Control Rod Survivability During a LOCA

Prepared for the PWR Owners Group

By

AREVA and Westinghouse

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Utility Member	Plant Site(s)	Participant	
		Yes	No
AmerenUE	Callaway (W)	X	
American Electric Power	D.C. Cook 1&2 (W)	X	
Arizona Public Service	Palo Verde Unit 1, 2, & 3 (CE)	X	
Constellation Energy Group	Calvert Cliffs 1 & 2 (CE)	X	
Constellation Energy Group	Ginna (W)	X	
Dominion Connecticut	Millstone 2 (CE)	X	
Dominion Connecticut	Millstone 3 (W)	X	
Dominion Kewaunee	Kewaunee (W)	X	
Dominion VA	North Anna 1 & 2, Surry 1 & 2 (W)	X	
Duke Energy	Catawba 1 & 2, McGuire 1 & 2 (W), Oconee 1, 2, 3 (B&W)	X	
Entergy Nuclear Northeast	Indian Point 2 & 3 (W)	X	
Entergy Operations South	Arkansas 2, Waterford 3 (CE), Arkansas 1 (B&W)	X	
Exelon Generation Co. LLC	Braidwood 1 & 2, Byron 1 & 2 (W), TMI 1 (B&W)	X	
FirstEnergy Nuclear Operating Co	Beaver Valley 1 & 2 (W), Davis-Besse (B&W)	X	
Florida Power & Light Group	St. Lucie 1 & 2 (CE)	X	
Florida Power & Light Group	Turkey Point 3 & 4, Seabrook (W)	X	
Nuclear Management Company	Prairie Island 1&2, Pt. Beach 1&2 (W)	X	
Nuclear Management Company	Palisades (CE)	X	
Omaha Public Power District	Fort Calhoun (CE)	X	
Pacific Gas & Electric	Diablo Canyon 1 & 2 (W)	X	
Progress Energy	Robinson 2, Shearon Harris (W), Crystal River 3 (B&W)	X	
PSEG - Nuclear	Salem 1 & 2 (W)	X	
Southern California Edison	SONGS 2 & 3 (CE)	X	
South Carolina Electric & Gas	V.C. Summer (W)	X	
So. Texas Project Nuclear Operating Co.	South Texas Project 1 & 2 (W)	X	
Southern Nuclear Operating Co.	Farley 1 & 2, Vogtle 1 & 2 (W)	X	
Tennessee Valley Authority	Sequoyah 1 & 2, Watts Bar (W)	X	
TXU Power	Comanche Peak 1 & 2 (W)	X	
Wolf Creek Nuclear Operating Co.	Wolf Creek (W)	X	

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Utility Member	Plant Site(s)	Participant	
		Yes	No
British Energy	Sizewell B	X	
Electrabel (Belgian Utilities)	Doel 1, 2 & 4, Tihange 1 & 3	X	
Kansai Electric Co., LTD	Mihama 1, Ohi 1 & 2, Takahama 1 (W)	X	
Korea Hydro & Nuclear Power Corp.	Kori 1, 2, 3 & 4 Yonggwang 1 & 2 (W)	X	
Korea Hydro & Nuclear Power Corp.	Yonggwang 3, 4, 5 & 6 Ulchin 3, 4 , 5 & 6(CE)	X	
Nuklearna Electrarna KRSKO	Krsko (W)	X	
Nordostschweizerische Kraftwerke AG (NOK)	Beznau 1 & 2 (W)	X	
Ringhals AB	Ringhals 2, 3 & 4 (W)	X	
Spanish Utilities	Asco 1 & 2, Vandellos 2, Almaraz 1 & 2 (W)	X	
Taiwan Power Co.	Maanshan 1 & 2 (W)	X	
Electricite de France	54 Units	X	

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Executive Summary

The purpose of this “White Paper” is to document generically for all U. S. Pressurized Water Reactors (PWRs) that the first three 10 CFR 50.46 Acceptance Criteria (1. Peak Cladding Temperature ≤ 2200 °F, 2. the local oxidation ≤ 17% ECR, and 3. the whole core hydrogen generation ≤ 1%), also protect the control rods. Under these conditions, the control rods will remain intact (i.e., 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) and the control rod condition will not adversely impact the 10 CFR 50.46 criteria.

