List of Acronyms

C/HM	carbon-to-heavy-metal atom ratio
DHRS	decay heat removal system
EAB	exclusion area boundary
EMDAP	evaluation model development and assessment process
HRR	Heat Rejection Radiator
LPZ	low population zone
LWR	light water reactors
MAR	radioactive material at risk for release
MHA	maximum hypothetical accident
MHTGR	Modular High Temperature Gas-Cooled Reactor
MOOSE	Multiphysics Object Oriented Simulation Environment
PHSS	pebble handling and storage system
~~PHX~~	~~primary heat exchanger~~
PIRT	Phenomena identification and ranking table
PSP	primary salt pump
RCSS	reactivity control and shutdown system
RF	release fraction
RG	regulatory guide
SSCs	structures, systems, and components
TRISO	tri-structural isotropic

3 CAPABILITY OF EVALUATION MODELS

3.1 OVERVIEW OF EVALUATION MODELS FOR POSTULATED EVENTS

The safety analysis of postulated events requires the use of several EMs. This section describes the capability of the evaluation models by providing the list of postulated events that the EMs are used to analyze, the important phenomena that must be captured by the EMs, and the figures of merit that must be evaluated by the EMs.

3.2 EVALUATION MODEL APPLICABILITY

3.2.1 Postulated Event Categories and Duration of Evaluation

The postulated events include any potential upset to plant operations, within the plant design basis, that causes an unplanned transient to occur. The effects of postulated events are mitigated by design features. Any event excluded (prevented by design) must be described in the licensing application. Consistent with NUREG 1537, the postulated events with similar characteristics and modeling approaches are grouped into categories. The postulated events are grouped into the following categories:

- Salt Spills
- Insertion of Excess Reactivity
- Increase in Heat Removal
- Loss of Forced Circulation (Loss of Normal Electrical Power events are bounded by this event group)
- Internal Hazard Events
- External Hazard Events
- Pebble Handling and Storage System Malfunction
- Radioactive Release from a Subsystem or Component
- ~~Primary Heat Exchanger Tube Break~~
- General Challenges to Normal Operation

The limiting event for each category is analyzed from the event initiation until the plant reaches a safe state. The safe state is defined for each category of events as a point where the transient figures of merit have stabilized in a safe condition. For any events that occur when fuel is loaded in the core, the plant must be in a safe shutdown condition, where the control and shutdown elements insert to shut down the reactor and maintain long term reactivity control, and the decay heat is removed either through parasitic heat losses, or by the decay heat removal system. The decay heat removal system (DHRS) is always on when the anticipated reactor decay heat load is greater than parasitic heat loss. Similar to other passive reactor designs, Hermes relies on passive heat removal that does not require operator intervention for up to 72 hours. Therefore, the transient methods for each category of postulated event require that an analysis shows the event reaches and maintains a safe state for up to 72 hours following the initiation of the transient.

3.2.2 Postulated Events

This section provides a narrative description of each postulated event category. In each category, the narrative is accompanied by the event-specific characteristics that define a safe state, and the figures of merit that the design is evaluated against to ensure the limiting postulated event for the category remains bounded by the MHA. The general narrative for each postulated event category is provided in this section to provide context for the figures of merit. The event-specific details and analysis methods are provided in Section 4.5.

3.2.2.1 Salt Spills

A hypothetical double-ended guillotine break in the primary salt piping during normal operation causes Flibe to spill from the primary heat transport system. Salt spills are detected directly or indirectly by the reactor protection system, which initiates control and shutdown elements insertion, fulfilling the reactivity control function. The primary coolant pump trip and anti-siphon features of the primary system limit the amount of spilled Flibe. The reactor decay heat removal system limits reactor temperature and fulfills the decay heat removal function. In the reactor, air that enters the reactor system from the break reacts with Flibe to form volatile products and oxidizes unsubmerged structural graphite and pebble carbon matrix of unsubmerged pebbles. A fraction of the radionuclides that are normally circulating in the Flibe are released into the facility air when aerosols are generated from the salt that exits the pipe. The Flibe spills onto the reactor cell floor and forms a pool. The reactor cell floor is assumed to be designed to preclude Flibe-concrete reactions. Additional radionuclides in the spilled Flibe are released through evaporation until the top surface of the Flibe pool is solidified.

