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# Resistance of Alloys 690, 152 and 52 to PWSCC

## *"White Paper" on Research Findings since Publication in 2004 of MRP-111*

**Alloy 690 Meeting**
**NRC RES**
**May 1-2, 2008**

**Al Ahluwalia-EPRI MRP**

# “White Paper” on PWSCC of Alloys 690/152/52 - Background

- Alloy 690 and its weld metals, Alloys 152 and 52(M), have been shown to be highly resistant to PWSCC in most laboratory experiments
- They have also been free from cracking in operating reactors, to date after over 15 years of operation
- Remaining challenge is to ***quantify*** the longevity of these materials with respect to PWSCC and provide a technical basis for the development of future inspection requirements for repaired or replaced components
- EPRI report 1009801 (MRP-111) from March 2004 evaluated all field and laboratory data then available and recommended additional research to close remaining knowledge gaps
- Since then, both the MRP and various other organizations worldwide have sponsored a variety of testing programs, most still ongoing
- The present, interim or “white paper” report (MRP-237) updates the knowledge-base as of early 2008
- It is intended to provide a common basis for discussion and help in strategic planning

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# "White Paper" on PWSCC of Alloys 690/152/52 - MRP-111 findings (2004)

- Improvement factor ($IF_R$) for Alloy 690 was ***conservatively*** estimated to be ≥ 26 relative to Alloy 600MA and ≥ 13 relative to 600TT material, based on results from accelerated testing of SG tubing
- It was anticipated that higher factors could be established as Alloy 690 material test data became available for longer test durations and were confirmed by further in-service inspection results
- The following, main knowledge gaps were identified:
  - *Lack of data on thick-walled Alloy 690 material, or on weld metals*
  - *Possible effects of product form (plate, tube, rolled/forged/extruded bar) and alloy chemistry or thermomechanical processing unclear*
  - *No plausible estimates of crack growth rates available*
  - *Possibility of increased PWSCC susceptibility in Alloy 690 HAZs*
  - *Confirmation needed of the limited relevance of so-called "low-temperature crack propagation" (LTCP) to Alloy 690 and its weld metals in primary water* (not addressed in present white paper)

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# "White Paper" on PWSCC of Alloys 690/152/52 - Relevant research programs since 2004

- Investigations in deaerated high-temperature water by Bechtel Bettis Inc. and Lockheed Martin (KAPL labs) within the US naval reactor program
- Investigations in simulated primary water at high temperature by
  - *Argonne National Laboratory (ANL) on behalf of the US NRC*
  - *AREVA (France) for the Framatome Owners Group (FROG)*
  - *CEA (France) as part of a national program with EDF and AREVA*
  - *CIEMAT (Spain) on behalf of the EPRI MRP*
  - *General Electric Global Research (GE-GRC) for the EPRI MRP*
  - *INSS (Japan) as part of a Japanese national program*
  - *Mitsubishi Heavy Industries (MHI) together with Japanese partners*
  - *Pacific Northwest National Laboratory (PNNL) for the US NRC*
  - *University of Tohoku (Japan) co-sponsored by the EPRI PSCR program*
- Investigations in high-temperature, undoped steam by AREVA (France) for the EPRI Primary Systems Corrosion Research Program
- Initiation studies in Finland (HUT and VTT) on weld metals using doped steam
- Investigations in supercritical water
  - *University of Michigan for US DOE and EPRI MRP*
  - *Westinghouse Electric Company LLC on behalf of the EPRI MRP*

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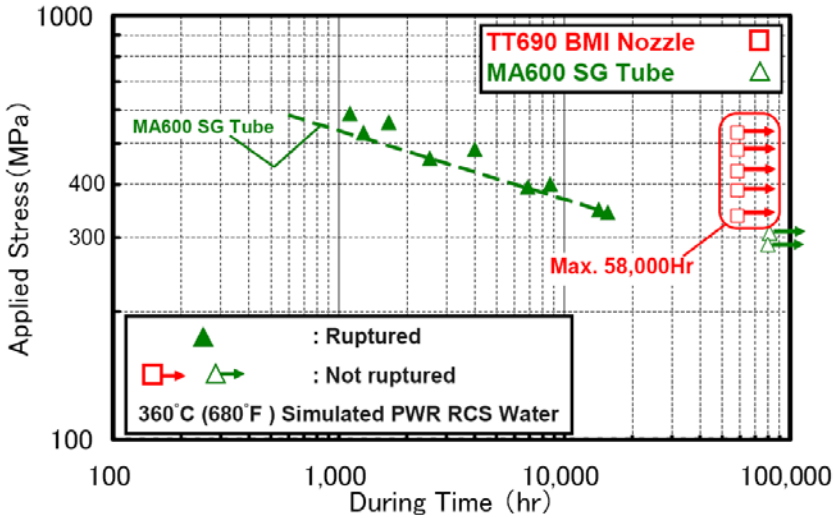
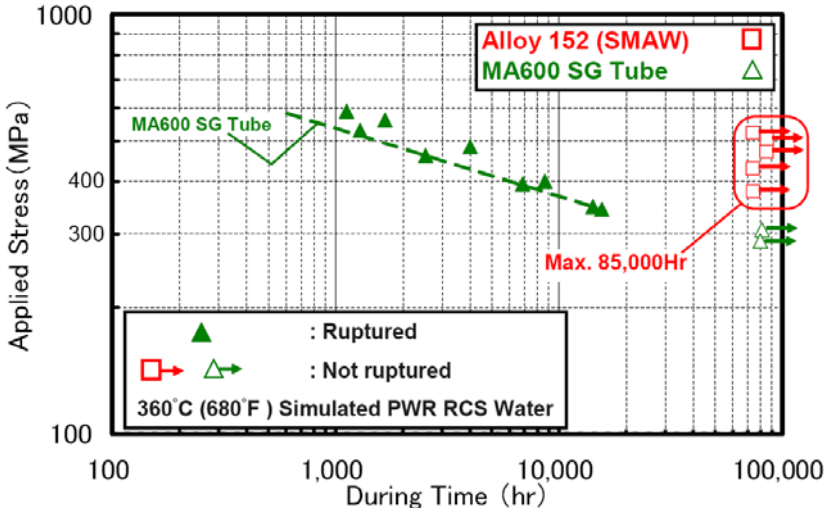
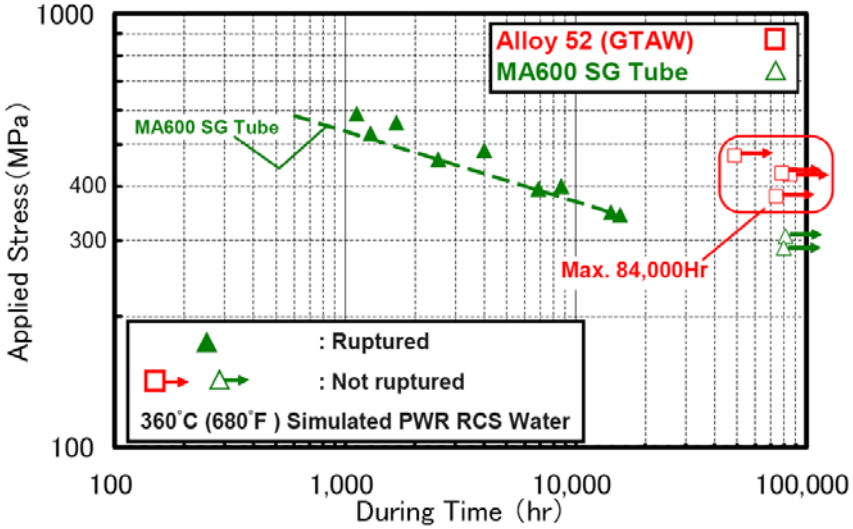
# "White Paper" on PWSCC of Alloys 690/152/52 - Crack Initiation




