# THE VERSATILE TEST REACTOR (VTR) APPROACH TO SODIUM FIRE HAZARDS ANALYSIS AND PROTECTION SYSTEM METHODOLOGY

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## Abstract

The Versatile Test Reactor (VTR) is a sodium-cooled fast spectrum test reactor currently being developed in the United States (U.S.) to enable accelerated testing of advanced reactor fuels and materials. The design of the VTR includes the development and design of a sodium fire protection system (SFPS) and mitigation strategy for the facility to ensure that the consequences of any postulated sodium leaks are minimized. Presented in the paper is a brief description of sodium fires and sodium-water reactions considered in the design along with a description of previously proposed and/or utilized SFPS components. Next, a description of the evolution of SFPSs in the U.S. and of the software tools currently being utilized to support the development of the VTR strategy are presented. Finally, an overview of the VTR sodium fire mitigation strategy is provided for each of the major areas of the facility where significant volumes of sodium will be located.

## 1. INTRODUCTION

The Versatile Test Reactor (VTR) is a fast spectrum test reactor currently being developed in the United States (U.S.) under the direction of the U.S. Department of Energy, Office of Nuclear Energy. The mission of the VTR is to enable accelerated testing of advanced reactor fuels and materials. The conceptual design of the VTR is that of a 300 MW(th) metallic-fueled pool-type sodium-cooled fast reactor (SFR). The VTR project is led by U.S. National Laboratories in collaboration with industry partners including General Electric-Hitachi (GEH) and Bechtel National Inc.

The design of the VTR includes the development and design of a sodium fire protection system (SFPS) and mitigation strategy for the Reactor Facility rooms housing both primary and secondary sodium piping and components. To design such a system and mitigation approach, it is important to review and understand the lessons learned from previous reactor designs and sodium fire testing programs. The evolution of SFPSs from previously built and operated reactors such as the Experimental Breeder Reactor II (EBR-II) and the Fast Flux Test Facility (FFTF) to proposed reactor designs such as the Clinch River Breeder Reactor (CRBR), PRISM, the Sodium Advanced Fast Reactor (SAFR), and the Large-Scale Prototype Breeder (LSPB) is summarized. Additionally, software tools (NACOM and SOFIRE-II) utilized to analyze sodium fire scenarios for the VTR are briefly described along with a summary of current software verification and validation (V&V) efforts. Finally, based on the evolution of and lessons learned from previous SFPSs and the results from preliminary sodium fire analyses, the current design philosophy for the VTR SFPS and mitigation approach is presented.

## 2. SODIUM FIRES

Liquid sodium coolant at normal SFR operating temperatures (approximately 350 °C – 550 °C) will readily ignite in air environments. The severity of the resulting fire scenario depends on several factors including sodium temperature, amount of available oxygen, geometric factors (size and configuration of leaked sodium volume), and the type of fire (pool fire versus spray fires which are both described in this paper). To minimize the consequences associated with sodium fires, SFPS and mitigation strategies are utilized to provide a means of detecting, locating, containing, and suppressing the fires.

Under certain postulated conditions, a postulated sodium leak from a pipe or other sodium component can result in a spray fire which occurs as drops of sodium travel through a gas that contains a sufficient amount of oxygen to support sodium combustion. The drops may be the result of liquid sodium jet breakup, dripping from components, or splashing of sodium off of surfaces. The ignition and burning rate of sodium sprays depends on environmental and spray characteristics such as sodium drop size, sodium temperature, velocity, fall height, and oxygen concentration and air/oxygen entrainment. Sodium spray fires have the potential to rapidly transfer most of the sodium thermal energy and heat released from sodium combustion directly to the atmosphere resulting in environmental temperatures and pressures significantly higher than that of sodium pool fires. In most scenarios, spray fires always burn at a higher rate than a pool fire containing the same amount of sodium because the sodium is burning in a highly divided state (increased surface area over which combustion can occur). The consequences of large sodium spray fires are severe enough that the goal of any successful SFPS and mitigation strategy should be to preclude their occurrence.

For sodium leaks that do not disperse into drops and ignite (or drops that do not fully burn while traveling in air), the sodium can collect upon structures and/or surfaces forming a sodium pool. The ignition and burning rate of sodium pools depends on environmental and pool characteristics such as the pool surface area, sodium temperature, oxygen mode of transport to the sodium pool surface (or flame region just above the pool surface), and the formation or deposition of reaction products on the pool surface.

