Research and Inspection Initiatives and Results Related to Cast Austenitic Stainless Steel (CASS) Reactor Internals

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Outline

- **Background**
  - Cast austenitic stainless steel (CASS) as a raw material fabrication method for various sizes and applications
  - CASS for nuclear reactor plant internals
  - Inspections for CASS components (pre-service and in-service)
- **Research for Nuclear Reactor Plant Internals**
  - Aging effects due to thermal exposure in service
  - Aging effects due to neutron exposure in service
- **Industry Recommended Screening Approach for CASS Reactor Internals**
- **Industry Assessments of In-service CASS Internals To Date**
- **Summary of Industry CASS Working Group Position on CASS Thermal and Irradiation Embrittlement**
- **Identification of Gaps and Potential for Future Research**

Background
Cast Stainless Steel as a Raw Material Fabrication Method

- Original near net-shape fabrication technique as used in heavy industry routinely since 1960-70s
- High quality "stainless steel" properties in complex parts





- Heavy section parts can be many tons
- CASS compositions developed to resist solidification cracking during cool down

Background
Cast Stainless Steel as a Raw Material Fabrication Method

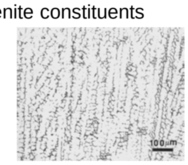
Subsequent application to precision castings of small, relatively complex parts

- Smaller parts might be only a few pounds
- Cool down shrinkage stresses are less than for big castings
- CASS composition for small castings are less complex – fewer alloy additions

Background
Cast Stainless Steel as a Raw Material Fabrication Method

CASS = a "composite duplex structure" composed of ferrite and austenite constituents

Macroscopic view of CASS:
- Uniform structure
- Large elongated grains
- Little porosity
- Alloy balanced to avoid cracking during cool down in production



At higher magnification CASS structure is a distribution of the ferrite phase through the higher volume austenite phase
- Ferrite "sheathed within austenite" at low ferrite content
- Ferrite laths interconnected at higher ferrite content
- Less ferrite is needed to accommodate the significantly lower cooling strains in smaller CASS parts

Background
Cast Stainless Steel as a Raw Material Fabrication Method

- Well recognized fabrication technique with standardized international specifications which are consistent and controlled as shown below
- Intentional alloy variation for smaller castings is towards leaner alloys with less ferrite in the structure (< 20%) – also generally low Mo content
- Larger castings have higher ferrite content (>20%) – intentional addition of Mo

NFA	EN	DIN	BS	ASTM	NOMINAL CHEMISTRY
GX2CrNi19-11 Z 2 CN 18-10	GX2CrNi19-11	G-X 2 CrNiN 18 9	304C12	CF3 CF3A CPF3 - CPF3A	Fe Balance C 0.03 wt% P 0.04 wt% max Si 2 wt% max Mn 1.5 wt% max Cr 17-21 wt% Ni 8-12 wt%
GX5CrNi19-10 Z 6 CN 18-10	GX5CrNi19-10	G-X 6 CrNi 18 9 G-X 6 CrNi18 10	304C15	CF8 CF8A - CF10 CPF8 - CPF8A	Fe Balance C 0.08 wt% P 0.04 wt% max Si 2 wt% max Mn 1.5 wt% max Cr 18-21 wt% Ni 8-11 wt%
GX5CrNiNb19-11 Z6 CNNb 18-10	GX5CrNiNb19-11	G-X 5 CrNiNb 18 9	347C17	CF8C CPF8C	+ Nb 1.0 wt% max
GX2CrNiMo19-11-2 Z2 CND 18-12	GX2CrNiMo19-11-2	G-X 2 CrNiMoN 18 10	316C12	CF3M / CF3MN CF 3 MN	+Mo 2-3 wt%
GX5CrNiMo19-11-2 Z6 CND 18-12	GX5CrNiMo19-11-2	G-X 6 CrNiMo 18 10	316C16	CF8M CPF8M	+Mo 2-3 wt%

- Key grades: CF3 & CF8 low Mo (0.5% max.), CF3M & CF8M high Mo (2-3%)
- Latitude is intentional for alloying chemistry variation within the specs