**Lack of any crack initiation in long-term testing of actively loaded tensile specimens in Japanese program**

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# "White Paper" on PWSCC of Alloys 690/152/52 - Crack Initiation: CONCLUSIONS

- Crack initiation through PWSCC from a smooth surface appears to be very difficult, if not impossible, for Alloy 690 in its normal metallurgical condition
- Situation is similar, but slightly less clear for Alloys 52/152 (limited susceptibility recently found in doped steam tests)
- Minimum ***relative improvement factors ($IF_R$)*** for initiation of 40 to 100 times for Alloy 690TT, and at least 60 times for Alloys 52 and 152, can be justified with regard to PWSCC of Alloys 600 and 182
- These estimates are ***conservative*** and likely to rise further with continued testing, since very little PWSCC originating at specimen surfaces has been seen to date

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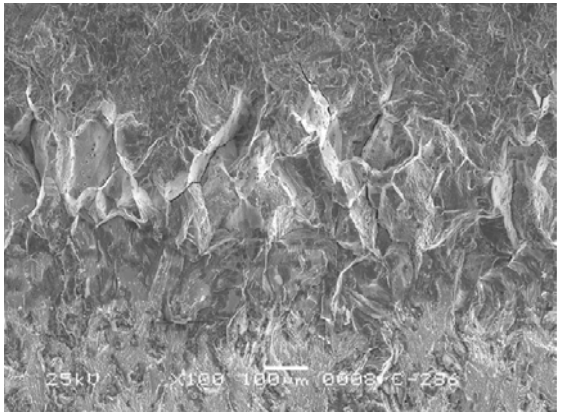
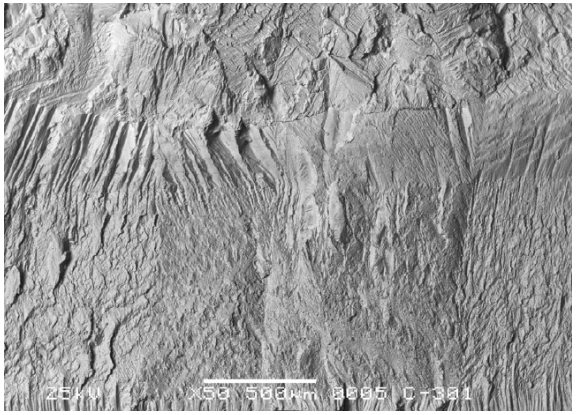
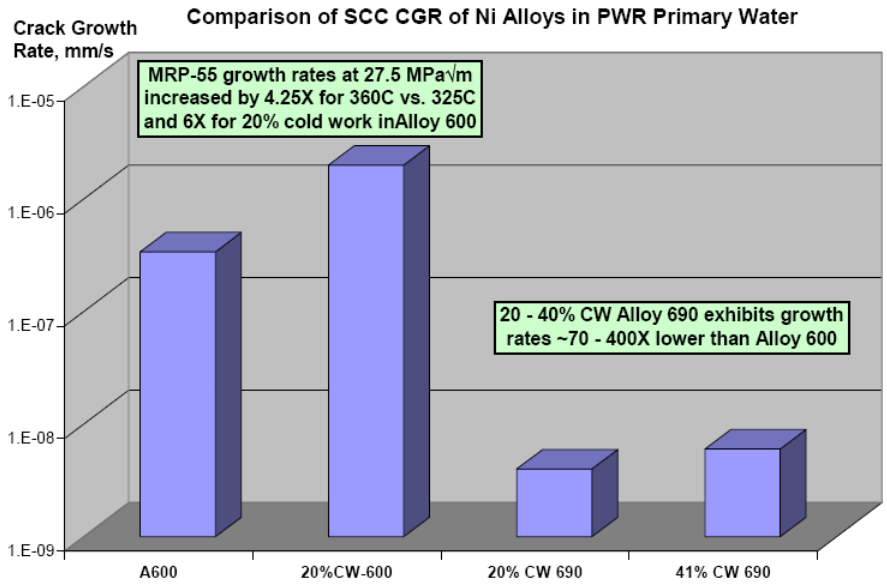
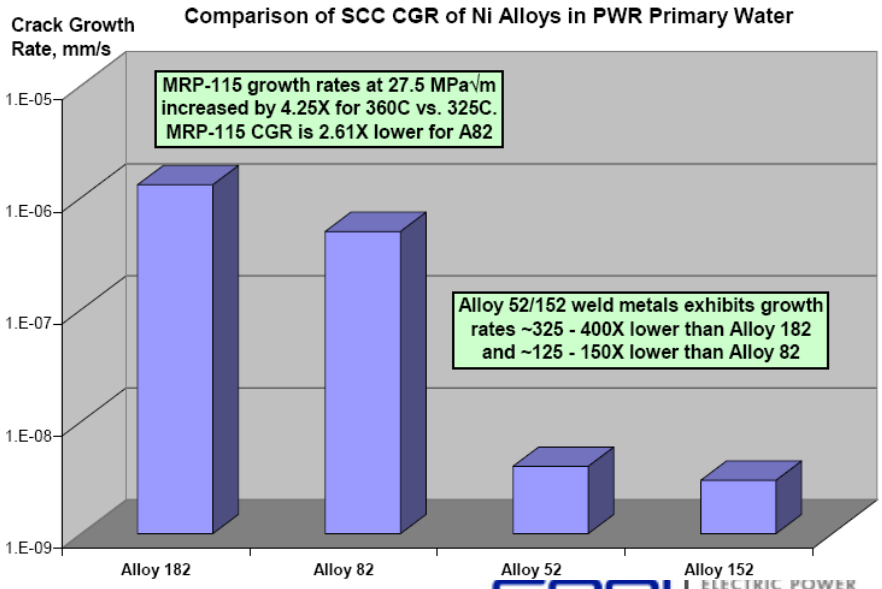
# “White Paper” on PWSCC of Alloys 690/152/52 - Crack Growth: Low CGRs in first MRP tests at GE





