Safety Design Strategy for the Microreactor Applications Research Validation and Evaluation (MARVEL) Project

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ABSTRACT

The purpose of the Microreactor Applications Research Validation and Evaluation (MARVEL) project is to meet the U.S. Department of Energy (DOE) research and development (R&D) needs by designing and building a nuclear microreactor application test platform at Idaho National Laboratory (INL) that will offer experimental capabilities for performing R&D on various operational features of microreactors and improving integration of microreactors to end-user applications, such as energy storage and water purification. The MARVEL is proposed to be located at the INL Transient Reactor Test (TREAT) facility in the north high-bay equipment pit.

Per the criteria in DOE-STD-1189-2016, "Integration of Safety into the Design Process," MARVEL has the potential to: 1) change an existing process or add a new process resulting in the need for a safety basis change requiring DOE approval; 2) utilize new technology or government furnished equipment (GFE) not currently in use or not previously formally reviewed/approved by DOE for the affected facility (TREAT); 3) create the need for new or revised safety structures, systems, and components (SSCs); and 4) involve a hazard not previously evaluated in the documented safety analysis (DSA). Therefore, the MARVEL has been determined to meet the definition of a major modification and will be managed accordingly.

In accordance with DOE-STD-1189-2016, this safety design strategy (SDS) documents the expectations and the format for integrating the major modifications to the TREAT facility and describes the actions necessary to update or revise the existing TREAT facility safety basis. A major modification requires the development of a preliminary DSA (PDSA) per 10 *Code of Federal Regulations* (CFR) 830.206, "Preliminary Documented Safety Analysis." Additionally, safety analysis documentation must meet the requirements as set forth in 10 CFR 830, "Nuclear Safety Management," Subpart B, "Safety Basis Requirements."

MARVEL will not be governed by DOE O 413.3B, "Program and Project Management for the Acquisition of Capital Assets"; however, the spirit of the order shall be followed where appropriate. DOE O 420.1C, "Facility Safety," and the expectations of DOE-STD-1189-2016 provide for identification of hazards early in the project and use of an integrated team approach to design safety into the project. This SDS provides the basic safety-in-design principles and concepts using a graded approach based on the importance to nuclear safety of the MARVEL SSCs.

REVISION HISTORY LOG

Rev.	Date	Affected Pages	Revision Description
0	12/08/21	All	See DCR 677003. New issue.

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FIGURES

TABLES

ACRONYMS

AC	alternating currant
ALARA	as-low-as-reasonably-achievable
ANS	American Nuclear Society
AR	augmented requirements
ASME	American Society of Mechanical Engineers
CD	control drum
CFR	*Code of Federal Regulations*
DBA	design basis accident
DC	direct current
D&D	decontamination and decommissioning
DID	defense-in-depth
DOE	Department of Energy
DOT	Department of Transportation
DSA	documented safety analysis
ECU	engine control units
EG	evaluation guideline
ESF	engineered safety feature
F/CS	filtration/cooling system
FSAR	final safety analysis report
FSF	fundamental safety function
GDC	general design criteria
GFE	government furnished equipment
HC	hazard category
HVAC	heating, ventilating, and air conditioning
I&C	instrumentation and control
IE	initiating event
IHX	intermediate heat exchanger
INL	Idaho National Laboratory
IRF	inherent reactivity feedback
kW	kilowatt
kWe	kilowatt-electric
kW_{th}	kilowatt-thermal
LBE	licensing basis event
LCO	limiting condition for operation
LLW	low-level waste
LMP	Licensing Modernization Process
LOCA	loss of coolant accident
LOOP	loss of off-site power
LWR	light-water reactor

