US-EPR Technology Manual

Chapter 6.0

REACTOR BUILDING AND SUPPORTING SYSTEMS

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

6.0 REACTOR BUILDING AND SUPPORTING SYSTEMS

Learning Objectives:

1. State the purposes of the US-EPR containment building.

2. State the purpose of the US-EPR shield building.

3. State the purpose of the US-EPR annulus ventilation system.

4. Explain the provisions incorporated into the US-EPR design for severe accident mitigation.

5. Describe the expected ex-vessel melt progression during a severe accident.

6. Describe how the severe accident heat removal system protects the containment during severe accidents.

6.1 Reactor Building

6.1.1 Reactor Building Structure

The Seismic Category I reactor building consists of a cylindrical, reinforced-concrete outer shield building, a cylindrical, post-tensioned, reinforced-concrete inner containment building with a 0.25-in.-thick steel liner, and an annular space between the two buildings. The shield building protects the containment building from external hazards. The containment building contains the reactor coolant system (RCS) and portions of associated structures, systems, and components. In the event of a loss-of-coolant accident (LOCA) or severe accident, the containment building serves to retain all radioactive material and to withstand the maximum pressure and temperature resulting from the release of stored energy.

Figures 6-1 and 6-2 provide different representations of the Nuclear Island. The Nuclear Island includes the reactor building, the four safeguard buildings, and the fuel building, all located on a common basemat. The reactor building is located at the center of the Nuclear Island.

The reactor building is designed to withstand internal accidents as well as external hazards, including the following: aircraft hazard, explosion pressure wave, seismic events, missiles, tornado, and fire. The US-EPR design bases are expected to envelope potential sites in the central and eastern U.S.

The shield building provides a hardened structure designed to withstand an aircraft hazard. The containment building interior structures and equipment are thus decoupled from the impact forces of an aircraft hazard. Figure 6-2 is a general plant layout drawing showing the concept for protection against an aircraft hazard.

The common basemat of the Nuclear Island ensures that overturning of structures due to a seismic event or aircraft hazard will not occur.

The shield building is designed to withstand the potential effects of an external explosion.

The design pressure and temperature of the containment building are defined by the following events:

- Double-ended rupture of a reactor coolant pipe (large-break LOCA [LBLOCA]),
- Main steam line break, and
- Severe accidents.

Sprays or fan coolers are not required to mitigate short-term containment pressure or temperature responses to design-basis accidents or for long-term containment pressure response. The residual heat removal system (RHRS) has the capability to reduce the pressure to half the peak in less than eight hours after a LOCA.

The design pressure and temperature of the containment are 62 psig and 338°F, respectively. The maximum pressure and temperature for a LBLOCA or a steam line break are below the design values of the containment.

The containment has an allowable flooding volume of approximately 46,500 ft^3, which is sufficient to protect safety-related components against flooding after a piping failure.

Containment Building Details

The key dimensions of the Containment Building are:

Free volume (approx.)	2.82×10^6 ft^3
Internal diameter	153.5 ft
Thickness of cylindrical wall	4.27 ft
Thickness of dome	3.28 ft
IRWST volume	511,700 gal

The reactor pool (reactor cavity with storage compartment above the reactor pressure vessel [RPV], used during refueling), the in-containment refueling water storage tank (IRWST), and the core melt spreading compartment are among the major internal structures. Figure 6-3 shows the positions of the IRWST and the spreading area relative to the reactor cavity. The containment building also houses the reactor vessel, pressurizer, steam generators, steam generator blowdown flash tank, and a portion of the main steam and feedwater lines.

Shield Building Details

The approximate dimensions of the shield building wall are:

- Cylindrical portion up to safeguard building height:

Internal diameter	174 ft
Thickness	4.3 ft

- Cylindrical portion above safeguard building height:

Inside diameter	174 ft
Thickness	5.9 ft
Dome diameter/thickness	217 ft / 5.9 ft

Basemat Details

The reactor building basemat is reinforced concrete. The basemat is approximately 10 ft thick. A circumferential prestressing gallery of vertical tendons for the containment cylindrical wall is situated underneath the basemat. The containment building steel liner continues into the basemat to prevent the release of radioactivity to the ground.

6.1.2 Annulus

The annulus between the shield building and the containment building is ventilated by the annulus ventilation system (AVS). The AVS is designed to contain leakage from the primary containment by maintaining a subatmospheric pressure in the annulus. The AVS consists of three trains: one train is used during normal plant operation, and the other two trains are used to mitigate potential accidents. AVS design and performance parameters are presented in Table 6-1.

The normal-operation filtration train is shown in Figure 6-4. The full-capacity normal-operation filtration train is designed to maintain a subatmospheric pressure in the annulus, to maintain the annulus temperature above 45°F to prevent boron precipitation in the extra borating system piping, and to provide conditioned air in the annulus for personnel accessibility.

During normal operation, the conditioned air is drawn from the nuclear auxiliary building ventilation supply shaft and distributed in the bottom of the annulus to four different locations. A subatmospheric pressure of less than or equal to -0.8 in. water gauge is maintained in the annulus during normal operation. The exhaust air is drawn from the top of annulus by the nuclear auxiliary building ventilation system exhaust fans, filtered by the nuclear auxiliary building filtration trains, and discharged through the vent stack.

The AVS accident filtration trains are shown in Figure 6-5. These filtration trains constitute an engineered safety feature (ESF) system and are used during postulated accidents to contain leakage from the primary containment by maintaining a subatmospheric pressure in the annulus. The exhaust air from either train is filtered before release to the environment via the vent stack. Each of the two full-capacity ESF trains includes a prefilter, an upstream high efficiency particulate air (HEPA) filter, an iodine absorber, a downstream HEPA filter, and a fan.

During a postulated accident, the ESF filtration trains collect any containment leakage into the annulus, remove airborne radioactivity through the filtration elements, and release the filtered air to the vent stack. The AVS accident trains reduce the pressure in the annulus to no more than -0.25 in. water gauge and maintain that pressure. The system is capable of maintaining a uniform negative pressure throughout the secondary containment structure following the design-basis LOCA.

The two ESF trains are physically separated due to their installation in separate rooms of the fuel building, which are also in separate fire areas. The two ESF trains are powered by different electrical divisions backed by separate emergency diesel generators.

The normal-operation filtration train is in service during normal plant operation, including cold shutdowns and outages. The supply air from the AVS maintains the annulus temperature between 45°F and 113°F. In the case of a postulated accident, a containment isolation signal causes the normal-operation filtration train to automatically isolate. Both accident filtration trains start on receipt of the containment isolation signal.

High energy piping traversing the annulus is routed in guard pipes.

6.1.3 Containment Isolation

Containment isolation valves minimize the release of radioactive fluids to the environment in the event of an accident with fission product releases in the containment.

The isolation function is assured through penetration and isolation valve arrangements. Mechanical and electrical penetrations are designed to withstand the consequences of external hazards and an accident in the containment.

The type, number, and arrangement of isolation valves are in accordance with U.S. requirements for existing pressurized water reactors. These requirements consider isolation valves on piping for systems in normal operation and in accidents. They apply to systems that are part of the reactor coolant pressure boundary, that are connected directly to the containment atmosphere, or which form a closed loop inside of containment.

The single-failure criterion is satisfied for piping directly connected to the RCS or to the containment atmosphere with the installation of a minimum of two valves for each line. The two valves operate independently of each other, with one installed inside the containment and one outside.

The exception to this principle involves the lines from the IRWST sumps to the safety injection system (SIS) and severe accident heat removal system (SAHRS) pumps, each of which has only one isolation valve. In this case, the piping between the pump and the valve is contained in a sealed envelope (guard pipe), thus providing a double leak-tight penetration barrier. This double barrier is designed to be leak-tight and to withstand the design-basis environmental conditions inside the containment (from the containment penetration to the containment isolation valve) and takes into account a single failure (functional failure or passive failure).

The containment is designed for an integrated leak rate equal to or less than 0.5% per day of the containment free volume at the containment design pressure and temperature. The containment integrated leak rate will be verified through tests.

6.2 Severe Accident Mitigation

6.2.1 Severe Accident Progression

The US-EPR employs an ex-vessel strategy for the mitigation of severe accidents. As such, both in-vessel and ex-vessel processes and phenomena contribute to the eventual end state. To introduce the principal severe accident phenomena for the more likely scenarios, a hypothetical bounding severe accident is described in this section.