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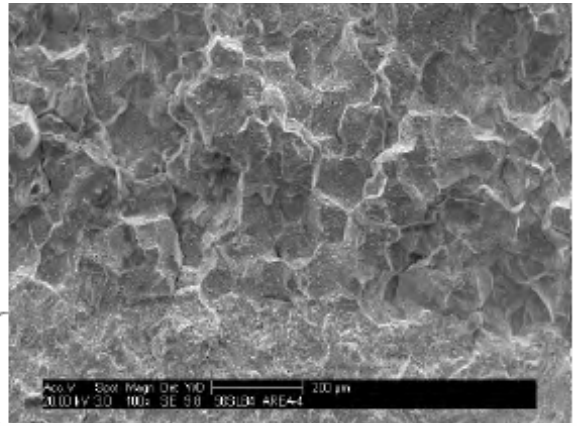
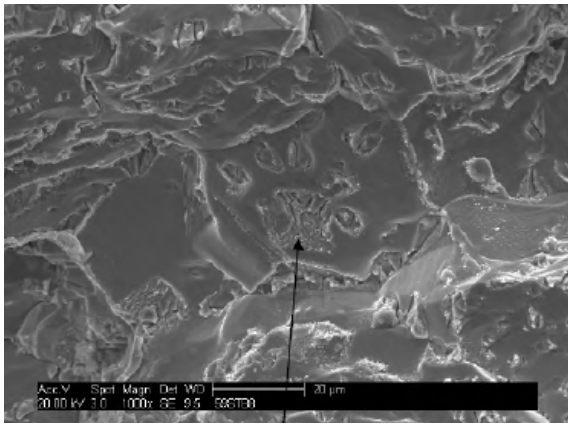
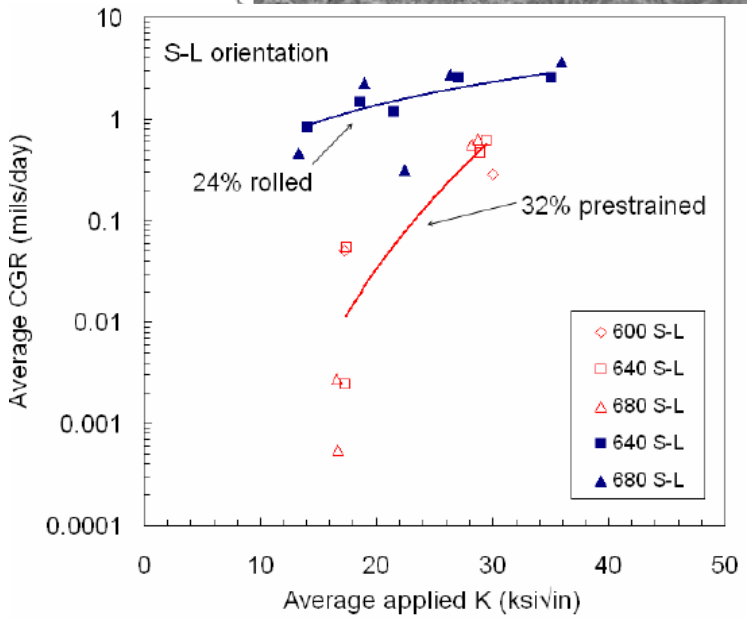
# "White Paper" on PWSCC of Alloys 690/152/52 - Crack Growth: High CGRs in some Bettis tests