A safe state is established when:

- The core is subcritical and long-term reactivity control is assured.
- The decay heat is being removed and long-term cooling is assured, where figures of merit temperatures are steadily decreasing and the Flibe temperature inside the reactor vessel remains above Flibe freezing temperature during the mission time of the decay heat removal system.
- Flibe stops spilling out of the break and the resulting Flibe pool freezes.

This narrative captures the limiting event of this postulated event category. Other events grouped in this category include:

- Spurious draining and smaller leaks from the primary heat transport system
- Leaks from other Flibe containing systems and components (e.g., inventory management system fill/drain tank, inventory management system piping, chemistry control system piping, heat rejection radiator (HRR) tube)
- Leaks up to the hypothetical double-ended guillotine primary salt piping break size
- Mechanical impact or collision events involving Flibe containing structures, systems, and components (SSCs) (except the vessel)
- ~~Leaks from the primary heat rejection system that contains a non-Flibe coolant, which may contain non-zero amount of Flibe from heat exchanger leaks~~

The pipe break on the hot leg is assumed to be the limiting scenario. However, the event-specific methods in Section 4.5 describe a spectrum of break sizes and scenarios is analyzed to confirm the bounding salt spill event. The break sizes and locations determine the amount of mechanical aerosol

- Change in reactivity due to shifting of graphite reflector blocks
- Venting of gas bubbles accumulated in the active core
- Local phenomena leading to step insertion of reactivity
- Local negative reactivity anomaly (e.g., inadvertent single element insertion, cover gas injection)
- Reactivity insertion events during startup

The control element withdrawal at maximum speed, described above, is assumed to be the limiting event of this category. However, the amount and rate of reactivity insertion from other grouped events under insertion of excess reactivity (e.g., during the pebble loading error event, venting of accumulated gas bubbles in the active core) is compared with those from the control element withdrawal events. Additionally, the reactivity insertion due to Increase in Heat Removal events and design basis seismic event, respectively, is compared to the reactivity insertion of control element withdrawal events.

In order to ensure that the design features mitigating a reactivity insertion event are sufficient to keep the consequences bounded by the MHA, the following key figures of merit must be evaluated:

- Peak TRISO temperature to limit diffusion of radionuclides
- Peak TRISO temperature to limit incremental TRISO layer failures
- Peak Flibe-cover gas interfacial temperature to limit evaporation mass transfer of radionuclides
- Peak vessel and core barrel temperatures to prevent vessel failure and maintain long term cooling
- Peak temperature of structural graphite to limit the tritium release
- Peak temperature of pebble carbon matrix to limit the amount of tritium release

3.2.2.3 Increase in Heat Removal

The primary coolant pump overspeeds, causing a surge insertion of cold Flibe into the core. The event is detected by the reactor protection system, which initiates control and shutdown elements insertion, fulfilling the reactivity control function. The reactor protection system also trips the primary coolant pump. The reactor decay heat removal system limits reactor temperature and fulfills the heat removal function.

A safe state is established when:

- The core is subcritical and long-term reactivity control is assured.
- The decay heat is being removed and long-term cooling is assured, where figure of merit temperatures are steadily decreasing and Flibe temperature remains above Flibe freezing temperature during the mission time of the decay heat removal system.

This narrative captures the limiting event of this postulated event category. Other events grouped in this category include:

- Increase in heat removal due to overspeed of ~~intermediate salt pump~~ heat rejection blower
- Increase in heat removal during low power operation

The increase in heat removal events are demonstrated to be bounded by the insertion of excess reactivity postulated event.

In order to ensure that the design features mitigating an increase in heat removal event are sufficient to keep the consequences bounded by the MHA, the following key figures of merit must be evaluated:

- Peak TRISO temperature to limit diffusion of radionuclides
- Peak TRISO temperature to limit incremental TRISO layer failures
- Peak Flibe-cover gas interfacial temperature to limit evaporation mass transfer of radionuclides
- Peak vessel and core barrel temperatures to prevent vessel failure and maintain long term cooling
- Peak temperature of structural graphite to limit the tritium release
- Peak temperature of pebble carbon matrix to limit the amount of tritium release

3.2.2.4 Loss of Forced Circulation

The failure of the primary salt pump results in the loss of forced circulation. The reduced flow is detected directly or indirectly by the reactor protection system, which initiates control and shutdown elements insertion, fulfilling the reactivity control function. The reactor decay heat removal system limits reactor temperature and fulfills the heat removal function.