An issue was raised regarding the survivability of control rods during a Design Basis LOCA. The issue 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. If the Ag-In-Cd melt were released from the control rods during the 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 would 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 “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.

Eutectic 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.

The contact between the control rod sheath and the guide thimble tube creates the potential for a eutectic reaction between zirconium/nickel and zirconium/iron. Thus, guide thimble tube designs using Zircaloy-4, M5™ or ZIRLO™ are treated the same since each material is 98% zirconium. Likewise, control rod sheath designs with either Stainless Steel or Inconel are treated the same since both have the nickel and iron required for the eutectic reaction.

Based on the assessment presented in the “White Paper”, it is concluded that as long as the fuel continues to meet 10 CFR 50.46 Acceptance Criteria, then control rod survivability is ensured and will not impact any of the 10 CFR 50.46 analyses. Therefore, no additional actions are necessary.

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Control Rod Survivability During a LOCA

Background:

On April 13, 2006, AREVA filed an interim 10 CFR Part 21 report with the USNRC related to control rod performance during a LOCA[1] event. The 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. A limited number of plants have reported estimated or calculated control rod temperatures that could be achieved during a LOCA event, and included this information in their UFSARs. AREVA has reported that the historical values reported were potentially non-conservative.

The issue, as summarized by AREVA, was related to maintaining local core cooling, a coolable geometry and long-term core cooling after the initiation of a LOCA. The melting temperature of the silver-indium-cadmium absorber material is well established as 1470 °F. If the material were to exceed this temperature and melt, it would be contained within the clad of the rodlet. However, if the 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. AREVA cited severe accident tests reported in a 1985 conference paper[2] that indicated that the eutectic reaction could result in localized melting of the zircaloy guide tube and the stainless steel control rod cladding at approximately 2138 °F. This localized melting of the control rod resulted in expulsion of essentially all of the molten Ag-In-Cd absorber material above the elevation of failure. After this occurred in the test, the molten absorber material reacted with the cladding on the fuel rods, flowed downward, and solidified when it reached the lower regions of the assembly where the coolant temperatures were lower. For this severe accident test, this led to localized flow blockage within the fuel assembly.

As noted in AREVA's Interim Report[1], Section 6.15 of NUREG-1230[3] (Control Rod Performance) cited several severe accident tests that demonstrated eutectic temperature reactions for core materials. This section discusses experimental results as noted below:

> "Recent information from experiments in the NIELS facility at Kernforschungszentrum Karlsruhe (KfK) in Germany (6.15.4), using zircaloy guide tubes and stainless steel control rods show that, at low pressure, failure can occur around 2138 °F (1443 K). This failure is probably due to a eutectic reaction between stainless steel and zircaloy. The iron-zircaloy and nickel-zircaloy phase diagrams predict that a eutectic reaction can happen around 1736 °F (1220 K). Although the observed zircaloy guide tube failures are less violent than those that would occur in a stainless steel guide tube, they may, in the long run, cause more damage to the rest of the core because the failure has been observed to be a small hole in the zircaloy and stainless steel that allows the Ag-In-Cd alloy to spray out onto the hot fuel rods. This alloy is liquid at about 1430 °F to 1520 °F (1050 to 1100 K). All the liquid above the hole was expelled during the experiment and then was observed to flow to the bottom of the rod bundle and block the inlet. Ag also has a eutectic reaction with zircaloy and has been observed to erode or melt the zircaloy cladding."

Introduction:

While the facts stated above about eutectic reactions are valid, care must be used in reviewing severe accident test results (papers). This point will be elaborated on in more detail later in this paper. As noted in the "Concluding Statement of Position of the Regulatory Staff"[(4)] 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)."