MARVEL	Microreactor Applications Research Validation and Evaluation
MFC	Materials and Fuels Complex
MMD	major modification determination
NaK	sodium potassium eutectic
NDC	NPH design category
NEI	Nuclear Energy Institute
NFPA	National Fire Protection Association
NPH	natural phenomenon hazard
NRC	Nuclear Regulatory Commission
NSR	nonsafety-related
PCAT	primary coolant apparatus test
PCS	primary coolant system
PDC	principal design criteria
PDSA	preliminary documented safety analysis
PPS	plant protection system
QA	quality assurance
R&D	research and development
RG	regulatory guide
RPS	reactor protection system
RSS	radiation shielding system
SAR	safety analysis report
SBE	safety basis event
SC	safety-class
SDIT	safety design integration team
SDS	safety design strategy
SFR	sodium-cooled fast reactor
SMP	safety management program
SR	safety-related
SS	stainless steel
SSCs	structures, systems, and components
TED	total effective dose
TPC	total project cost
TPN	TREAT Private Network
TREAT	Transient Reactor Test (TREAT) facility
TS	technical specification
U	uranium
U-ZrH	uranium zirconium hydride
wt%	weight percent
ZPPR	Zero Power Physics Reactor

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Safety Design Strategy for the Microreactor Applications Research Validation and Evaluation (MARVEL) Project

1. INTRODUCTION

In accordance with DOE-STD-1189-2016, "Integration of Safety into the Design Process,"[1] this safety design strategy (SDS) describes the overall safety strategy and any high-cost and safety-related (SR) design decisions for the Microreactor Applications Research Validation and Evaluation (MARVEL) project at the Idaho National Laboratory (INL) Transient Reactor Test (TREAT) facility. This document also identifies key assumptions or inputs that may represent potential risks to design decisions and expected safety deliverables throughout the project.

A major modification determination (MMD) for the MARVEL project was documented in MMD-119, "10 CFR 830 Major Modification Determination for Microreactor Applications Testbed."[2] Per the criteria in DOE-STD-1189-2016 and LWP-18113, "Integration of Safety into the Design Process,"[3] MARVEL at the TREAT facility has the potential to: 1) change an existing process or add a new process resulting in the need for a safety basis change requiring Department of Energy (DOE) approval; 2) utilize new technology or government furnished equipment (GFE) not currently in use or not previously formally reviewed/approved by DOE for the affected facility (TREAT); 3) create the need for new or revised safety structures, systems, and components (SSCs); and 4) involve a hazard not previously evaluated in the documented safety analysis (DSA). Therefore, MARVEL meets the definition of a major modification and will be managed accordingly.

MARVEL safety basis documentation will meet the requirements of 10 *Code of Federal Regulations* (CFR) 830, "Nuclear Safety Management," Subpart B, "Safety Basis Requirements."[4] In accordance with DOE-STD-1189-2016, this SDS documents the expectations and the format for integrating the major modifications to the TREAT facility and describes the actions necessary to update or revise the existing TREAT facility safety basis. This SDS *does not* describe discreet revisions to the TREAT facility safety basis (e.g., safety analysis report [SAR] and technical specifications [TS]). The resulting changes to the TREAT SAR and TS will be developed as part of the project as discussed in Section 10.

DOE O 413.3B, "Program and Project Management for the Acquisition of Capital Assets,"[5] Section 3, "Applicability," states:

> *The requirements identified in this Order are mandatory for all DOE Elements (unless identified in Paragraph 3.c., Equivalencies/Exemptions) for all capital asset projects having a Total Project Cost (TPC) greater than or equal to $50M, except that during the project development phase, Under Secretaries may reduce the threshold to $10M for nuclear projects or complex-first-of-a-kind projects.*

The costs of the MARVEL project are estimated to be less than $50M, and therefore, MARVEL is not governed by DOE O 413.3B. DOE O 420.1C, "Facility Safety,"[6] and the expectations of DOE-STD-1189-2016 provide for identification of hazards early in the project and use of an integrated team approach to design safety into the project. This SDS provides the basic safety-in-design principles and concepts using a graded approach based on the importance to nuclear safety of the MARVEL SSCs.

2. SUMMARY DESCRIPTION OF THE MARVEL PROJECT

The information in this section is summarized from INL/LTD-20-57892, “An Initial Microreactor Design for Near-Term Demonstration,”[7] and updated with the most current project design and operations information. The purpose of the MARVEL project is to develop a nuclear microreactor applications test bed at INL to perform research and development (R&D) on various operational features of microreactors to ultimately improve integration of microreactors to end-user applications.