The principal consideration in identifying the hypothetical bounding severe accident is the role of the primary depressurization system (PDS). The consequence of this highly reliable feature is the rapid depressurization of the RCS. Rapid depressurization removes a degree of uncertainty associated with postulated scenarios, since many such events become very similar to a large-break LOCA (LBLOCA). Therefore, for the purpose of identifying important US-EPR severe accident phenomena, the hypothetical bounding severe accident is an initiating large primary system pipe rupture coincident with a station blackout (SBO). Subsequent accumulator injection is credited to initially flood the core, providing the hydrogen source (i.e., water) necessary to maximize hydrogen generation.

6.2.1.1 In-Vessel Melt Progression

Characteristic of an SBO, the complete failure of all active safety systems is assumed. Without safety injection the core begins to heat up and progressively dry out. Unmitigated fuel ballooning, rupture, and melting follow. Exothermic chemical reactions, primarily between zirconium and residual water and steam, result in significant hydrogen generation. The hydrogen presents a combustion hazard, particularly in the containment, where mixture with oxygen is expected. Eventually, a molten corium pool will form inside the core; the pool then expands towards the heavy reflector and the lower core support plate. As the event progresses, intact fuel elements surrounding the corium pool are eventually destroyed.

Since the melt is primarily oxidic, its contact with the heavy reflector does not lead to instant failure but to a slow, crust-limited heatup. Due to their large collective mass and correspondingly high heat capacity, the heavy reflector and lower support plate act as a temporary internal crucible, retaining the core within its boundary. As a consequence, it is expected that this intermediate molten pool will already contain a large fraction of the core. Melt-through of the heavy reflector, driven by natural convection, is expected to occur in the upper region of the molten pool. During melt relocation into the lower plenum, the continued heating within the core coupled with the out-flowing melt is expected to widen the initial hole, allowing more core melt to relocate.

As a result of the contact with the residual water in the lower head, the released melt may form a partially fragmented debris bed or an encrusted molten pool, or both. After evaporation of the residual water, a secondary molten pool forms within the lower plenum. The lower support plate will then be heated from both sides, by convection from above and by thermal radiation from below.

The two pools will evolve independently. Within the upper pool, the remaining fuel and solid debris will heat up. Newly created melt will exit through the existing hole in the heavy reflector and become incorporated into the lower pool. During this process the average temperature of the lower head will steadily increase; the heating leads to its deformation by thermal expansion and creep. Downward expansion of the lower head is ultimately limited by the concrete support structures provided at the bottom of the reactor cavity, the concrete enclosure surrounding the reactor pressure vessel. These structures preserve sufficient space for the outflow of melt and the later formation of a molten pool in the reactor cavity.

At some point, the RPV lower head fails thermally. Without lower head penetrations, this can begin as a local failure at a location in the upper part of the melt-contacted region. In this configuration, only part of the contained melt is released with the first pour. After this first relocation, further outflow into the reactor cavity depends on the development of the melt configuration within the RPV. Under the expected dry conditions, the lower head is subject to radiant heating from the surface of the molten pool and from the surrounding aerosol-rich gas. This heat flux accelerates the global failure of the lower head and lower internals of the RPV.

6.2.1.2 Ex-Vessel Melt Progression

After release from the RPV, a period of melt retention in the reactor cavity occurs, followed by the spreading, flooding, quenching, and long-term cooling of the melt. The temporary retention phase accommodates the uncertainty associated with different RPV failure modes and release rates. The release of corium from the RPV into the reactor cavity will likely not take place in a single release, but over a period of time. Without a retention phase, the release of corium over an undefined period of time could result in potentially unfavorable conditions for subsequent melt spreading.

The melt retention phase is characterized by molten core/concrete interaction (MCCI) which ablates a layer of sacrificial concrete before the corium flows into a lateral compartment for spreading. The surface of the reactor cavity that comes into contact with the corium is lined with a uniform thickness of sacrificial concrete. The sacrificial concrete is backed by a refractory layer of sintered zirconia bricks, except for a rectangular melt plug at the center of the reactor cavity floor. The melt plug is composed of sacrificial concrete, with a thickness equal to the rest of the reactor cavity sacrificial concrete, but is backed by an aluminum gate atop a steel framework. This is the only part of the reactor cavity sacrificial concrete that is not backed by zirconia bricks and therefore constitutes the defined failure area that allows the corium to be released into the spreading compartment.

The length of the temporary retention phase is driven by the release rate of corium from the RPV. There is a defined amount of concrete that is ablated during the MCCI. The energy required for MCCI comes from the decay heat in the melt. For fast releases of corium from the RPV, there is an abundance of energy, and the MCCI proceeds quickly. Alternatively, for slow releases of corium from the RPV, the decreased amount of energy in the melt reaching the reactor cavity causes the MCCI to proceed at a slower rate. This leads to a longer retention phase, which allows more of the melt to accumulate in the reactor cavity. The energy balance gives the melt retention phase a self-adjusting characteristic that decouples the spreading process from the uncertainties of the in-vessel phase of the severe accident.

In addition to melt accumulation, the retention period also gives the corium beneficial properties that contribute to successful melt spreading. The admixture of a defined amount of concrete into the corium limits the spectrum of possible melt states prior to spreading and generates more predictable melt properties. In addition, the temporary retention of the melt reduces the final temperature of the melt prior to spreading, and the admixture of the concrete maintains the viscosity of the melt in a favorably low range.

After penetrating the sacrificial concrete, the melt heats and quickly fails the metallic gate and support structure. Upon failure, the gate opens a release path for the melt into the melt discharge channel, which couples the reactor cavity to the spreading compartment. The flow of the hot melt through the gate erodes the surrounding material and expands the opening.

Following the failure of the melt plug, the melt flows through the discharge channel in a single pour. After passing the outlet of the melt discharge channel, the melt pours onto the floor of the spreading compartment, where it is distributed over a large surface area. The floor and walls of the spreading compartment are composed of sacrificial concrete. Beneath the sacrificial concrete is a cast iron cooling structure, which is flat on the side facing the spreading compartment and finned on the opposite side to enhance heat transfer. The layer of sacrificial concrete in the spreading compartment protects the cooling structure from the thermal loads of melt spreading and provides a time delay to allow the cooling structure to fill with water.

The spreading of the melt passively actuates spring-loaded valves that initiate a gravity-driven flow of cooling water from the IRWST. The incoming cooling water is distributed by means of a central supply duct underneath the spreading compartment, which overflows and fills the cooling structure. The cooling water then rises up the walls of the cooling structure and pours onto the surface of the melt from the circumference. The rate of water ingress is limited to a maximum flow rate to avoid any energetic fuel/coolant interactions (FCIs). Water overflow continues until the spreading compartment and IRWST water levels equalize, resulting in the submersion of the spreading compartment, the transfer channel, and a portion of the reactor cavity.

6.2.2 Severe Accident Mitigation Features

The US-EPR has design features to address a variety of severe-accident challenges, including hydrogen generation and control, core debris coolability, high-pressure melt ejection (HPME), FCI, containment bypass, and equipment survivability. The following sections summarize those features.

6.2.2.1 Hydrogen Generation and Control

The generation of hydrogen can occur in the US-EPR during a severe accident due to oxidation on fuel rod surfaces, MCCI, and oxidation of the core support material. The largest contributor to hydrogen generation is the oxidation of the fuel rod cladding, which can vary depending on the timing of the melt progression. The combustible gas control system (CGCS) and hydrogen monitoring system (HMS) are design features incorporated in the US-EPR to comply with the hydrogen generation and control requirements of 10 CFR 50.44(c) as follows:

- The CGCS provides for a mixed atmosphere within the containment.

- The CGCS limits the overall hydrogen concentration in containment to 10% by volume during and following an accident that results in a fuel cladding/coolant reaction involving 100% of the cladding surrounding the active fuel region.

- The CGCS remains functional during and after exposure to the accident environmental conditions.

- The HMS continuously measures the hydrogen concentration in containment during and after the accident, and remains functional during and after exposure to the accident environmental conditions.

- The CGCS effectively reduces the pressure and thermal loadings from a potential combustion event, protecting the containment from possible structural failure.

The CGCS is divided into two subsystems corresponding to their operational functions:

- Hydrogen reduction system, and
- Hydrogen mixing and distribution system.

The hydrogen reduction system consists of 41 large and 6 small passive autocatalytic recombiners (PARs) installed in various parts of the containment. The PARs are arranged inside the equipment rooms to support global convection within the containment; they thereby homogenize the atmosphere and reduce local peak hydrogen concentrations. Recombiners are also included in the containment dome to cope with stratification and to improve depletion after atmospheric homogenization.