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 mentioning of oxidation, while associated with the fuel cladding in this context, will be shown to have an effect on the zirconium-nickel/zirconium-iron eutectic reactions between guide thimble tubes and control rod cladding.

This paper will describe the various control rod designs that exist in Pressurized Water Reactors (PWRs) in the U. S. and their susceptibility to eutectic reactions. A review of more recent severe accident papers will also provide an insight that these eutectic reactions will not result in loss of local or long-term core cooling or a loss of coolable geometry (i.e., refer to the discussion in the Assessment section). However, if the design basis for the ECCS Acceptance Criteria is exceeded (i.e., entering severe accident regime), than eutectic reactions could cause significant core degradation.

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. The following is a general listing of these designs followed by a discussion of their susceptibility to eutectic reactions.

1. Full Length Ag-In-Cd absorber with a Stainless Steel clad rodlet
2. Full Length Ag-In-Cd absorber with a Stainless Steel clad rodlet that has Chrome plating or Ion-Nitride plating.
3. Full Length Ag-In-Cd absorber with an Inconel 625 clad rodlet

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[*] As stated in the first sentence of the quote, the specific eutectic reaction was zirconium-nickel/zirconium-iron associated with fuel rod cladding and the spacer grids. However, the same eutectic reaction could occur between the control rod and the guide thimble tube. The purpose of the quote is to demonstrate that the AEC was aware of eutectic reactions and had considered such reactions as part of the 10 CFR 50.46 rulemaking.

4. Hybrid Designs:
   - B_4C absorber with Ag-In-Cd absorber in the lower portion of the control rod with a Stainless Steel clad rodlet
   - B_4C absorber with Ag-In-Cd absorber in the lower portion of the control rod with an Inconel 625 clad rodlet
5. Full length B_4C absorber with an Inconel 625 clad rodlet
6. Full length Hafnium absorber with a Stainless Steel clad rodlet (no longer in use)

There may be other variations on the above designs, but the key to identifying the designs are the materials used. As noted previously, the eutectic reactions of concern are zirconium-nickel and zirconium-iron. Therefore, the 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 key 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.

The Stainless Steel or Inconel 625 rodlets all have the nickel/iron necessary for eutectic reactions. As documented in Reference 5 (experimental results), the lowest eutectic reaction observed was between Fe-Zr at approximately 1742 °F[†] on the Zr rich side. The eutectic temperature on the Fe rich side is at about 2373 °F. The eutectic reaction between Ni-Zr occurs between 1760 °F and 2138 °F. These reactions and their corresponding reaction rate equations will be examined in the next section. Again, it is important to remember that the eutectic reactions are between zirconium-nickel/zirconium-iron, thus Stainless Steel and Inconel are treated as the same (since both materials have the nickel and iron) and Zircaloy-4, M5™ and ZIRLO™ are treated the same (since these materials are all 98% zirconium).

The Ag-In-Cd absorber material melts at approximately 1470 °F[(6)], but is contained within a Stainless Steel or Inconel rodlet. The Ag-In-Cd absorber does not eutectically react with the rodlet materials; however, it does react with zirconium. The Ag-In-Cd absorber in hybrid designs is typically located in the bottom of the control rod and should remain below the melting point of the Ag-In-Cd absorber material during a LOCA.

The B_4C absorber material melts at approximately 4477 °F[(6)]. The B_4C absorber does have a eutectic reaction with Stainless Steel or Inconel that commences at 1880 °F; however, rapid liquidification does not occur until approximately 2330 °F[(7)]. This eutectic reaction is a nickel-boron/iron-boron/chromium-boron eutectic.

