Control Rod Survivability During a LOCA

NRC/PWROG Meeting
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Agenda

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- Control Rod Designs
- Assessment
  - Neutronics Aspects
  - Eutectic Interactions
  - Heating Rates
  - Control Rod Internal Pressure
- Conclusions

Overview

- The purpose of the presentation is to demonstrate that for all U. S. Pressurized Water Reactors (PWRs) that control rods will survive a design basis LOCA (this is in response to a Condition Report for B&W NSSS)

- The first three 10 CFR 50.46 Acceptance Criteria also ensure control rods survivability

- Under a design basis LOCA, the control rods will remain intact
  - The Ag-In-Cd absorber material will continue to be contained within the control rod sheath during a design basis Loss-Of-Coolant-Accident (LOCA)
  - The control rod condition will not adversely impact the 10 CFR 50.46 post-LOCA criteria

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Overview (cont.)

- This assessment is centered on eutectic reactions between zirconium based guide thimble tubes and Stainless Steel or Inconel sheath control rods and the potential of the control rod failing and releasing molten Ag-In-Cd absorber material onto the fuel rods and into the primary coolant

- Eutectic reaction is defined as "Of, pertaining to, or formed at the lowest possible temperature of solidification for any mixture of specified constituents"

- To understand the behavior, an analogy is used: water freezes at 32 °F – add salt, and the transition temperature of the water (i.e., solid to liquid) is reduced to a value less than 32 °F

- With the above stated issue, it is related to two metals in contact with each other and the eutectic melting temperature is lower than the melting temperature of either material individually

Overview (cont.)

- If molten Ag-In-Cd is released from the control rods during a LOCA, it could cause further eutectic reactions with the zirconium based fuel rods and could solidify when in contact with the primary coolant – thus causing potential flow blockage of the core which could impact the other two criterion of the 10 CFR 50.46 Acceptance Criteria: 4) maintaining a coolable geometry, and 5) ensuring long-term core cooling

- The assessment ("White Paper") addresses the various control rod designs (materials) and the potential eutectic reactions that could exist, the one noted above being the most limiting

- A secondary issue is associated with the control rod internal pressure and the mechanical integrity of the control rod

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Background

- On April 13, 2006, an interim 10 CFR Part 21 report was filed with the USNRC related to control rod performance during a LOCA event

- Issue relates to the continued applicability of historical Babcock and Wilcox control rod heat-up analyses performed for plants with full-length silver-indium-cadmium (Ag-In-Cd) control rods clad with stainless steel

- Issue related to maintaining local core cooling, a coolable geometry and long-term core cooling after the initiation of a LOCA

- Melting temperature of the silver-indium-cadmium absorber material is well established as 1470 °F

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Background (cont.)

- If the Ag-In-Cd absorber material were to exceed its melt temperature, it would be contained within the clad of the control rod rodlet
- If the control rod rodlet cladding were to be in contact with a guide tube, made of a zirconium-based alloy, a eutectic reaction could begin at approximately 1715 °F
- Localized melting of the control rod could result in release of molten Ag-In-Cd absorber material above the elevation of failure
- In severe accident tests, this has led to localized flow blockage within the fuel assembly (NUREG-1230)

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Historical Perspective

- As noted in the "Concluding Statement of Position of the Regulatory Staff" on "Acceptance Criteria for Emergency Core Cooling Systems for Light-Water Cooled Nuclear Power Reactors":

  "A 2300 °F limit is also sufficient in the staff's present opinion to limit cladding damage by eutectic formations, even though the staff Supplemental Testimony suggested 2200 °F limit to preclude a damaging amount of zirconium-nickel or zirconium-iron eutectic (Exhibit 1113, Section 19). The staff clarified that earlier suggestion by stating in response to questioning that if effects of grid spacer flux depression, cladding pre-oxidation, and other factors were considered, a peak cladding temperature of 2300 °F would be sufficiently low to limit damage by eutectics (Transcript 20, 538-41)."

Historical Perspective (cont.)