The MARVEL concept is a 100-kilowatt (kW) thermal (kWth) and approximately 20-kW electric (kWe) generating microreactor that can be integrated with multiple applications, such as cogeneration (heat and power), hydrogen generation, etc., to solve associated R&D challenges. The microreactor technology leverages the last six decades of nuclear research performed by the collective nuclear industry.

The MARVEL system will be located in the INL TREAT facility in the north high-bay equipment pit. Additional space within the TREAT building may be required for heat rejection and instrumentation and control (I&C) equipment, and other equipment may be located outside the building. Utilizing the existing TREAT facility simplifies the overall safety basis.

Figure 1 shows a lateral conceptual rendering of the MARVEL microreactor system on the left and cross-sectional rendering of the core on the right. The overall MARVEL design parameters are summarized in

Table 1.

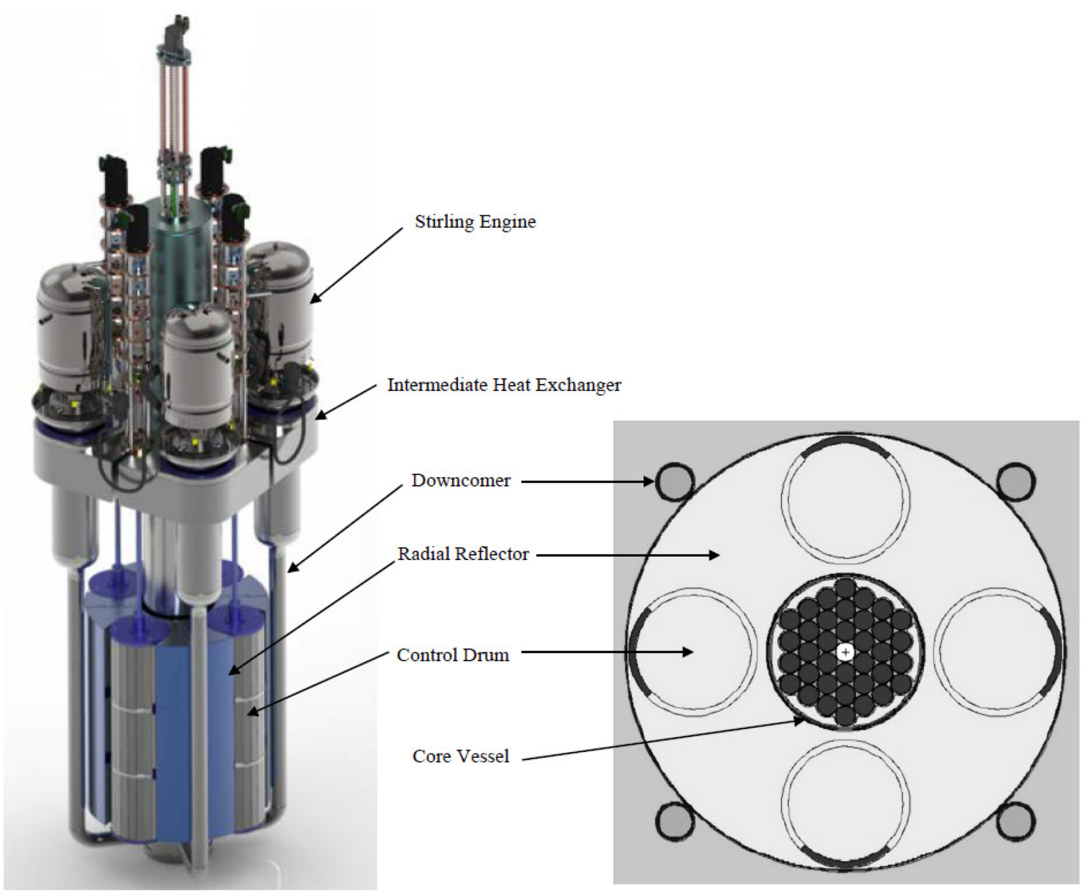

Figure 1. MARVEL conceptual design illustration.

Table 1. MARVEL overall design parameters.