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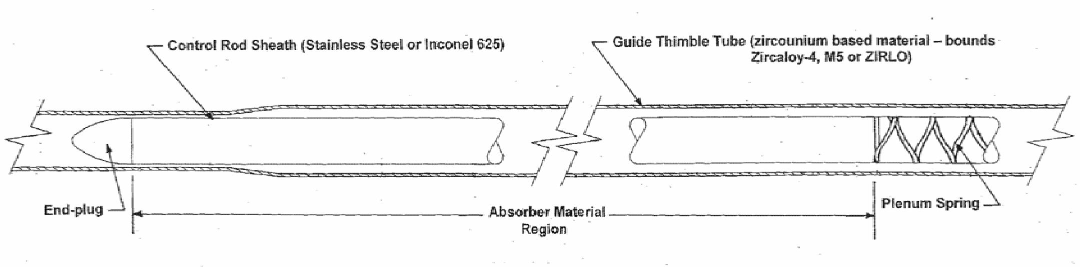
† This paper does not specifically endorse any specific temperatures since the values do not seem to be exact. Reference 5 is a newer source of information than was quoted in Reference 1, and by the same organization, thus it is logical to assume that the values noted in Reference 5 are probably more accurate.

The chrome-plated control rod design would have a eutectic reaction with zirconium at approximately 2336 °F[(8)*]. The ion-nitride plated control rod design does not have a eutectic reaction with the zirconium. Examination of plated control rods, during plant inspections, has shown some limited wear of the plating. The size of the affected area varies by plant, but is usually about 0.5 inches in length. However, the plating does potentially provide some additional margin to eutectic reactions between the control rod and the zirconium based guide thimble tube if it has not been worn through. A more detailed discussion of the eutectic reactions is provided in the Assessment section below.

The hafnium absorber material melts at approximately 3902 °F. The hafnium absorber does not have a eutectic reaction with Stainless Steel or zirconium based material. This absorber is no longer used in control rod applications.

Of the possible identified reactions, the eutectic reactions between the zirconium based guide thimble tube and the control rod are the most important, since it is necessary to exceed the design basis criteria of 10 CFR 50.46 before the other eutectic reactions have any significant effect.

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



Assessment:

Neutronic 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[(1)].

Eutectic Interactions

As noted previously, there are several eutectic reactions that can occur between the guide thimble tube, the control rod cladding, and the absorber material. These eutectic reactions 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 reactions[(5)]. Oxidation also affects the eutectic reactions[(5)] by preventing the eutectic

* Note: Reference 5 documents this eutectic reaction (Cr-Zr) occurs between 2430 °F and 2898 °F.

reactions until the oxide layer is "dissolved"(5)†. To elaborate on this point, a thin oxide layer of approximately 10 μm would take approximately 2 minutes to dissolve at 2200 °F, 5 minutes at 2102 °F, 10 minutes at 2012 °F and 15 minutes at 1832 °F (Figure 26 of Reference 5).

Whether an oxide coating exists or not, the eutectic reactions can begin only after 'hard contact' (between the guide thimble tube and the control rod sheathing) is achieved, and once achieved, takes time to impact the integrity of the boundary. More recent severe accident reports provide insight in this area. Reference 5 provides reaction rate equations for Zircaloy and Stainless Steel. As noted previously, Stainless Steel and Inconel claddings are treated the same since it is the zirconium-nickel/zirconium-iron eutectic that is of concern. The table provided below summarizes "burn through" calculations that use these reaction rate equations and taking 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. Thus, "burn through" depicts the time for through-penetration, or a break-down in one of the two barriers between the primary coolant and the control rod material.

Assuming a temperature of 2200 °F for the guide thimble tubes, it would take only about 2-4 seconds for the zircaloy guide thimble tube wall to "burn-through" at 2200 °F for Westinghouse and B&W designs, and 23 seconds for the CE designs. Assuming the same temperature for the control rod sheathing; however, it would take approximately 32 minutes for the CE control rods to "burn-through", 13 minutes for the B&W control rods, and 8 minutes for the Westinghouse control rods. Under these conditions, the minimum time to burn-through both the control rod sheath and guide thimble tube is 8 minutes. This is longer than the entire duration of most Large Break LOCA transients, and is longer than the duration of the transient where these high cladding temperatures are experienced.