A safe state is established when:

- The core is subcritical and long-term reactivity control is assured.
- The decay heat is being removed and long-term cooling is assured, where figures of merit temperatures are steadily decreasing and Flibe temperature remains above Flibe freezing temperature during the mission time of the decay heat removal system.

This narrative captures the limiting event of this postulated event category. Other events grouped in this category include loss of forced circulation due to:

- Blockage of flow path external to the reactor vessel in the primary heat transport system,
- Spurious pump trip signal
- Pump seizure
- Shaft fracture
- Bearing failure
- Pump control system errors
- Supply breaker spurious opening
- Loss of net-positive suction head (e.g., pump overspeed, low level)
- Loss of normal electrical power
- Flibe freezing inside heat rejection radiator tubes
- Loss of normal heat sink

There are two bounding events within this event category to evaluate the long-term passive cooling performance. One is to bound the overheating consequence, and another is to bound the downcomer freezing consequence. Two scenarios are considered for these two bounding events:

- Inventory management system
- ~~Primary heat rejection system~~

This narrative captures the limiting event of this postulated event category. Other events grouped in this category include:

- Individual boundary breaches or leaks from any of the above systems due to internal hazards or random failure
- Radioactive release from SSCs (e.g., residual Flibe in the primary salt pump (PSP), dust in PHSS piping) isolated for maintenance

The key figure of merit for this event is:

- Amount of materials at risk released

The limiting event for this category is assumed to be a seismic event that results in the failure of all systems or components not qualified to maintain structural integrity in a safety shutdown earthquake. The amount of MAR in these systems is assumed to be limited to an upper bound limit such that the total amount of materials at risk released is bounded by the amount released during the MHA. Therefore, no additional transient analysis is needed.

3.2.2.7 Not Used~~Primary Heat Exchanger Tube Break~~

~~A complete break of one primary heat exchanger tube occurs. The positive pressure difference maintained between the primary loop and intermediate loop prevents nitrate from entering the primary loop but forces the primary Flibe coolant into the intermediate loop and mixes with the intermediate nitrate salt coolant. The symptom of the tube break is detected by the reactor protection system which initiates control and shutdown elements insertion, fulfilling the reactivity control function. The reactor protection system also initiates intermediate coolant pump trip and a primary coolant pump trip to limit nitrate ingress into the reactor vessel. The reactor decay heat removal system limits reactor temperature and fulfills the heat removal function.~~

~~A safe state is established when:~~

- ~~The core is subcritical and long-term reactivity control is assured.~~
- ~~The decay heat is being removed and long-term cooling is assured, where figure of merit temperatures are steadily decreasing and Flibe temperature remains above Flibe freezing temperature during the mission time of the decay heat removal system.~~
- ~~The Flibe leak from the primary loop into the intermediate loop is contained and nitrate ingress into the reactor system is limited.~~

~~This narrative captures the limiting event of this postulated event category. Another event grouped in this category is a primary heat exchanger tube leak. A conservative amount of Flibe is assumed to flow into the secondary loop to mix with the nitrate salt. This amount is assumed to be the same or bounded by the volume of Flibe spilled during a postulated pipe break event. The core response and dose consequence due to loss of Flibe into the intermediate loop during a primary heat exchanger tube break is bounded by those of a pipe break during a salt spill postulated event. If a primary heat exchanger tube leak is small enough to be undetected, the small amount of graphite dust in the Flibe coolant reacts exothermically with the secondary loop nitrate salt coolant, causing the nitrate salt temperature to~~

~~increase slightly and reduce the heat removal from the primary loop. The small decrease in heat removal is bounded by the loss of forced circulation postulated event.~~

3.2.2.8 Internal and External Hazards

The internal hazard events in the Hermes design basis include:

- Internal fire
- Internal water flood

The external hazard events in the Hermes design basis include:

- Seismic event
- High wind event
- Toxic release
- Mechanical impact or collision with SSCs
- External flood

The reactor can be shutdown manually (e.g., during a toxic release) or automatically (e.g., water flood causing a loss of electrical power). The decay heat removal system performs its function to limit reactor temperature and fulfill the heat removal function.

The key figures of merit for internal and external hazard events are

- The SSCs associated with engineered safety features are available to mitigate the events.
- The amount of materials at risk in SSCs not protected from the hazard are limited.