The hydrogen mixing and distribution system is designed so that adequate communication exists throughout the containment to facilitate atmospheric mixing. Several of the equipment rooms surrounding the RCS are isolated from the rest of the containment during normal operation. In the event of an accident, communication is established between these normally segregated compartments, thereby eliminating potential dead-end compartments where noncondensable gases can accumulate. This ability to transform the containment into a single convective volume is supported by a series of mixing dampers and blowout panels.

The HMS monitors the hydrogen and steam concentration in the containment. The HMS provides information to the main control room regarding the hydrogen concentration and its distribution within containment. The measuring points are arranged in different compartments of the containment to monitor the time dependence of the hydrogen distribution during a severe accident. The hydrogen concentration is monitored in the upper dome, steam generator compartments, pressurizer compartment, and annular rooms.

6.2.2.2 Core Melt Stabilization System

Melt retention within the RPV is not a design goal for the US-EPR. Rather, the US-EPR is equipped with an ex-vessel system to accommodate molten debris, including the entire core inventory and reactor internals. The goal of this system is to eliminate the potential for containment failure by any means associated with the core melt, including the interaction between the core melt and the containment structure and the effects of melt cooling (i.e., overpressurization of containment). When the molten debris has reached its final destination in the spreading room, is being cooled by water from the IRWST, and is no longer a threat to containment integrity, the core melt is considered "stabilized." This condition is attained through the combined effects of the following portions of the core melt stabilization system (CMSS):

- Reactor cavity,
- Melt plug,
- Melt discharge channel, and
- Spreading area and cooling structure.

The reactor cavity utilizes a combination of sacrificial concrete and a protective layer of refractory material to provide a stage of temporary melt retention. The melt plug and gate are located in the reactor cavity and support melt retention by providing a defined failure location. The melt discharge channel utilizes a steel duct lined with refractory material to direct the conditioned melt from the reactor cavity to the lateral spreading compartment. The spreading area consists of a dedicated cooling structure lined with sacrificial concrete to promote stabilization of molten debris. The general configuration of the CMSS is shown in Figure 6-6.

Reactor Cavity

The reactor cavity refers to the region between the RPV and the surrounding structural concrete closest to the lower head. Following RPV failure, the reactor cavity receives core melt. The initial conditions for core melt in the reactor cavity are determined by the course of in-vessel core degradation, by in-vessel core melt relocation and quenching, and finally by the sequence of melt release after failure of the lower head. All of these processes involve a degree of uncertainty. To make the US-EPR melt stabilization concept tolerant of such uncertainties, the reactor cavity provides a period of temporary melt retention. This period of temporary retention addresses the fact that the release of molten material from the vessel will, most likely, not occur in one pour, but over a period of time.

Temporary retention is provided by a layer of sacrificial material that is penetrated by the melt before it can escape from the cavity. The corresponding delay, determined by the time needed for the melt to penetrate the sacrificial layer and to destroy the metallic gate, ensures, for the more likely scenarios, that practically the entire core inventory is collected in the cavity prior to spreading and stabilization – even in the case of an incomplete first release of the melt from the RPV.

The sacrificial layer consists of a 19.7-in. layer of siliceous concrete with high iron-oxide content. The sacrificial concrete within the reactor cavity serves to limit the spectrum of potential melt states by homogenizing the thermo-chemical conditions of the melt release from the vessel. Therefore, the retention phase serves to condition the melt so that the spreading process and subsequent measures are independent of the uncertainties associated with in-vessel melt progression and the RPV failure mode. One advantage of the high iron-oxide content of the reactor cavity concrete is that it oxidizes the remaining zirconium and uranium within the melt that can attack the zirconia bricks, thus protecting the structural concrete of the cavity. A high iron-oxide concrete also leads to a low melt temperature and viscosity for spreading. A high SiO_2 composition also benefits the process through the formation of silicates that lower the radionuclide release from the corium pool.

The sacrificial concrete layer is backed with a refractory material that confines the melt and insulates the RPV support structure from a local penetration of the sacrificial concrete. The refractory material consists of zirconia bricks, which have a low thermal conductivity and a mechanical strength greater than that of concrete. This protective layer “guides” the melt toward the metallic gate of the melt plug.

Melt Plug and Gate

The upper part of the melt plug is a layer of sacrificial concrete with the same composition as the sacrificial layer within the cavity. However, this layer of concrete is not backed by refractory blocks, but by an aluminum plate (referred to as the gate) atop a steel framework. At the end of the retention phase, the melt plug and gate are designed to fail open with sufficient cross-sectional area to achieve a complete and rapid relocation of the accumulated melt into the lateral discharge channel leading to the spreading compartment.

The concrete cover of the plug is an integral part of the sacrificial layer in the cavity, and it has the same thickness of 19.7 in. Due to the large diameter of the cavity, the ablation front is expected to be relatively even, and the entire surface of the gate is expected to be fully uncovered within a short time.

Once the molten debris comes into contact with the gate, the intensity of the convection within the molten pool is expected to quickly destroy the gate. The outflow of melt is limited by the residual concrete layer. The resulting rate of melt discharge after opening the full cross-section of the residual melt plug is substantially greater than that necessary to provide adequate spreading in the spreading compartment. If the gate initially fails over less than its full cross-section, the diameter of the opening steadily increases due to the heat transfer from the flowing melt. Hole-widening effects make the discharge process self-adjusting; for a small initial opening, the duration of the discharge and the time of interaction will be correspondingly longer.

Melt Discharge Channel

Following the failure of the cavity retention gate, the melt flows through the transfer channel in a single pour. After passing the outlet of the melt discharge channel, the melt flows over the surface of the spreading compartment.

The melt discharge channel consists of a steel structure that is embedded in the structural concrete of the containment. The bottom, side walls, and top of this structure are layered with refractory material. This protective layer of zirconia bricks has a low thermal conductivity and eliminates the possibility of blockages forming as a consequence of melt freezing.

Spreading Area and Cooling Structure

As previously discussed, the CMSS is designed for the passive transport of molten debris through the discharge channel and into the spreading compartment. The spreading area is an approximately 1872-ft^2 horizontal concrete surface over which the molten debris disperses. Spreading increases the surface-to-volume ratio of the molten debris to allow effective stabilization via subsequent cooling. The spreading area is located in the lower portion of the containment and is surrounded by the IRWST. The configuration of the spreading area surface is shown in Figure 6-7.

The spreading compartment design prevents the accumulation of a large amount of water, so that molten debris spreads under dry conditions. The spreading compartment is a dead-end room and is isolated from the rest of containment by flood and splash walls. These features prevent the direct inflow of water from sprays, leaks, or pipe breaks. Only a limited amount of condensate may form inside the room. Though dry conditions are not required for successful spreading, they make the distribution more predictable and reduce the potential for fuel/coolant interactions.

The spreading area is essentially a shallow crucible within which molten debris can be stabilized. A layer of sacrificial concrete within the spreading compartment covers a dedicated cooling structure used to cool the molten debris on all sides with water from the IRWST. This dedicated cooling structure consists of a number of cast iron cooling elements that line the floor and side walls of the spreading compartment. To enhance heat transfer, the horizontal and vertical plates have fins that form rectangular cooling channels. The sacrificial concrete layer protects the cooling structure against thermal loads resulting from melt spreading. It also delays melt contact with the metallic cooling structure, so that the cooling elements will be flooded with water from the IRWST prior to the initial contact between them and the molten debris. The structural elements are joined by flexible connections, so that the cooling structure withstands expansion and deformation.

Prior to core melt, the normally closed, de-energized motor-operated isolation valves of the passive flooding lines are manually opened by the operator. The arrival of the melt into the spreading compartment triggers the opening of spring-loaded valves that initiate the gravity-driven flow of water from the IRWST into the spreading compartment. Initially, a cable holds each spring-loaded valve closed. Within the spreading compartment the cable is attached to a thermally sensitive initiator, consisting of a material with a low melting point. When the initiator is destroyed during contact with molten debris, the loss of cable tension causes the spring-loaded actuator to open the flooding valve, and water flows from the IRWST.

The water first fills the central supply duct underneath the spreading area. From there, it enters the horizontal cooling channels and then fills the space behind the sidewall cooling structure (Figure 6-8). Finally, the water pours onto the surface of the melt; the overflow continues until the hydrostatic pressures in the IRWST and in the spreading room are equal. Both the spreading room and the IRWST are open to the containment atmosphere, with communication sufficient to prevent a buildup of pressure as steam is generated in the spreading room. In parallel with the inflow of water, the melt interacts with the sacrificial concrete covering the horizontal and vertical cooling plates. The time required to erode the sacrificial concrete allows the walls of the cooling structure to be cooled on the outside prior to their first contact with the molten corium.

