Overview of LWRS activities in aging of Cast Austenitic Stainless Steels

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Light Water Reactor Sustainability

Light Water Reactor Sustainability R&D Program

The DOE-NE Light Water Reactor Sustainability Program Supports Decisions on Long-Term Operation

Vision

- *Enable existing nuclear power plants to safely provide clean and affordable electricity beyond current license periods (beyond 60 years)*

Program Goals

- Develop fundamental scientific basis to understand, predict, and measure changes in materials as they age in reactor environments
- Apply this knowledge to develop methods and technologies that support safe and economical long-term operation of existing plants
- Research new technologies that enhance plant performance, economics, and safety

Scope

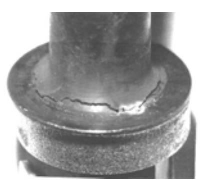
- Materials Aging and Degradation
- Advanced Instrumentation and Controls
- Risk-Informed Safety Margin Characterization
- Reactor Safety Technology
- *Advanced Nuclear Fuels*

LWRS Integrated Program Plan (INL/EXT-11-23452, Rev. 2) Available on www.inl.gov/lwrs

2

Extension of service life may cause new challenges for materials service

- Increased lifetime leads to increased exposures
  - Time at temperature
  - Stress
  - Coolant
  - Neutrons
- Extending reactor life to 60, 80 years or beyond will likely increase susceptibility and severity of known forms of degradation
- New mechanisms of materials degradation are possible



- The motivation of the Materials Aging and Degradation Pathway is to deliver fundamental understanding to enable and support nuclear power plant (NPP) life extension decisions in a timely manner

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3

Materials Aging and Degradation tasks provide results in several ways

- **Measurements of degradation**: High quality data will provide key information for mechanistic studies, but has value to regulators and industry on its own.
- **Mechanisms of degradation:** Basic research to understand the underlying mechanisms of selected degradation modes will lead to better prediction and mitigation.
- **Modeling and simulation:** Improved modeling and simulation efforts have great potential in reducing the experimental burden for life extension studies. These methods can help interpolate and extrapolate data trends for extended life.
- **Monitoring:** While understanding and predicting failures are extremely valuable tools for the management of reactor components, non-destructive monitoring must also be utilized.
- **Mitigation strategies:** While some forms of degradation have been well-researched, there are few options in mitigating their effects. New technologies may overcome limits of degradation in key components and systems.

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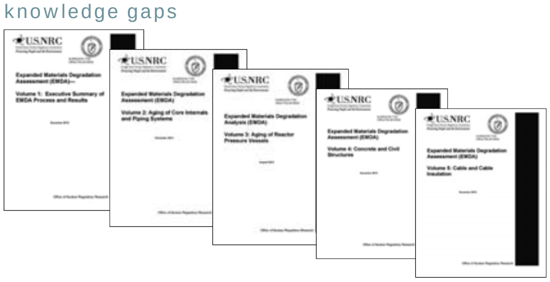
4

NRC and DOE have investigated issues of reactor aging beyond 60 years to identify possible knowledge gaps



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5

The EMDA addressed CASS steels in some depth

- A variety of different degradation modes were considered for these alloys in BWR and PWR environments.
- One potential knowledge gap for CASSs was identified for both PWR and BWR environments using the PIRT data.
- All "low knowledge" scores for CASS are shown to the right
- Specifically, the effects of long-term thermal aging for extended operating periods may drive changes in mechanical or corrosion performance that are relatively unknown.
- This finding is consistent with EPRI's MDM conclusions.

