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Your ref: Docket No. 52-006
Our ref: DCP/NRC1706

June 1, 2004

SUBJECT: Transmittal of Revised Responses to AP1000 DSER Open Items

This letter transmits Westinghouse revised responses for Open Items in the AP1000 Design Safety Evaluation Report (DSER). A list of the revised DSER Open Item responses transmitted with this letter is Attachment 1. The non-proprietary responses are transmitted as Attachment 2.

Please contact me at 412-374-4728 if you have any questions concerning this submittal.

Very truly yours,

R. P. Vijuk

R. P. Vijuk, Manager
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/Attachments

1. List of the AP1000 Design Certification Review, Draft Safety Evaluation Report Open Item Responses transmitted with letter DCP/NRC1706
2. Non-Proprietary AP1000 Design Certification Review, Draft Safety Evaluation Report Open Item Responses

D063

DCP/NRC1706
Docket No. 52-006

June 1, 2004

Attachment 1

AP1000 Design Certification Review
Draft Safety Evaluation Report Open Item Non-Proprietary Responses

Table 1 **"List of Westinghouse's Responses to DSER Open Items Transmitted in DCP/NRC1706"**	
ACRS Issue 5, Rev 1	

DCP/NRC1706
Docket No. 52-006

June 1, 2004

Attachment 2

AP1000 Design Certification Review
Draft Safety Evaluation Report Open Item Non-Proprietary Responses

AP1000 DESIGN CERTIFICATION REVIEW

Draft Safety Evaluation Report Open Item Response

DSER Open Item Number: **ACRS ISSUE 5 Rev 1**

Original RAI Number(s): **None**

Summary of Issue:

In-Vessel Retention/Fuel-Coolant Interactions (FCI): The assessment of in-vessel retention has not included exothermic intermetallic reactions which have been shown by some prototypic experiments to be important. If these factors are properly accounted for, the associated energetics of any resulting ex-vessel steam explosions are likely to be greater than has been currently evaluated. We would like to review the FCI models used and see additional justification that the initial conditions related to intermetallic reactions will not give rise to an energetic FCI that could fail containment.

Westinghouse Response:

ACRS has questioned whether the ex-vessel steam explosion analyses performed for AP1000 and AP600 bounds a postulated steam explosion from a vessel breach at the bottom of the reactor vessel (reference 1).

The ex-vessel steam explosion analysis of record (reference 2) assumes that the vessel fails at the top of the oxide debris near the top of the lower head hemisphere.

A vessel breach at the bottom of the vessel head can be postulated to occur if bottom heavy metal layer of uranium, zirconium and iron forms in the debris bed and produces a thermal loading to the vessel wall that cannot be cooled by the boiling heat transfer at the lower head external surface. The thermal loading from the in-vessel debris bed is postulated to be produced by decay heat in the bottom metal layer and a potential exothermic chemical reaction that occurs as vessel wall steel is mixed into the zirconium/uranium rich bottom metal layer (reference 3). The critical heat flux, which defines the upper bound of cooling capacity, is smallest at the bottom of the reactor vessel (reference 4). Therefore, a high heat flux from the bottom metal pool may be postulated to exceed the critical heat flux at the bottom of the reactor vessel thus producing failure of the vessel wall. The vessel failure at the bottom of the vessel would release the molten bottom metal layer into the cavity water pool and potentially produce a steam explosion.

It is the Westinghouse position that, while such a debris bed configuration may be postulated, it is unlikely to produce vessel failure. Including a bottom vessel head failure in the AP1000 PRA will not significantly increase the risk of the plant. Therefore, the ex-vessel steam explosion analyses already performed bounds the consequences of a vessel failure at the bottom of the head.

To examine the likelihood of the formation of a bottom metal layer that challenges the lower head integrity can be decomposed into a series of questions and analyzed on a decomposition event tree (Figure 1):

1. Is the reactor vessel reflooded during the progression of the core damage sequence?
2. Does the in-vessel melt progression prevent mixing of a significant mass of zirconium with the molten oxide debris?
3. Given a bottom metal layer, does the bottom metal layer have less decay heat that it takes to melt the vessel wall?
4. Given a melting metal wall, does the chemical reaction produce less heat than required to exceed the critical heat flux at the external surface of the vessel?

1. Is the reactor vessel reflooded during the progression of the core damage sequence?

If the reactor vessel is reflooded, the reactor vessel wall is cooled from the outside and the debris bed is cooled from the inside. The mass of debris that relocates to the lower head is limited. Therefore, the challenge to the reactor vessel wall is mitigated. Approximately 50 percent of the AP1000 core damage frequency results in a reflooded reactor vessel from the progression of the severe accident sequence. Therefore, the failure probability at node 1 is assigned 0.5.