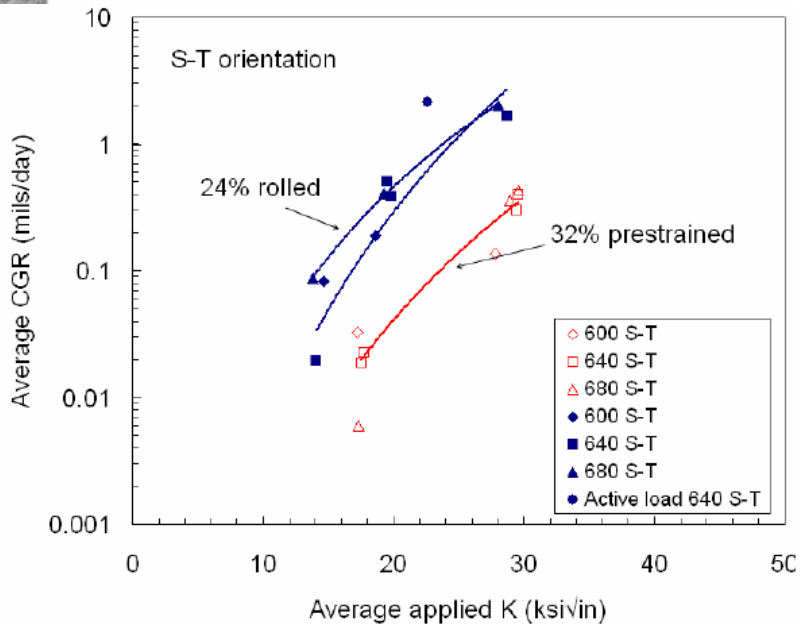
IG SCC

TG Precrack





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# "White Paper" on PWSCC of Alloys 690/152/52 - Bettis Evaluation of SCC Susceptibility

| Material/Condition | Number of specimens tested | Number showing measurable SCC | Number with POCKETS of SCC | Number with NO SCC | Test conditions where NO SCC observed | Relative SCC Ranking |
|---|---|---|---|---|---|---|
| VIM-1, HTA1, Anneal | 18 | 0 | 0 | 18 | All temps, K~12 to 30 ksi√in | 1 |
| AOD-1, HTA1, 12% roll | 19 | 0 | 3 | 16 | L-T, S-T, S-L, all temps, <30 ksi√in | 2 |
| AOD-1, HTA1, 24% roll | 19 | 5 | 0 | 14 | L-T, S-T, S-L, all temps, <30 ksi√in | 3 |
| VIM-1, HTA2, 12% roll | 19 | 11 | 6 | 2 | L-T: 680°F,<30 ksi√in | 4 |
| VIM-1, HTA1, 12% | 19 | 11 | 3 | 5 | L-T: 680°F, <30 ksi√in<br>S-T: all temps, <17 ksi√in | 5 |
| VIM-1, HTA1, tensile strain | 30 | 23 | 1 | 6 | L-T: all temps, <20 ksi√in<br>S-T: 680°F, ~17 ksi√in | 6 |
| AOD-2, 30% roll | 25 | 21 | 3 | 2 | L-T, 680°F, K~18 ksi√in | 7 |
| VIM-1, HTA2, 24% roll | 18 | 16 | 0 | 2 | L-T: 680°F, <30 ksi√in | 8 |
| VIM-1, HTA1, 24% roll | 19 | 18 | 0 | 1 | L-T: 680°F, ~18 ksi√in | 9 |

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# "White Paper" on PWSCC of Alloys 690/152/52 - Key Points on 690 Fabrication from Bettis Study

- Only the more susceptible material (VIM/ESR plate) was tested in the fully annealed condition, and then showed <u>no susceptibility to crack advance through SCC</u>
- Uni-directional cold rolling induced some SCC susceptibility in both materials, even at the 12% level, but much more strongly at the 24% level in the VIM/ESR plate
- Raising the cold rolling level to 30% also led to high susceptibility in the more resistant AOD/ESR plate
- Uni-directional tensile straining (to around 33%) also resulted in moderate susceptibility of the VIM/ESR plate, but was not as detrimental as 24% cold-rolling, even though it resulted in a higher yield strength
- There was no apparent effect of a lower or higher final annealing temperature (before additional TT treatment) on behavior of the VIM/ESR plate
- Results on omission of the additional TT treatment with one lot of the AOD/ESR plate do not appear to have been reported yet
- Findings clearly imply that SCC susceptibility is associated with the creation of heterogeneous microstructures in the test materials, in which case strong effects of specimen orientation on CGRs would be expected

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# "White Paper" on PWSCC of Alloys 690/152/52 - Additional Findings from Bettis Study: K Effects

- For the most susceptible materials and worst CGR orientation, only a low (~ $K^1$) dependence on stress intensity was found over the tested range of approx. 13 to 42 MPa√m
- Higher values (up to an exponent of 6.2) were quoted for lower susceptibility conditions, but
  - *likely that these have been biased by difficulty in initiating uniform crack advance at low $K_I$ values in constant displacement (bolt-loaded) specimens*
  - *true K dependency may have been masked to some extent by load-relaxation during autoclave heat-up and/or during crack advance*