These time-at-temperature calculations assume that both materials would be present, and maintained at 2200 °F, for the entire time. The reaction rate varies significantly with temperature. For illustration purposes, the following table includes a "burn through" calculation assuming a temperature of 2012 °F . At this temperature, the minimum burn-through is calculated to be greater than 8 hours, a factor of 60 increase. This calculation reveals that the "burn through" rate increases dramatically with temperature. Since Large Break LOCA peak cladding temperatures vary throughout the transient, the reaction rate will also vary, further increasing the time required to achieve "burn-through".

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† 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. 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.

* "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.

Factoring in oxide coatings or control rod plating adds margin to the prevention of the eutectic reactions.

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.

Thus by maintaining the temperatures less than the 10 CFR 50.46 Acceptance Criteria illustrates that the control rods would not "burn-through".

Reaction Rate Equations (Reference 5)

Zircaloy-4 $x^2 / t\,(cm^2 / \sec) = (2.78\,x10^{19})(e^{(-642864\ /RT)})$

Stainless Steel $x^2 / t\,(cm^2 / \sec) = (1.08\,x10^{19})(e^{(-688790\ /RT)})$

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

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

As mentioned in the Introduction, care in reviewing severe accident results is necessary. This is a three-dimensional situation, where the upper portion of the test assembly melts, with the control rods failing in this region. The temperatures in the upper portions of these test assemblies under severe accident conditions are usually at 3300 °F and above[(5)(9)]. However, the thermocouples are often located in lower sections of the test bundle, either in the guide thimble or attached to the control rod, where the temperatures are much lower. Consequently, control rod failure may be reported to occur at much lower temperatures than are actually experienced where the failure occurs. If one uses the reaction rate equations noted above for these severe accident conditions, the stainless steel control rod would essentially "burn-through" in only 0.005 seconds[†].

† As documented in Reference 5, "these equations can be extrapolated to lower temperatures, but not to higher temperatures since a fast and complete liquification of the materials take place at about 1250 °C" (2282 °F). The example noted above is simply to illustrate that the upper portions of test assemblies in severe accidents are melting instantaneously whereas the lower portions of the assemblies will retain some semblance of a normal fuel assembly.

Heating Rates

The other issue identified in Reference 1 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 considered to play a minimal role in control rod heating and have not been explicitly modeled.

The preliminary control rod temperature analyses performed for a B&W or Westinghouse designed plant and described in the interim Part 21 notification[1] were performed by taking the total decay heat times a gamma heating ratio to determine the gamma energy deposition. The following table gives representative hot spot 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 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

The gamma energy deposition in the control rod and other components decreases as the decay heat declines. The Reference 1 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. 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 Reference 1 evaluation and the control rod temperatures decrease by 200 °F to 300 °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.

While the temperature predictions for the plant control rod absorber during a LBLOCA still exceed the melt temperature of the Ag-In-Cd, it is much lower than initial prediction. In addition, it was observed experimentally in LOFT[10] that the heating rate of the control rod decreases due to absorption of decay heat by the latent heat of melting for the Ag-In-Cd absorber material. This slower heating rate will delay the time when the control rod sheath and guide thimble interface temperature reaches the onset of the eutectic melting and the onset of significant metal-water reaction by up to roughly 100 seconds. In a fast LBLOCA transient, the reduction of the control rod heatup rate allows additional time for the quench front to advance thereby limiting the maximum temperature that the control rod can achieve.

The preliminary analyses and LOFT[10] experimental data show that the control rod temperatures rise at a slower rate than the fuel pin. The lower energy deposition into the control rod versus that of the fuel is sufficient to compensate for the lower heat capacity of the absorber material, the reduced heat removal from the control rod, and a delayed quench of the control rod inside a guide thimble tube when compared to a fuel rod in an open flow channel. While the peak control rod temperature will occur after that of the fuel rod, the maximum temperature of the control rod should be 300 °F to 400 °F less than the fuel pin peak cladding temperature during a LBLOCA transient.