6.2.2.3 Severe Accident Heat Removal System

The SAHRS works along with the CMSS to cool the molten debris. The SAHRS is a dedicated system which removes the heat generated in the containment during a severe accident (Figure 6-9). The SAHRS has four modes of operation, each playing a role in containment heat removal and in controlling the environmental conditions within the containment so that its fission-product-retention function is maintained. These modes of SAHRS operation include:

- Passive cooling of molten debris,
- Active spray for environmental control of the containment atmosphere,
- Active recirculation cooling of the molten debris and containment atmosphere, and
- Active backflush of the SAHRS pump suction strainer.

The SAHRS equipment is located in the containment and in safeguard building 4, and includes:

- A suction line from the IRWST,
- Containment isolation valves,
- A recirculation pump,
- A heat exchanger for containment heat rejection,
- Discharge lines to the containment spray header, the cooling structure which surrounds the spreading compartment, and the sump screen, and
- Support from a dedicated cooling chain via plant auxiliary systems.

The SAHRS heat exchanger transfers the residual heat from the containment to the ultimate heat sink via dedicated component cooling water system (CCWS) and essential service water system (ESWS) trains. During operation, the three possible flow paths downstream of the pump and the heat exchanger are:

- To the containment spray system with a ring header and spray nozzles,
- To the cooling structure and spreading area of the CMSS, and
- To a sump-screen flushing device which removes accumulated debris.

Table 6-2 lists SAHRS design and operating parameters.

Passive Cooling of Molten Debris

In this mode the SAHRS provides water to the cooling structure surrounding the spreading compartment. Once molten debris is within the spreading compartment, water from the IRWST passively starts to fill the cooling structure. This dedicated flooding line is equipped with a flow limiter downstream of the IRWST outlet, which limits the flow such that its subsequent complete vaporization does not present a containment-overpressurization challenge. This passive flow of water fills the cooling structure within five minutes. Water then overflows into the spreading compartment until it is hydrostatically balanced with the remaining water in the IRWST. This flooding submerges the spreading area and transfer channel, as well as a portion of the reactor cavity, thereby cooling any residual debris in those areas.

Operating in this passive mode, IRWST water supplied by the SAHRS boils off and is released into the free volume of the containment through the steam chimney directly above the spreading compartment (see Figure 6-9). As this process continues, the temperature and pressure within the containment steadily increase; however, the US-EPR containment is designed with sufficient free volume and structural heat sinks that the atmospheric conditions of the containment do not approach design limits for several hours following the onset of core damage.

Active Containment Spray

The US-EPR containment has sufficient capacity to allow a grace period of several hours before operator action is needed to prevent the pressure and temperature within the containment from exceeding design limits. When operating in the containment spray mode, the SAHRS takes suction from the IRWST; coolant then flows through a heat exchanger outside containment on its way to the spray headers located in the upper volume of the containment. The spray water condenses atmospheric steam, thereby reducing containment pressure and temperature. The resulting condensate flows back into the IRWST for continued recirculation. To initiate the SAHRS containment spray mode, the operator performs the following steps:

1. Start the dedicated cooling train (i.e., start the ESWS and CCWS pumps dedicated to the SAHRS).

2. Activate the motor-operated valves in the suction line between the IRWST and the SAHRS pump.

3. Open the valve allowing the SAHRS pump to discharge directly to the spray header nozzles located in the reactor building dome.

4. Start the SAHRS pump.

Given the deliberate steps required to actuate the SAHRS, inadvertent actuation of the SAHRS is not a credible event.

Active Recirculation Cooling

As a core-melt accident progresses, it can become necessary to use the recirculation function of the SAHRS to further control the environmental conditions within the containment. As previously discussed, the containment spray can be used to condense atmospheric steam; the condensate returns to the IRWST, where it can be used as additional inventory for continued passive cooling of the molten debris. Once the containment spray has sufficiently reduced containment pressure, the SAHRS can be switched to a long-term recirculation mode in which the SAHRS feeds water directly into the spreading area. As a result, the water pool in the cooling channels and on top of the melt becomes subcooled. Decay heat is now removed from the melt by single-phase flow, instead of by evaporation; and containment pressure is reduced.

In this mode of operation, the water in the spreading compartment rises to the top of the steam outlet chimney, overflows onto the containment floor, and drains back into the IRWST, from which it can be recirculated into the spreading area cooling system. Because the spreading compartment and the reactor cavity are connected through the gate and transfer channel, water also enters the reactor cavity and submerges the vessel up to the level of the RCS piping. This arrangement establishes long-term cooling of any debris that has remained within the transfer channel, the reactor cavity, or the vessel itself.

Sump Strainer Backflush

The final mode of operation of the SAHRS is to provide a backflushing function for the sump strainer. Operation in this mode serves to dislodge any debris from the sump strainer that might compromise the ability of the SAHRS to draw water from the IRWST. Only a fraction of the nominal SAHRS flow is used for backflushing; therefore, the system can operate in this mode while continuing operation in another containment-cooling mode.

SAHRS Dedicated Cooling Chain

To support the active heat removal modes of the SAHRS, portions of the CCWS and ESWS are used to form a dedicated cooling chain to transfer heat to the ultimate heat sink. This cooling chain is dedicated to severe accident operation and is not used to support normal plant operations or to mitigate the effects of a design-basis event. The SAHRS, the CCWS, and the ESWS are designed to receive power from either the normal offsite grid, an emergency diesel generator (EDG), or an SBO diesel generator.

The CCWS train consists of a pump located upstream of a dedicated heat exchanger, a surge tank connected to the pump suction line, and a demineralized water supply line with a pressurizing pump. This portion of the cooling chain feeds water to the shell side of the SAHRS heat exchanger, where containment heat is removed. The heated component cooling water flows through the tube side of the CCWS heat exchanger, which interfaces with the ESWS. The CCWS train is at a higher pressure than that of the interfacing SAHRS to prevent contamination of the cooling chain by leakage of radioactive water through the SAHRS heat exchanger.

Table 6-1 Design and Performance of Annulus Ventilation System

Design Feature	Value
Maximum annulus pressure during normal operation [2]	≤ -0.8 inches water gauge
Maximum annulus pressure during postulated accidents [2]	≤ -2.5 inches water gauge
Minimum annulus temperature (all modes)	45°F
Maximum relative humidity at iodine filters (postulated accident)	70%
Design pressure	2.77 inches water gauge
Design temperature	212°F
Electrical heater power (each train)	6 kW
Minimum rated efficiency – Pre-filter	55-65%
Minimum rated efficiency – HEPA filters	99.95%
Minimum rated efficiency – Iodine adsorbers [1]	99%
Fan design air flow	60 – 1177 cfm

Note:

1. Laboratory test results for both elemental iodine and organic iodine, based on four (4) inch deep bed of carbon.

2. The subatmospheric pressure in the annulus will be equal to or lower than the value listed.

Table 6-2 SAHRS Design and Operating Parameters

Parameter	Value
SAHRS Pump	
Type	Single-stage centrifugal
Nominal flow rate	232 lb/sec
Nominal discharge head	498 ft
Design pressure	436 psig
Design temperature	324°F
SAHRS Heat Exchanger (Tube Side)	
Nominal flow rate	208 lb/sec
Tube material	Austenitic stainless steel
Design pressure	436 psig
Design temperature	324°F
SAHRS Heat Exchanger (Shell Side)	
Nominal flow rate	307 lb/sec
Shell material	Ferritic steel
Design pressure	500 psig
Design temperature	215°F
Containment Spray Nozzles	
Number	75
Nominal flow rate	208 lb/sec
Design pressure	436 psig
Design temperature	324°F
Passive Outflow Restrictor	
Maximum Passive Flow Rate	220 lb/sec

