4.6 OFF-NORMAL AND ACCIDENT EVENTS[1]

In accordance with NUREG 1536 the HI-STORM 100 System is evaluated for the effects of off-normal and accident events. The design basis off-normal and accident events are defined in Chapter 2. For each event, the cause of the event, means of detection, consequences, and corrective actions are discussed and evaluated in Chapter 11. To support the Chapter 11 evaluations, thermal analyses of limiting off-normal and accident events are provided in the following.

To ensure a bounding evaluation for the array of fuel storage configurations permitted in Section 2.1, a limiting storage condition is evaluated in this section. The limiting storage condition is previously determined in the Section 4.5 and adopted herein for all off-normal and accident evaluations.

4.6.1 Off-Normal Events

4.6.1.1 Off-Normal Pressure

This event is defined as a combination of (a) maximum helium backfill pressure (Table 4.4.12), (b) 10% fuel rods rupture, and (c) limiting fuel storage configuration. The principal objective of the analysis is to demonstrate that the MPC off-normal design pressure (Table 2.2.1) is not exceeded. The MPC off-normal pressures are reported in Table 4.4.9. The result[2] *is confirmed to be below the off-normal design pressure (Table 2.2.1).*

4.6.1.2 Off-Normal Environmental Temperature

This event is defined by a time averaged ambient temperature of 100^{o}F for a 3-day period (Table 2.2.2). The consequences of this event are bounded by the "Off-Normal Pressure" event evaluated earlier in this subsection.

4.6.1.3 Partial Blockage of Air Inlets

The HI-STORM 100 System is designed with debris screens installed on the inlet and outlet openings. These screens ensure the air passages are protected from entry and blockage by foreign objects. As required by the design criteria presented in Chapter 2, it is postulated that two of the four air inlet ducts in the aboveground HI-STORM overpack are blocked. The resulting decrease in flow area increases the flow resistance of the inlet ducts. The effect of the increased flow resistance on fuel temperature is analyzed for the normal ambient temperature (Table 2.2.2) and a limiting fuel storage configuration. The computed temperatures are reported in Table 4.6.1 and the

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1 *A new standalone Section 4.6 is added in CoC Amendment 3 to address thermal analysis of off-normal and accident events. The results are evaluated in Chapter 11.*

2 *Pressures relative to 1 atm absolute pressure (i.e. gauge pressures) are reported throughout this section.*

corresponding MPC internal pressure in Table 4.6.2. The results are confirmed to be below the temperature limits (Table 2.2.3) and pressure limit (Table 2.2.1) for off-normal conditions.

4.6.2 Accident Events

4.6.2.1 Fire Accidents

Although the probability of a fire accident affecting a HI-STORM 100 System during storage operations is low due to the lack of combustible materials at an ISFSI, a conservative fire event has been assumed and analyzed. The only credible concern is a fire from an on-site transport vehicle fuel tank. Under a postulated fuel tank fire, the outer layers of HI-TRAC or HI-STORM overpacks are heated for the duration of fire by the incident thermal radiation and forced convection heat fluxes. The amount of fuel in the on-site transporter is limited to a volume of 50 gallons.

(a) HI-STORM Fire

The fuel tank fire is conservatively assumed to surround the HI-STORM Overpack. Accordingly, all exposed overpack surfaces are heated by radiation and convection heat transfer from the fire. Based on NUREG-1536 and 10 CFR 71 guidelines [4.6.1], the following fire parameters are assumed:

1. *The average emissivity coefficient must be at least 0.9. During the entire duration of the fire, the painted outer surfaces of the overpack are assumed to remain intact, with an emissivity of 0.85. It is conservative to assume that the flame emissivity is 1.0, the limiting maximum value corresponding to a perfect blackbody emitter. With a flame emissivity conservatively assumed to be 1.0 and a painted surface emissivity of 0.85, the effective emissivity coefficient is 0.85. Because the minimum required value of 0.9 is greater than the actual value of 0.85, use of an average emissivity coefficient of 0.9 is conservative.*

2. *The average flame temperature must be at least 1475°F (800°C). Open pool fires typically involve the entrainment of large amounts of air, resulting in lower average flame temperatures. Additionally, the same temperature is applied to all exposed cask surfaces, which is very conservative considering the size of the HI-STORM cask. It is therefore conservative to use the 1475°F (800^{o}C) temperature.*

3. *The fuel source must extend horizontally at least 1 m (40 in), but may not extend more than 3 m (10 ft), beyond the external surface of the cask. Use of the minimum ring width of 1 meter yields a deeper pool for a fixed quantity of combustible fuel, thereby conservatively maximizing the fire duration.*