- While the final rulemaking for the Emergency Core Cooling Systems (ECCS) Acceptance Criteria settled on 2200 °F for a peak cladding temperature, the above statement shows that the AEC was aware of eutectic reactions

- In addition, the presence of oxidation, while associated with the fuel cladding in this context, reduces the zirconium-nickel/zirconium-iron eutectic reactions between guide thimble tubes and control rod cladding

Control Rod Designs

- There are several control rod designs that exist today in U. S. PWRs
- These designs were supplied by the original NSSS vendors
- These designs have been duplicated by current fuel vendors (i.e., the same design has been maintained for replacement control rods) or newer replacement designs have been developed that are equivalent to the original control rods in terms of form, fit, and function

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Control Rod Designs (cont.)

There may be other variations on the designs, but the key to identifying the designs are the materials used

- Full Length Ag-In-Cd absorber with a Stainless Steel clad rodlet
- Full Length Ag-In-Cd absorber with a Stainless Steel clad rodlet that has Chrome plating or Ion-Nitride plating.
- Full Length Ag-In-Cd absorber with an Inconel 625 clad rodlet
- Hybrid Designs:
  - B4C absorber with Ag-In-Cd absorber in the lower portion of the control rod with a Stainless Steel clad rodlet
  - B4C absorber with Ag-In-Cd absorber in the lower portion of the control rod with an Inconel 625 clad rodlet
- Full length B4C absorber with an Inconel 625 clad rodlet
- Full length Hafnium absorber with a Stainless Steel clad rodlet (no longer in use)

Control Rod Designs (cont.)

- The eutectic reactions of concern are zirconium-nickel and zirconium-iron
- Stainless Steel clad rodlets and the Inconel 625 clad rodlets are treated the same, since both have the nickel or iron necessary for a eutectic reaction
- The other aspect to identifying the various designs is the absorber material used and how it will react at the elevated temperatures experienced during a design basis Loss of Coolant Accident (LOCA)
- Some of the designs also have either a plated coating or an ion-nitride surface treatment (the presence of either of these surface treatments can slow or stop the eutectic reaction rates when there is no wear through the protective layer)

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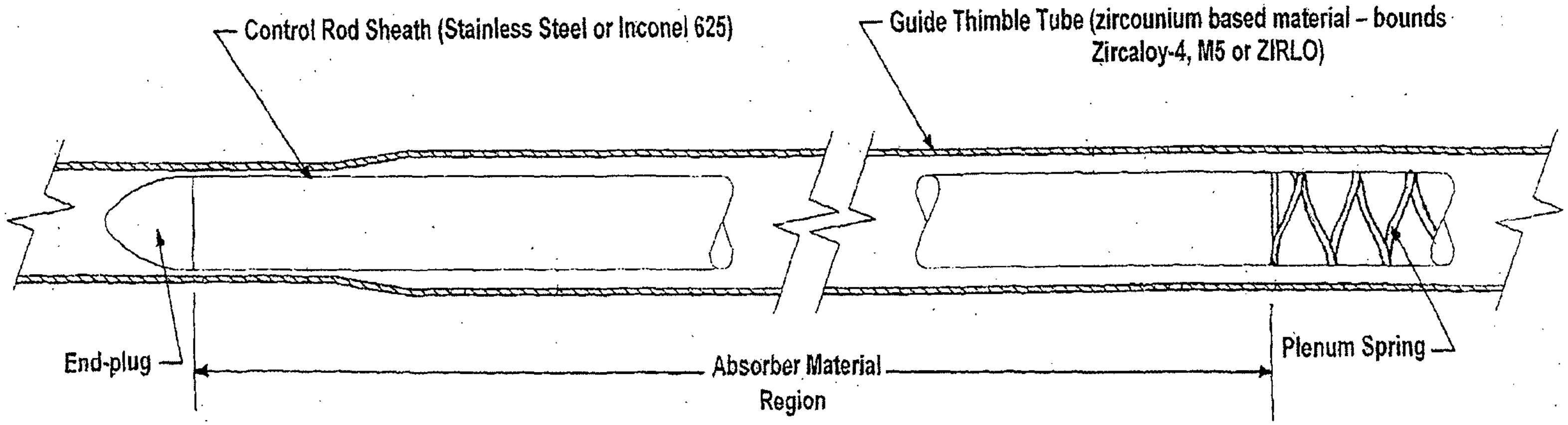
Control Rod Designs (cont.)