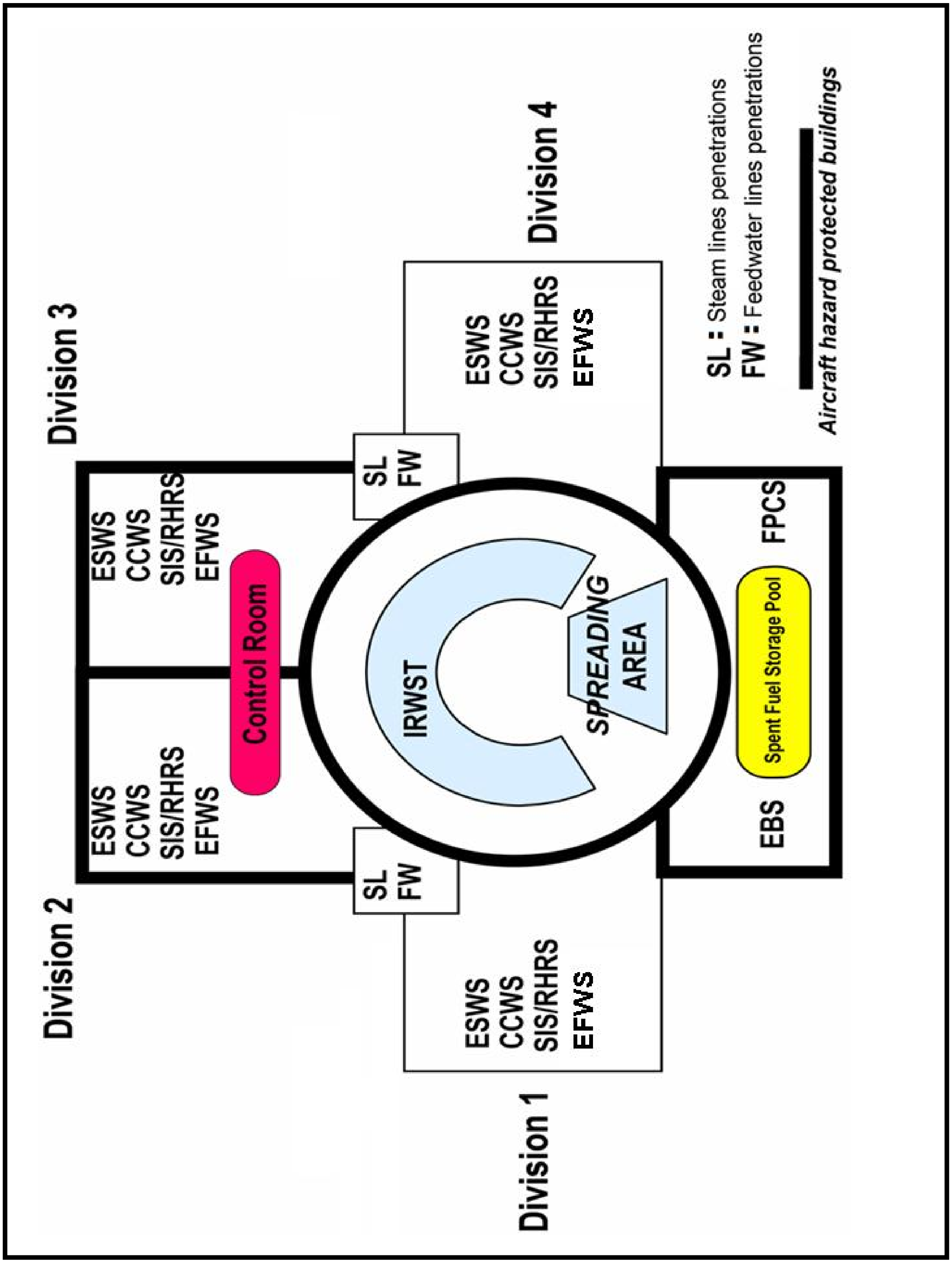

Figure 6-1 Simplified Nuclear Island Building Layout

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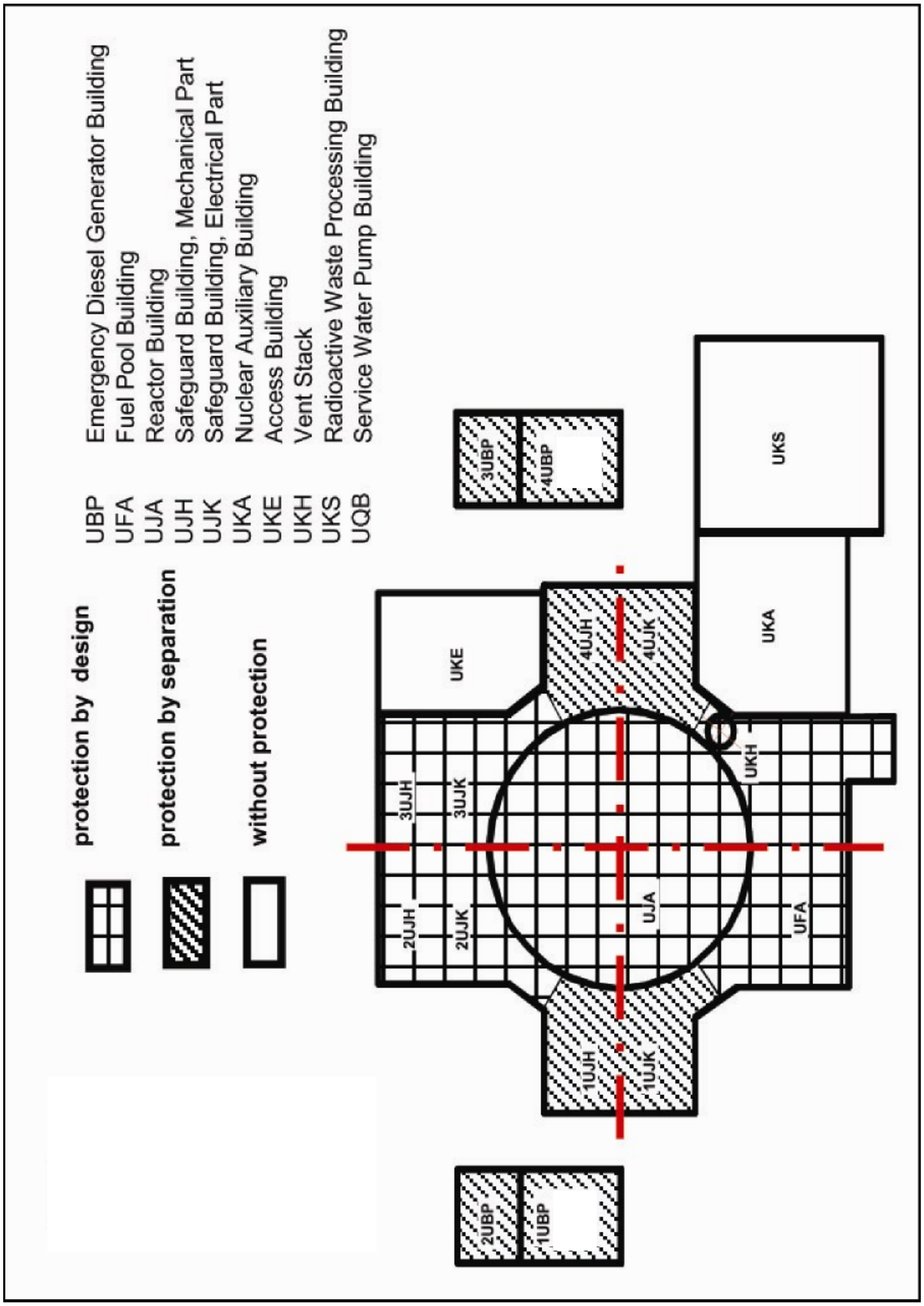