Engineered safety features contained within areas protected from or able to withstand the intensity of the hazard loading for hazard events initiated outside those areas (e.g., fire) maintain their capability to bring the plant to a safe state following a postulated event. The SSCs within those areas are designed to withstand an upper bound hazard loading intensity associated with the area (e.g., SSCs can withstand an upper bound heat load and the associated area is equipped with fire detection and suppression systems to limit the heat load).

For SSCs not protected with such an area, the amount of materials at risk are assumed to be limited to an upper bound limit such that the amount of materials at risk released is bounded by the amount released during the MHA.

During a seismic event, the packing fraction of the pebble bed would increase due to shaking of the pebble bed, and the graphite reflector blocks would shift. This results in an increase in reactivity, causing an increase in fuel temperature. The increase in reactivity due to increase in packing fraction of the pebble bed and maximum displacement of graphite reflector blocks during a seismic event is bounded by the insertion of excess reactivity event where the control element is inadvertently withdrawn. Increase in packing fraction in the core is equivalent to removal of Flibe which is a negative reactivity impact. The overall carbon-to-heavy-metal atom ratio (C/HM) stays fairly constant within the core. However, on the periphery of the bed close to the reflector, the C/HM is higher than the bed itself. This causes a situation where the reduction in that C/HM brings about a positive reactivity insertion in the core. Neutronics models with various packing fractions (lattice models) is used to demonstrate that the impacts are small.

Mechanical aerosols could also be generated due to splashing of Flibe in the reactor during a seismic event. The amount of aerosols generated during a seismic event is bounded by the amount of aerosols generated by the salt spill event where a pipe breaks.

3.2.2.9 General Challenges to Normal Operation

A general challenge to normal operation occurs that requires an automatic or manual shutdown of the plant. The disturbance is detected directly or indirectly by the reactor protection system, which initiates control and shutdown elements insertion, fulfilling the reactivity control function. The reactor decay heat removal system performs its function to limit reactor temperature and fulfill the heat removal function.

Grouped events include spurious trips due to control system anomalies, operator errors and equipment failures. This event group also includes scenarios where operators choose to manually shutdown the plant. Also included are faults in the reactivity control and shutdown system, electrical system, ~~primary~~ heat rejection system and other plant systems that would challenge normal operations.

This group also contains inert gas system disturbances, and instrumentation and control (I&C) faults. This event group is bounded by the Loss of Forced Circulation postulated event.

3.2.3 Evaluation Models Used to Analyze Postulated Events

Table 3-1 provides the list of postulated event categories, and the EM used to analyze them. Not all postulated events grouped in the categories are explicitly analyzed with the EMs described in this report. Section 4.5 describes the event-specific analysis methodology, which in some cases provides the justification for a postulated event or a postulated event category being bounded by a more limiting postulated event.

3.3 PHENOMENA IDENTIFICATION AND RANKING TABLES

The Phenomena Identification and Ranking Table (PIRT) process is an integral part of the Evaluation Model Development and Assessment Process laid out in RG 1.203. A PIRT relies on expert judgment to identify and rank key phenomena for a specific system undergoing a specific time phase of a specific transient. The PIRT process generates a prioritized list of key phenomena that need to be characterized and modeled to predict response to specific transients. It also ranks the knowledge level for each key phenomenon for each component, thus identifying critical gaps in the understanding of specific phenomena.

Kairos Power has performed a series of PIRTs for KP-FHRs. The list of PIRTs relevant to the development of safety analysis EMs, which leverage different sets of panel experts, include:

- Thermal fluids PIRT
- Radiological source term PIRT (Summary provided in Reference 3)
- Fuel Element PIRT (Summary provided in Reference 7)
- Neutronics PIRT (Summary provided in Reference 8)
- High-temperature structural materials PIRT (Summary provided in Reference 9)

The thermal fluids PIRT was performed to identify key thermal hydraulics phenomena important to safety, prioritize thermal hydraulics tests and EM development. The PIRT helps inform which areas of

During a salt spill event, aerosols can be generated through jet breakup, and spilling and splashing. The airborne release fractions due to aerosolization must be limited so that the dose consequences of the salt spill events are bounded by the MHA.