4. *The convection coefficient must be that value which may be demonstrated to exist if the cask were exposed to the fire specified. Based upon results of large pool fire thermal measurements [4.6.2], a conservative forced convection heat transfer coefficient of 4.5 Btu/(hr$\times$ft^2$\times$°F) is applied to exposed overpack surfaces during the short-duration fire.*

Based on the 50 gallon fuel volume, the overpack outer diameter and the 1 m fuel ring width [4.6.1], the fuel ring surrounding the overpack covers 147.6 ft^2 and has a depth of 0.54 in. From this depth and a constant fuel consumption rate of 0.15 in/min, the fire duration is calculated to be 3.62 minutes. The fuel consumption rate of 0.15 in/min is a lowerbound value from a Sandia National Laboratories report [4.6.2]. Use of a lowerbound fuel consumption rate conservatively maximizes the duration of the fire.

To evaluate the impact of fire heating of the overpack, a two-dimensional, axisymmetric model of the overpack cylinder was developed with an initial temperature corresponding to normal storage conditions and design heat load. In this model the outer surface and top surface of the overpack were subjected for the duration of fire (3.62 minutes) to the fire conditions defined in this subsection. In the post-fire phase, the overpack cools to an ambient temperature preceding the fire. The transient study is conducted for a period of 5 hours, which is sufficient to allow temperatures in the overpack to reach their maximum values and begin to recede.

Due to the severity of the fire condition radiative heat flux, heat flux from incident solar radiation is negligible and is not included. Furthermore, the smoke plume from the fire would block most of the solar radiation. It is recognized that the ventilation air in contact with the inner surface of the HI-STORM Overpack with design-basis decay heat and normal ambient temperature conditions varies between 80°F at the bottom and 220°F at the top of the overpack. It is further recognized that the inlet and outlet ducts occupy a miniscule fraction of area of the cylindrical surface of the massive HI-STORM Overpack. Due to the short duration of the fire event and the relative isolation of the ventilation passages from the outside environment, the ventilation air is expected to experience little intrusion of the fire combustion products. As a result of these considerations, it is conservative to assume that the air in the HI-STORM Overpack ventilation passages is held constant at a substantially elevated temperature (300°F) during the entire duration of the fire event.

The thermal transient response of the storage overpack is determined using the ANSYS finite element program. Time-histories for points in the storage overpack are monitored for the duration of the fire and the subsequent post-fire equilibrium phase.

Heat input to the HI-STORM Overpack while it is subjected to the fire is from a combination of an incident radiation and convective heat fluxes to all external surfaces. This can be expressed by the following equation:

$$q_F = h_{fc}(T_A - T_S) + \sigma\varepsilon[(T_A + C)^4 - (T_S + C)^4]$$

where:

q_F *=Surface Heat Input Flux (Btu/ft²-hr)*
h_{fc} *= Forced Convection Heat Transfer Coefficient (4.5 Btu/ft²-hr-°F)*
σ *= Stefan-Boltzmann Constant*
T_A *= Fire Temperature (1475°F)*
C= Conversion Constant (460 (°F to °R))
T_S *= Surface Temperature (°F)*

ε = Average Emissivity (0.90 per 10 CFR 71.73)

The forced convection heat transfer coefficient is based on the results of large pool fire thermal measurements [4.6.2].

After the fire event, the ambient temperature is restored and the storage overpack cools down (post-fire temperature relaxation). Heat loss from the outer surfaces of the storage overpack is determined by the following equation:

$$q_S = h_S (T_S - T_A) + \sigma\varepsilon [(T_S + C)^4 - (T_A + C)^4]$$

where:

q_S *=Surface Heat Loss Flux (W/m^2 (Btu/ft^2-hr))*
h_S *= Natural Convection Heat Transfer Coefficient (Btu/ft^2-hr-^{o}F)*
T_S *= Surface Temperature (^{o}F))*
T_A *= Ambient Temperature (^{o}F)*
σ *= Stefan-Boltzmann Constant*
ε = Surface Emissivity
C= Conversion Constant (460 (^{o}F to ^{o}R))

In the post-fire temperature relaxation phase, h_s is obtained using literature correlations for natural convection heat transfer from heated surfaces [4.2.9].

During the fire the overpack external shell temperatures are substantially elevated (~550^{o}F) and an outer layer of concrete approximately 1 inch thick reaches temperatures in excess of short term temperature limit. This condition is addressed specifically in NUREG-1536 (4.0,V,5.b), which states that:

> *"The NRC accepts that concrete temperatures may exceed the temperature criteria of ACI 349 for accidents if the temperatures result from a fire."*

These results demonstrate that the fire accident event analyzed in a most conservative manner is determined to have a minor affect on the HI-STORM Overpack. Localized regions of concrete are exposed to temperatures in excess of accident temperature limit. The bulk of concrete remains below the short term temperature limit. The temperatures of steel structures are within the allowable temperature limits.