Background
CASS for Nuclear Reactor Plant Use

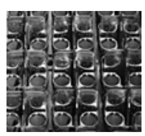
- CASS is a flexible production method for delivering stainless steel corrosion resistant properties to complex parts, i.e., hard to produce from wrought material
- CASS materials are routinely used in both pressure boundary components (Class 1 piping, elbows, etc.) and reactor internals
- CASS components are typically quite ductile as-cast, with ductility approaching that of wrought materials, but …
- Changes in mechanical properties of CASS are typically associated with exposure to nuclear plant operating conditions
  - Elevated temperature over a period of time - called thermal embrittlement (TE)
  - Neutron fluence - called irradiation embrittlement (IE)
- Testing of CASS materials by NRC has implied there might be a reduction in fracture toughness due to a combined effect of thermal and neutron exposure
- The industry evaluation has concluded that the materials selected by NRC to develop screening criteria for reactor vessel aging assessments are not representative of reactor internals
- Industry believes these TE and IE effects are separate and distinct

CASS Use in BWR and PWR Internals

- Example BWR internals applications
  - Jet pump components (e.g., nozzles, elbows, brackets)
  - Core spray sparger nozzles/elbows
  - Fuel support castings
  - Control rod guide tube base
  - Low pressure core injection (LPCI) coupling

Jet Pump

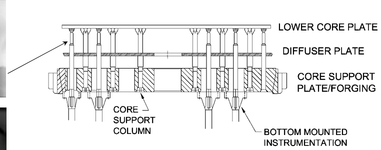
Core Spray Sparger Nozzles/Elbows



Fuel Support Castings

CASS Use in BWR and PWR Internals

- Example PWR internals applications
  - Core support columns
  - Control element assembly (CEA) shrouds and bases
  - Bottom mounted instrumentation (BMI) column cruciforms
  - Lower support column bodies



(Construction photos of typical lower support columns, showing limited accessibility of fully enclosed region)

Background
Inspections for CASS Components (Pre-service and In-service)

- Pre-service inspections as defined by buyer specification, typically radiography exams for bulk variations, plus visual and dye penetrant exams for any surface-breaking flaws
- Inspection techniques are confounded by internal grain structure and orientation effects
  - For very large components, ultrasonic (UT) inspections are noisy due to grain structure interference
  - Due to signal noise, UT is not able to reliably detect tight crack-like indications of interest in examinations compared to UT of wrought components
- Current field inspection techniques are restricted to visual surface exams or limited UT exams of adjacent pressure boundary piping construction welds
- For reactor internal components, in-service VT-3 visual examinations are called out for general condition of the part

10

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Background
Inspections for CASS Components (Pre-service and In-service)

- Example of buyer specification. Component of interest is the Westinghouse lower core support columns fabricated from CASS

Pre-Service Inspection via PT and Radiography

(Maximum defect size, No distribution – Coarse Scale, Binary Assessment.)

1. Surfaces examined shall be free of laps, fissures, cracks or other defects causing linear indications.
2. No non-linear indications with a maximum dimension over T/10(2) or 1/8 inch, whichever is lesser are permitted.
3. In any most unfavorably selected 6 square inch area (min. dimension 1 inch) there shall be no more than 6 indications whose sum of maximum dimensions is greater than 1/4 inch.
4. There shall be no more than 3 indications linerarly disposed.

11

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CASS Use in BWRs and PWRs

- Summary
  - RCS piping applications
    - Class 1 pressure boundary components
    - Very large and thick items
    - Always high Mo CASS materials used (typically CF8M)
    - High ferrite content
    - High safety consequence with failure
  - Reactor internals applications
    - Not pressure boundary components
    - CASS items typically much smaller than RCS piping items
    - High Mo CASS materials rarely used in internals (typically CF3 or CF8)
    - Generally lower ferrite content
    - Consequences of failure much less severe than for pressure boundary failures
    - Most CASS items are part of highly redundant and resilient systems
  - CASS materials thoroughly inspected prior to installation