3.4.2.7 Volatile products from Flibe chemical reactions

Flibe could be exposed to air during a salt spill event. The key release pathway of radionuclide from Flibe is through evaporation, which is a function of vapor pressure of the radionuclide species. When Flibe is exposed to air, the Flibe-air chemical reaction does not result in reactive vaporization which would form radionuclide chemical species that have a higher vapor pressure than those already exists in Flibe circulating activity. For example, CsF dissolved in Flibe does not react with air to form a highly volatile cesium hydroxide. As such, Flibe-air reaction does not result in significant additional release of radionuclides from Flibe through evaporation.

The reactor cell floor is assumed to be designed to preclude Flibe-concrete reaction. When Flibe is spilled, it has the potential to come in contact with stainless steel and insulation material. Flibe interactions with stainless steel and insulation do not result in formation of radionuclide chemical species that have a higher vapor pressure than those already exists in Flibe circulating activity. Therefore, Flibe-stainless steel and Flibe-insulation reactions in the Hermes design basis do not result in additional release of radionuclides from Flibe through evaporation.

During a salt spill event, Flibe is not exposed to water, and therefore no Flibe-water reaction need to be considered. However, if a common cause failure (e.g., seismic) causes a water-containing SSC and Flibe-containing SSC to fail concurrently, the amount of water that Flibe could be exposed to is assumed to be limited to an upper bound limit by design. When interacting with this upper bound amount of water, Flibe redox potential is still maintained within the bounds of salt chemistry conditions defined for the evaporation model; therefore, does not result in additional release of radionuclides from Flibe through evaporation.

~~During a postulated event that involves the primary heat exchanger (PHX), Flibe could mix with nitrate salt and react chemically. The volatile products formed from Flibe and nitrate mixing are addressed in Section 4.5.~~

3.4.2.8 Mass loss of structural graphite and pebble carbon matrix

Pebbles and structural graphite not submerged in Flibe can oxidize when exposed to air. If the mass loss of the pebble carbon matrix does not extend to the fueled zone, tritium release is the only additional MAR release pathway to be considered when fuel pebble oxidizes. Tritium is puff released from oxidized pebble carbon matrix and oxidized structural graphite. In the MHA analysis, the assumed temperature for pebble carbon matrix is so high that all available tritium is effectively puff-released from the pebble carbon matrix. The portion of structural graphite unsubmerged in Flibe is small. The inventory of tritium puff released (instead of as a function of temperature) from oxidization of structural graphite not submerged in Flibe is accommodated by the following inherent conservatism in the treatment of tritium in the MHA:

- Conservative inventory of tritium available for release
- Conservatively high assumed temperature of pebbles
- Moderator pebbles assumed to have the same temperature as fuel pebbles

3.4.2.9 Peak structural graphite temperature

nodal diagram is depicted in Figure 4-2. Table 4-2 summarizes KP-SAM components used for each region in the sample nodal diagram.

Note that the PHX is replaced with the HRR in the Hermes design. The PHX in the KP-SAM model will also be replaced with HRR.

A hot channel factor method conservatively envelopes the maximum bulk coolant temperature in the core for fuel performance analysis:

$$T_{flibe-hcf} = T_{flibe-lp} + \left(T_{flibe-max} - T_{flibe-lp}\right) * hcf_{flow} * hcf_{power} \tag{11}$$

where,

$T_{flibe-hcf}$ = conservative maximum coolant temperature

$T_{flibe-lp}$ = lower plenum coolant temperature

$T_{flibe-max}$ = calculated peak coolant temperature

hcf_{flow} = direct flow hot channel factor

hcf_{power} = direct power hot channel factor

In this highly simplified method, it is assumed that anything that could skew the reactor power profile or coolant distribution within the core happens in coincidence. The method is made further conservative by scaling the gradient between the KP-SAM calculated peak coolant temperature and the lower plenum temperature instead of taking the coolant temperature to be at the node with maximum fuel temperature.

The direct power hot channel factor (e.g., 1.3) accounts for radial peaking and uncertainties in the neutronic calculations. Power measurement uncertainty is handled explicitly by biasing the reactor power in the model. The direct flow hot channel factor (e.g., 1.2) and is intended to take into account any kind of bulk flow maldistribution from sources such as pump intake placement that could be present in the core. It is not necessary to derive a subfactor for flow bypassing the core and traveling through the reflector because this is modeled explicitly.

Once a reactor trip is initiated and the control and shutdown elements start to insert, the reactor power transient is mainly affected by the negative reactivity insertion by the control and shutdown elements insertion. The position dependent control and shutdown element worth is determined by nuclear core analysis and is applied in the safety analysis with added uncertainties. The most limiting minimum control system worth is used, considering the reactor core fuel cycle, which is assumed to be the equilibrium core. The element insertion speed is conservatively applied, as well.

