluated to obtain a “complete” set of data on these materials (cold work- direction & degree, HAZ, material melt, microstructure etc.)
- An expert panel meeting of international organizations & companies is planned on November 8-9, 2007 to:
  - Scrub through the findings of the white paper and hopefully reach a consensus on data gaps
  - Organize a loose collaboration among testing organizations (e.g. MRP, NRC, UNESA etc.) to facilitate coverage of data gaps using, as much as possible, consistent test methods and environments:
    - Specimen configuration and size
    - Crack initiation
    - Transitioning to PWSCC
    - Cycling and hold times
    - K variation
    - Crack growth monitoring
    - Water chemistry
    - CGR calculation
    - Post-test assessment
    - Etc.

Alloy 600/82/182 CGR “Low K” Testing

Initiation and Short Crack Growth Can Dominate Component Life



"Low K" PWSCC CGR Testing Project: Engineering Consequences of K_{th} in MRP-55

- Explicit warnings were included in the MRP-55 report (later incorporated as a Code Case into ASME Section XI) that adequate supporting data at low K were not available
- ***But***, the prescriptive nature of the ASME Code does not lend itself to adequate consideration of such issues
- Thus, the Code procedure now adopted for determining the PWSCC crack growth in RPV head penetrations simply implies that the CGR is zero for K factor values < 9 MPa$\sqrt{m}$
- Since most PWSCC in plant situations originates from smooth surfaces, there is a ***physical disconnect*** here
- Key behavior of shallow cracks (below NDE detection limit) is unknown
- Field evidence suggests that they may often grow so slowly that they account for the major portion of service life

"Low K" PWSCC CGR Testing Project: Situation for weld Metals (Alloys 182/132/82)

- In 2004, the PWSCC Expert Panel spent considerable time discussing whether or not to impose a K_{th} in a similar way for the weld metals
- ***No*** stress intensity factor threshold for PWSCC of Alloys 82/182/132 was imposed in MRP-115, since no screened CGR data were available for 182/132 at K_I-values < ~ 20 MPa$\sqrt{m}$ and for 82 < ~ 27 MPa$\sqrt{m}$
- Furthermore, for the weld metals, no field data are available that might allow such a threshold to be reasonably estimated
- Earlier efforts (MRP-21) to derive a CGR curve for Alloy 182 from a much more limited dataset did not explicitly address this K_{th} issue, but simply ***assumed*** a value of 9 MPa$\sqrt{m}$ (as in MRP-55 for base metal)

"Low K" PWSCC CGR Testing Project: Further Work by MRP

- Carry out CGR testing of both Alloy 600 base metal and Alloy 182/82 weld metals at low values of stress intensity (in the 5 – 20 MPa$\sqrt{m}$ range)
- Main problems involved in doing this were originally described in detail in Appendix E to MRP-115:
  - Stress corrosion cracking is a time-dependent process: for this reason, K_{th} is not an absolute material property, but depends on the test duration (as well as on environment and test method used)
  - The greater the degree of patience and care exercised by the experimentalist, the lower the value of K_{th} often determined

“Low K” PWSCC CGR Testing Project:

- EPRI learned that related work was already ongoing in laboratories outside the US and contacted the appropriate organizations to assess the potential for cooperation
- Planned testing partners are
  - Studsvik, Sweden (already completed testing of Alloy 182 at low K-values under a Ringhals sponsored program)
  - AREVA, Germany (already working on Alloy 182 and 82 under BWR conditions in the context of a VGB program)
- These separate (but linked) test programs are expected to start in late 2007

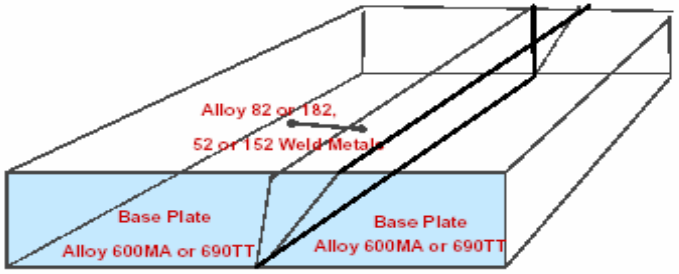
Alloy 600/690 HAZ CGR Testing

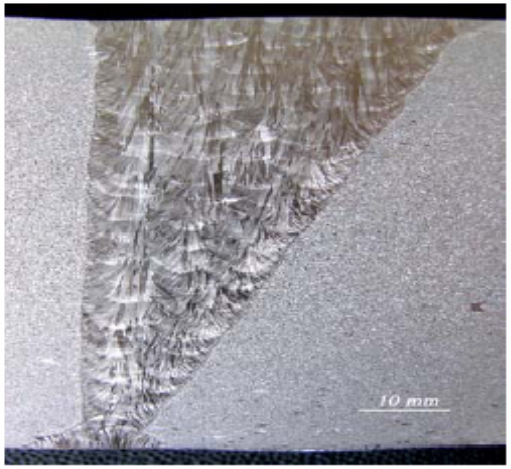
Alloy 600/690 HAZ CGR - Background

- PWSCC of Alloy 600 and its weld metals extensively studied, but not true of weld HAZ
- Potential concerns due to effect of localized deformation close to fusion line
- In addition, the heat input from welding could lead to a more susceptible microstructure locally by taking into solution otherwise beneficial grain boundary carbide precipitates
- A paper addressing these concerns was presented by George Young from the Lockheed Martin Corporation (KAPL labs) at the NRC conference on Vessel Head Penetration Inspection, Cracking and Repairs in Gaithersburg, MD (Fall 2003)
  - For an Alloy 600 heat of low susceptibility – the cracks typically grew ~30X faster in the weld HAZ
- Finding could potentially challenge the MRP-55 CGR disposition curve

EPRI MRP HAZ PWSCC Project at CIEMAT

- EPRI fabricated welds for the HAZ crack growth rate testing





Target Weld

- Alloy 600 LTMA and HTMA plates welded using either 82 or 182
- Alloy 690TT plates welded using either 52 GTAW or 152
- Test program currently underway at CIEMAT