Figure 6-2 Aircraft Hazard Protection

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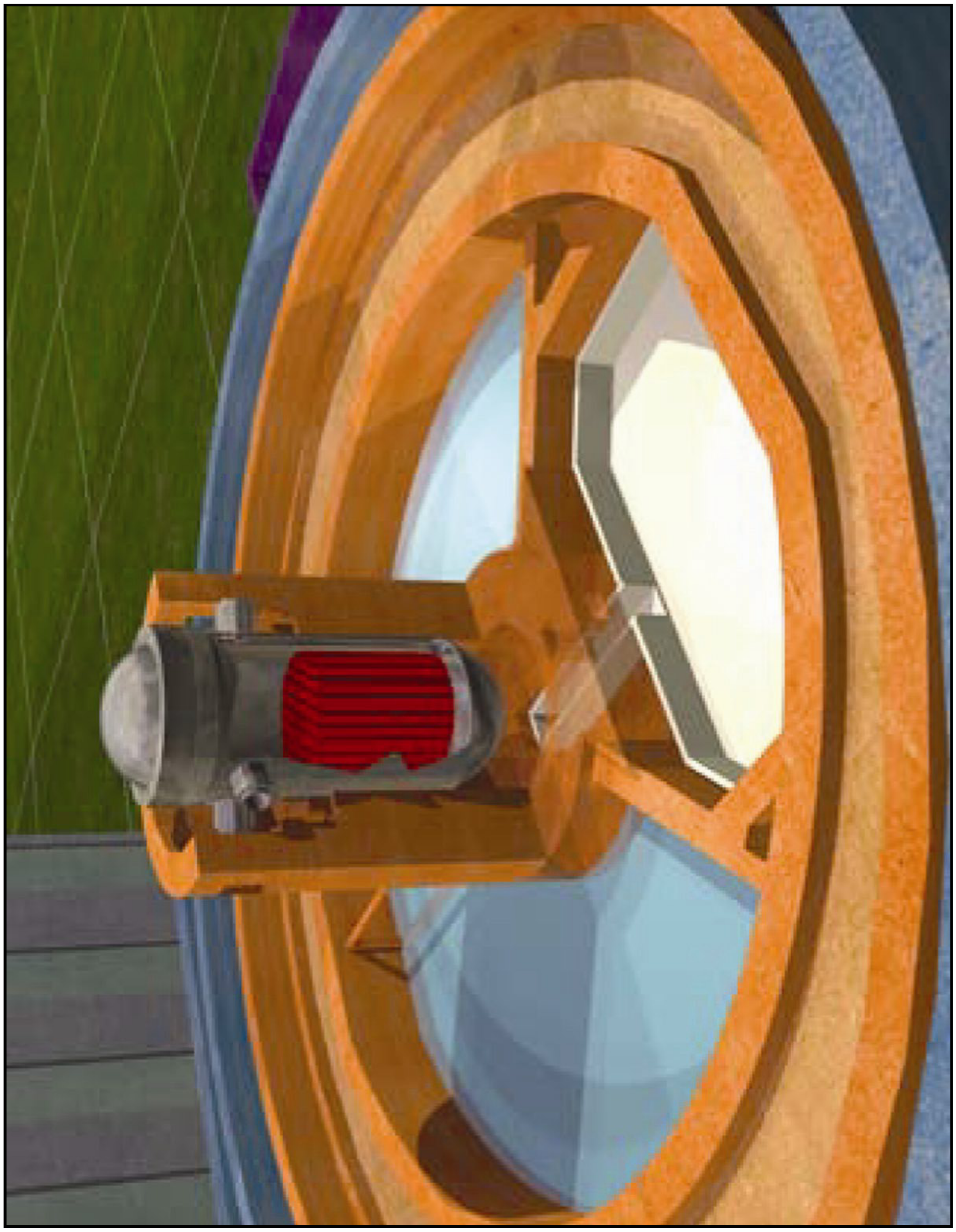

Figure 6-3 IRWST and Core Melt Spreading Area

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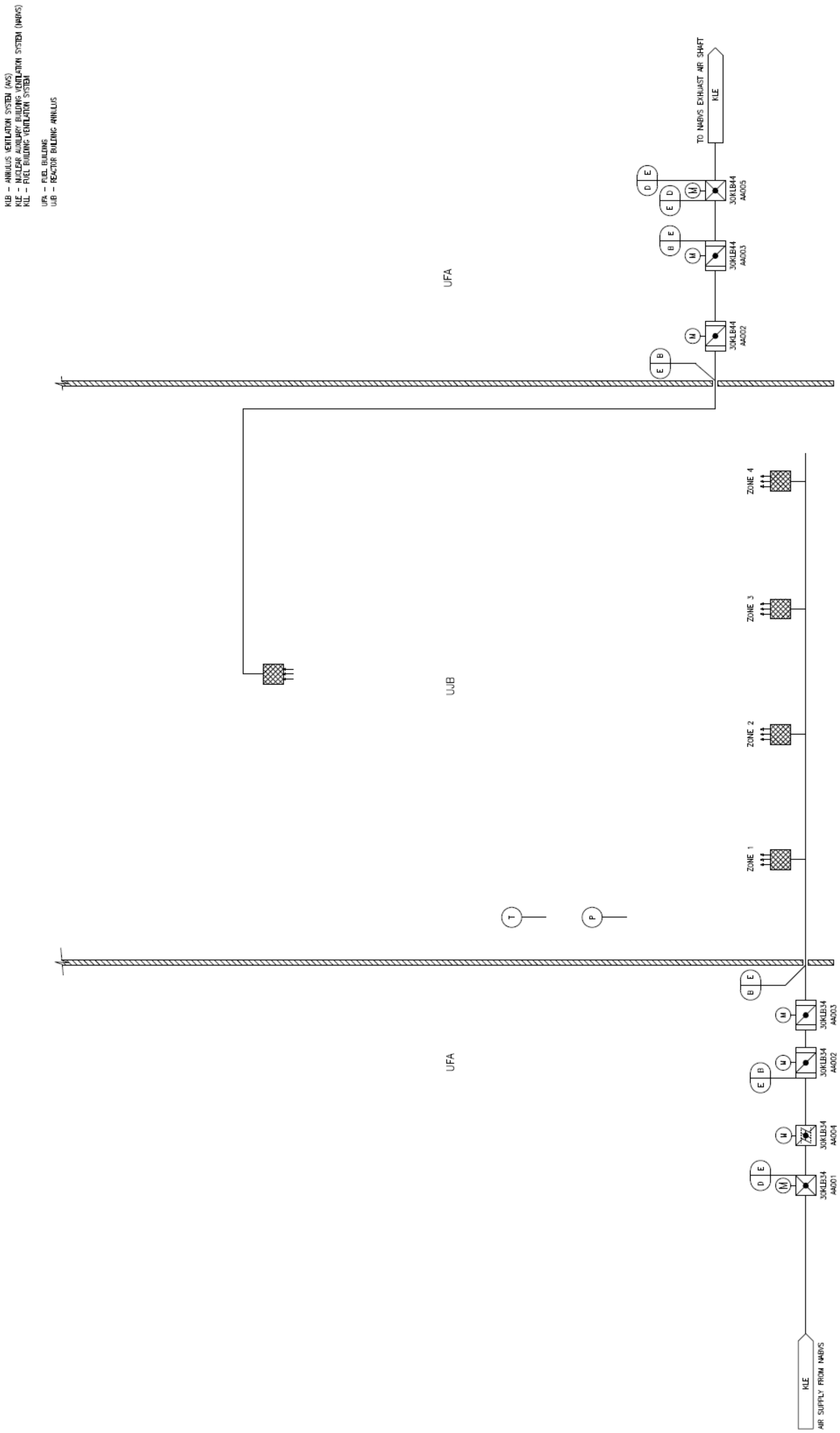

Figure 6-4 Annulus Ventilation System Normal-Operation Train

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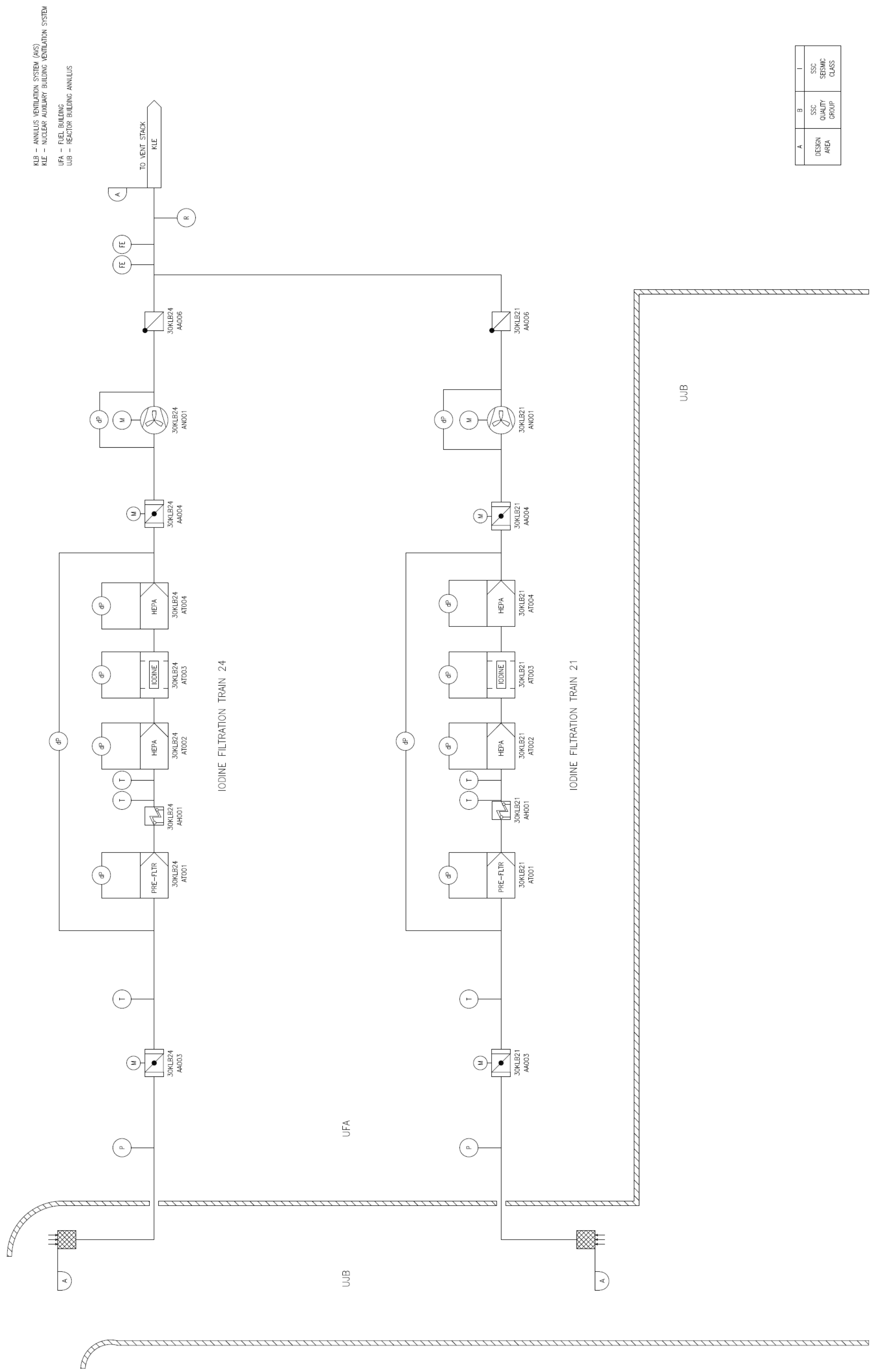