12

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Research into CASS for Nuclear Reactor Plant Use

- CASS materials could exhibit loss of toughness during long time thermal or irradiation exposures in service
  - Thermal embrittlement is due to:
    - Response of the ferrite phase to exposures at elevated temperatures (above 280°C) which results in hardening and embrittlement
    - Austenite phase does not embrittle
  - Ferrite embrittles as a function of time at temperature
    - Once ferrite has embrittled to a critical degree, then TE controls in aging process, regardless of exposure to neutrons
    - If the critical ferrite embrittlement has not yet occurred, then IE could control the aging process
  - Irradiation embrittlement is due to:
    - Creation of lattice defects from high energy neutron bombardment
  - Both ferrite and austenite phases embrittle with neutron fluence
    - Rate of irradiation embrittlement is different
      - Ferrite embrittlement occurs rapidly (effects complete by <<1 dpa)
      - Austenite embrittlement occurs less rapidly (effects are observed between ~0.5 and 10 dpa)
- Ferrite level has a marked effect on overall susceptibility of CASS to embrittlement of either kind
- Embrittlement of CASS has been an industry concern for many years, yet evidence of age-related degradation has not been observed in service

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Research into CASS for Nuclear Reactor Plant Use

- U.S. industry and regulatory driven research efforts have explored embrittlement of CASS as documented in NUREG/CR documents
  - Thermal Embrittlement – NUREG/CR-4513, 5385, 6142, 6177, 6428
  - Irradiation Embrittlement – NUREG/CR-6960, 7027
- Industry and regulator evaluations are analyzing the same database of information
- Some research efforts assess welds as surrogates for castings
- Focus on J-R curves as measure of fracture toughness

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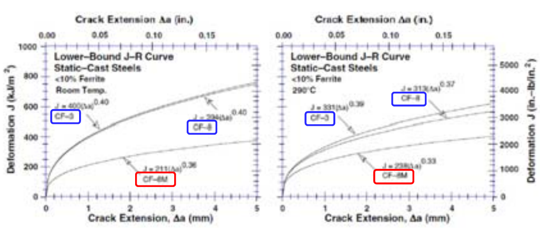
Research into CASS for Nuclear Reactor Plant Use

- Effect of thermal embrittlement on fracture toughness for three alloy variants – CF3, CF8, and CF8M



(Low ferrite levels)

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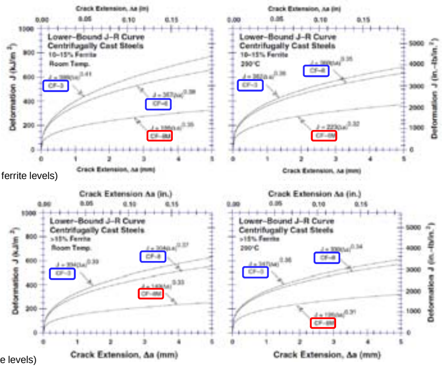
Research into CASS for Nuclear Reactor Plant Use



(Moderate ferrite levels)

(High ferrite levels)

16

Research into CASS for Nuclear Reactor Plant Internals

- Initial research results focused on thermal effects and compositions (high Mo content) that would be more susceptible to thermal embrittlement
- Grades CF3, CF8, CF8M and welds were initially considered in a single database
- Consideration of loss of toughness led to the identification of a threshold tearing resistance of J=255 kJ/m^2 for 2.5 mm (0.1 inch) crack for safety of pressure boundary applications
- NUREG assessments initially developed a single lower bound curve for all CASS grades; reflecting CF8M as lower bound

CASS	J-values at 2.5 mm of Crack Extension (kJ/m^2)	Comments
CF3	364 to 478	>>255 kJ/m^2
CF8	343 to 451	>>255 kJ/m^2
CF8M	161 to 259	Might be < 255 kJ/m^2

- Most recent industry reassessment of this database concludes that CF3 and CF8 retain much higher toughness than CF8M

