November 19, 2004

MEMORANDUM TO: Carl J. Paperiello, Director
Office of Nuclear Regulatory Research

FROM: Jack E. Rosenthal, Chairman ***/RA/***
Generic Issue Review Panel
Office of Nuclear Regulatory Research

SUBJECT: RESULTS OF INITIAL SCREENING OF GENERIC ISSUE 196, "BORAL DEGRADATION"

In accordance with Management Directive (MD) 6.4, "Generic Issues Program," the Generic Issue Review Panel has completed the initial screening of Generic Issue (GI) 196, "Boral Degradation," and has concluded that the safety concern is a new generic safety issue (GSI). Boral is used as a neutron absorber in the long-term, dry storage casks for spent reactor fuel, and water intrusion into the Boral composite material could result in its chemical breakdown. This degradation of Boral could produce an inadvertent criticality, resulting in high neutron and fission gamma radiation fields which can be hazardous to personnel, unless adequate shielding is in place. Therefore, the panel recommends that work on GSI-196 continue to the technical assessment stage. Your approval of the panel's recommendations is required so that RES can proceed to the next step of the MD 6.4 process.

Attachments:
1. Summary of GI-196 Review Panel Meeting
2. GSI-196 Evaluation

Approved: ***/RA/*** Date: 11/19/2004
Carl J. Paperiello, Director, RES

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SUMMARY OF GI-196 REVIEW PANEL MEETING

MONDAY, JULY 26, 2004

Venue: T10-C02

Attendees (7):

Panel Members (5)
Jack Rosenthal, (SMSAB/DSARE/RES), Chairman
Richard B. Codell (NMSS/DWM/EPAB)
James Davis (RES/DET/MEB)
Kryzsztof Parczewski (NRR/DE/EMCB)
Christopher Ryder (NMSS/DWM/EPAB)

Others (2)
Harold J. Vandermolen (ARREB/DSARE/RES)
Ronald C. Emrit (ARREB/DSARE/RES)

The meeting to screen GI-196, "Boral Degradation," was called to order at 9:00 a.m. by Chairman *Jack Rosenthal*, and *Harold Vandermolen* proceeded to give a brief explanation of the MD 6.4 process which was being implemented with the convening of the panel. *Vandermolen* then began a step-by-step explanation of his analysis of the issue and invited questions as he proceeded. After the panel members agreed that the panel's decision should be based on a consensus of the five members, there was a general discussion of the safety implications of the issue.

Rosenthal began the discussion by asking NMSS panel members whether there was any guidance from NMSS risk-informed studies that would be helpful to the panel. He believed that the issue represented an unanalyzed event and that there were many casks involved. He expressed his concern for the reliance on the NRC institutional memory to maintain administrative controls and procedures. He firmly believed that the potential problem of boral degradation should not be left for future engineers to resolve.

Ryder stated that, although there had been a number of discussions between DOE and the NRC, DOE was not aware of any problem with Boral. However, he agreed that the issue presented an unanalyzed condition that needed to be addressed in the short term, rather than rely on the NRC institutional memory for future possible action.

Codell informed the panel that a number of calculations of various potential failure scenarios had been completed, but he remained concerned about the stability of boron carbide and whether there were any other cask failure modes. He believed that the NRC should look at the integrity of Boral for hundreds of years, and find ways of inspecting the casks before they are flooded. Any further work on the issue should include a consideration of all failure mechanisms, including water reacting with the casks, galvanic action, and loss of containment.

Davis, who had served on a Point Beach inspection team, gave the panel his insights of the inspection where the team found that hydrogen generated by spent fuel had raised the lid on a storage cask.

Parczewski believed that there was not enough information to reach a conclusion on the safety significance of the issue and more testing will be required. He informed the panel that the Boral manufacturer has efforts underway to improve the quality of Boral.

The panel unanimously agreed to accept the analysis and its conclusion that a technical assessment of the issue be pursued. The meeting was adjourned at 10:13 a.m.

ISSUE 196: BORAL DEGRADATION

DESCRIPTION

Historical Background

This issue was raised by a staff member, based on his experience in the Office of Nuclear Material Safety and Safeguards.[1854, 1855] The concern arose out of the observation that spent fuel pool racks using Boral for neutron absorption had experienced some problems with swelling and degradation of the Boral plates over long periods of time. Because the Boral material is commonly used for neutron absorption and shielding in a wide spectrum of applications, this degradation may have a number of implications for safety purposes. However, this issue specifically addresses the use of Boral in long-term dry storage casks for spent reactor fuel.

