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MFN 08-801, Supplement 1

Docket No. 52-010

April 22, 2009

U.S. Nuclear Regulatory Commission
Document Control Desk
Washington, D.C. 20555-0001

Subject: **Response to Portion of NRC Request for Additional Information Letter No. 300 Related to ESBWR Design Certification Application ESBWR RAI Numbers 19.2-95 S01 and 19.2-100 S01**

Enclosure 1 contains the GE Hitachi Nuclear Energy (GEH) response to the subject NRC RAIs transmitted via the Reference 1 letter. RAIs and previous responses were transmitted in References 2 and 3.

If you have any questions or require additional information, please contact me.

Sincerely,

Richard E. Kingston

Richard E. Kingston
Vice President, ESBWR Licensing

Reference:

1. MFN 09-082, Letter from U.S. Nuclear Regulatory Commission to Robert E. Brown, GEH, *Request For Additional Information Letter No. 300 Related To ESBWR Design Certification Application*, dated January 27, 2009.

2. MFN 08-616, Letter from U.S. Nuclear Regulatory Commission to Robert E. Brown, GEH, *Request For Additional Information Letter No. 230 Related To NEDE-33392, "BIMAC Test Report*, dated August 4, 2008.

3. MFN 08-801, *Response to Portion of NRC Request for Additional Information Letter No. 230 Related to ESBWR Design Certification Application ESBWR RAI Numbers 19.2-93 through 19.2-119 dated November 3, 2008*

Enclosure:

1. Response to Portion of NRC Request for Additional Information Letter No. 300 Related to ESBWR Design Certification Application Probabilistic Risk Assessment RAI Numbers 19.2-95S01 and 19.2-100 S01

cc:	AE Cubbage	USNRC (with enclosure)
	JG Head	GEH/Wilmington (with enclosure)
	DH Hinds	GEH/Wilmington (with enclosure)
	eDRFSection	0000-00101-0305 RAI 19.2-95 S01
		0000-00100-0959 RAI 19.2-100 S01

Enclosure 1

MFN 08-801, Supplement 1

Response to NRC Request for

Additional Information Letter No. 300

Related to

ESBWR Design Certification Application

RAI Numbers 19.2-95 S01 and 19.2-100 S01

NRC RAI 19.2-95 (original)

Question Summary Core melt situations where GDCS pools are depleted, preventing the deluge function

Full Text

The GDCS's main function is to serve as an emergency cooling supply to the core in any event that threatens the reactor coolant inventory. In addition, if the vessel fails, it is important to ensure that the GDCS can provide sufficient water to cool the debris in the lower drywell by utilizing the BiMAC. Please provide documentation of any core melt situations in which the GDCS pools have already been depleted by providing water to the vessel, and there is not sufficient inventory for ex-vessel cooling. Describe the amount of water that is required to sustain the BiMAC system.

GEH Response (original)

A core melt situation with a depletion of the GDCS pools by providing water to the vessel requires a failure of containment heat removal. This sequence would be a Class II sequence.

The amount of water necessary for the BiMAC to function corresponds to a pool depth sufficient to cover the inlets to the BiMAC downcomers. The water level in the lower drywell would be greater than 10 m (33 ft) if the two smaller pools drained through the deluge lines. Assuming 502 m^3 (17,700 ft^3) of drainable volume in each smaller pool and a lower drywell area of 99 m^2 (1060 ft^2).

NRC RAI 19.2-95 S01

Question Summary : Provide realistic estimates of water inventory and height of the water pool necessary for the BiMAC to function properly.

Full Text:

GEH has responded that the quantity of water necessary for BiMAC functionality is equal to that required to cover the downcomer inlets. It is recognized that this is the minimum amount of water required. However, this minimum quantity may not be sustainable for continuous BiMAC operation due to the potential for depletion because of evaporation (especially during the initial melt quenching period). The GEH response alluding to the water level in the lower drywell region assumes a full water inventory in the GDCS reservoirs. In reality under accident conditions, the GDCS water inventory is *in the form of steam and condensation inside PCCS and may not be sufficient to replenish the GDCS inventory. Therefore, the GDCS pools may not necessarily be at its maximum when the deluge lines into the lower drywell region are actuated.*

1. Please provide the height of the water pool inside the drywell floor that would be considered adequate for the sustained operation of BiMAC accounting for the partial depletion of the GDCS inventory (and without complete replenishment)? Provide the GDCS inventory required to achieve this height?

2. Please provide the upper and lower bounds and the basis for these estimates for:

(a) The available GDCS inventory at the time of actuation of the deluge lines, and

(b) The height of the water pool in the lower drywell region when the BiMAC system begins operation.