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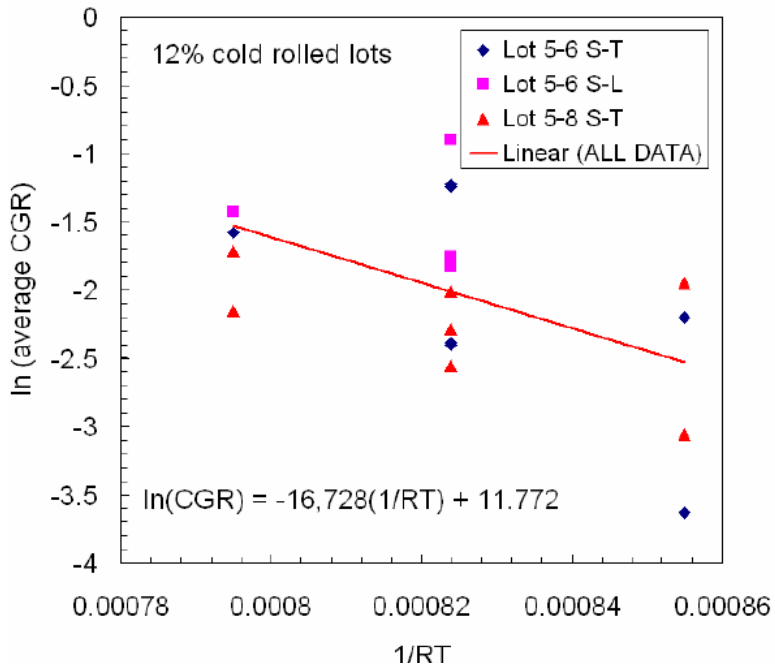
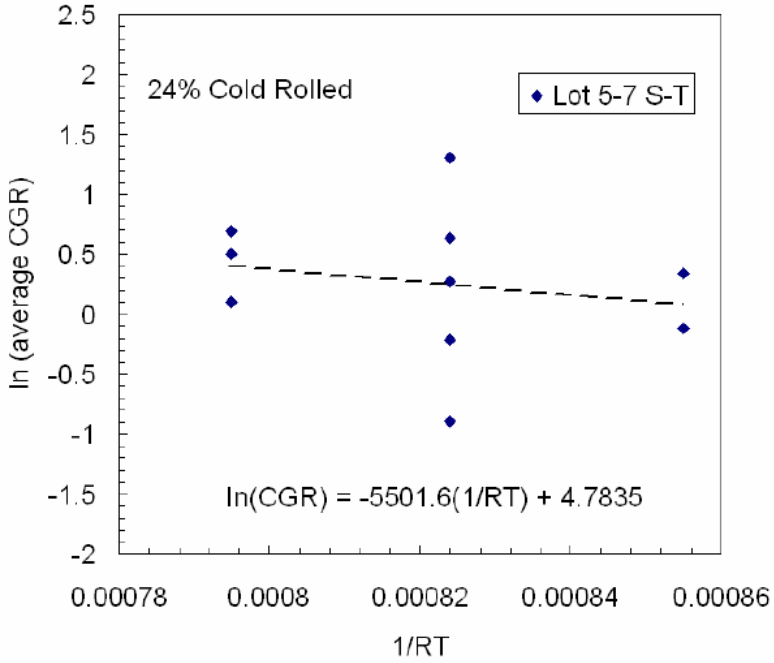
# "White Paper" on PWSCC of Alloys 690/152/52 - Additional Findings from Bettis Study: T Effects

- Surprisingly low dependence on temperature for crack advance in cold-worked Alloy 690 material, with apparent activation energies as low as 5 kcal/mole being derived in one case of high SCC susceptibility

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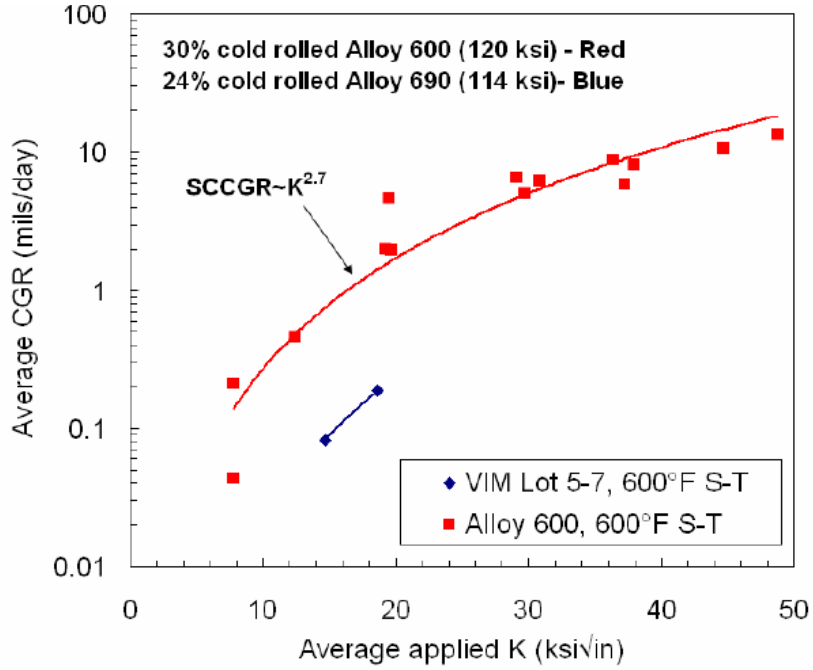
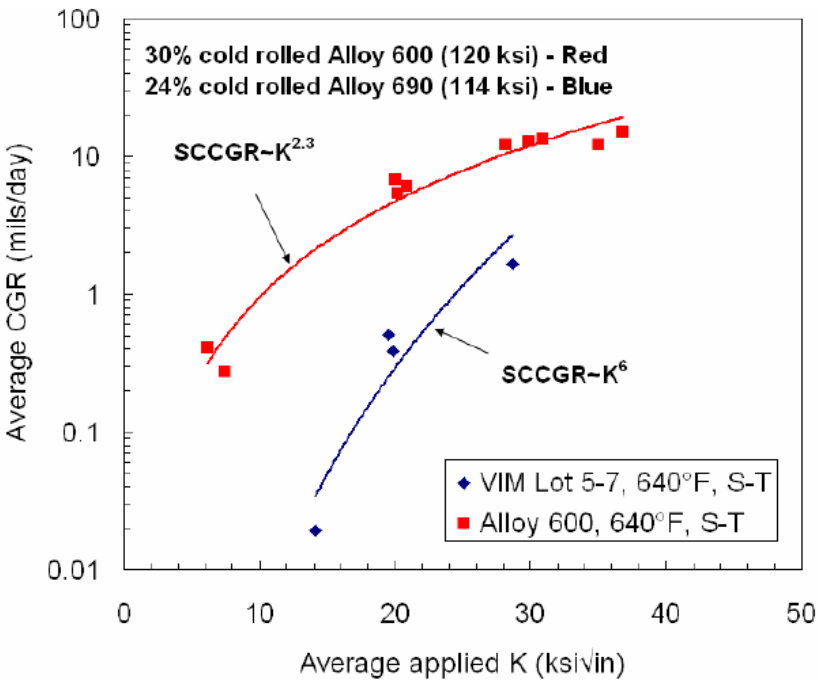
# "White Paper" on PWSCC of Alloys 690/152/52 - Bettis Study: Direct Comparison with Alloy 600