4.2 FUEL PERFORMANCE

The code KP-BISON is used to model fuel performance using the methodology described in Reference 7. The evaluation model for postulated events uses KP-BISON with a conservative approach to assess the pre-transient fuel failure probability and radionuclide release during normal operation to inform the state of the fuel at event initiation. The modeling of the normal operation phase relies on two bounding trajectories (i.e., physical paths followed by the fuel pebbles in the core along which they accumulate burnup and fast fluence) to ensure conservative pre-transient fuel failure probabilities and fission product release fractions:

  - Aerosol generation rate and amount due to single phase coolant jet.
  - Fission product evaporation rates and amount from the spilled Flibe pool and from the in-vessel Flibe free surface.
- Air ingression and graphite oxidation models – general gas flow model is available in KP-SAM; a KP-SAM input model is used to perform the analysis:
  - General gas flow model including buoyancy driven counter current flow limits the oxygen concentration in the cover gas space.
  - Graphite oxidation model provides bounding graphite density reduction rate.
  - A special KP-SAM input model will capture the major components involving air ingression and graphite oxidation models.
- Acceptance criteria – the third method discussed in Section 3.4, using both direct dose calculation for some release pathways and figures of merit for other pathways, is used to demonstrate that this postulated event is bounded by the MHA.

4.5.1.1 Initial Conditions

The initial conditions for the limiting scenario must be provided and justified. The limiting scenario is assumed to occur when the reactor is operating at full power and operating pressure and has been operating long enough for the fuel to contain fission products at equilibrium concentrations. Therefore, the maximum possible decay heat is available at the start of the event. Although the hypothetical double-ended guillotine hot leg break at the ~~PHX~~ HRR inlet is considered the bounding case, the entire spectrum of break sizes and location must be considered to confirm that the double-ended guillotine break is bounding.

The initial conditions for the amount and distribution of MAR immediately before the break must be determined to calculate a source term for this event. As this event does not involve the PHSS, the MAR in PHSS is excluded from the analysis. The initial MAR distribution is summarized below:

Fuel Pebble MAR

The majority of the MAR is contained by the TRISO particles in the fuel pebbles in the core. The inventory of MAR in the fuel is established through code analysis using Serpent2. The defect ratio of TRISO particles, the additional in-service failure of the particles, and the fraction of heavy metal contamination are specified through fuel qualification requirements (Reference 12).

Flibe in MAR in the Primary System

A conservative amount of MAR in the Flibe is assumed in the circulating activity in the coolant. Note there may exist small amount of graphite dust which is suspended within the Flibe. The dust behaves as getter and absorber of tritium. The chemistry control system ensures the loading of graphite dust is within acceptable bounds.

Graphite and Metal Structures MAR

The limiting loss of forced circulation scenario is described in Section 3.2.2. The analysis of the limiting event in this category includes a systems analysis with conservative neutronics input.

4.5.3.1 Initial Conditions

The initial conditions of the transient are biased to ensure a conservative evaluation of the figures of merit. The limiting loss of forced circulation scenario is assumed to initiate from the highest possible reactor power because the higher power provides the highest heat input to challenge the identified figures of merit. However, sensitivities must be performed to ensure that loss of forced circulation events from lower power levels do not unexpectedly challenge a figure of merit. Initial condition values are provided in Table 4-5.

4.5.3.2 Transient Analysis Methods

The important thermal and hydraulic phenomena during the transient include the flow friction (negative head) at the pump, heat transfer between the coolant and various interfacing structures such as pebble, reactor vessel wall and internals. Because the forced circulation is lost, the fluid friction through the coolant loop, including the reactor core, is more important than other events where forced flow is maintained.

KP-SAM is used to analyze the event progression with inputs from the neutronics EM and provides inputs to the structural integrity EM. Upon a loss of forced circulation, the reactor experiences an immediate increase in the fuel (pebble) temperature because of the reduced heat transfer to the coolant. The coolant temperature also rises because heat removal from the reactor core to the ~~PHX~~ HRR is reduced and eventually stops. The increased temperature of the coolant could challenge the integrity of reactor vessel and core barrel structures.