In addition to sodium-air reactions, sodium-water reactions are also possible following a postulated sodium leak. Facility design decisions can minimize the possibility of sodium-water reactions. An example of this is ensuring that systems containing water and systems containing sodium are not co-located, however, sodium-water reactions can occur if leaked sodium contacts concrete. In these reactions, water (steam) evaporates from the concrete reducing its structural strength and reacts with the liquid sodium resulting in the production of sodium hydroxide, sodium monoxide, and gaseous hydrogen. Additional reaction products can erode the concrete and further reduce its structural integrity.

## 3. SODIUM FIRE PROTECTION SYSTEMS

It is important to recognize that SFPSs and mitigation strategies have evolved through the years in the U.S. from the approach implemented at EBR-II to the proposed approaches for the SAFR, PRISM, and LSPB designs. This evolution was driven by lessons learned, improved analysis capabilities, and experiment testing programs. Another important evolution driver was the result of evolving safety philosophies which were trending toward more passive solutions and away from crediting active systems. General perspectives on the evolution of SFPSs in the U.S. can be found in papers presented at the International Atomic Energy Agency (IAEA) Internal Working Group on Fast Reactors (IWGFR) Specialists' Meeting on Sodium Fires, Design and Testing [1] which was held in 1988.

### 3.1. Sodium Fire Protection System Components Considered in the U.S.

To discuss the evolution of SFPSs, it is necessary to have a basic understanding of typical types of components that have been utilized in previous sodium fire mitigation strategies. Brief summary descriptions are provided here for major components of SFPSs.

Compartment Liners

Comprised of steel plates that cover the walls, floors, and ceilings of a compartment. The plates are welded together at their common edges to form the pressure boundary of a compartment and serve to protect the concrete behind the liner from direct chemical and thermal attack from any leaked sodium and from the cell atmosphere should it be heated and laden with aerosols from a sodium fire. Historically utilized in loop-type SFR compartments containing primary reactor sodium components.

Catch Pans

Similar to the floor liner component of compartment liners in that they are typically made of steel designed to protect concrete from direct contact with sodium and have an insulating layer underneath to thermally protect concrete beneath the catch pan. Unlike compartment liners, catch pans do not typically form a pressure boundary for a compartment. Catch pans are used to confine leaked sodium to a fixed area or to direct leaked sodium to a drain in the catch pan. If utilized to confine sodium (as opposed to draining), these components are typically designed to contain an assumed amount of sodium postulated to leak in the compartment in which the pans are located. Catch pans without a drain may be sub-divided to reduce the surface area of a leak sodium pool to minimize the pool burning rate. An example of a typical catch pan configuration is provided in Fig. 1.

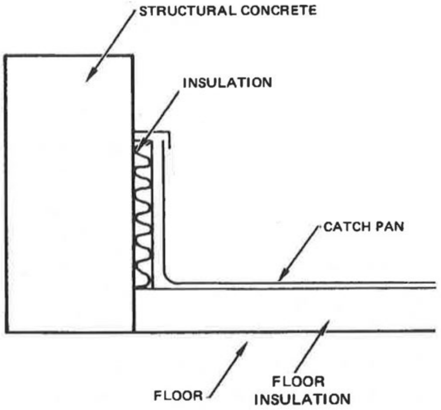

*FIG. 1. Example of a typical catch pan configuration.*

Suppression Deck System

Similar to a catch pan in that it is designed to contain sodium in a fixed place or allow it to drain, however, suppression decking is used to significantly reduce the burning rate of a sodium pool by limiting the transport of oxygen to the pool surface. Suppression deck system designs are typically more complex than catch pans and include components such as deck surface grating or plates, drain pipes, vent pipes, supporting structures, and insulating materials. The systems are typically designed to passively minimize the burning rate of sodium. An example of a suppression deck system proposed for CRBR is provided in Fig. 2.