Having evaluated the effects of the fire on the overpack, we now evaluate the effects on the MPC and contained fuel assemblies. Guidance for the evaluation of the MPC and its internals during a fire event is provided by NUREG-1536 (4.0,V,5.b), which states:

> *"For a fire of very short duration (i.e., less than 10 percent of the thermal time constant of the cask body), the NRC finds it acceptable to calculate the fuel temperature increase by assuming that the cask inner wall is adiabatic. The fuel*

temperature increase should then be determined by dividing the decay energy released during the fire by the thermal capacity of the basket-fuel assembly combination."

The time constant of the cask body (i.e., the overpack) can be determined using the formula:

$$\tau = \frac{c_p \times \rho \times L_c^2}{k}$$

where:

c_p *= Overpack Specific Heat Capacity (Btu/lb-^{o}F)*
ρ *= Overpack Density (lb/ft^3)*
L_c *= Overpack Characteristic Length (ft)*
k *= Overpack Thermal Conductivity (Btu/ft-hr-^{o}F)*

The concrete contributes the majority of the overpack mass and volume, so we will use the specific heat capacity (0.156 Btu/lb-^{o}F), density (142 lb/ft^3) and thermal conductivity (1.05 Btu/ft-hr-^{o}F) of concrete for the time constant calculation. The characteristic length of a hollow cylinder is its wall thickness. The characteristic length for the HI-STORM Overpack is therefore 29.5 in, or approximately 2.46 ft. Substituting into the equation, the overpack time constant is determined as:

$$\tau = \frac{0.156 \times 142 \times 2.46^2}{1.05} = 128\, hrs$$

One-tenth of this time constant is approximately 12.8 hours (768 minutes), substantially longer than the fire duration of 3.62 minutes, so the MPC is evaluated by considering the MPC canister as an adiabatic boundary. The fuel temperature rise is computed next.

Table 4.5.2 lists lower-bound thermal inertia values for the MPC and the contained fuel assemblies. Applying a conservative upperbound decay heat load (38 kW (1.3x10^5 Btu/hr)) and adiabatic heating for the 3.62 minutes fire, the fuel temperature rise computes as:

$$\Delta T_{fuel} = \frac{\text{Decay heat} \times \text{Time duration}}{\text{(MPC + Fuel) heat capacities}} = \frac{1.3 \times 10^5 \text{ Btu/hr} \times (3.62/60) hr}{(2240 + 4680) \text{ Btu/}^o F} = 1.1^\circ F$$

This is a very small increase in fuel temperature. Consequently, the impact on the MPC internal helium pressure will be quite small. Based on a conservative analysis of the HI-STORM 100 System response to a hypothetical fire event, it is concluded that the fire event does not adversely affect the temperature of the MPC or contained fuel. We conclude that the ability of the HI-STORM 100 System to cool the spent nuclear fuel within design temperature limits during and after fire is not compromised.

(b) HI-TRAC Fire

In this subsection the fuel cladding and MPC pressure boundary integrity under an exposure to a short duration fire event is demonstrated. The HI-TRAC is initially (before fire) assumed to have a design basis decay heat and has reached steady-state (maximum) temperatures. The analysis assumes a fire from a 50 gallon transporter fuel tank spill. The fuel spill is assumed to surround the HI-TRAC in a 1 m wide ring. The fire parameters are same as that assumed for the HI-STORM fire. Based on the fuel spill defined above the HI-TRAC fire duration is computed as 4.8 minutes.

From the HI-TRAC fire analysis, a bounding MPC temperature rise rate is determined. The total temperature rise (ΔT) is obtained by the product of the rate of temperature rise and fire duration reported above. In this manner the final MPC (fuel and MPC contents) temperature is computed. The MPC pressures are also computed using the MPC temperature rise (ΔT) and Ideal Gas Law. The temperatures and pressures are reported in Table 4.6.7. The results are confirmed to be below the accident temperature and pressure limits (Tables 2.2.3 and 2.2.1).