- 690 CGRs are a factor of 5 to 10 lower than for 600 material of comparable yield strength

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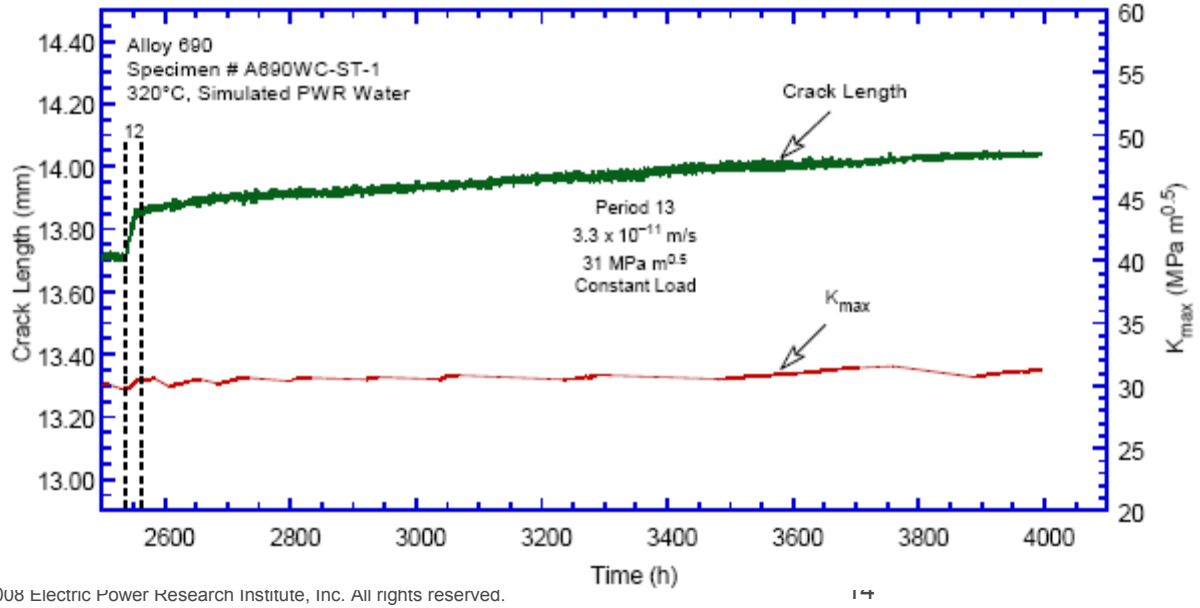
# "White Paper" on PWSCC of Alloys 690/152/52 - Crack Growth: Medium CGRs in some ANL tests