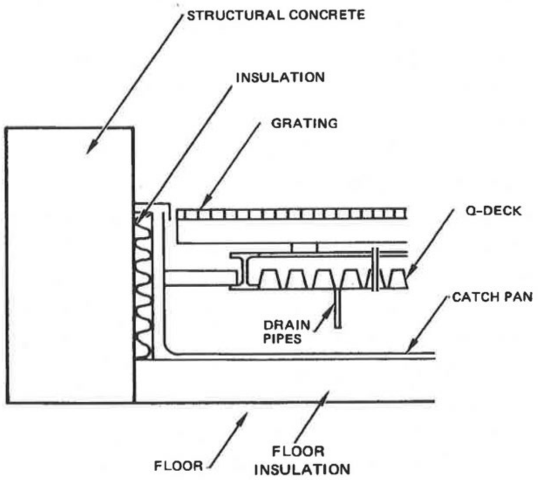

*FIG. 2. CRBR style suppression deck system.*

Pipe Insulation Jackets/Leak Jackets

Pipe insulation jackets wrap around and completely enclose sodium piping to both thermally insulate the pipe to reduce heat losses to the surroundings and to provide protection against sodium spray fires. They are typically comprised on in inner steel wrapper, an insulated layer, and an outer steel wrapper. Pipe leak jackets are similar to insulation jackets except they have an engineered drain pathway designed to direct leaked sodium from the annulus between the sodium pipe outer wall and the leak jacket inner steel wrapper to another component such as a catch pan, suppression deck, or drain/smothering tank.

Double-walled Piping

Pipe-in-pipe design utilized to reduce the likelihood of a sodium leak into a compartment by providing multiple barriers between the sodium and the compartment atmosphere. During normal operation, sodium is contained inside the inner pipe (carrier pipe) wall, but if a leak/rupture were to occur in the inner pipe, sodium would leak into the annulus between the carrier pipe outer wall and the guard pipe (the outer pipe) inner wall. The annulus between the carrier and guard pipe is inerted to limit sodium chemical reactions with oxygen or moisture and the guard pipe may be sloped in a way such that any leaked sodium from the carrier pipe can drain to a collection area or tank. Thermal insulation for double-walled piping is located outside the guard pipe.

Leaked Sodium Drain Tank/Vault

A steel tank (separate from a sodium loop drain tank) or steel lined vault designed to contain the maximum amount of sodium that may leak in a given area. Insulation is utilized around the tank or behind the steel liner to thermally protect concrete. This component is typically part of a larger system of leak jackets, catch pans, drain pipes, etc., that direct any leaked sodium into the tank/vault. Limits the amount of sodium burning or the sodium burning rate to oxygen remaining inside of the tank of circulating into the tank through the drain network. Also includes vents to protect from over-pressurization due to sodium burning (system typically not inerted).

### 3.2. Evolution of Sodium Fire Protection Systems and Mitigation Strategies

When reviewing sodium fire mitigation strategies of previous reactors and proposed reactor designs, one thing that stands out is how different the strategies are from one reactor plant design to another. These differences lead to questions such as why does the mitigation strategy for FFTF differ from that of EBR-II or the strategy for CRBR differ from that of FFTF? No SFRs have been built in the U.S. after FFTF, but several designs were proposed and each has differing methods for mitigating sodium leaks even though in some cases, the same organizations were responsible for developing those strategies. What was changing throughout the years to drive this evolution? This section of the paper will provide a brief overview of some of the major shifts in sodium fire mitigation strategy philosophies which will help provide a foundation for the current philosophy for the VTR.

The design basis for the EBR-II (a pool-type SFR) containment, which was a welded steel shell lined with concrete, was a massive sodium spray fire following a hypothetical dispersal of primary sodium upward into the containment. The containment shell structure was designed to withstand the temperatures from a massive sodium fire. The extent of sodium burning inside containment would be limited by the mass of oxygen available. Containment inerting was not utilized for sodium fire mitigation at EBR-II. The mitigation strategy did incorporate an early form of a sodium fire suppression deck system in some areas of the plant to prevent spilled sodium from interacting with the underlying concrete floor. The floor/deck consisted of steel plates with holes through which sodium could drain onto an underlying steel catch pan. The holes would limit the transport of oxygen to the surface of a sodium pool after spilled sodium had collected on the catch pan thereby reducing the sodium burning rate relative to sodium spreading over a steel floor without holes and burning as a sodium pool. In addition to the suppression deck system, the EBR-II mitigation strategy included large pressurized dispensers of dry extinguisher powder that would be actuated remotely after completion of a sodium spill. The powder used was MET-L-X of which the main ingredient is sodium chloride. In addition, MET-L-X contains a polymer for sealing and other additives to render it free-flowing and to cause heat caking (or crusting) that denies the burning material oxygen. MET-L-X dispensers were located throughout cells containing primary and intermediate sodium piping and components.