17

Screening for Thermal Embrittlement of CASS Derived from Research Database

Molybdenum (Wt%)	Casting Method	Ferrite Content %	Susceptibility Determination
High 2.0-3.0	Static	>14%	Potentially Susceptible to TE
		= or< 14%	Not Susceptible to TE
	Centrifugal	>20%	Potentially Susceptible to TE
		= or< 20%	Not Susceptible to TE
Low 0.5 max	Static	>20%	Potentially Susceptible to TE
		= or< 20%	Not Susceptible to TE
	Centrifugal	All	Not Susceptible to TE

- Susceptibility determination
  - Defined in GALL Rev. 2 & included in industry documents
  - Derived from industry and ANL analyses of measured data
  - Modification of initial correlations (EPRI TR-106092) to include conservatisms based on chemical composition
    - Use of Hull calculation method for ferrite content

18

Research into CASS for Nuclear Reactor Plant Internals

- Later research efforts addressed effects of irradiation embrittlement on toughness of CASS (e.g., NUREG/CR-6960 in 2008)
- NUREG documentation has addressed all CASS and austenitic steel welds in a single database
- Recognition that the database is sparse and it is very difficult to obtain suitable specimens
- Existing NUREG evaluation of the irradiation effects database continues to consider all CASS grades as a single entity
- NRC position is to use the worst case CASS data (CF8M) to produce a lower bound IE screening criteria
- Industry notes that ferrite level and Mo content have as significant an impact on IE as they do on TE
- Industry proposes that ferrite level and Mo content should both be considered in IE screening

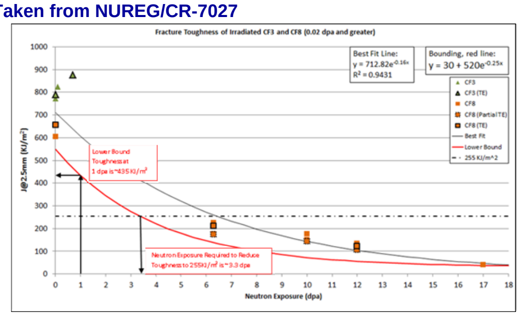
19

Industry Research into CASS for Nuclear Reactor Plant Internals (Data included in NUREG/CR-7027 Database)

- Focused on CF3 and CF8, low ferrite content (<20%) materials typical of reactor internals components
- "Full Thermal Age" was ineffective in the embrittlement of low ferrite content CF8 → testing showed high toughness
- "Full Thermal Age" plus 0.08 dpa irradiation was ineffective in the embrittlement of low ferrite content CF3 fuel nozzle → testing showed high toughness
- Effect of irradiation becomes significant but it is not saturated at 6-10 dpa
- Saturation of loss of toughness appears to occur beyond 12 dpa
- Thermal aging prior to irradiation has no significant effect on post irradiation toughness – full thermal age + irradiation has greater remaining toughness than partial thermal age + similar irradiations (6.3 to 12 dpa)
  - ***Data supports recognition of higher toughness retention in low ferrite CF3 and CF8 materials → supports generation of CF3/CF8-only irradiation embrittlement curve***

20

Industry Research into CASS for Nuclear Reactor Plant Internals Analysis of Irradiated CF3 and CF8 Fracture Toughness Data Taken from NUREG/CR-7027



- CF3 and CF8 grades with low ferrite content retain toughness much better than CF8M after irradiation exposure, consistent with TE

21

Research-Based Industry Approach to Screening of Reactor Internals for Service-Induced Embrittlement

Recommended Process

Screening Order

- Screen first for thermal embrittlement then for irradiation embrittlement
- Screening is performed to "screen in" – all CASS that does not screen in for TE is next screened for IE
- Only CASS not screened in for both TE then IE is screened out

IE Screening

- Screening criterion for IE is 1 dpa (i.e., 6.7 x 10^{20} n/cm^2 (E >1 MeV))

Rationale

TE only occurs in ferrite

IE occurs initially in ferrite, subsequently at much higher fluence level in austenite