Table 9.107. Summary of SCC scores for CASS in PWR environments

Material/Environment	Degradation Mode	Average Knowledge	Average Susceptibility
CASS HAZ in primary water – low fluence irradiation up to 0.5 dpa	SCC	1.86	[illegible]
CASS in primary water – low fluence irradiation up to 0.5 dpa	SCC	1.79	[illegible]
CASS in primary reactor water – no irradiation	SCC	1.89	[illegible]
CASS HAZ in primary reactor water – no irradiation	SCC	2.14	[illegible]
CASS in borated demineralized water	SCC	[illegible]	[illegible]
CASS HAZ in primary reactor water at lower temperature	SCC	2.14	[illegible]
CASS HAZ in borated demineralized water	SCC	2.14	[illegible]
CASS in primary reactor water at lower temperature	SCC	2.22	[illegible]

Table 9.111. Summary of FR scores for CASS in BWR environments

Material/Environment	Degradation Mode	Average Knowledge	Average Susceptibility
CASS in reactor water – no irradiation	FR	[illegible]	[illegible]
CASS in reactor water – low fluence irradiation up to 0.5 dpa	FR	2.00	[illegible]
CASS in saturated wet steam	FR	2.11	[illegible]

Table 9.114. Summary of SCC scores for CASS in BWR environments

Material/Environment	Degradation Mode	Average Knowledge	Average Susceptibility
CASS in reactor water – no irradiation	SCC	1.89	[illegible]
CASS in reactor water – low fluence irradiation up to 0.5 dpa	SCC	2.00	[illegible]
CASS in deoxygenated reactor water	SCC	2.00	[illegible]
CASS in reactor water – low fluence irradiation up to 0.5 dpa	[illegible]	2.11	[illegible]
CASS in reactor water – no irradiation	[illegible]	2.00	[illegible]

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6

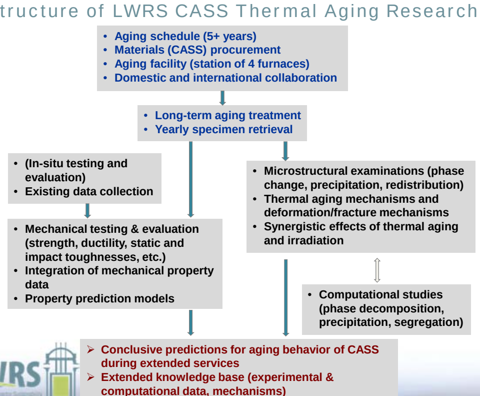
The LWRS program has designed a research effort to address some of these potential gaps for 2nd license renewal

- Cast stainless steels (CASS) are highly corrosion-resistant iron-chromium-nickel alloys with austenite-ferrite duplex structure.
- Massive amounts of CASS are used for the majority of pressure-boundary components in LWR coolant systems and have performed exceptionally well with few failures
- Relatively few critical degradation modes of concerns are expected within the current designed lifetime of 30-40 years.
- On the integrity of CASS components beyond this timeframe, however, no conclusive prediction can be made because no direct experience exists and no sufficient database, for fracture toughness in particular, has been built.
- Furthermore, the accelerated aging experiments in the past, typically near or at 400 °C, were yet to be validated for simulation of lower temperature phenomena.
- ***This aging research aims to systematically build a scientific knowledge base for the thermal aging behavior of cast stainless steels (CASS) within a limited time of five years.***
- ***The ultimate goal of this research is to provide conclusive predictions for the integrity of the CASS components of LWR power plants during the extended service life up to and beyond 60 years.***

The LWRS activities follows a science-based scope to deliver mechanistic understanding

- A large group of CASS materials has been obtained from multiple sources and aged at a wide temperature range of 290–400°C for 0.2–5 years or longer. Materials will be periodically retrieved and evaluated.
- The property degradation of CASS due to thermal aging will be evaluated by direct measurements of mechanical property changes, including J-R fracture, Charpy impact, and tensile tests.
- Detailed microstructural and computational studies are carried out to understand key mechanisms and to predict aging behavior over extended lifetime.
  - Aging and embrittlement mechanisms
  - Deformation and fracture mechanisms in aged CASS
  - Use high resolution microscopy and computer simulation
  - Check the relevance of accelerated aging experiment to real aging phenomena.
- Newly produced data will be compared and integrated with existing data to draw final conclusions.