Figure 6-5 Annulus Ventilation System Accident Trains

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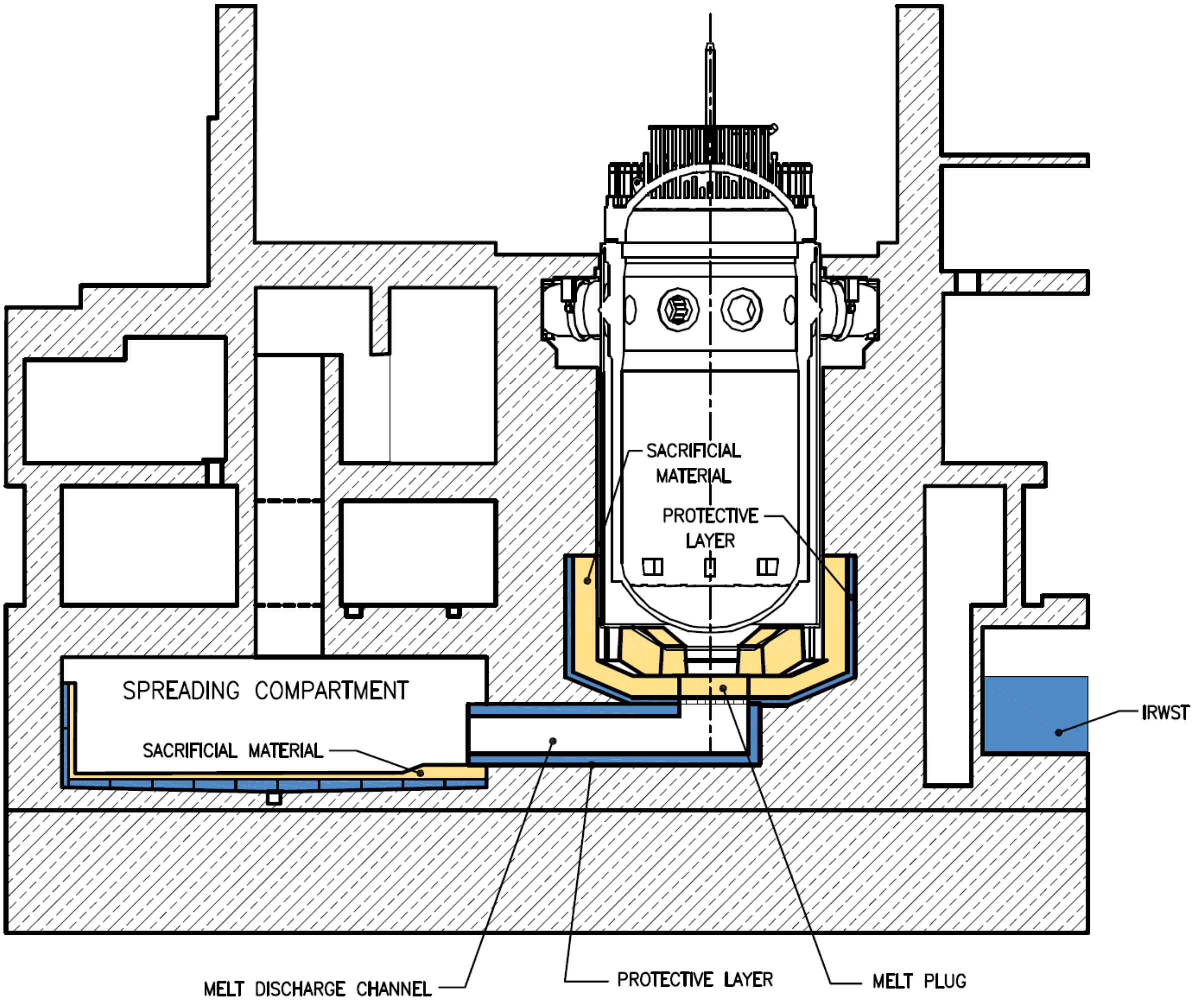

Figure 6-6 Core Melt Stabilization System

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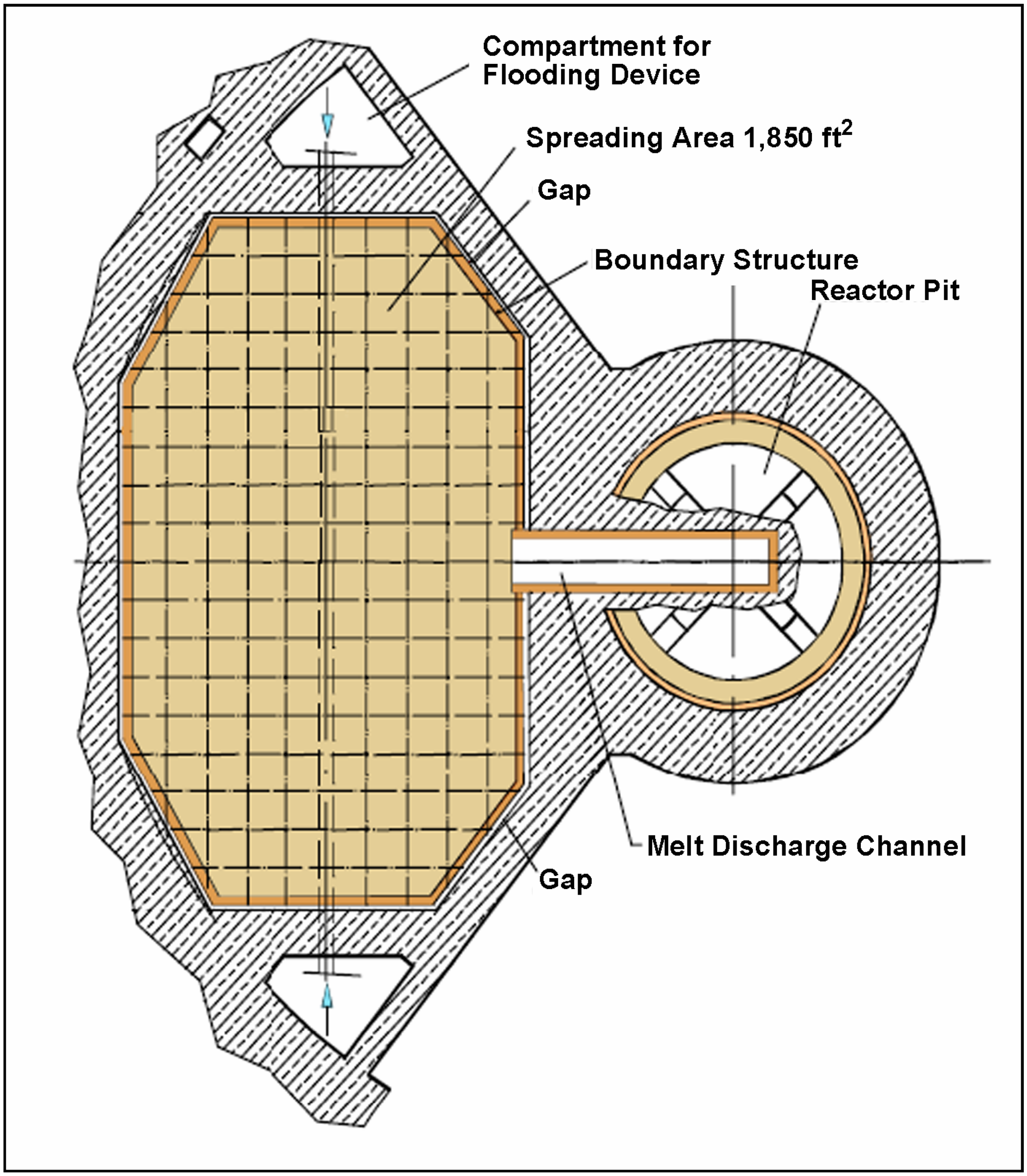