4.6.2.2 Jacket Water Loss

In this subsection, the fuel cladding and MPC boundary integrity is evaluated for a postulated loss of water from the HI-TRAC water jacket. The HI-TRAC is equipped with an array of water compartments filled with water. For a bounding analysis, all water compartments are assumed to lose their water and be replaced with air. As an additional measure of conservatism, the air in the water jacket is assumed to be motionless (i.e. natural convection neglected) and radiation heat transfer in the water jacket spaces ignored. The HI-TRAC is assumed to have the maximum thermal payload (design heat load) and assumed to have reached steady state (maximum) temperatures. Under these assumed set of adverse conditions, the maximum temperatures are computed and reported in Table 4.6.3. The results of jacket water loss evaluation confirm that the cladding, MPC and HI-TRAC component temperatures are below the limits prescribed in Chapter 2 (Table 2.2.3). The co-incident MPC pressure is also computed and compared with the MPC accident design pressure (Table 2.2.1). The result (Table 4.6.2) is confirmed to be below the limit.

4.6.2.3 Extreme Environmental Temperatures

To evaluate the effect of extreme weather conditions, an extreme ambient temperature (Table 2.2.2) is postulated to persist for a 3-day period. For a conservatively bounding evaluation the extreme temperature is assumed to last for a sufficient duration to allow the HI-STORM 100 System to reach steady state conditions. Because of the large mass of the HI-STORM 100 System, with its corresponding large thermal inertia and the limited duration for the extreme temperature, this assumption is conservative. Starting from a baseline condition evaluated in Section 4.4 (normal ambient temperature and limiting fuel storage configuration) the temperatures of the HI-STORM 100 System are conservatively assumed to rise by the difference between the extreme and normal ambient temperatures (45^oF). The HI-STORM extreme ambient temperatures computed in this manner are reported in Table 4.6.4. The co-incident MPC pressure is also computed (Table 4.6.2) *and compared with the accident design pressure (Table 2.2.1). The result is confirmed to be below the accident limit.*

4.6.2.4 <u>100% Blockage of Air Inlets</u>

This event is defined as a complete blockage of all four bottom inlets. The immediate consequence of a complete blockage of the air inlets is that the normal circulation of air for cooling the MPC is stopped. An amount of heat will continue to be removed by localized air circulation patterns in the overpack annulus and outlet ducts, and the MPC will continue to radiate heat to the relatively cooler storage overpack. As the temperatures of the MPC and its contents rise, the rate of heat rejection will increase correspondingly. Under this condition, the temperatures of the overpack, the MPC and the stored fuel assemblies will rise as a function of time.

As a result of the considerable inertia of the storage overpack, a significant temperature rise is possible if the inlets are substantially blocked for extended durations. This accident condition is, however, a short duration event that is identified and corrected through scheduled periodic surveillance. Nevertheless, this event is conservatively analyzed assuming a substantial duration of blockage. The event is analyzed using the FLUENT CFD code. The CFD model is the same as that constructed for normal storage conditions (see Section 4.4) except for the bottom inlet ducts, which are assumed to be impervious to air. Using this model, a transient thermal solution of the HI-STORM 100 System starting from normal storage conditions is obtained. The results of the blocked ducts transient analysis are presented in Table 4.6.5 and confirmed to be below the accident temperature limits (Table 2.2.3). The co-incident MPC pressure is also computed and compared with the accident design pressure (Table 2.2.1). The result (Table 4.6.2) is confirmed to be below the limit.

4.6.2.5 <u>Burial Under Debris</u>

Burial of the HI-STORM 100 System under debris is not a credible accident. During storage at the ISFSI there are no structures over the casks. Minimum regulatory distances from the ISFSI to the nearest ISFSI security fence precludes the close proximity of substantial amount of vegetation. There is no credible mechanism for the HI-STORM 100 System to become completely buried under debris. However, for conservatism, complete burial under debris is considered.

To demonstrate the inherent safety of the HI-STORM 100 System, a bounding analysis that considers the debris to act as a perfect insulator is considered. Under this scenario, the contents of the HI-STORM 100 System will undergo a transient heat up under adiabatic conditions. The minimum available time ($\Delta\tau$) for the fuel cladding to reach the accident limit depends on the following: (i) thermal inertia of the cask, (ii) the cask initial conditions, (iii) the spent nuclear fuel decay heat generation and (iv) the margin between the initial cladding temperature and the accident temperature limit. To obtain a lowerbound on $\Delta\tau$, the HI-STORM 100 Overpack thermal inertia (item i) is understated, the cask initial temperature (item ii) is maximized, decay heat overstated (item iii) and the cladding temperature margin (item iv) is understated. A set of conservatively *postulated input parameters for items (i) through (iv) are summarized in Table 4.6.6. Using these parameters $\Delta\tau$ is computed as follows:*

$$\Delta \tau = \frac{m \times c_p \times \Delta T}{Q}$$

where:

$\Delta\tau$ = *Allowable burial time (hr)*
m = *Mass of HI-STORM System (lb)*
c_p = *Specific heat capacity (Btu/lb-^oF)*
ΔT = *Permissible temperature rise (^oF)*
Q = *Decay heat load (Btu/hr)*

Substituting the parameters in Table 4.6.6, a substantial burial time (34.6 hrs) is obtained. The co-incident MPC pressure is also computed and compared with the accident design pressure (Table 2.2.1). The result (Table 4.6.2) is confirmed to be below the limit.