GEH Response

1. A water pool with a height of 2.0 m (6.6 ft) would cover the inlets to the BiMAC downcomers. This height requires a pool inventory approximately 200 m^3 (7000 ft^3). The depletion during initial melt quenching was conservatively estimated by determining the energy removed in cooling a full core pool, 260 metric tons (5.7×10^5 lbm) at 2600 K (4200 °F), to solid conditions at saturated water temperature at containment design pressure and 1 hour of decay heat. This energy would evaporate approximately 230 m^3 (8100 ft^3) of water without credit for energy required to raise the whole water pool to saturation temperature.
2. The GDCS pools would be full at the time of deluge actuation. The only mechanism to drain the GDCS pools would be GDCS injection which if successful would prevent core damage unless containment heat removal fails. If containment heat removal fails, the sequence would be a Class II sequence.
    a. The minimum inventories at Technical Specification low level of 6.5 m (SR 3.5.2.1) (21 ft) is calculated using pool areas minus non drainable water volume described in DCD Table 6.2-3. The upper bound inventory is calculated assuming a high water level of 6.7 m (22 ft) based on difference between low level and normal level, also using pool areas minus non drainable water volumes described in DCD Table 6.2-3. The available inventories are as follows:
        i. Each Small pool: 492.9 to 509.9 m^3 (17,410 to 18,010 ft^3)
        ii. Large pool: 650.2 to 672.2 m^3 (22,960 to 23,740 ft^3)
    b. The heights of the water pool in the lower drywell region when the BiMAC system begins operation using the success criteria of two pools are:

i. Two small pools: 10.0 to 10.3 m (32.8 to 33.8 feet)
ii. One small pool and large pool: 11.5 to 11.9 (37.7 to 39.0 feet)

Successful operation of the BiMAC function requires successful operation of functions which supply water to the BiMAC, condense steam produced and re-circulate the condensate back to the BiMAC. These functions include deluge, containment isolation, and containment heat removal and are considered in the Level 2 PRA.

DCD Impact

No DCD changes will be made in response to this RAI.

No changes to NEDO-33201 or NEDE-3392P will be made in response to this RAI.

NRC RAI 19.2-100 (original)

Question Summary: Thermal load boundary conditions used in the experiments justification

Full Text

The molten pool and core debris thermal state depends on the total mass, configuration and the boundary conditions at the outer edges. Please elaborate on the assumption of decoupling between the cooling afforded by BiMAC channels and molten pool thermal loads. Please justify the thermal load boundary conditions used in the experiments and the ESBWR BiMAC design.

GEH Response (original)

The BiMAC channels will absorb, in a self-adjusting manner all power delivered to them, unless this power exceeds the critical power (sufficient to cause burnout). Under this condition the pool boundary maintains a solid layer, and the inner surface of it is at the liquidus. These ideas, and the associated “decoupling”, have been expounded and became standard knowledge and practice during the development of the in-vessel retention concept for PWRs.

NRC RAI 19.2-100 S01

Question Summary: Provide details of CFD modeling, and the supporting benchmarking studies, used to establish the thermal load boundary conditions for the BiMAC experiments.

Full Text:

GEH’s response does not address the second part of the RAI (“Please justify the thermal load boundary conditions used in the experiments and ESBWR BIMAC design.”). The thermal load boundary conditions will depend on a number of factors including the melt condition, crust formation (its thickness and physical condition), and the split in the heat flux (upward versus downward). These aspects of the melt pool affect the pool thermal state, which will in turn affect the rate of heat transfer into BiMAC. It is recognized that the boundary conditions for the experiments were guided by the results of the CFD simulation; however, the details of the CFD model, assumptions, and its experimental validation basis, have not been provided. These are essential if the CFD simulations are to be the sole basis for the heat flux boundary conditions.

Please provide the details of the CFD model, assumptions, numerical solution technique, and the supporting experimental validation basis that justify its use to arrive at the thermal boundary conditions for the experiments. Also, please provide the supporting experimental benchmarking studies, including the uncertainties in the CFD-based predictions of the thermal boundary conditions.

GEH Response

[REFERENCE]

1. GE Hitachi ESBWR NEDO-33201 Rev. 3, Chapter 21, General Electric-Hitachi (GEH) (May 2008)

The supplemental question is focused differently than the original one, and in responding we must clarify certain statements that are in the way to understanding the technical basis of what we have done. This we do first, in the following 4 points. To further clarify, we provide several paragraphs of the technical-historical perspective that formed the basis of our methodology in assessing thermal loads for the BiMAC.

1. It is claimed that GEH does not address "….the thermal boundary conditions…" used in our CFD simulations. This claim is not understood because we clearly stated that "…the inner surface of it [meaning the pool] is at the [melt] liquidus", and this is <u>all that is needed</u> as boundary condition in the simulations.
2. The new question states that "*The thermal load boundary conditions will depend on a number of factors including the melt condition, crust formation (its thickness and physical condition), and the split in the heat flux (upward versus downward)".* Actually the split in heat flux is the result of such a simulation (in fact the only reason for doing it)…not an input. Moreover, in our previous response we explained that in such a setting crusts adjust to the thermal loads, rather than the other way around. The reason for this adjustment can be found in a number of previous ROAAM documents, starting with the one on the Mark-I Liner Attack issue resolution document done for the US NRC *(NUREG/CR 5423, August 1991)*. More recently this was also explained in the in-vessel retention document for the AP600 *(DOE/ID-10460, October 1996)*. As stated in the original response this is standard knowledge by now.
3. It is stated that *"however, the details of the CFD model, assumptions, and its experimental validation basis, have not been provided."* GEH would like to point to Appendix D to the SAT report [1] which was meant to fulfill exactly this purpose. So, we will reiterate. First and foremost, our approach is to use CFD <u>simulations</u>, not <u>modeling</u> (the later is a lower grade of an approach, involving assumptions that may be of dubious quality). By contrast, in our CFD we solve directly the Navier-Stokes equations, and, as stated above, the boundary

