NRC Research on Cast Austenitic Stainless Steel

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2015 Regulatory Information Conference
Bethesda, MD
March 12-2015

NRC Research Program on Cast Stainless Steels (CASS)

- **Purpose**
  - Provide background on CASS use, properties, and susceptibility to embrittlement
  - Summarize basis for current position on screening criteria developed as guidance to address thermal and irradiation embrittlement in CASS
  - Provide motivation behind NRC's ongoing research to investigate the combined effects of irradiation and thermal aging on CASS fracture toughness properties
  - Summarize the objectives, initial results, and status of NRC's research program
- **Key Messages**
  - CASS is susceptible to loss of fracture toughness due to combined effects of both thermal and irradiation embrittlement.
  - Little data exists on these combined effects
  - Initial results suggest that, in some CASS alloys, both thermal aging and irradiation damage contribute to loss of fracture toughness even at low neutron fluence levels
  - Work is ongoing to address these effects and identify current research gaps

Cast Austenitic Stainless Steels (CASS)

- **CASS are used in light water reactors (LWRs) for components with complex shapes**
  - Pump casings, valve bodies, coolant piping, control rod guide tube spacers and housing etc.
- **The most widely used CASS steels are corrosion-resistant CF grades**
  - Typically CF grade CASS (CF-3, CF-8 and CF-3M ,CF-8M) whose compositions are similar to those of 300-series austenitic stainless steels (SSs)
    - CF-3 and CF-8 contain 19% Cr and 9% Ni
    - CF-3M and CF-8M contain Molybdenum in addition (up to ~ 3%)
  - Because of relatively high Cr content, CF Grade steels possess
    - Good corrosion and oxidation resistance and mechanical properties
      - The strength and ductility are comparable to wrought SS

CASS Microstructural Effects

- **Microstructure of CASS**
  - δ-ferrite and γ-austenite duplex microstructure
  - Duplex microstructure ➔ provides mechanical strength of CASS
    - ➔ Tensile strength and yield strength increases with (δ)-Ferrite up to 40% both at room temperature and elevated temperature
  - δ-Ferrite ➔ Prevents the tendency for hot cracking → welding
    - ➔ Improves the resistance to sensitization and stress corrosion cracking (SCC)
- **Presence of δ-ferrite**
  - Detrimental effect on fracture resistance when exposed to 300-500°C
    - ➔ δ-ferrite is vulnerable to low-temperature thermal aging
      - ➢ As a result tensile strength increases while ductility decreases
- **Mechanism for reduction in fracture toughness due to thermal aging**
  - Nucleation of Cr–rich α' phase (by spinodal decomposition) and growth of α'-phase
  - Precipitation of nickel– and silicon–rich G phase, γ-austenite, and $M_{23}C_6$carbides
  - Large $M_{23}C_6$ carbides and/or Cr_2N nitrides precipitate at the ferrite/austenite phase boundary

Note: Thermal aging: Exposure of a material to high temperatures for an extended period (in this case heating to 400°C and for ~ 10,000 hrs)

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Aging Management of CASS Reactor Vessel Internal Components

- Aging management of CASS components is needed for license renewal (LR) of LWRs under 10 CFR Part 54
- NUREG/CR-4513, Rev. 1 "Estimation of Fracture Toughness of Cast Stainless Steels During Thermal Aging in LWR Systems," (ML052360554) provides a detailed analysis of CASS fracture toughness (FT) after thermal aging, by defining "lower-bound FT J-R curves" for certain CASS categories
  - Three different categories (a) low ferrite (< 10%), (b) medium ferrite (10-15%) and high ferrite (>15%)
- Grimes Letter (ML003717179) provides screening criteria for ferrite levels as a function of composition and type of casting
  - Effect of thermal embrittlement (TE) on FT should be considered if screening criteria are exceeded
  - Acceptability of FT level associated with screening criteria was demonstrated by generic flaw tolerance analyses for CASS piping components

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Aging Management of CASS Reactor Vessel Internal Components

- Grimes letter prohibited application of the TE screening criteria to RVI components receiving neutron exposures greater than 0.00015 displacements per atom (dpa) [10^{17} n/cm^2 (E > 1 MeV)]
  - NRC requires licensees/applicants to consider embrittlement due to both thermal aging and neutron irradiation
- Grimes letter did not address CASS components exposed to both thermal aging and neutron irradiation because FT data after simultaneous thermal exposure and significant neutron flux was <u>not</u> available
  - For such components, the Grimes Letter requires a component-specific evaluation that could include screening based on stress or enhanced inspections
- Since the Grimes Letter was issued, FT data for CASS materials subject to both thermal aging and neutron irradiation has been published in NUREG/CR-7027, "Degradation of LWR Core Internal Materials Due to Neutron Irradiation." (ML110100377)
  - NUREG/CR-7027 proposed a lower bound estimate for the FT for CASS materials due to neutron irradiation above approximately 0.3 dpa.