2.8 E-8 mm/s at 28 MPa√m for the S-L specimen;

3.3 E-8 mm/s at 31 MPa√m for the S-T specimen




Alloy 690 with ~26 % cold work from unidirectional rolling tested at 320 C

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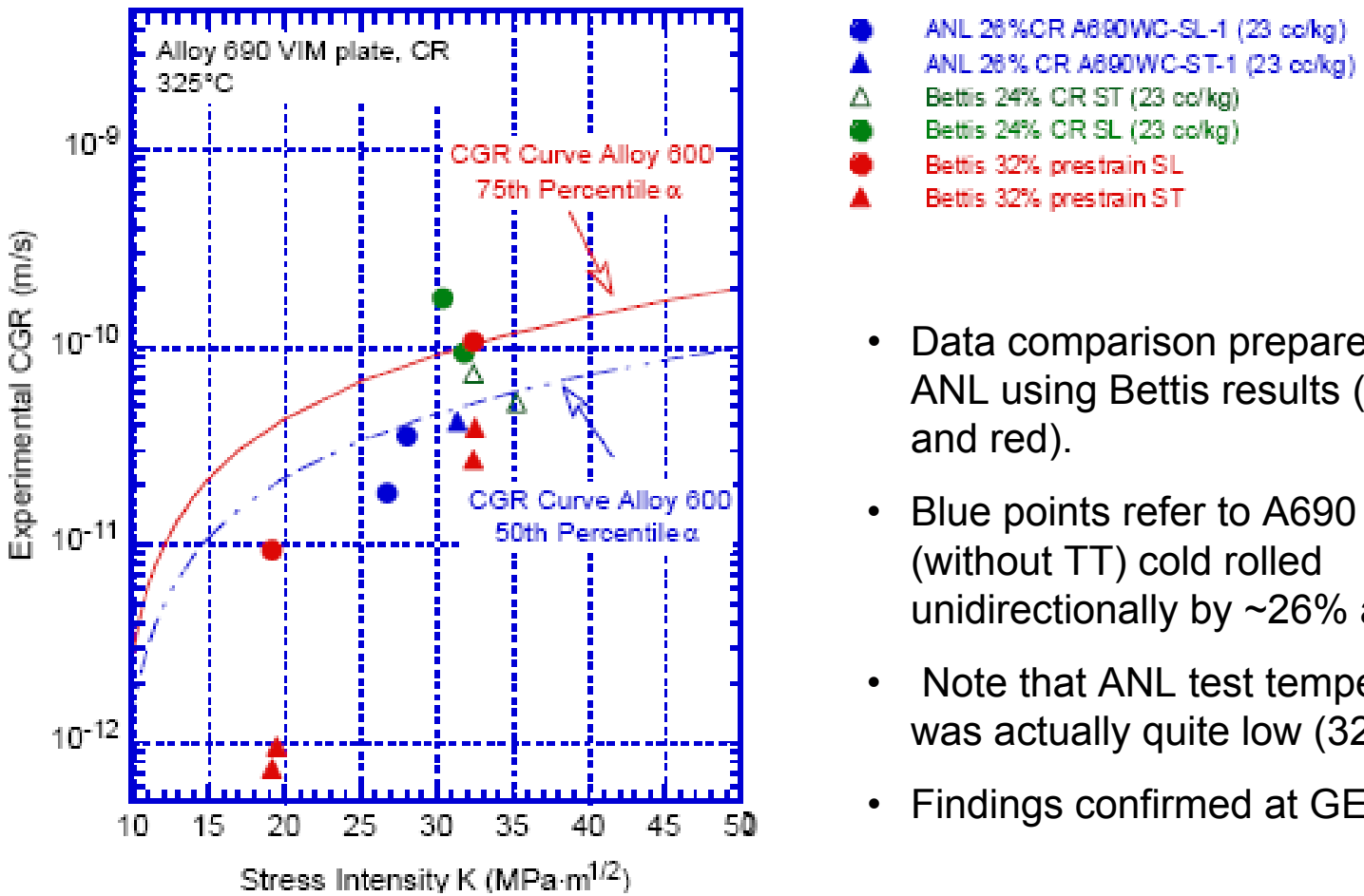
# "White Paper" on PWSCC of Alloys 690/152/52 - Crack Growth: Medium CGRs in some ANL tests




- Data comparison prepared by ANL using Bettis results (green and red).
- Blue points refer to A690 (without TT) cold rolled unidirectionally by ~26% at ANL.
- Note that ANL test temperature was actually quite low (320 °C)
- Findings confirmed at GE-GRC

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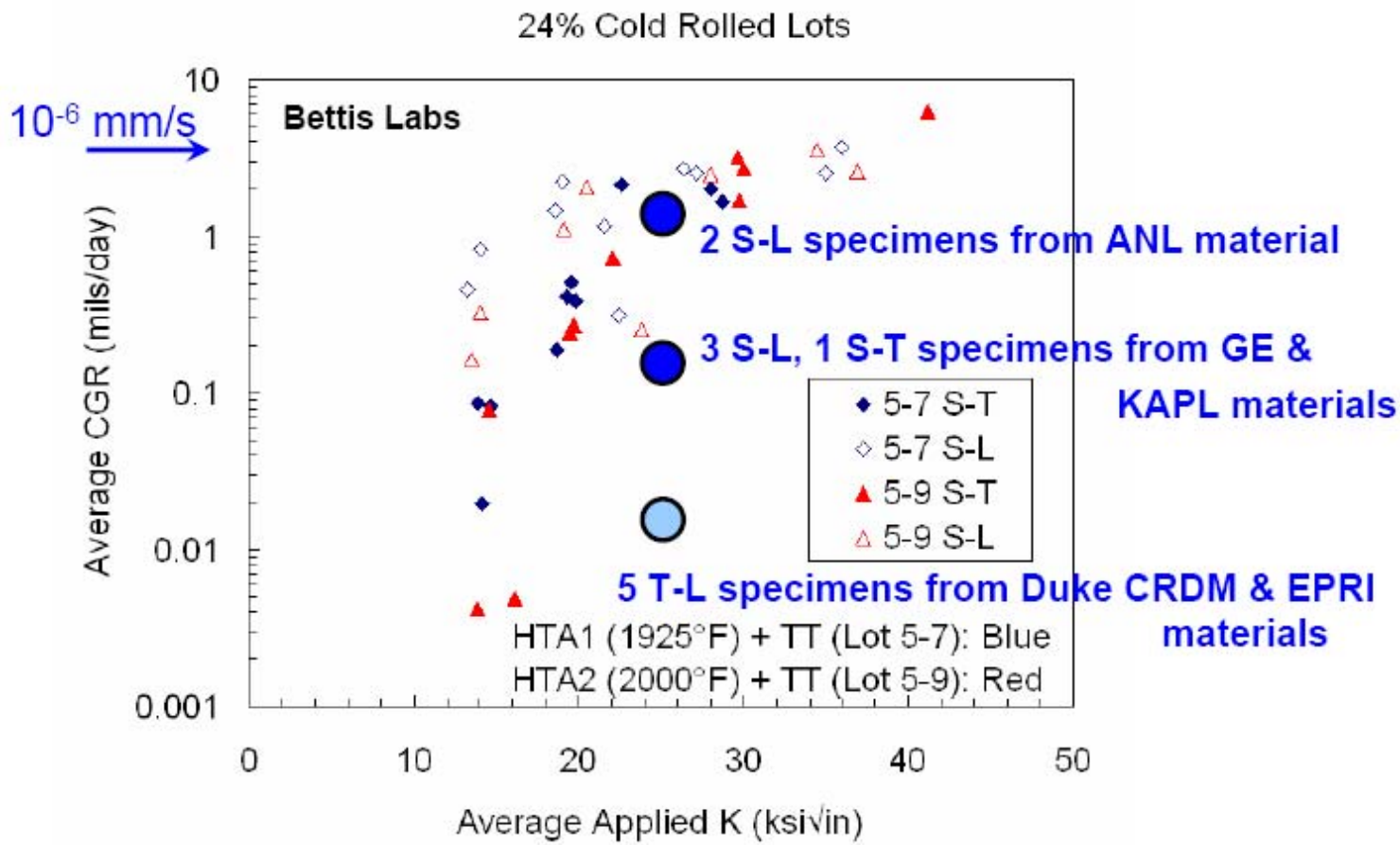
# "White Paper" on PWSCC of Alloys 690/152/52 - Crack Growth: Confirmation of 1-D effects on CGR at GE