- Illustrated below is a simplified schematic of a control rod in a guide thimble tube



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Assessment

- Neutronics Aspects:
  - The heating up of the control rods during a LOCA transient does not have any impact on their ability to carry out their primary mission: absorb neutrons and maintain the core in a sub-critical state

- Eutectic Interactions:
  - Eutectic reaction can only occur when the materials in question are in direct "hard" contact with each other
  - Removal of one of the materials will cease the eutectic reaction
  - Oxidation also affects the eutectic reaction by preventing the eutectic reaction until the oxide layer is "dissolved"*

* The term "dissolved" refers to the incubation period that is necessary to dissolve the ceramic ZrO_2 layer and form a metallic α-Zr(O) layer which allows the interactions with nickel and iron to take place.

Assessment (cont.)

- Eutectic Interactions:
  - A thin oxide layer* of approximately 10 μm would take approximately:
    - 2 minutes to dissolve at 2200 °F (1200 °C)
    - 5 minutes to dissolve at 2102 °F (1100 °C)
    - 10 minutes to dissolve at 2012 °F (1000 °C)
    - 15 minutes to dissolve at 1832 °F (900 °C)
  - Factoring in oxide coatings or control rod plating adds margin to the prevention of the eutectic reactions

* This initial in-reactor oxidation layer, on the guide thimble tube ID, is an extremely hard oxide layer that is not expected to wear off due to control rod insertion movement. It is noted that the oxidation layer could be worn off due to mechanical interactions with the control rod at the locations where the control rods are "parked". These locations are usually at the top of the fuel.

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Assessment (cont.)

- Eutectic Interactions:
  - Eutectic reactions can begin only after 'hard contact' is achieved (i.e., between the guide thimble tube and the control rod sheathing)
  - Eutectic reactions take time to impact the integrity of the boundary
  - The table on the following slide summarizes "burn through" calculations for typical guide thimble tube wall thickness and control rodlet wall thickness for the three U.S. NSSS designs (i.e., Westinghouse, CE and B&W))
  - "Burn through"* is a term used in this paper that describes the time required for the calculated reaction to travel through the reference thickness, such as the control rod sheath or guide thimble tube

* "Burn-through" actually refers to the amount of the base material consumed (i.e., the Zircaloy-4 reaction rate equation would specify how much of the Zircaloy-4 would be consumed by the eutectic reaction). It takes both materials to be present for a eutectic reaction rate to take place. Removal of one of the materials or changes in temperature will have a significant effect on the reaction rate.

Assessment (cont.)

Reaction Rate Equations (KfK-4670)

Zircaloy-4 $x^2 / t\,(cm^2/\sec) = (2.78 x 10^{19})(e^{(-642864\ /RT)})$

Stainless Steel $x^2 / t\,(cm^2/\sec) = (1.08 x 10^{19})(e^{(-688790\ /RT)})$

$R = 8.314\ J/mol \cdot K$

Design	Reference Wall Thicknesses found in FSARs (in)	Minimum Burn-through (sec) @ 2200 °F (1200 °C)	Minimum Burn−through (sec) @ 2012 °F (1100 °C)
Westinghouse 17x17 Guide Thimble	0.014	2.7	~ 124
Westinghouse 14x14 & 15x15 Guide Thimble	0.015	3.1	~ 143
Westinghouse 16x16 Guide Thimble	0.016	3.6	~ 163
CE 14x14 Guide Thimble	0.04	23.2	~ 1059
CE 16x16 Guide Thimble	0.04	23.2	~ 1059
B&W TMI-1 Guide Thimble	0.016	3.7	~ 169
CE Inconel Control Rodlets	0.035	1942.9	>> 50000
B&W TMI-1 Inconel Control Rodlet	0.023	802.5	~ 48210
Westinghouse SS Control Rodlets	0.018	513.6	~ 30853

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Assessment (cont.)

- Eutectic Interactions:
  - For a Small Break LOCA scenario, industry experience is that the PCTs are typically lower for Small Breaks than for Large Breaks
  - Therefore, even though the time-at-temperature is longer, the burn-through rates are significantly longer such that the eutectics would be less limiting than they are for a Large Break LOCA
  - Additionally, because the Small Break LOCA is a longer event, the decay heat and gamma energy deposition that could provide heating after core uncovery are much lower than in the Large Break scenario

Assessment (cont.)