Safety Significance

Composition of Boral "Boral" is the trade name for a product of AAR Advanced Structures of Livonia, Michigan. Boral is a neutron absorber plate material which uses boron carbide for neutron absorption. One isotope of boron, specifically boron-10 (or ^{10}B), has a thermal neutron absorption cross section of over 3800 barns. Moreover, the nuclear reaction is unusual in that the resulting compound nucleus emits an alpha particle rather than de-exciting by gamma emission. Thus, unlike many other high cross section nuclides, boron-10 does not emit high energy secondary gammas, which (along with the high cross section) makes it an excellent shielding material. Consequently, Boral plate is widely used in many industrial, medical, and laboratory applications.

Boral is made by mixing boron carbide granules and aluminum powder inside an aluminum box, heating the box and its content to form an ingot, and then hot rolling the ingot to form a plate consisting of a coarse core of B_4C-Al composite material bonded between two thin sheets of aluminum cladding.

Experience with Boral One of the uses of Boral is in spent fuel pool racks. When the current generation of reactors was first built, spent fuel racks ensured subcriticality by using rack designs which kept the spent fuel assemblies widely separated. (The thermal neutron absorption cross section of the hydrogen in the water was sufficient to keep the array subcritical. In PWR pools, boric acid is dissolved in the water as well.) However, as more and more spent fuel was discharged into these pools, it was necessary to install new racks which held the spent fuel assemblies in a much more compact array. To ensure subcriticality, the new spent fuel racks incorporated Boral sheets between the fuel assemblies.

The Boral sheets were sandwiched (clad) within seal-welded stainless steel cover plates, apparently to keep water from contacting the Boral. Nevertheless, there were several instances (dating back to 1983) where the stainless steel cover plates experienced bulging, to the point where mechanical interference with the fuel assemblies became a problem. It was discovered upon investigation that there had been water ingress into the stainless steel sandwich, and the aluminum in the Boral had reacted chemically with the water to produce hydrogen gas and aluminum oxide. The hydrogen gas pressure had built up to the point where the stainless steel cladding bulged.

One fix was to clip the corners of the stainless steel cladding, allowing the hydrogen gas to escape. However, in follow-up investigations, it was found in some cases that the corrosion reactions resulted in a partial debonding of the Boral's aluminum cladding from the composite core absorber material, with some limited losses of B_4C granules and aluminum binder from the edges of the Boral plates.

A similar occurrence was discovered at an early generation BWR, where the spent fuel had been stored in the spent fuel pool since 1985. This plant had installed Boral cans around each fuel assembly, but without stainless steel cladding. It was discovered that there were blisters on about 5% of the Boral cans. The blisters were generally one inch in diameter or less, and tended to occur near the edge of the Boral sheet, where the internal composite core was in contact with the pool water.

Long-term dry spent fuel storage casks Calculations showed that the observed B_4C losses did not result in a significant loss of shutdown margin in spent fuel pools, and that is not the focus of this generic issue. Instead, the question involves the situation with long term dry spent fuel storage casks. To understand the safety significance, it is necessary to first review the cask design and intended use. For the purposes of this screening analysis, the Holtec[1856] design was used. (Other designs exist, with somewhat different capacities, etc., but the designs are rather similar, and the differences should not affect any conclusions.)

These casks are intended for spent fuel which has been out of the reactor and in the spent fuel pool for a long time. As time goes on, the inventories of the various radioactive species in a spent fuel assembly will decrease in accordance with the half-life of each nuclide. Decay heat production will slowly diminish, and after several years, will be low enough that liquid coolant is no longer necessary to keep the spent fuel from overheating. (It is still necessary for shielding, however.) The Holtec HI-STORM design uses a multipurpose cannister (MPC) which can hold many fuel assemblies. (The MPC-24 will hold 24 PWR fuel assemblies; the MPC-68 will hold 68 BWR fuel assemblies.) Each MPC design consists of a sealed metallic canister, and the external dimensions are the same regardless of the intended contents. Once loaded, the MPC is backfilled with helium and sealed. The MPC can be placed into either a HI-TRAC transfer cask or a HI-STORM storage "overpack." The transfer cask uses lead and a water jacket for shielding, whereas the storage overpack is intended for long-term storage, and uses plain concrete for shielding. Cooling is passive; the large storage overpack incorporates air ducts for natural convection cooling.

The MPC designs include "baskets" to hold fuel assemblies, heat conduction elements that help transfer heat to the MPC shell, and Boral sheets between the baskets to provide reactivity control. Criticality is a concern; these MPCs hold about one-third of a full core for a small reactor such as Yankee Rowe.