The strategy incorporated at EBR-II represents the safety philosophy and knowledge of sodium fires that existed when the plant was designed. Some aspects of this strategy were incorporated into FFTF, while others changed significantly. The FFTF (a loop-type SFR) SFPS strategy [2] incorporated a steel-lined containment structure that housed the major primary sodium components, but unlike EBR-II, the environment inside containment was inerted with nitrogen to minimize the burning of and aerosol formation from any leaked radioactive primary sodium. Areas of the plant that housed intermediate heat transport system (IHTS) piping and components contained air environments such that any leaked sodium was assumed to result in a fire. To minimize the consequences of the sodium leaks in these areas, insulation jackets were utilized on all IHTS piping and a newer (compared to that of EBR-II) design of suppression decking was incorporated to contain leaked sodium. Additionally, in these areas, an active nitrogen injection system was credited with being able to minimize sodium burning following a leak by a method referred to as "space isolation." The goal of the nitrogen injection system was to exclude additional oxygen from entering the compartment by maintaining a slight positive pressure in the compartment which would allow time for the sodium to the cool to a sufficiently low temperature such that continued burning was unlikely. It was envisioned that nitrogen injection would limit the amount of sodium that could burn to that able to react with the oxygen initially inside of the cell.

An important step in the evolution of SFPSs between EBR-II and FFTF was the move away from large dry powder injection systems. While dry powders had proved effective on suppression of small sodium pool fires in small-scale experiments, larger-scale testing had demonstrated limitations of dry power systems on larger surface area fires (areas greater than 100 sq. ft. (9.3 $m^2$)) [3].

Utilizing lessons learned from both EBR-II and FFTF along with experience and knowledge resulting from both small- and large-scale testing programs, the CRBR sodium fire mitigation strategy was developed during the conceptual design phase of the facility. CRBR (a loop-type SFR) utilized a very similar sodium fire mitigation strategy [4] to that of FFTF for areas containing primary sodium piping and components; a steel-lined containment structure with inerted rooms. However, for areas of the plant that contained IHTS piping and components, the strategy differed significantly. While small- and large-scale experiments demonstrated that nitrogen injection systems could be effective in minimizing sodium burning, the effectiveness of such a system in the actual facility was much less due to larger than expected compartment leak rates. Nitrogen injected in one area would leak into another such that large a volume of nitrogen would need to be continually injected into the area that contained the leaked sodium in order to maintain a slightly positive compartment pressure. The amount of time required for nitrogen injection along with the volume required to maintain the pressure difference made the system ineffective and impractical. In addition to the limitations of the nitrogen injection system, overall mitigation philosophies of the time were transitioning away from active systems and favoring more passive means of mitigation [5]. This resulted in the CRBR mitigation strategy being completely passive incorporating a combination of sodium piping leak jackets (an evolution of the FFTF insulation jackets), catch pans, and a newly designed and purely passive suppression deck system that would contain leaked sodium. The new suppression deck system was much more sophisticated than those incorporated into previous designs and its development was supported by large-scale testing programs [4]. The overall strategy was for leaked sodium from an IHTS pipe to be captured in the leak jacket of the pipe and directed to engineered drains connected to the leak jacket which would drain the sodium to either (depending on which area of the facility the leak occurred in) a catch pan or the surface of the suppression deck system. Catch pans were sloped such that any leaked sodium that entered the catch pan would be directed to drains that either (again, depending on the facility area that the leak occurred in) led to another catch pan or the surface of the suppression deck system. In this way, a flow path was established for any leaked sodium to eventually end up in the suppression deck system where burning would be minimized, and the sodium would eventually freeze.

The CRBR sodium fire mitigation approach represented a major step forward in the evolution of SFPSs, but also led to additional issues and concerns. First, due to the proposed path of leaked sodium from a pipe leak jacket to the suppression deck system, a fire in one room of the facility could result in fires in multiple rooms as the sodium in each of the draining catch pans would burn as it was draining to the next catch pan or suppression deck system. Second, experiment testing of the CRBR leak jacket design demonstrated that as much as 5% of the leaked sodium could leak out of the joints of the leak jacket (as opposed to following the planned pathway to the leak jacket drain), if the leak jacket annulus were pressurized up to approximately 2 psig (13.8 kPa). The sodium leaking from the joints of the leak jacket would then be free to drip from the surface of the leak jacket and burn as a spray while falling to a catch pan. While it is anticipated that all sodium leaks begin as small weeping leaks that may grow with time and that these leaks are easily detectable such that actions can be taken before larger leaks occur, bounding and conservative pipe failures, postulated sodium leak volumes, and the desire to not credit human actions or active systems can result in large temperature and pressure loadings due to 5% of the assumed leaked volume burning as a spray fire. Finally, concerns centered around the ability of the newly designed suppression deck system to thermally protect concrete (keep concrete temperatures below 100 °C) on the sides of and below the suppression deck system. This concern depends heavily on the available floor area of the room in which the suppression deck system is located because that area along with the volume of leaked sodium determines the depth of the sodium pool in the suppression deck system. For the CRBR, the sodium pool depth maximum was approximately 9 inches (0.229 m) which required approximately 12 inches (0.305 m) of insulation to thermally protect the concrete. For sodium pools much deeper than 9 inches (0.229 m), the thickness of required insulation can make the suppression deck system design impractical. These issues and concerns resulted in further evolutions of SFPSs for areas containing IHTS piping and components.