- Heating Rates:
  - The other issue identified in the Interim Part 21 was one of heating rates on the guide thimble tube material, the control rodlet material and the absorber material
  - The decay heat contribution to heating of a control rod is a function of assembly design, local peaking, gamma energy deposition at full power, the transient decay heat, and the fraction of decay heat that is from gamma power
  - Other contributions to heating such as from delayed neutrons or beta decay from activated absorber material have been determined to play a minimal role in control rod heating and have not been explicitly modeled

Assessment (cont.)

- Heating Rates:
  - The preliminary control rod temperature analyses performed for a B&W or Westinghouse designed plant and described in the Interim Part 21 notification were performed by taking the total decay heat times a gamma heating ratio to determine the gamma energy deposition
  - The Interim Part 21 evaluations used transient gamma energy rates based on an ORIGEN2 run whose output data did not include all of the short lived isotopes
  - It was found that the misleading data table was subsequently removed in more recent versions of the ORIGEN code

Assessment (cont.)

- Heating Rates:
  - Use of the misleading ORIGEN2 data applied considerable conservatism to the control rod temperature evaluation because it allowed little reduction of the gamma energy deposition with time post trip
  - Use of the corrected data resulted in much lower transient energy deposition into the control rod than the Interim Part 21 evaluation and the control rod temperatures decrease from ~ 1950 °F to ~ 1700 °F to 1800 °F
  - While these evaluations did not account for energy deposition from metal-water reaction with the zirconium based guide thimble tube, the new guide tube temperatures were predicted to be in the range of 1500 °F to 1700 °F, where the metal-water energy contributions are relatively small

Assessment (cont.)

- Heating Rates:
  - The following table gives representative maximum values for the key components to this analysis at the time of reactor shutdown with their approximate transient energy contributions (based on 177 fuel assembly lowered-loop B&W plant with realistic decay heat and a core power of 2,568 MWt with RPD (FQ) of 3.0)

Material	Representative Initial Energy Deposition (W/cc)	Transient Energy Multiplier
Absorber (Ag-In-Cd)	33	~ 0.5 of Decay Heat (from γ)
Cladding (Stainless Steel or Inconel 625)	24	~ 0.5 of Decay Heat (from γ)
Guide Thimble Tube (zirconium based)	20	~ 0.5 of Decay Heat (from γ)
Fuel	60	Decay Heat

Assessment (cont.)

- Control Rod Internal Pressure:
  - Another issue associated with the guide thimble/control rod eutectic reactions is the internal pressure inside the control rods
  - The increase in internal control rod pressure is due to the expansion of any backfill gas and possibly the vaporization of cadmium from the Ag-In-Cd absorber material as the temperatures escalate during the transient
  - The overpressure within the control rod was investigated to ensure that mechanical failure of the control rod does not occur during a postulated LOCA transient

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Assessment (cont.)

- Control Rod Internal Pressure:
  - Tests were conducted by Westinghouse to demonstrate that the control rods can withstand LOCA conditions (i.e., 2200 °F for an extended period of time that would envelope a Design Basis 10 CFR 50.46 LOCA transient) and not fail due to hoop stress from Cadmium vapor overpressure
  - These tests confirm that the Westinghouse control rod will not fail due to hoop stress from Cadmium vapor overpressure
  - Since the Westinghouse design control rods have the thinnest Stainless Steel clad wall thickness, these tests validate that this issue is implausible for any control rods previously or currently fabricated by Westinghouse for the Westinghouse and CE control rod designs

Assessment (cont.)

- Control Rod Internal Pressure:
  - Westinghouse conducted a total of four tests to confirm that cadmium vapor overpressure hoop stress failure did not occur
  - The first three tests confirmed no failure
  - The last test was a "proof of principle" – "test to failure"
  - All tests used a typical Westinghouse control rod segment with a proportional amount of Ag-In-Cd absorber to simulate a full sized control rod (i.e., equivalent void volume)
    - Test 1: Heated to 1800 °F for 5 minutes – No failure
    - Test 2: Heated to 1800 °F for 10 minutes – No failure
    - Test 3: Heated to 2200 °F for 10 minutes – No failure
    - Test 4: Heated to 2200 °F for 30 minutes - Weepage

Assessment (cont.)

