Amd 11 RAI Supplemental Information

RAI 8-1 Supplement

As discussed in Chapters 1 and 2, and Section 3.0 of the FSAR, the primary function of the plain concrete in the HI-STORM overpack is shielding against gamma and neutron radiation. Concrete in the HI-STORM 100 overpack is considered as a structural member only for missile impact evaluations. Supplements 15 and 25 of HI-2012769 (previously submitted with Holtec Letter 5014827) were revised to consider a 50% reduction in concrete compressive strength to account for degradation in strength when exposed to elevated temperatures caused by the scenarios listed below.

1. During and after 30-day 100% vent blockage accident with a maximum local temperature of 450°F.
2. After governing 32-hour 100% vent blockage accident with a maximum local temperature of 572°F (when the concrete returns to the normal condition temperatures after 32 hours).

In the event of 30-day 100% vent blockage condition, thermal degradation mechanisms of concrete are identified as follows.

Creep
Creep is defined as an increase in strain with time under a constant stress. When concrete is subjected to a low uniaxial load, it initially deforms elastically and then creeps if the load is sustained. The mechanism of creep in concrete is believed to be mainly due to the deformation of the cement gel and the diffusion of absorbed moisture. At room temperature, the primary factors influencing the development of creep in concrete structures are the type of aggregates and the water/cement ratio. Similar to other solids, the creep in concrete increases with temperature. It is caused by the diffusion of solid particles and moisture into the gaps of the material [4].

Creep in concrete is a function of the evaporable water and reduces to zero when no evaporable water is present. As mentioned earlier, the principal loading on concrete is self-weight of the concrete columns that results in a non-challenging bearing stress. Hence, creep under this low state of stress is not credible for HI-STORM systems.

Shrinkage
Shrinkage in concrete occurs because of drying and autogenous volume change. High shrinkage occurs when the bulk of the capillary-held water in the concrete mix is lost. The magnitude of shrinkage generally increases with a temperature rise and the process is usually completed when the temperature reaches the level of about 105°C (221°F) ([1], [4]). Any further rise in temperature does not increase the shrinkage in concrete by significant amounts as compared to room temperature.

Coefficient of Thermal Expansion (CTE)
The mean CTE represents the change in length per unit length per degree of temperature change in going from ambient to the indicated temperature. In concrete, the magnitude of the coefficient is

influenced by the type of aggregates and moisture condition. The use of an aggregate with low thermal expansion significantly reduces the thermal stress in concrete due to elevated temperature. The CTE remains approximately constant through a rise in temperature up to 300°C (572°F) and increases with further rise in temperature [4]. For typical concrete material used in HI-STORM systems, the aggregate minimum value of CTE is 6.0E-06 in/in/°F [5]. A relatively lower value of CTE means lower induced thermal stress and strain. As the maximum local temperature (See Table 4.6.9) experienced by concrete during the 30-day vent blockage event is within this stable CTE temperature range, the concrete remains in a state of low stress. Hence, micro-cracking due to a difference in CTE between the aggregate and cement paste is not a concern in the event of 30-day vent blockage event.

Thermal Cycling

Thermal cycling causes progressive degradation of concrete compressive strength. Most of the damage occurs during the initial stage. Progressive deterioration of the mechanical characteristics with an increasing number of cycles is observed in concrete. At higher temperatures, most of the damage is caused in the first thermal cycle and is usually associated with a loss of bond between the aggregates and the matrix. In concrete exposed to 300°C (572°F), a reduction of about 45% in compressive strength was observed after the first cycle and an insignificant reduction was observed after 20 cycles at the same temperature ([2] and [4]). As noted above, the compressive strength of concrete is conservatively reduced by 50% in tornado borne missile impact analyses (Supplements 15 and 25 of [3]). The evaluations in [3] conclude that the concrete in overpack, post 50% strength reduction, is acceptable during and after the 30-day vent blockage accident, and during the long term normal condition.

Spalling

Spalling is defined as the breaking up of layers of concrete from the surface when it is exposed to high and rapidly rising temperatures along with a build-up of pore pressure. Typically, spalling of normal concrete, used in HI-STORM overpacks, occurs due to rapid increase in temperature by 20° - 32°C/min ([6] and [8]), and spalling in high strength concrete occurs at a relatively low heating rate (5°C/min [7]) due to its lower permeability. Based on the thermal evaluations presented in FSAR Section 4.6 for 100% vent blockage at design basis maximum heat load, the rate of temperature rise with time is significantly less than 5°C/min. The critical temperature range for spalling to occur in an exposed concrete surface is 375°C - 425°C for normal weight concretes [8]. As mentioned earlier, the maximum local temperature experienced by concrete is well below spalling threshold. It is also noted that high strength concretes are more susceptible to spalling. The strength of the confined concrete used in HI-STORM overpack is 3300 psi minimum which may increase up to 5000 psi after curing and settling. Hence, spalling of overpack concrete is not credible during the 30-day vent blockage event or other design basis off-normal and accident events.

Dehydration

Exposure of concrete to elevated temperatures can affect its properties due to the dehydration or loss of absorbed and chemically combined water. Concretes below the temperature of 200°C (392°F) show small changes in compressive strength [1]. Per Carette et al. [2], approximately 45% reduction in compressive strength and about 5% reduction in weight is observed in limestone concrete (water to cement ratio, w/c = 0.33) exposed for one month at 300°C (572°F). The calculated maximum local temperature during the 30-day vent blockage accident (See Table 4.6.9) is significantly below this value.