2. Does the in-vessel melt progression prevent mixing of a significant mass of zirconium with the molten oxide debris?

A bottom metal layer may be postulated only when a significant quantity of unoxidized zirconium mixes with steel and UO_2 in the oxide layer. However, the mixing of the constituents in the RASPLAV test is not considered to be applicable to the large-scale reactor relocation scenario (reference 5). In the melting and relocation analyses performed for the AP1000, it was shown that almost all of the unreacted zirconium in the damaged core is frozen at the top of the lower core support plate. The frozen zirconium does not participate in the formation of the lower head debris configuration until the lower support plate is subsumed and melted by the oxide debris from below. The melting temperature of the lower support plate and zirconium is much less than the oxide debris. Therefore, the formation of a significant bottom metal layer is considered to be unlikely. The failure of this node is assigned a probability of 0.1 on the decomposition event tree.

3. Given the formation of a bottom metal layer, does the bottom metal layer have less decay heat than it takes to melt the vessel wall?

A conservative analysis of the heat loading from a bottom metal layer is presented in reference 6. This analysis considers only the thermal loading from decay heat in the bottom metal layer and does not include any heat from a chemical reaction from mixing steel from the melting vessel wall into the uranium/zirconium rich bottom metal layer. The analysis considers 7000 kg of unoxidized zirconium, and 3000 kg of stainless steel reacting with the oxide to produce the bottom metal pool. The reaction is assumed to produce a bottom metal pool that is 40 weightpercent uranium (reference 7). One hundred percent of the decay heat associated with an equivalent volume of oxide required to produce the uranium content of the bottom metal layer is mixed in with the uranium in the bottom metal pool along with the remaining iron and zirconium. The fraction of the decay heat is a very conservatively chosen upper bound value that was intended to cover all uncertainties such as the potential chemical reaction heat. The analysis shows that in this configuration, the resulting heat load to the lower head melts the inside vessel wall, but is not sufficient to exceed the critical heat flux. The lower head is predicted to not fail.

If the analysis is performed specifically including the potential heat of mixing the melting vessel wall into the uranium/zirconium rich bottom metal pool, it is appropriate to make the decay heat assumption in the pool a less conservative estimate. According to peer reviewer comments in reference 8, the actual upper bound of the decay heat that could be mixed in the metal pool is approximately 20 percent of the decay heat from the equivalent volume of uranium dioxide instead of 100 percent.

Based on reference 6, the maximum bottom metal layer volume is 1.53 m^3 with a thickness of 0.58m. With 100% of the associated decay heat, the volumetric heat density is 1.38 MW/m^3. Therefore, for the realistic upper bound value of 20%, the volumetric heat density is 0.28 MW/m^3. The total decay heat in the bottom metal layer is 0.43 MW. The area of the layer in contact with the reactor vessel is 7.34 m^2. The area upward to the oxide layer is assumed to be adiabatic. The thermal conductivity of the metal layer is high, so it is assumed to generate a uniform heat flux over the vessel wall. Therefore, the heat flux to the vessel is 58 kW/m^3. Given the vessel wall thickness of 0.1524 m and a thermal conductivity of 32 W/m-K, the inside wall temperature at this heat flux is 650°K, well below the melting temperature of the vessel wall.

The calculation of the inside vessel wall temperature assumes that the heat transfer from the oxide layer is negligible. Based on the volumetric heat density and the thickness of the heavy metal layer, the top surface temperature at the interface of the oxide layer and the heavy metal layer is approximately 2600°K, which is close to the temperature of the oxide crust layer. Therefore, the adiabatic top surface assumption is reasonable at this decay heat level.

In this case, with 20 percent decay heat, the analysis of the heat load to the vessel wall shows that the vessel wall does not melt. Therefore, the rate of mixing is limited to solid phase diffusion of the wall into the molten pool, which is quite slow. The heat of reaction is therefore very small, will not become a runaway reaction, and can be removed by the external vessel cooling.

Therefore, the reactor vessel is not expected to fail at the bottom metal layer. Node 2 is assigned a failure probability of 0.1.

4. **Given melting of the vessel wall at the bottom metal layer, does the chemical reaction produce less heat than required to exceed the critical heat flux at the external surface of the vessel?**

An analysis of the AP1000 lower head using reaction kinetics from reference 3concludes that even if the vessel wall is melting, the heat of mixing the steel into the heavy metal layer is not expected to produce a runaway reaction or fail the vessel wall. However, this phenomenon is considered to be complex. It is therefore conservatively assigned a failure probability of 0.5 on the decomposition event tree.

Failure at node 4 results in vessel failure. If the vessel fails into the reactor cavity, the containment is assumed to fail immediately from an ex-vessel steam explosion in the PRA. This assumption is carried through in this analysis. The initial conditions in this case are for a vessel failure that occurs close to the bottom of the reactor vessel. This type of vessel failure has not been investigated in the AP1000 PRA severe accident analyses. Therefore, it is appropriate to assume early containment failure for this vessel failure condition.