## Comparison of GE & Bettis Data

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# "White Paper" on PWSCC of Alloys 690/152/52 - Crack Growth: CONCLUSIONS

- For thick-walled Alloy 690 material in the normal metallurgical condition, susceptibility to ***crack growth*** through PWSCC appears to be very marginal at the most.
- Using sophisticated testing methods, it has been possible to produce small amounts of intergranular cracking in some of the specimens tested to date, but the CGRs are extremely low and ***of no engineering significance*** (< 0.05 mm/yr)
- This remains valid in most cases even after the introduction of significant amounts of ***cold work*** into the material.
- The calculated $IF_R$ with respect to CGRs in Alloy 600MA is ***at least 70 times*** (and probably nearer to 400 times if the comparison takes proper account of cold work levels).

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# "White Paper" on PWSCC of Alloys 690/152/52 - Crack Growth: CONCLUSIONS (con.)

- Rapid, intergranular crack growth (at rates only slightly slower than for Alloy 600) in both high-temperature pure water and simulated primary water can be triggered in certain directions within Alloy 690 base material by the introduction of ***inhomogeneous*** cold work (either from uni-directional rolling, or by tensile prestraining)
- This also appears to lead to significant ***changes*** in the dependence of measured CGRs on stress intensity, test temperature and dissolved hydrogen levels
- The ***limits*** of such bimodal behavior (slow/fast CGRs) have not yet been satisfactorily established and there is no real mechanistic understanding of the phenomenon

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# "White Paper" on PWSCC of Alloys 690/152/52 - Crack Growth: CONCLUSIONS (con.)

- Significant intergranular cracking has also been observed in Alloy 690 (particularly after the introduction of 10 % homogeneous cold work) during testing in a ***supercritical environment*** containing lithium, boron and hydrogen
- There is currently ***no established basis*** for extrapolating the measured CGRs at 385 C down to subcritical temperatures in order to make detailed comparisons with the existing databases for primary water
- At present, the situation regarding possible PWSCC ***crack growth*** in the weld metals Alloy 52 (or 52M) and 152 is complex and much testing is still planned or in progress
- Unlike PWSCC in Alloys 182 and 82, the fracture surfaces here appear to be predominantly transgranular

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# “White Paper” on PWSCC of Alloys 690/152/52 - Overall Status

- Appreciable progress towards demonstrating satisfactory, long-term, PWSCC resistance of thick-section Alloy 690 and its weld alloys by laboratory testing has been made since the publication in 2004 of MRP-111
- Perhaps inevitably, however, some conditions have been found that appear to lead to “bimodal” behavior of Alloy 690 with regard to slow/fast crack growth through SCC
- Further laboratory testing and engineering analysis are still needed to reach the original goal of demonstrating long-term absence of PWSCC in thick-walled plant components made from Alloy 690 and its weld metals
- Strategic planning now in progress should help to share the burden of this between the various programs worldwide

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# Alloys 690/52/152 Degradation Research Data Gaps

1. Lack of crack initiation data on any of the heterogeneously deformed Alloy 690 materials that have shown high susceptibility to crack growth through PWSCC.
2. Incomplete knowledge of the way in which certain Alloy 690 bulk material conditions (particularly unidirectional deformation) can sometimes impair its otherwise excellent resistance to PWSCC crack growth.
3. Possibility of enhanced PWSCC susceptibility in the base material adjacent to welds in thick-walled Alloy 690 as a result of both microstructural changes and the introduction of high residual strains.
4. Uncertainty as to what Alloy 690 material conditions must still be considered potentially relevant to actual plant components (including in localized situations, such as weld heat-affected zones).
5. Controversy as to whether LTCP could be a real degradation mechanism in the field for Alloy 690 and its weld metals, or is just a laboratory phenomenon.
6. Lack of conclusive evidence that weld fabrication defects might not lead to PWSCC susceptibility in Alloys 52(M) and 152.
7. Contradictory laboratory findings as to the possibility of measuring significant PWSCC crack growth rates in Alloys 52(M) and 152.
8. Residual uncertainty as to whether or not weld compositional variations (including dilution effects) and actual welding procedures might affect both PWSCC and LTCP behavior.
9. Absence of detailed information on actual replacement components in the field.
10. No crack growth rate disposition curves as a basis for justifying continued plant operation if service-induced cracks were to be found in Alloys 690/52(M)/152, or if their existence has to be postulated for analysis purposes

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