The IHTS sodium fire mitigation strategies of PRISM, LSPB, and SAFR are all modifications of the CRBR strategy [1]. The PRISM strategy [1] proposed leak jackets similar to those of the CRBR that drain directly onto a suppression deck system which is also similar to that proposed for CRBR. The LSPB strategy [6] proposed using CRBR-style leak jackets, catch pans, and a suppression deck system with an overflow drain path to a separate sodium leak tank. The SFPS design team of LSPB carried out evaluations of different modifications to the CRBR strategy in an attempt to address concerns about spray fires associated with the 5% of leaked sodium leaking out of the joints of the pipe leak jackets. Ultimately, the LSPB design recommended installing intermediate floors with catch pans on each floor in higher elevation rooms to limit the sodium dripping fall height. As previously stated, to address the CRBR strategy concerns about the depth of a sodium pool in the suppression deck system, the LSPB strategy was to have an overflow drain path in the suppression deck system that would limit the depth of the sodium in it. The overflow drain path routed sodium to a separate tank that was located outside the area where the IHTS piping and components were located. The SAFR strategy [1] proposed using CRBR-style leak jackets, catch pans, and a drain pipe network that routed sodium directly from the leak jackets and catch pans to a vault located outside the reactor facility building footprint.

## 4. SODIUM FIRE ANALYSIS SOFTWARE TOOLS

Two sodium fire software tools are currently being utilized for VTR to assess the effectiveness of proposed SFPSs and mitigation approaches. The NACOM code [7] is utilized for analysis of sodium spray fire scenarios and the SOFIRE II code [8] is utilized for sodium pool fire scenarios. These tools were selected for use because the original unmodified source code models only a sodium spray fire or sodium pool fire, is readily available, and is documented in user's manuals containing sample problems. Thus, each individual code enables users to investigate loadings from only a sodium spray fire or only a sodium pool fire without the effects of sodium burning in other modes. This is a benefit in developing individual elements of a sodium fire mitigation approach.

For the sodium fire computer codes utilized, verification and validation (V&V) as well as quality assurance are of importance. Verification presently includes understanding the modeling incorporated in each software package and how it is implemented in the source code. The goals of the verification effort include determining whether the authors of the source code made any errors either in formulating the model equations, formulating the modeling in Fortran statements, formulating numerical solutions, or through accidental mistakes such as typographical errors. The Fortran source code for each tool was examined line-by-line and any errors and uncertainties in the source code were identified. Additionally, specific deficiencies in model formulations and implementation were identified as well as areas where modeling improvements and error corrections were warranted.

Quality assurance requires that the software tools be placed under version control. When mistakes are discovered or if deficiencies in modeling are identified, the code is corrected or improved, and saved as a distinct version in a version control repository. In specific instances, modeling improvements as well as error corrections have been made to both NACOM and SOFIRE II for use in the VTR Project. Those improvements have been implemented as new versions under the version control regime.

Validation of the software tools includes comparisons between computational results and meaningful experiment data. For the sodium fire tools, the purpose of validation is to understand the computational results versus experiment data, whether there be agreement or disagreement, so that the tools can be best applied in development and performance assessments of the sodium fire mitigation approaches, and the results of calculations for applications to the sodium fire mitigation approaches are appropriately interpreted. NACOM results has been compared [9] with data from the AB5 [10] and AB6 [11] experiments carried out at the Hanford Engineering Development Laboratory (HEDL). Both experiments involved injection of a sodium spray into a closed vessel; AB5 had a fast injection rate and AB6 a slow injection rate. SOFIRE II results has been compared [12] with the AB1 [13] and F2 [14] experiments at HEDL. The AB1 test involved a sodium pool fire inside of a closed vessel. F2 mocked up sodium pool fires in a portion of a Fast Flux Test Facility (FFTF) secondary sodium loop piping tunnel. Reasonably good agreement was obtained between software calculations with appropriate input assumptions and experiment data (see [9][12] for specific comparison results).