The Boral sheets are necessary when the MPC is being loaded with spent fuel. Once the MPC is removed from the spent fuel pool, drained, and seal-welded, the lack of water as a moderator makes criticality unlikely. The MPC can reside within the HI-STORM storage overpack for many years.

Safety Concern The HI-STORM dry storage system is designed for long term storage, but is not intended to be a permanent repository. Eventually, these MPC units will be transferred to transfer casks and shipped to a permanent repository. The criticality concern affects any MPC units that, years later, must be reopened for repairs of any kind. One scheme for doing so is to re-immerse the MPC in water for shielding, and perform the repair operations under water. Water immersion has several advantages, including shielding, a lower working temperature, a transparent medium, and some limiting of the spread of any contamination.

However, if the MPC is re-flooded with water, the Boral sheets again become necessary to ensure a subcritical configuration. When the MPC was first loaded with fuel, these Boral sheets will have been soaked in water, with some water ingress into the coarse B_4C-Al composite material within the aluminum cladding. (The edges of the sheet are not sealed; the composite material, which is porous, will be exposed to the water.) The vacuum drying is likely to leave some residual water within the composite core. During long-term storage, these sheets will then be subjected to temperatures on the order of 500EF for many years. This is a more severe environment than that experienced by Boral sheets immersed in the spent fuel pool, where blistering has been observed after several years in warm water. It is likely that steam blisters will form in the short term, and possibly hydrogen blisters in the long term.

Thus, if there is any problem with the integrity of the Boral sheet, it is possible that, under such conditions, the material may crumble or otherwise relocate in storage, or may be physically damaged when "quenched" by reflooding of the MPC. Moreover, the blistering will displace some of the water, which will affect reactivity somewhat even if the B_4C-Al composite material does not relocate.

It is possible to form a critical array with sixteen to twenty fresh BWR fuel assemblies in cold clean water (NUREG-75/110, pp. 4-14).[1857] PWR assemblies, which are generally equivalent to four BWR assemblies each, would be expected to approach criticality with a commensurately smaller number. Of course, the fuel stored within the MPC will be, except in a few cases, fuel with significant burnup. Nevertheless, this spent fuel was still capable of producing some power (with equilibrium xenon and at reactor temperatures) before it was discharged. (Equilibrium xenon is typically worth 2.5% to 3% $\Delta K/K$, and the moderator and Doppler defects are generally worth 3% to 4% in addition.)

Thus, although this spent fuel is not likely to achieve high power levels, it is quite credible that reflooding an MPC unit will result in an inadvertent criticality if the Boral neutron absorber is not present. Such an event might not damage the fuel cladding, but it would certainly produce high neutron and fission gamma radiation fields, which can be quite hazardous to personnel unless adequate shielding is in place.

There are two other aspects to such an inadvertent criticality event. First, there will not be any "scram" system or similar safety system available to rapidly insert negative reactivity, and it may not be immediately obvious to the personnel what should be done to terminate the event.

Second, the existing neutron flux from transuranics in the spent fuel may not be high enough to ensure a controlled startup. This can lead to a classic criticality accident, where a critical configuration is achieved, but nothing happens because there are not enough neutrons to start the chain reaction. Then, as the evolution continues, the configuration might be significantly supercritical before the reaction starts, and when it does start, neutron flux will escalate with a very fast period, leading to a very hazardous situation.

Possible Solution

The proposed solution for this generic issue is in two steps. The first step would be to test samples of Boral under conditions duplicating the environmental conditions that would be experienced in these MPC units. This experiment can be done quite readily, and at a modest cost. If there is no evidence for crumbling or relocation of the B_4C-Al composite material, the issue would be considered resolved.

However, if the experimental evidence indicates that relocation of the B_4C-Al composite material is credible, the second step would be to ensure that these MPC units either are repaired under dry conditions, or that the water used in submerged operations contain a soluble neutron absorber such as boric acid (or some other means be used for reactivity control).

Alternatively, it is the staff's understanding that the manufacturer has been conducting research to find ways to improve the performance of Boral. This also could resolve the issue.

PRIORITY DETERMINATION

Screening Criteria

The usual criteria for screening generic issues, specifically core damage frequency, large early release frequency, and person-rem per reactor-year, are not applicable to this issue. However, there are some statements in the regulations that address accidental criticalities.

10CFR72, Part 72.124, "Criteria for nuclear criticality safety," states, in part:

> (a) *Design for criticality safety.* Spent fuel handling, packaging, transfer, and storage systems must be designed to be maintained subcritical and to ensure that, before a nuclear criticality accident is possible, at least two unlikely, independent, and concurrent or sequential changes have occurred in the conditions essential to nuclear criticality safety.