condition is clear and simple—an isothermal boundary at the melt liquidus. The solution is obtained in the sense of Large Eddy Simulation (the method is called Implicit LES, or ILES) and it requires no turbulence model—all but the finest scales of motion are captured naturally in such a simulation. All this can be found in Appendix D of the SAT report. Therein also we show the validation comparisons with experiments. To this day, this is the state of the art in this area, also followed by the IBRAE Institute (Strizov, Bolsov, et al) in Russia, which is one of the few places in the world that are still involved in this kind of research.

4. We deem that the 2D simulations results are conservative. Subsequent 3D simulations presented in the Addendum to Section 21.5.4.3 of the SAT confirm that this is indeed the case. These may be viewed as sensitivity studies that bound other uncertainties. On the other hand, the bounding nature of the whole-core pool, already discussed in the SAT report, cannot be emphasized enough.

The subject of volumetrically heated pool heat transfer is pertinent to astrophysical problems as well as nuclear safety. As such it has attracted attention from physicists, on basic grounds as well as by engineers and engineering scientists. In the nuclear context is was essentially opened in the 1970's during the first assessments of core debris coolability in liquid metal cooled fast reactors. Experimentally this work was limited to small scales and rather low Rayleigh numbers (*Ra*) due to difficulties in creating the needed volumetric heating rates in the laboratory. There seemed to be confusion about internal and externally driven natural convection, and the theoretical approaches were rough, based on eddy diffusivity models. On the nuclear side the work was terminated with the LMFBR program.

The subject was reopened in the 1990's. On one hand by the need to address in-vessel retention (IVR) for PWRs (Theofanous et al, DOE/ID-10460), and on the other hand by theoretical physicists who speculated a different scaling regime at the extremely high Ra pertinent to astrophysical phenomena (called "hard turbulence"). In addressing the IVR we invented a new concept for experimentation that allowed us to work at ½ scale and also meet the Ra similarity requirements of a whole-core pool in a PWR. This is the ACOPO experiment. Besides providing the essential data for addressing robust heat flux distributions to the boundaries of such pools, this experiment provided the basis for unifying the "internal" and "external" problems (Theofanous, T. G. and S. Angelini, "Natural Convection for In-Vessel Retention at Prototypic Rayleigh Numbers," *Nuclear Engineering and Design* **200** 1-9,2000), and furthermore it debunked the speculations about hard turbulence. Some years later a group of physicists, with the lead of Srinivasan reported in Nature large scale experiments with liquid Nitrogen that agreed with our scaling laws and with our conclusions about hard turbulence.

The bottom line of all this is that we understand, both physically and quantitatively, volumetrically heated pools over the complete range of Ra, extending well beyond those of interest to nuclear technology. A key point is that the up-to-down power split, which is a principal quantity of interest to IVR as well as BiMAC is known quantitatively from properly scaled experiments.

This understanding and the quantitative aspects as reflected by the ACOPO experiment have been engendered in numerical simulations principally by work of Dr. T-N Dihn (a co-author of the SAT report), and also by workers at IBRAE as part of the RASPLAV program and its descendant programs. Early work demonstrated that eddy diffusivity based models cannot capture the anisotropy of turbulence in such flows—it varies with location and Ra. Instead it became clear that a no-turbulence-model (no sub-grid scale model utilized) Direct Numerical Simulation (DNS) approach captures naturally this anisotropy and is able to reproduce experimental results as demonstrated in the figures of Appendix D of SAT, and the papers cited therein. The specifics, in summary, are as follows:

We solve the Navier-Stokes equations, at high enough resolution (fine grids, no sub-grid scale model), under isothermal boundary conditions (all pool boundaries set at the melt liquidus), at third order spatial discretization. Each calculation is carried out long enough to reach quasi-steady state, and it is repeated with finer grids to show convergence at the large eddy simulation limit in which the computation is conducted. Moreover, we have carried out both in 2D and 3D simulations (these are rather computationally intensive), and showed that the 2D simulations are conservative in regards to the power split. Finally we showed (again as cited in Appendix D) that such numerical simulations can capture ab initio the onset of Rayleigh-Bernard convection, that is the self-organized pattern found in our experiments with the (fundamentally oriented) BETA facility.

DCD Impact

No DCD changes will be made in response to this RAI.

No changes to NEDO-33201 or NEDE-33392P will be made in response to this RAI.