## 5. VTR SODIUM FIRE PROTECTION SYSTEM AND MITIGATION STRATEGY

The VTR facility presents some unique challenges compared to previous SFRs. First, unlike some previous facilities, not all areas containing primary sodium components will be inerted. If any areas of the VTR facility will be inerted, it will likely be limited only to relatively small compartments containing primary sodium purification system components. Second, because the facility utilizes sodium-to-air heat exchangers which are located outside, there are relatively long sodium pipe runs which translates into a relatively large secondary sodium volume. Third, previous facilities were able to rely on both small- and large-scale sodium fire testing capabilities that existed in the U.S. or were constructed to support development of their SFPS components and strategies. It is currently assumed that no large-scale facilities will be available to support the development of new component designs. This means that the VTR SFPS strategy will have to rely on previously designed and tested components and strategies.

Utilizing lessons learned from EBR-II and FFTF operational experience, results from previous small- and large-scale experimental testing programs, historical sodium fire analyses, the documented evolution of sodium fire protection systems in the U.S., and software tools such as NACOM and SOFIRE-II, the VTR SFPS and mitigation strategy are currently being developed. While this is an ongoing process and subject to change, the overall goals and design philosophy of the strategy are more stable. Similar to previously described SFPSs and mitigation strategies, the VTR philosophy is different for different areas of the facility which each have their own challenges. Due to the preliminary nature of the development of the VTR SFPS, analyses results are not provided here, but options for the SFPS are summarized.

### 5.1. Reactor Room/Head Access Area

In the areas containing the primary sodium system components (reactor vessel, reactor head, etc.) the mitigation strategy is to incorporate multiple barriers between primary/secondary sodium coolant and the compartment air atmosphere. This not only reduces the probably of a radioactive sodium fire occurring, but also protects safety class components associated with fundamental safety functions such as reactivity control and decay heat removal.

The barriers between the primary/secondary system sodium and the compartment atmosphere in this area are passive such that no actions are needed for the barriers to perform their desired functions. A good example of the type of components that may be utilized to fulfil this function is double-walled piping with an inerted annulus between the two pipe walls which can be monitored for sodium leakage. Other components/system likely to be located in this area such as the primary sodium purification system, are expected to also have multiple barriers and may incorporate inerted enclosures to minimize the consequences from postulated sodium leaks.

### 5.2. Reactor Building Outside the Reactor Room

Areas outside the VTR reactor room contain secondary sodium piping and components. In these areas, sodium leaks from a maximum hole size equal to that specified for a leak before break scenario for moderate energy system piping are analyzed. That maximum leak size is equal to one-half the pipe outer diameter multiplied by one-half the pipe wall thickness. A goal of the sodium fire protection system for this area is to maintain concrete floor, walls, and ceiling temperatures below 150 °F (66 °C) to minimize the release of free water. Analysis results demonstrate this can be accomplished by utilizing a combination of leak jackets, catch pans, drain pipes, and sodium collection tank. The floor area of the building combined with the total volume of sodium available to leak in these areas make a suppression deck system impractical. To meet the 66 °C goal, sodium spray fires must be minimized by either collecting any sodium leaking from the sodium pipe leak jacket joints and directing it to drain pipes or by adding catch pans at multiple elevations to significantly minimize the sodium drip fall height. Both of these options and combinations of the two are currently being assessed for the VTR design."

### 5.3. Outside the Reactor Building

Secondary sodium piping connects the intermediate heat exchangers located in the reactor vessel to sodium-to-air heat exchangers located outside the reactor facility. Sodium fire and sodium-water reaction concerns outside the reactor facility differ from those inside. For example, piping located outside can be exposed to different environmental conditions (rain, snow, etc.), such that weather protection of components should be considered. Another important consideration in this area is separation between the two secondary system trains such that a fire or sodium-water reaction resulting from the leak in one train does not affect the functionality of the second. Inside the facility, the two secondary sodium trains are located in separate fire zones, except in the reactor room where additional physical barriers separate the systems. The fire zones provide separation via distance and physical barriers such as walls. A similar level of separation should be provided outside the facility. This could be accomplished in multiple ways. For example, the piping outside the facility could be separated by a distance sufficient to ensure proper separation, routed in separate underground pipe tunnels, or in above ground structures that provide adequate assurance of separation while also providing weather protection. In addition to weather protection and separation, other SFPS concerns can be addressed using a similar strategy to that proposed for inside the building where leaked sodium is routed to a sodium collection tank via leak jackets and drain pipes.

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