Table 4.6.1

OFF-NORMAL CONDITION MAXIMUM HI-STORM TEMPERATURES[3]

Location[4]	***Off-Normal Ambient Temperature***[5] ***(^oF)***	***Partial Inlet Ducts Blockage (^oF)***
Fuel Cladding	731	*751*
MPC Basket	728	*734*
MPC Shell	489	*514*
Overpack Inner Shell	342	*386*
Lid Concrete Bottom Plate	322	*408*
Lid Concrete Section Temperature	266	*291*

Table 4.6.2

OFF-NORMAL AND ACCIDENT CONDITION MAXIMUM MPC PRESSURES

Condition	***Pressure (psig)***
Off-Normal Conditions	
Off-Normal Ambient	101.4~~99.3~~
Partial Blockage of Inlet Ducts	103.1~~101.2~~
Accident Conditions	
Extreme Ambient Temperature	104.4~~102.2~~
100% Blockage of Air Inlets	121.4~~119.2~~
Burial Under Debris	134.8~~132.2~~
HI-TRAC Jacket Water Loss	118.8~~116.7~~

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3 *The temperatures reported in this table are below the off-normal temperature limits specified in Chapter 2, Table 2.2.3.*

4 *Temperatures of limiting components reported.*

5 *Obtained by adding the off-normal-to-normal ambient temperature difference of 20^oF (11.1^oC) to normal condition HI-STORM temperatures reported in Section 4.4.*

Table 4.6.3

HI-TRAC JACKET WATER LOSS ACCIDENT MAXIMUM TEMPERATURES

Component	***Temperature (°F)***
Fuel Cladding	*898*
MPC Basket	*885*
MPC Shell	*594*
HI-TRAC Inner Shell	*499*
HI-TRAC Enclosure Shell	*280*

Table 4.6.4

EXTREME ENVIRONMENTAL CONDITION MAXIMUM HI-STORM TEMPERATURES

Component	***Temperature[6] (°F)***
Fuel Cladding	756~~755~~
MPC Basket	753~~752~~
MPC Shell	514~~512~~
Overpack Inner Shell	367~~366~~
Lid Concrete Bottom Plate	347~~338~~
Lid Concrete Section Temperature	291~~298~~

6 *Obtained by adding the extreme ambient to normal temperature difference (45°F) to normal condition temperatures reported in Section 4.4.*

Table 4.6.5

SUMMARY OF HI-STORM 100 32-HOURS BLOCKED INLET DUCTS THERMAL ANALYSIS

Component	***Initial Temperatures (^oF)***	***Peak Temperatures (^oF)***
Fuel Cladding	*728*	*916*
MPC Basket	*711*	*904*
MPC Shell	*490*	*630*
Overpack Inner Shell	*356*	*533*
Lid Concrete Bottom Plate	*389*	*416*
Lid Concrete Section Temperature	*279*	*311*

Table 4.6.6

SUMMARY OF INPUTS FOR BURIAL UNDER DEBRIS ANALYSIS

Thermal Inertia Inputs: *M (Lowerbound HI-STORM 100 Weight)* *Cp (Carbon steel heat capacity)*[7]	 *150000 lb* *0.1 Btu/lb-^oF*
Cask initial temperature	*728°F*
Q (Decay heat)	*$1.3x10^5$ Btu/hr*
ΔT (clad temperature margin)[8]	*300°F*

7 *Carbon steel has the lowest heat capacity among the principal materials employed in MPC and overpack construction (carbon steel, stainless steel and concrete).*
8 *The clad temperature margin is conservatively understated in this table.*

Table 4.6.7

HI-TRAC FIRE ACCIDENT MAXIMUM TEMPERATURES AND PRESSURES

Component	***Initial Temperature (^oF)***	***Bounding Temperature Rise (^oF)***	***Peak Temperature (^oF)***
Fuel Cladding	*777*	*27*	*804*
MPC Shell	*507*	*27*	*534*
Pressures (psig)			
Component	*Initial*	*Pressure Rise*	*Peak Pressure*
MPC	106.8~~105~~	3.2~~3.2~~	110.1~~108.2~~