10CFR72, Part 72.236, "Specific requirements for spent fuel storage cask approval and fabrication," goes on to say:

> (c) The spent fuel storage cask must be designed and fabricated so that the spent fuel is maintained in a subcritical condition under credible conditions.

It also states:

> (h) The spent fuel storage cask must be compatible with wet or dry spent fuel loading and unloading facilities.

The essence of these statements is that an accidental criticality is not to occur, i.e., the probability of such an event should be low. For the purpose of this screening analysis, and in the absence of any formal guidance, a probability of 0.1 of an inadvertent criticality event will be used as a screening threshold.

Frequency Estimate

It is not possible to perform a probabilistic analysis in the usual sense, since there is no data upon which to base the analysis. Nevertheless, it is possible to have some qualitative probabilistic insights into the likelihood of such an event.

The central question of this generic issue is, will there be extensive blistering and degradation of the Boral sheets? If the blistering is extensive, it is quite likely that, in at least some of the MPCs, there will be an axial location where there is insufficient boron absorption to maintain a subcritical condition. It will be assumed that at least one MPC in 100 will be damaged to the extent that an inadvertent criticality is possible if the MPC is refilled with water. This is, of course, an educated guess. However, if blistering is this extensive, it should be detectable by a few experiments.

At the time of writing of this analysis, there are approximately 117 reactors with spent fuel pools, twelve of which are no longer operating. A simple tabulation was used to estimate the number of MPC units needed for this entire population, assuming a 40-year lifetime (or the actual lifetime for the shutdown units), a 1.5 year fuel cycle, a third core replacement for each fuel cycle, and the Holtec design of 68 BWR fuel assemblies per MPC, or 24 PWR assemblies per MPC. The result was an estimate of 8,783 MPC units. If a 20-year license extension is assumed for the units not already shut down, this number increases to 12,850 MPC units.

Based on this, it is reasonable to assume that the total number of MPCs needed to accommodate the present generation of power reactors is on the order of 10^4 units.

For an inadvertent criticality event to occur, two events must happen. First, the Boral sheets in an MPC unit must be damaged to the point where criticality becomes possible. Second, this same MPC unit must be flooded with water for repair.

Based purely on engineering judgment, it is hoped that less than 1% of the MPCs will need to be opened and reflooded for any reason. However, as a practical matter, it is doubtful that this number of MPCs which must be opened will be less that one per thousand, based on general engineering experience. For now, it will be assumed that the number opened will be at least one per thousand, the lower limit.

Putting these figures together, with a population of 10,000 MPC units, and assumptions that at least one unit per thousand will be opened underwater for repair (or any other reason), and at least one per hundred will be damaged to the point where criticality is possible, the total number of criticality incidents will be at least 0.1.

The probability of at least one criticality is then given by the Poisson formula:

$$P(n \geq 1) = 1 - e^{-x}$$

where x is the expected number of criticalities. If x, the expectation value, is 0.1 or greater, the probability of at least one event is 0.095 (essentially equal to the expectation value) or greater. Thus, under these assumptions, this generic issue meets the screening criterion described earlier.

Other Considerations

The semi-quantitative estimate developed above assumes that the likelihood of opening the MPC underwater, and the likelihood of damage such that criticality is possible, are independent. This may not be completely true. For example, if an MPC unit were involved in a transportation accident of any kind, the robustness of the MPC and its transfer cask would preclude any release of radioactive material to the surroundings. However, the physical assault might cause relocation of the B_4C-Al composite material, and also increase the likelihood of the MPC being opened for inspection. This would tend to increase the probability of an accidental criticality above that estimated by the assumption of randomness above.

CONCLUSION

Based on the likelihood of an accidental criticality described above, and on the relatively modest resources needed for resolution, it is recommended that this generic issue continue to the technical assessment stage.

REFERENCES

1854. Memorandum to F. Eltawila from D. Carlson, “Proposed Generic Safety Issue: Boral Degradation,” November 4, 2003. [ML033090600]

1855. Memorandum to D. E. Carlson from F. Eltawila, “Generic Issue 196: Boral Degradation,” November 10, 2003, [ML033160580]

1856. “Final Safety Analysis Report for the Holtec International Storage and Transfer Operation Reinforced Module Cask System (HI-STORM Cask System),” Docket 72-1014, July 19, 2000. [ML003777866]

1857. NUREG-75/110, “Safety Evaluation Report for Preliminary Design Approval for GESSAR-238 - Nuclear Island Standard Design,” U.S. Nuclear Regulatory Commission, December 1975.