Quantification of the Decomposition Event Tree

The Decomposition Event Tree is quantified in Figure 1. The base large release frequency from the internal event at power PRA is $2x10^{-8}$ per reactor-year. The increase to the large release frequency from a steam explosion induced by the failure of IVR due to the formation of a bottom metal layer that dissolves the lower head is $6.0x10^{-10}$ per reactor-year, or a 3% increase. The conditional containment failure probability increases from 8.1 percent to 8.3 percent. This increase in large release frequency is considered to be negligible and does not impact the results of the PRA.

References

1. ACRS Letter Mario V. Bonaca, ACRS, to William D. Travers, USNRC, ACRS Reviews of the Westinghouse Electric Company Application for Certification of the AP1000 Plant Design – Interim Letter, March 17, 2004.
2. AP1000 PRA, revision 6.
3. Argyropoulos and Sismanis, The Solution Kinetics of Zirconium in Liquid Steel, Steel Research 68, (1997) No. 8, p 345.
4. Theofanous, T.G., Limits of Coolability in the AP1000 Related ULPU-2400 Configuration V Facility, CRSS-03/06, June 2003.
5. Westinghouse Response to RAI 720.047.
6. Scobel, J.H. The Potential for AP1000 Reactor Vessel Failure Induced by a Stratified Debris Bed with a Bottom Metal Layer During IVR, International Conference on Advanced Nuclear Power Plants (ICAPP), Cordoba, Spain, May 2003.
7. Rempe, J.L., et. al, Potential for AP600 In-Vessel Retention through Ex-Vessel Flooding, INEEL/EXT-97-00779, December 1997.
8. Theofanous, T.G., et. al., In-Vessel Retention and Coolability of a Core Melt, DOE/ID-10460, July 1995

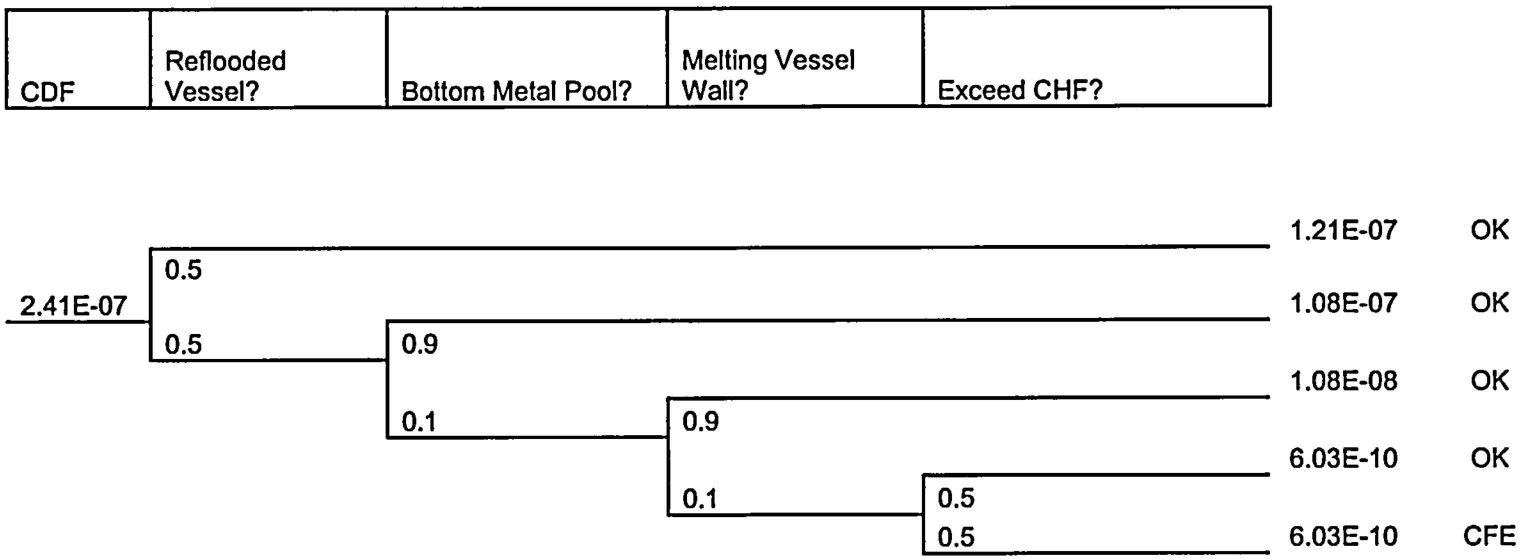
Design Control Document (DCD) Revision:

None

PRA Revision:

None

Figure 1
Decomposition Even Tree



Base LRF =	1.95E-08	per year
Increase to CFE =	6.03E-10	per year
Increased LRF =	2.01E-08	per year