- Control Rod Internal Pressure:
  - Test 3 confirmed that no hoop stress failure from Cadmium vapor overpressure would occur
  - Test 4 also confirmed that no hoop stress failure from Cadmium vapor overpressure would occur
  - Test 4 results show that no violent expulsion of Ag-In-Cd occurs
  - Test 4 results were revealing and substantiated by Reference 5, Section 3.1 *
  - Test 4 results are summarized below:
    - A release of approximately 1-2 cc's of absorber material "weeped" out
    - No high pressure failure occurred (i.e., no pure cadmium detected)
    - "Weepage" constituents included Ag, In, Cd, Fe, Cr, and Ni

* The weepage mechanism is associated with a silver/chromium binary reaction, where at elevated temperatures, for a sufficient length of time, the Stainless Steel grain structure grows and the chromium migrates to the grain boundaries. The silver will then follow the grain boundary and weep out.

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Assessment (cont.)

- Control Rod Internal Pressure:
  - Control rod designs for Westinghouse plants use stainless steel for the sheath with no initial pre-pressurization of the rods
  - At 1800 °F, the cadmium overpressure is small and the total hoop stress from the cadmium vapor and the heated fill gas pressure is roughly 1500 psi
  - This is well below the yield or ultimate stress for the stainless steel at 1800 °F
  - The expected duration of the control rod to experience these temperatures during a LOCA is well bounded by the results of the 10 minute test
  - Thus, the Ag-In-Cd control rods for Westinghouse plants are not expected to fail due to high internal pressure

Assessment (cont.)

- Control Rod Internal Pressure:
  - Ag-In-Cd control rod design for the B&W plants use Inconel 625 for the control rod sheath with a gas prefill pressure to prevent creep collapse of the sheath during normal operation
  - The partial pressure of the cadmium combined with the gas prefill partial pressure at the rod average temperature produces a hoop stress that could approach the yield or ultimate tensile strength of the control rod sheath at very high temperatures
  - However, at the time when the control rod reaches its maximum temperature of 1700 °F to 1800 °F, which was discussed earlier, the volume average temperature in the control rod is roughly 600 °F less than the peak temperature

Assessment (cont.)

- Control Rod Internal Pressure:
  - Using a control rod gas average temperature of 1200 °F produces a hoop stress from the partial pressure of the prefill gas in the range of 13,000 psi for Large Break LOCA scenarios
  - The rod average temperature is less than the cadmium boiling point; however, regions of the rod are above the cadmium boiling point
  - Therefore, combining a cadmium vapor pressure induced stress at 1800 °F of roughly 1000 psi results in a total hoop stress of roughly 14,000 psi
  - The yield and ultimate strengths of the Inconel 625 at 1800 °F are roughly 17,000 psi and 18,000 psi, respectively
  - Thus, the B&W plant control rods are not expected to fail due to high internal pressure

Conclusions

Based on the facts presented in this assessment, the following points are noted below in chronological order:

- The AEC was aware of eutectic reactions when the 10 CFR 50.46 rulemaking was approved
- Of all the control rod designs that exist in U.S. PWRs, the control rod design with full length Ag-In-Cd in either a Stainless Steel or Inconel 625 sheath control rod is the most limiting from a eutectic reaction standpoint
- Oxide coating on zirconium based guide thimble tubes will provide additional margin to preclude eutectic reactions
- Coatings on Stainless Steel sheath control rods provide additional margin to preclude eutectic reactions

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Conclusions (cont.)

- The eutectic reaction time necessary to "burn-through" the control rod is greater than the time spent at Peak Clad Temperature (PCT) that the design basis LOCA would experience
- Zirconium based guide thimbles would eutectically react with either Stainless Steel or Inconel 625 sheath control rods and would "burn-through" (be consumed) in only a few seconds at a PCT of approximately 2200 °F (i.e., the eutectic reaction would cease after the zirconium material was consumed)
- Molten Ag-In-Cd will continue to have the same cross-section of absorption for neutrons
- Eutectic reaction rates are slowed down dramatically (i.e., on the order of a factor of 60 at 2100 °F) at lower temperatures

Conclusions (cont.)

- The heating rates for the control rods show that the control rod temperatures will remain less than the PCT limit of 2200 °F, with maximum expected temperatures in the range of 1700 °F to 1800 °F
- Current control rod designs will not fail due to Cadmium vapor overpressure or internal pressure at the expected temperatures

In summary, control rod melt with absorber expulsion does not occur for any design basis scenario for any past or current control rods supplied to U.S. PWRs, manufactured by AREVA or Westinghouse, provided the fuel cladding meets the ECCS acceptance criteria of 10 CFR 50.46.

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