Based on these considerations, the peak control rod temperature is well bounded by the fuel rod cladding temperature, which is limited by 10 CFR 50.46 to 2200 °F. In the range of expected peak control rod temperatures from 1700 °F to 1800 °F, the eutectic burn-through rates for the sheathing are on the order of hours. As stated previously, the duration of the LBLOCA transient where these temperatures may be experienced is limited to minutes. Therefore, the revised heating rates support the conclusion that the peak control rod temperatures are in a range where the eutectic reaction between the control rod sheath and the guide thimble tube are not expected to result in a breach of the control rod.

<u>Control Rod Internal Pressure</u>

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.

As noted in Reference 2, in another severe accident test, the control rod failed due to cadmium vapor over-pressure at 2417 °F (1325 °C).

> "At about 1325 °C, as measured by the two colour pyrometer looking at the spacer, the vapour pressure within the control rod cladding was large enough to cause it to fail and the melt was violently expelled out, penetrating the guide tube."

This severe accident test involved a Stainless Steel control rod in a Stainless Steel guide thimble tube. Therefore, no eutectic reaction occurred between the control rod and the guide thimble tube. The other aspect of this test was the temperature measurement. The two color pyrometers were actually measuring the temperature of the spacer grid versus the actual control rod. This temperature would actually be less (relatively speaking) than what would have been measured on the control rod due to the steam cooling aspects of the grid environment and due to the fact that gamma heating of the grid material will be considerably less than the control rod. Thus, these control rods most likely failed due to melting (i.e., the melting temperature of Stainless Steel is reported as 1671 K to 1727 K or 2548 °F to 2649 °F[6]).

To substantiate this hypothesis, 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. 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". The tests are described below. 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

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 AREVA control rod designs for Westinghouse plants use stainless steel for the sheath with no initial prepressurization 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[11]. However, 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 AREVA Ag-In-Cd control rods for Westinghouse plants are not expected to fail due to high internal pressure.

The AREVA 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. 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[11]. Thus rupture of the sheath is not expected. In the unlikely event that the sheath did yield, it would expand outward and come into contact with the guide tube. The combined strength of the sheath and guide tube would prevent rod breach and preclude the flow of molten absorber material into the guide tube or fluid channel. The internal rod pressure would also decrease as the sheath yielded and increased the gas volume. The combination of the reduced pressure and additional material strength afforded by the guide tube further reduces the hoop stress. Thus, the B&W plant control rods are not expected to fail due to high internal pressure.

The hoop stress evaluations presented above are based on a minimum RCS pressure representative of the Large Break LOCA event, which is bounding of the higher RCS pressures experienced for a Small Break LOCA event. Therefore, considering the initial gas fill pressure at the rod average temperature along with the cadmium vaporization at the expected control rod temperatures and time-at-temperature, the potential hoop stress failure of the control rod from overpressure during a LOCA is not plausible.

Conclusions:

Based on the facts and details documents in this White Paper, the following key points are noted in chronological order as they are presented in the paper:

1. The AEC was aware of eutectic reactions when the 10 CFR 50.46 rulemaking was approved.

2. Of all the control rod designs that exist in U.S. PWRs, the control rods 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.

3. 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.

4. The eutectic reaction time necessary to “burn-through” the control rods is greater than the time spent at Peak Clad Temperature (PCT) that the design basis LOCA would experience.

5. 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. Thus, the eutectic reaction would cease after the zirconium material was consumed.

6. Molten Ag-In-Cd will continue to have the same cross-section of absorption for neutrons.
7. Eutectic reaction rates are slowed down dramatically (i.e., on the order of a factor of 60) at lower temperatures.

8. 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.

9. Current control rod designs will not fail due to Cadmium vapor overpressure or internal pressure.

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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