Figure 6-7 Core Melt Spreading Area

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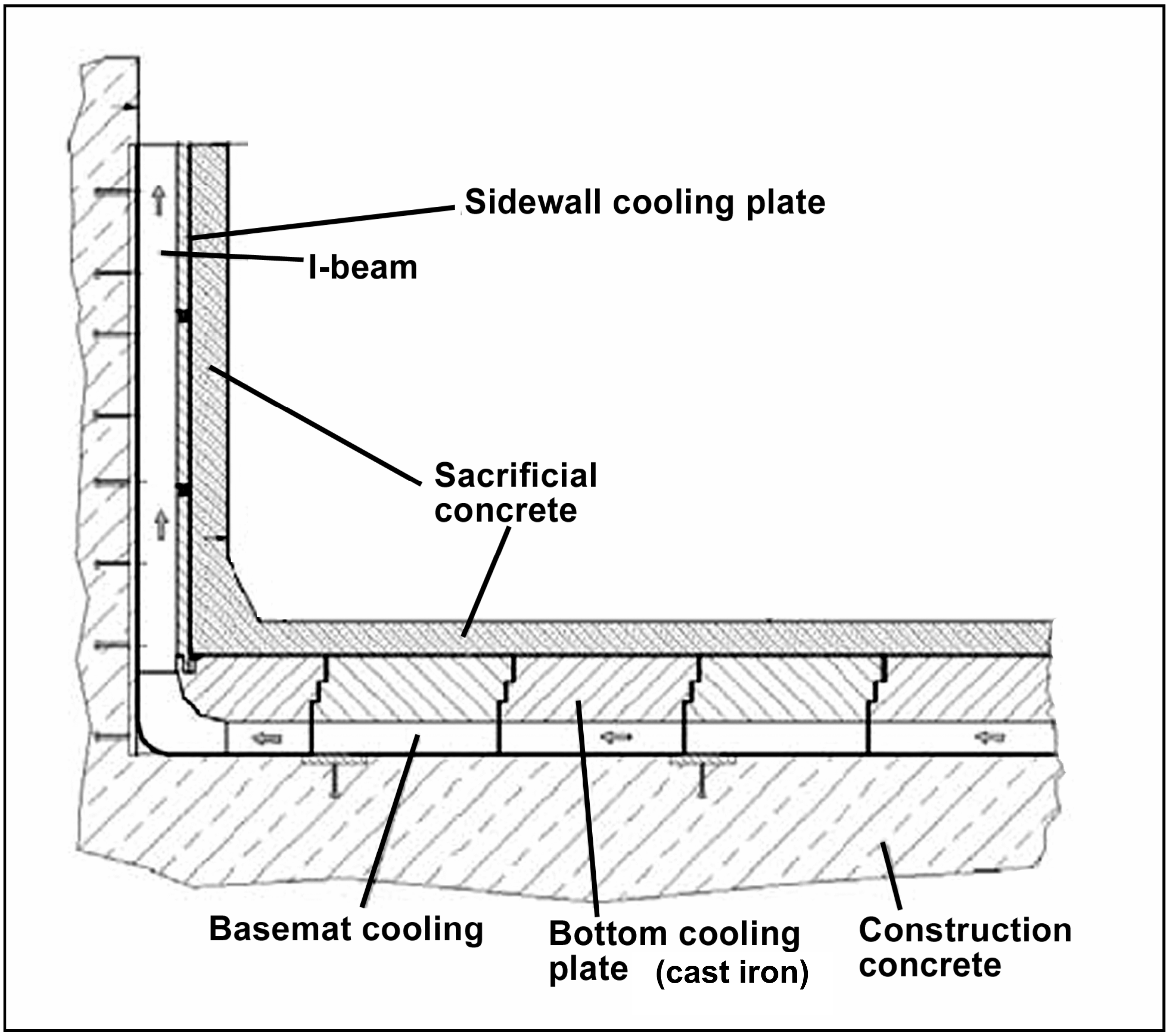

Figure 6-8 Detail of Core Melt Spreading Area and Cooling Structure

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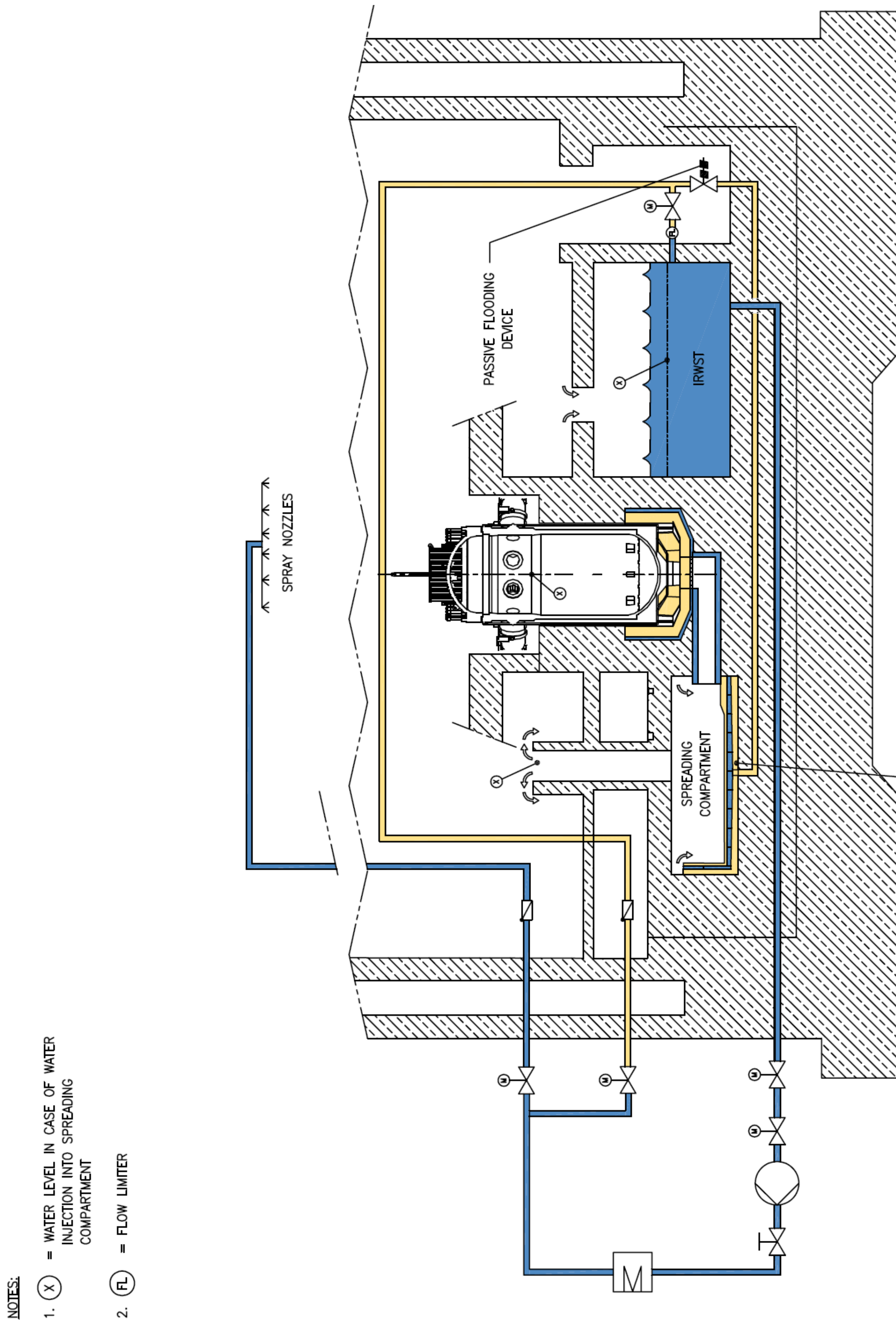

Figure 6-9 Severe Accident Heat Removal System

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