The nuclear fission power profile within the pebble bed is affected by the neutron flux distribution in the core region and the fuel burn-up status of the pebbles. The current approach to modeling core power density is an axially resolved radially averaged method and does not explicitly account for radial power peaking in the core. The radial power profile and its effect on the coolant and fuel temperatures are not explicitly modeled; therefore, local peak coolant and fuel temperatures are not fully resolved. The hot channel factor methodology described in Section 4.1 accounts for both power peaking and the possibility of flow being poorly distributed in the core.

The KP-SAM base model described in Section 4.1 is used to analyze a loss of forced circulation event with the following modifications:

- Typically, the interaction between the fluid system and pump, during the transient, is modeled using head and torque curves of the pump. For the loss of forced circulation analysis, the coolant flow response is modeled without the detailed pump characteristics, by conservatively assuming the pump head after the transient starts. Since the pump rotor is assumed to stop instantly, the pump torque information is not needed.
- The reactivity feedback effect on power is minimized for conservative calculation by using least negative reactivity coefficient values to minimize the effect of power reduction from the initial temperature increase by the reduced coolant flow.
- The uncertainties in material properties of the Flibe coolant and vessel structures are addressed conservatively. The thermal mass of the material is reduced such that the temperatures of fuel and vessel structure are predicted higher. The reactivity feedback effect is modeled in such a way that

where, x is the particle diameter, $\phi(x)$ is the distribution function of particle number densities (i.e., $\phi(x)dx$ is the fraction of the number of particles with diameter x), $\mu = \ln(d_g)$ is the mean of the log-normal distribution, d_g is the geometric mean diameter, $\sigma = \ln(\sigma_g)$ is the standard deviation of the distribution, and σ_g is the geometric standard deviation. For the log-normal distribution, the geometric mean diameter and standard deviations of the deposited dust particles need to be provided as input. The resuspended fraction F_{lift} of the dust particles is determined as the fraction of the dust particles with diameters larger than the cut-off diameter but smaller than the upper limit diameter of aerosol particles $d_{aer} = 50\ \mu m$, i.e.,

$$F_{lift} = \frac{\int_{d_{crit}}^{d_{aer}} \phi(x) x^3 dx}{\phi_3} \qquad (32)$$

where, d_{crit} is the cut-off lift diameter, $d_{aer} = 50\mu m$ is the upper limit of the aerosol particles, and ϕ_3 is the third moment of the number distribution. Inserting the log-normal distribution of Equation 31 into Equation 32 results in an analytical formulation of the resuspension mass fraction:

$$F_{lift} = \frac{erf\left(\frac{ln\, d_{aer} - \mu'}{\sigma\sqrt{2}}\right) - erf\left(\frac{ln\, d_{crit} - \mu'}{\sigma\sqrt{2}}\right)}{2} \qquad (33)$$

where, erf is error function, and $\mu' = \mu + 3\sigma^2$. The MAR in the resuspended dust particles is assumed to be released as aerosols promptly for conservativism.

~~4.5.5 Primary Heat Exchanger Tube Break~~

~~Postulated events that involve the PHX have the potential to release radionuclides from Flibe. MAR that is dissolved or entrained within the Flibe is subjected to a chemical transient when exposed to the oxidizing molten nitrate salt. This chemical transient could mobilize MAR through chemical reaction mechanisms or via mechanical aerosolization. Bubble bursting is the primary mode of aerosolization in which MAR could be mobilized by mechanical aerosolization. Gas production from the kinetically sluggish and endothermic reaction between Flibe and nitrate salt produce NOx gas bubbles as the two fluids mix. The driving pressure to cause these gas bubble bursts is low as the pressure at the salt free surface is near atmospheric. As a result, the release fraction of MAR through bubble burst aerosolization is bounded by the double-ended guillotine hot leg break event within the salt spills postulated event group.~~

~~Radionuclide chemistry in PHX failure events is evaluated using the radionuclide grouping structure in accordance with the mechanistic source term methodology (Reference 3). An encompassing analysis of all chemical reactions between radionuclides in the Flibe barrier and nitrate salt is not performed, but rather chemical releases are handled according to well established behaviors for each radionuclide group.~~

~~High volatility noble metals and gasses that exist within the Flibe of the PHTS are transported with a release fraction of 100%. This release fraction is equivalent to that used in the hot leg break postulated event.~~