Structure of LWRS CASS Thermal Aging Research



Production of Cast Stainless Steels (Model Alloys)

- ***Cast stainless steels (CASSs), weld alloys, and reference materials are being obtained from different sources.***
- **Production of four CASSs (CF3, CF8, CF3M, and CF8M) has been completed and cut to ϕ8 cm x h8 cm blocks (see right) prior to aging treatment or to machining specimens.**

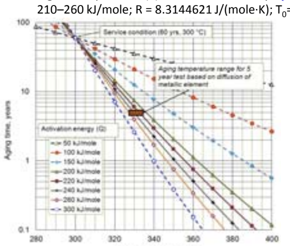
Mater. Code	Grade	Fe	C	Mn	Si	P	S	Cr	Ni	Mo	Note/Origin	Product #
DC-1	**CF3 (304L)**	Bal.	0.02	1.37	1.25	0.033	0.034	19.7	8.1	0.34	2 cast bars φ3 x L13.5 in from SFE, Inc	S05581C23
DC-2	**CF3M (316L)**	Bal.	0.02	1.16	1.20	0.033	0.022	19.1	9.9	2.3	2 cast bars φ3 x L13.5 in from SFE, Inc	S05581C24
DC-3	**CF8 (304)**	Bal.	0.05	1.08	1.26	0.032	0.025	18.5	8.5	0.29	2 cast bars φ3 x L13.5 in from SFE, Inc	S05581C25
DC-4	**CF8M (316)**	Bal.	0.05	0.72	1.04	0.032	0.026	18.6	10.0	2.3	2 cast bars φ3 x L13.5 in from SFE, Inc	S05581C26
Note: Product chemistries in wt.%; DC-DOE CASS; produced in Stainless Foundry & Engineering, Inc.												

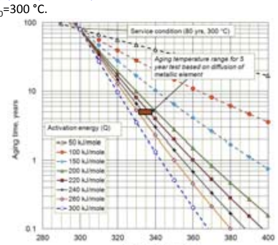
Aging Facility with Four Furnaces

- Four (4) large muffle furnaces (MTI Co. Model KSL-1200X-L) were installed at PNNL for long-term aging experiment. Each of these furnaces has a large chamber volume of 40×40×40 cm^3 (64 L) and capacity to heat up to 1100 °C at a maximum heating rate of 20 °C/ min. The chamber temperature is controlled by a UDIAN programmable controller at an accuracy of <±1°C using K-type thermocouple. Spatial variation within chamber is ±5 °C.
- Aging temperatures were set at 290, 330, 360, and 400 °C, respectively, for the furnaces from left to right.
- Model CASS and wrought stainless steels are under aging treatment; Loading of EPRI CASS materials will be done in March 2015.

Determination of Aging Temperatures

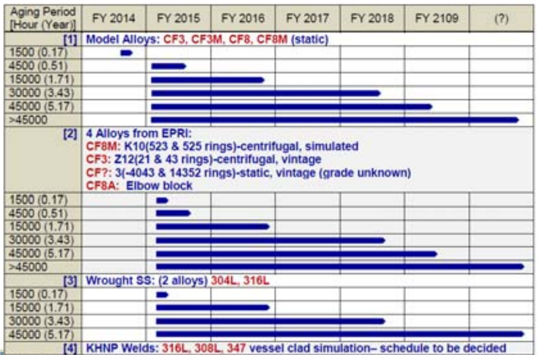
- Thermal activation based calculation for aging: the aging period in accelerated aging or at a higher temperature (T) can be calculated by $t(T) = t_0 \times e^{Q/RT}/e^{Q/RT_0}$, where Q = typically 210–260 kJ/mole; R = 8.3144621 J/(mole·K); T_0=300 °C.