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Neutron Irradiation Effects

- Thermal aging embrittlement of CASS has been studied extensively
- Limited data exist that illustrate the effects of neutron irradiation on CASS, especially at fluence less than 0.3 dpa
- No prior data exist on the interaction between thermal aging and neutron irradiation in CASS materials
  - ➢ Due to both experimental difficulties and cost associated with the measurement
- Effect of neutron irradiation
  - Formation and growth of lattice defects leads to higher strength, lower ductility and toughness
  - Degradation of δ-ferrite much faster than for austenite
    - *Fluence of ~ 10^{17} n/cm² → δ-ferrite and 10^{20} n/cm² → γ-austenite (NRC- NUREG 7027)*
    - *Fluence of 10^{17} - 10^{18} n/cm² → δ-ferrite and 2X 10^{20} – 6.7 X10^{20} n/cm² → γ-austenite (Industry - MRP-227 Meeting at USNRC Nov. 19th 2013)*
    - *Note: 10^{17} n/cm² ~ 0.00015 dpa and 2X 10^{20} – 6.7 X10^{20} n/cm² ~ 0.3 – 1 dpa*

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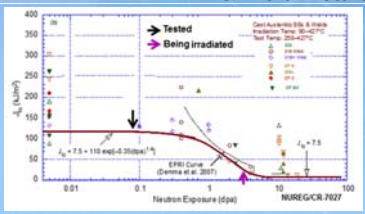
Effect of Neutron Dose on Fracture Toughness of CASS & Weld Metals



- Trend curve is essentially defined by the data for thermally aged and/or irradiated cast SSs and weld metals (i.e., minimum values of the J_{IC} data)
- Trend curve suggests a threshold dose of 0.3 dpa below which neutron irradiation has very little effect on FT, and a saturation dose of 5 dpa beyond which reduction in FT seems to saturate
- The disposition curve J_{IC} = 7.5+110 exp [-0.35(dpa)$^{1.4}$] is similar to the curve used in MRP 276-Fig. 3-2

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Scope and Objectives of NRC Research on CASS

- The scope of current study is to compile data and conduct confirmatory research and evaluate the effects of thermal and neutron embrittlement on the fracture toughness of CASS materials
- Objective of this research
  - (a) Update the methodology for estimating the reduction in fracture toughness of CASS materials
  - (b) Define threshold neutron dose (supported by experimental test data) above which irradiation effects contribute to embrittlement
  - (c) Identify gaps in information to address the effects of thermal & neutron embrittlement on structural & functional integrity of CASS components

Experimental Study of CASS

- This investigation addresses threshold neutron dose [Research Objective (b) on previous slide]
  1. Assess the extent of embrittlement of CASS from
     - Thermal aging (400°C, ~ 10,000 hrs)
     - Phase I: neutron irradiation (dose 0.08 dpa) ← low dose
     - Phase II: neutron irradiation (dose 3 dpa) ← high dose
  2. Evaluate SCC and FT performance in low electrochemical potential (ECP) environments
     - Simulated PWR water with 2 ppm lithium and 1000 ppm boron and high-purity water with dissolved oxygen (DO) < 10 ppb; conductivity ~ 20 µS/cm
- Work being conducted at Argonne National Laboratory (ANL)

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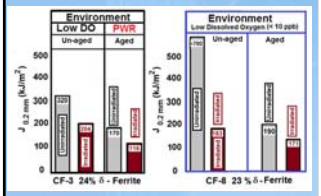
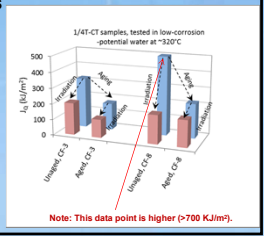
NRC Phase I Test Results:

Effects on Initiation Toughness (i.e., $J_{0.2mm}$)

- Thermal aging and irradiation have a more significant effect on FT of CF-8 grade compared to CF-3 grade
- Irradiation embrittlement of both CF-3 and CF-8 CASS is greater for un-aged materials than for thermally aged materials
- Combined effect of thermal aging and irradiation damage can further reduce the fracture resistance of CASS





Current Research Status

- Evaluation of high dose irradiated materials (Phase II)
  - Irradiated materials have been received and test preparation is underway
  - Testing and evaluation are expected to be completed in 2015
  - Results will be made available when complete
- Literature study underway to identify information gaps [Research Objective (c)].
  - Work is ongoing and is expected to be completed in 2015
  - Results will be made available when complete

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Summary

- CASS is susceptible to loss of fracture toughness due to both thermal and irradiation embrittlement. These mechanisms may combine to reduce toughness more than from either mechanism individually
- Little data exists which considers combined effects due to thermal and irradiation embrittlement
- Initial results from NRC-sponsored research suggests that both thermal aging and irradiation damage contribute to loss of fracture toughness in CASS with ferrite levels above 20% near the crack initiation point (i.e., $J_{0.2mm}$), even at low neutron fluence levels (i.e., 0.08 dpa)
- Additional work is planned in 2015 to continue to address combined effects as well as identify current research gaps

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Abbreviations

Abbreviation	Full Text
ANL	Argonne National Laboratory
CASS	cast austenitic stainless steel
CT	compact tension
DO	dissolved oxygen
dpa	displacements per atom
ECP	electrochemical potential
FT	fracture toughness
LR	license renewal
LWR	light water reactor
NRC	U.S. Nuclear Regulatory Commission
PWR	pressurized water reactor
SS	stainless steel
TE	thermal embrittlement

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