~~The dose consequence of releases from the low volatility noble metal and oxide groups are assumed to be de negligible as they remain in low volatility forms throughout the transients. Should the low~~

~~volatility noble metals chemically react with the molten nitrate salt, they are anticipated to form metal oxides with similarly low vapor pressures.~~

~~Radionuclides in the salt soluble fluoride group may chemically react with molten nitrate salt if the reaction products are more thermodynamically stable. The majority of salt soluble radionuclide species are low volatility metal fluorides when dissolved in Flibe. Upon reacting with nitrate salt these metal fluorides may undergo chemical reactions to form metal oxides and NOx gasses. The degree to which these reactions proceed is not important as both the reactant form, metal fluoride, and product form, metal oxide, are low volatility species. The reaction of the bulk Flibe and nitrate fluids is endothermic. Vaporization of the metal fluoride and metal oxide radionuclide species are therefore bound by vaporization in the salt spill postulated event as the temperature is lower due to the endothermic reaction. Insignificant high volatility reaction products form because radionuclide elements that may form high volatility reaction products has small inventory in the Flibe circulating activity, and therefore have negligible dose consequences.~~

Table 3-2: Derived Figures of Merit and Acceptance Criteria for Postulated Events

Figure of Merit	Acceptance Criterion	Applicable Events
Peak TRISO temperature-time	Generally bounded by temperature-time curves derived from the assumed MHA fuel temperature-time curve	Salt Spills, Reactivity Insertion, Increase in Heat Removal, Loss of Forced Circulation, PHSS break, Seismic~~, PHX Tube Break~~
Peak TRISO temperature-time	Below incremental TRISO fuel failure temperature	Salt Spills, Reactivity Insertion, Increase in Heat Removal, Loss of Forced Circulation, PHSS break~~, PHX Tube Break~~
Peak Flibe-cover gas interfacial temperature	Generally bounded by temperature-time curves derived from the assumed MHA Flibe-cover gas interfacial temperature-time curve	Salt Spills, Reactivity Insertion, Increase in Heat Removal, Loss of Forced Circulation, PHSS break~~, PHX Tube Break~~
Peak vessel and core barrel temperatures	Bounded by both the maximum allowable temperature derived to limit excessive creep deformation and damage accumulation and by 816°C (highest temperature considered by ASME Section III Division 5 for 316H)	Salt Spills, Reactivity Insertion, Increase in Heat Removal, Loss of Forced Circulation, PHSS break~~, PHX Tube Break~~
Minimum reactor vessel inner surface temperature	Above Flibe melting temperature	Loss of Forced Circulation
Airborne release fraction of spilled/splashed Flibe	Below airborne release fraction limit derived to bound total releases of the postulated event to less than the MHA	Salt Spills, Seismic~~, PHX Tube Break~~
Volatile product formation from Flibe-air reaction	Negligible amount of additional volatile products formed	Salt Spills, PHSS break~~, PHX Tube Break~~
Volatile product formation from Flibe chemical reaction with water, concrete, and/or construction materials (e.g., insulation, steel)	Negligible amount of additional volatile products formed	Salt Spill
~~Volatile product formation from Flibe chemical reaction with nitrate~~	~~Negligible amount of additional volatile products formed~~	~~PHX Tube Break~~
Mass loss of pebble carbon matrix due to oxidation	Mass loss does not extend into the fueled zone	Salt Spills, PHSS break
Mass loss of structural graphite due to oxidation	Bounded by the MHA release	Salt Spills, PHSS break

Figure of Merit	**Acceptance Criterion**	**Applicable Events**
Peak structural graphite temperature-time	Generally bounded by temperature-time curves derived from the assumed MHA structural graphite temperature-time curve	Salt Spills, Reactivity Insertion, Increase in Heat Removal, Loss of Forced Circulation, PHSS break~~,~~ ~~PHX Tube Break~~
Peak pebble carbon matrix temperature-time	Generally bounded by temperature-time curves derived from the assumed MHA pebble carbon matrix temperature-time curve	Salt Spills, Reactivity Insertion, Increase in Heat Removal, Loss of Forced Circulation, PHSS break~~,~~ ~~PHX Tube Break~~
Peak TRISO temperature-time ex-vessel	Generally bounded by temperature-time curves derived from the assumed MHA fuel temperature-time curve	PHSS break
Amount of materials at risk released	Less than limit derived to bound total releases of the postulated event to less than the MHA	PHSS break