- The accelerated aging temperatures to simulate the 60 and 80 year aging at 300°C in 5 years were about 330 and 335°C, respectively. A temperature increase of ~30°C is needed for inducing accelerated aging in 5 years.
- Four temperatures, 290, 330, 360, and 400°C, were chosen for aging temperatures, which can cover all representative temperatures: 290°C-the lowest aging T; 330°C-to simulate 300°C; 360°C to simulate 330°C; 400°C-the highest aging temperature in past studies.

Materials & Aging Schedule



Note: The aging periods were determined using Aging Parameter (aging effect) estimation. The longer term aging schedules may be changed in request of collaborators or by project schedule.

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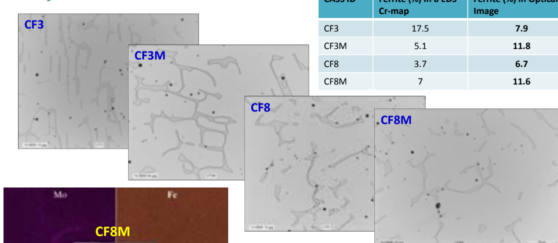
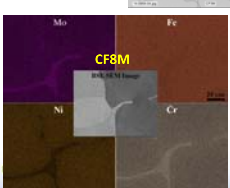
An example of baseline microstructure for model alloys



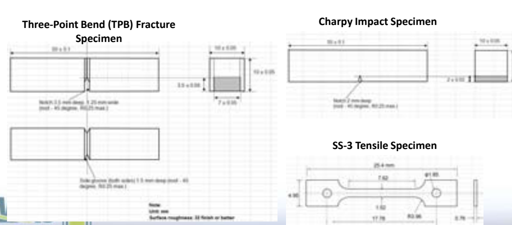
CASS ID	Ferrite (%) in a EDS Cr-map	Ferrite (%) in Optical Image
CF3	17.5	**7.9**
CF3M	5.1	**11.8**
CF8	3.7	**6.7**
CF8M	7	**11.6**



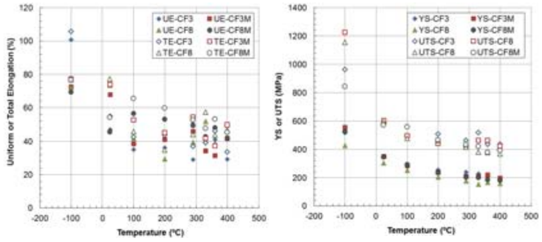
- Volume fraction of ferrite 7.9 & 6.7% for CF3 & CF8; 11.8 & 11.6% for CF3M & CF8M, respectively.
- EDS map shows elemental partitioning between ferrite (Cr enriched) and austenite (Ni & Mo enriched). Fe is relatively uniform.
- No model CASS have a volume fraction of > ~ 25%, above which the ferrite phase would show contiguity.

Mechanical Property Testing to Build Database

- Thermal aging effects will be evaluated by direct measurements of static & impact toughness parameters and tensile properties.
- In each year a mechanical testing campaign will be carried out for the CASS materials retrieved from furnaces after scheduled aging treatment.
- Deformation and fracture mechanisms in aged CASS will be investigated and correlated with the aging mechanisms explained by microscopy and simulation.



An example of baseline tensile data



- Both ductility and strength decreased with test temperature.
- Very high tensile strength (>800 MPa) and high total ductility (>70%) were measured at -100ºC (N100C), which might be because of highly linear dislocation slip or twinning.
- Over the aging temperature region (290-400ºC), both strength and ductility are not temperature dependent, which indicates that the same deformation mechanism is responsible.

Summary

- The DOE LWRS R&D program has initiated a national materials research effort to help provide fundamental and mechanistic knowledge to support extended reactor decisions.
- CASS steels are important components for the primary pressure boundary.
- The EMDA activity identified thermal aging as the largest potential knowledge gap for this system under 2nd license renewal conditions.
- LWRS has initiated a robust thermal aging program to provide mechanistic understanding and relevant data.
- Research is collaborative and well coordinated with partners around the world.

17

Discussion?

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18