CASS already screens in for TE which is ferrite controlled

Significant IE does not begin in the austenite until between 0.3 and 5.0 dpa

Research-Based Industry Approach to Screening of Reactor Internals for Service-Induced Embrittlement

- Initial screening for potential TE based on composition, type of casting, and ferrite content

Molybdenum (Wt%)	Casting Method	Ferrite Content %	Thermal Embrittlement Susceptibility	Irradiation Embrittlement Susceptibility
High 2.0-3.0	Static	>14%	Potentially Susceptible to TE – **Conduct inspection or component specific engineering evaluation**	*No need for IE screening*
		= or< 14%	*Not Susceptible to TE*	Screen for susceptibility to IE if fluence > 1 dpa. If screened-in, then **Conduct inspection or component specific engineering evaluation**
	Centrifugal	>20%	Potentially Susceptible to TE – **Conduct inspection or component specific engineering evaluation**	*No need for IE screening*
		= or< 20%	*Not Susceptible to TE*	Screen for susceptibility to IE if fluence > 1 dpa. If screened-in, then **Conduct inspection or component specific engineering evaluation**
Low 0.5 max	Static	>20%	Potentially Susceptible to TE – **Conduct inspection or component specific engineering evaluation**	*No need for IE screening*
		= or< 20%	*Not Susceptible to TE*	Screen for susceptibility to IE if fluence > 1 dpa. If screened-in, then **Conduct inspection or component specific engineering evaluation**
	Centrifugal	All	*Not Susceptible to TE*	Screen for susceptibility to IE if fluence > 1 dpa. If screened-in, then **Conduct inspection or component specific engineering evaluation**

- Subsequent IE screening performed only for those materials that did not screen in for TE
- Performed only to fluence criterion for embrittlement of austenite (i.e., ~1dpa)

Industry Assessments of In-service CASS Internals

- High Mo grades rarely used in internals; chemical composition data indicate ferrite content rarely above 20%
- Lower ferrite compositions that are used in reactor internals will not undergo thermal embrittlement in BWRs or PWRs
- BWR plant visual inspections to date have identified no age-related degradation in CASS components
- PWR plant visual inspections of CASS components are limited to date, and accessibility to some components within bottom of the reactor is restricted
- Current industry approach for CASS reactor internal components is to rely on engineering assessments supplemented by visual inspections for continued integrity of hardware, ref. EPRI reports BWRVIP-234, and MRP-276

Industry Assessments of In-service CASS Internals

- Screening of reactor internals components based on chemical composition, applied stress, and likelihood of degradation will provide reasonable assurance of continued safety
- Application of aggressive inspection methods for irradiated components inside the reactor is not warranted based on limited improvement in safety
- Risks associated with inspection include stuck inspection tooling, damaged parts, foreign objects lost in confined spaces – practical risk to plant owners is very real

Industry Recognized Gaps and Potential Research for Nuclear Reactor Plant Internals

Gaps:

- Existing data for assessment of the onset of embrittlement for relevant internals CASS compositions and potential irradiation exposures is sparse; needs are associated with:
  - CF3 and CF8
  - 15-20% ferrite
  - 0.2 dpa to 5-10 dpa fluence
- Resolution of combined TE + IE effects for relevant materials

Potential Research:

- Relevant materials
  - Testing materials taken from retired plants
  - Test reactor irradiations of specifically prepared CF3/CF8 materials with 15-20% ferrite content
- Standard J-R testing programs
- This potential research may span 5-10 years or more

Summary

- Assessment of CASS for reactor internals should focus on low-Mo CF3 and CF8 grades with ferrite content less than 20%
- Thermal aging embrittlement effects identified for high-Mo grades of CASS hardware should not be applied to low-Mo grades used in reactor internals
- The added effect of neutron irradiation embrittlement does not change these conclusions drawn with respect to low-Mo versus high-Mo fracture toughness
- Screening process for aging management of CASS reactor internals is reasonable and appropriate
- The existing industry position, based on the research and testing results, supports a sufficiently conservative and effective process for aging management of CASS used in reactor internals
- Further research using relevant reactor internals materials has the potential to validate the conservatism in the approach

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