The reduction in shielding with rise in temperature of the concrete and the surrounding SSCs is primarily due to vaporization of volatiles, including the contained water present in the concrete. Water and hydrogen is present in the concrete in two forms, chemically bound water/hydrogen, and physically bound water. Both forms are discussed below and a comparison with the concrete composition used in the analysis is performed.

Chemically bound water

The chemically bound water is present in calcium-silicate-hydrate (C-S-H) and Calcium Hydroxide and both are the products of the reaction of cement with water. Typical reaction is shown below.

$$2\,Ca_3SiO_5 + 7\,H_2O \longrightarrow 3\,CaO \cdot 2\,SiO_2 \cdot 4\,H_2O + 3\,Ca(OH)_2 + 173.6\text{ kJ}$$

Based on the reaction, the content of hydrogen in the final composition is calculated to be about 2.4 wt%. It should be noted that the hydrogen content value is for the cement and water mixture (gel). The overall concrete mixture is shown to be approximately one third cement and water, and two third aggregate [9]. Assuming the aggregate is completely dry, this would lead to a final content of hydrogen of about 0.8 wt%.

Also discussed in [9] are the decomposition reactions of the cement and water mixture. Based on the DTA/TG results shown, calcium hydroxide dissociates at around 530°C, and the dehydration of the C-S-H occurs around 740°C. Both the temperatures are well above the temperature of 300°C (572°F) which is the local temperature limit expected under the accident or transient conditions in the HI-STORM. Consequently, it would not be expected for the hydrogen content to drop below about 0.8 wt%, at 300°C (572°F), which is from chemically bound water and hydrogen.

Physically bound water

Physically bound water is present from excess water provided for the cement and water reaction, and also from any water included in the aggregate. The DTA/TG curve in [9] indicates a loss of physically bound water of about 6% from the cement and water mixture. After considering that cement and water is only about one third of the weight of the final concrete, this equates to about 2 wt%. The aggregate itself may also contain water, with values listed in [9] between 0.55 and 2.56 wt%. Hence, the overall the amount of physically bound water may approximately be 5 wt%. This would be equivalent to about 0.6 wt% hydrogen.

Based on the above analyses from chemically and physically bound water, the total amount of hydrogen in concrete would be expected to be in the order of 1.4 wt%, but no less than 0.8 wt%.

Concrete composition used for the HI-STORM system

The concrete composition used for the shielding analyses for the HI-STORM system is listed in Table 5.3.2 of the HI-STORM 100 FSAR. The assumed hydrogen content is 0.6 wt%. This is below the expected content listed above (below the content of the chemically bound hydrogen as well). Therefore, the hydrogen content in concrete composition is extremely conservative, as it assumes that no physically bound water is present. The maximum local temperature experienced by concrete is computed in FSAR Table 4.6.9. Per [9], as the chemically bound water or hydrogen will only be released at temperatures well above temperatures listed in Table 4.6.9, the proposed conditions are conservatively bounded by the HI-STORM concrete composition.

Dose rate effects

Holtec has performed analyses to determine the dose rates from HI-STORM in a hypothetical 100% duct blockage and extreme ambient temperature accident condition with duration of 30 days. The effect of hydrogen and water loss on the shielding performance of the concrete used in HI-STORM was evaluated and it was assumed that entire hydrogen and partial oxygen is lost from the affected region of concrete. This is an excessively conservative estimate of an upper bound dose rate effect. However, analyses [10] demonstrate that the hypothetical HI-STORM 100% duct blockage accident condition is bounded by the HI-TRAC accident condition discussed in Section 5.1.2 of the HI-STORM 100 FSAR [5].

Compressive Strength Impacts

To address a postulated accident that may occur during the 30-day vent blockage condition, a tornado borne missile impact for example, the compressive strength of the concrete is conservatively reduced by 50% even though the maximum temperature experienced by concrete during 30-day vent blockage accident is less than 450°F and is about 300°F during long term normal condition. The tornado missile impact analyses (Supplements 15 and 25 of HI-2012769 [3]) are revised to use the 50% reduction in concrete compressive strength. The evaluations in [3] conclude that the concrete in overpack, post 50% strength reduction, is acceptable during and after the 30-day vent blockage accident, and during the long term normal condition.

References

[1] Managing Aging Processes in Storage (MAPS) Report, Draft report, USNRC.

[2] Carette and Malhotra, “Performance of Dolostone and Limestone Concretes at Sustained High Temperatures” Temperature Effects on Concrete, ASTM STP 858, 1985, pages 38-67.

[3] Holtec Report HI-2012769, Revision 16. (Submitted with Holtec Letter 5014827)

[4] Kassir, Bandyopadhyay and Reich, “Thermal Degradation of Concrete in the Temperature Range from Ambient to 315°C (600°F)”, 1996.

[5] HI-STORM 100 FSAR

[6] Khoury, "Effect of Fire on Concrete and Concrete Structures" Progress in Structural Engineering and Materials 2(4): 429-447 and Khoury and Anderberg, "Concrete Spalling Review" Fire Safety Design 2000.

[7] Phan, Lawson and Davis, "Effect of Elevated Temperature Exposure on Heating Characteristics, Spalling, and Residual Properties of High Performance Concrete" Materials and Structures (RILEM), 83-91 2001.

[8] Deeny et al., "Spalling of Concrete: Implications for Structural Performance in Fire" 2013.

[9] Arioz O, “Effects of Elevated Temperatures on Properties of Concrete”, Fire Safety Manual, Vol 42, 2007.

[10] Holtec Report HI-2033074, Revision 8.

RAI 8-3 Supplement on Metamic-HT Fracture Toughness

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