Major Systems	Parameters	Value/Type	Units
Core	Thermal Power	100	kW_{th}
	Core Life	2	years
	Fuel Type	Uranium Zirconium Hydride (UZrH)	
	Fuel Uranium Enrichment	<19.75	wt%U235
	Maximum Uranium in Core	<30	kg U
	Number of Fuel Pins	36	
	Neutron Moderator	Hydrogen in U-ZrH	
	Peak Cladding Temperature	550	°C
Coolant	Heat-Transfer Method	Liquid-Phase Natural Circulation	
	Heat-Transfer Fluid (Sodium-Potassium Eutectic [NaK])	120	kg
Reactivity Controls	Reactivity Control	Vertical Control Drums and Inherent Reactivity Feedback (IRF)	
	Reactivity Control Method 1	Vertical Control Drums	
	Reactivity Control Motor Type	Radiation-resistance, High-temperature Stepper/Servo Motors	
	Bearing Type	Lubricant-free Thrust and Guide Bearings	
	Quantity of Reactivity Method 1	4	
	Reactivity Control Method 2	IRF	
Reflector & Shield	Neutron Reflector Material	Beryllium Oxide, Beryllium Metal	
	Neutron Absorber Material	Boron Carbide (B_4C)	
	Neutron Radiation Shield Material	Boron Carbide (within reactor)	
		Borated Polyethylene (outside the reactor)	
	Gamma Radiation Shield	Stainless Steel (within reactor)	
		Concrete (outside the reactor)	
Power Conversion	Power Conversion Technology	Frictionless, Free-Piston Stirling Engines (PCK80, Qnergy)	
	Power Conversion Efficiency @500° C inlet temperature	20-25	%
	Electrical Power	18-25	kW_e
	Number of Power Generators	4	
	Heat Rejection Loop	Water-Propylene Glycol, Closed Loop	
	Ultimate Heat Rejection Medium	Ambient Air	
	Raw Power Output (voltage)	295-365	VDC
	Maximum Power Output per Engine	7.1	kW_e
High Grade Heat Extraction	High Grade Heat Extraction Fluid	Helium or Nitrogen	

2.1 Reactor Structure System

The reactor structure system is the main structural member of the reactor and primary coolant flow path. It includes a machined billet/forging made from 316 stainless steel (SS) and supports the reactor related components located on the reactor, contains primary coolant, and prevents the core from being uncovered during a postulated loss of coolant accident (LOCA). It also supports the reactor vessel and primary coolant piping.

The MARVEL microreactor core barrel, or reactor vessel, is made from a 10-in. 316 SS, schedule 80 pipe. The lower section supports the reactor core fuel assembly, while the upper section supports the cover gas, drain and fill connections, and a safety valve. The upper and lower sections of the reactor core barrel are attached to the top and bottom of the primary support structure, which supports outer permanent reflectors and control drums (CDs) and transfers reactor loads to the pit floor via the guard vessel.

The primary output structure attaches to the reactor secondary support structure. It can also support a high-grade heat exchange unit, which is interchangeable with the Stirling engines. This unit may be exchanged as necessary to satisfy changing needs of the MARVEL microreactor. A new primary output structure may be designed and interchanged to reside on the secondary support structure.

2.2 Guard Vessel

The guard vessel, is a sealed container that secures the reactor onto the pit floor and prevents the core from being uncovered during a postulated LOCA by controlling the void space inside the guard vessel. If primary coolant leaks into the guard vessel, the fluid level in the guard vessel will rise as liquid level in the primary system falls, until both systems equilibrate. The reactor core and the primary coolant piping reside inside the guard vessel.

The guard vessel is the support structure for the reactor and associated primary and secondary components. It supports the reactor system loads, including seismic loads. Radiation shielding fills the interspace voids. The guard vessel has connections for purge gas and a safety valve and attachments for instrument cable routing for reactor instrumentation, including neutron detectors.

2.3 Core System

The primary function of the reactor core system is to supply a continuous, stable, and sustainable fission heat source (~100 kW_{th} maximum power level) for the duration of the operation of the system, i.e., four years. The MARVEL microreactor core is designed to operate continuously for two years, but the microreactor will not operate continuously. Instead, the MARVEL microreactor will turn on and off numerous times during its lifetime to support research needs. Operations are discussed later in this document. The core contains 36-fuel elements (also referred to herein as fuel pins) arranged in three hexagonal rings around a central hollow channel (Figure 2 and Figure 3) that is available for sensors and detectors.

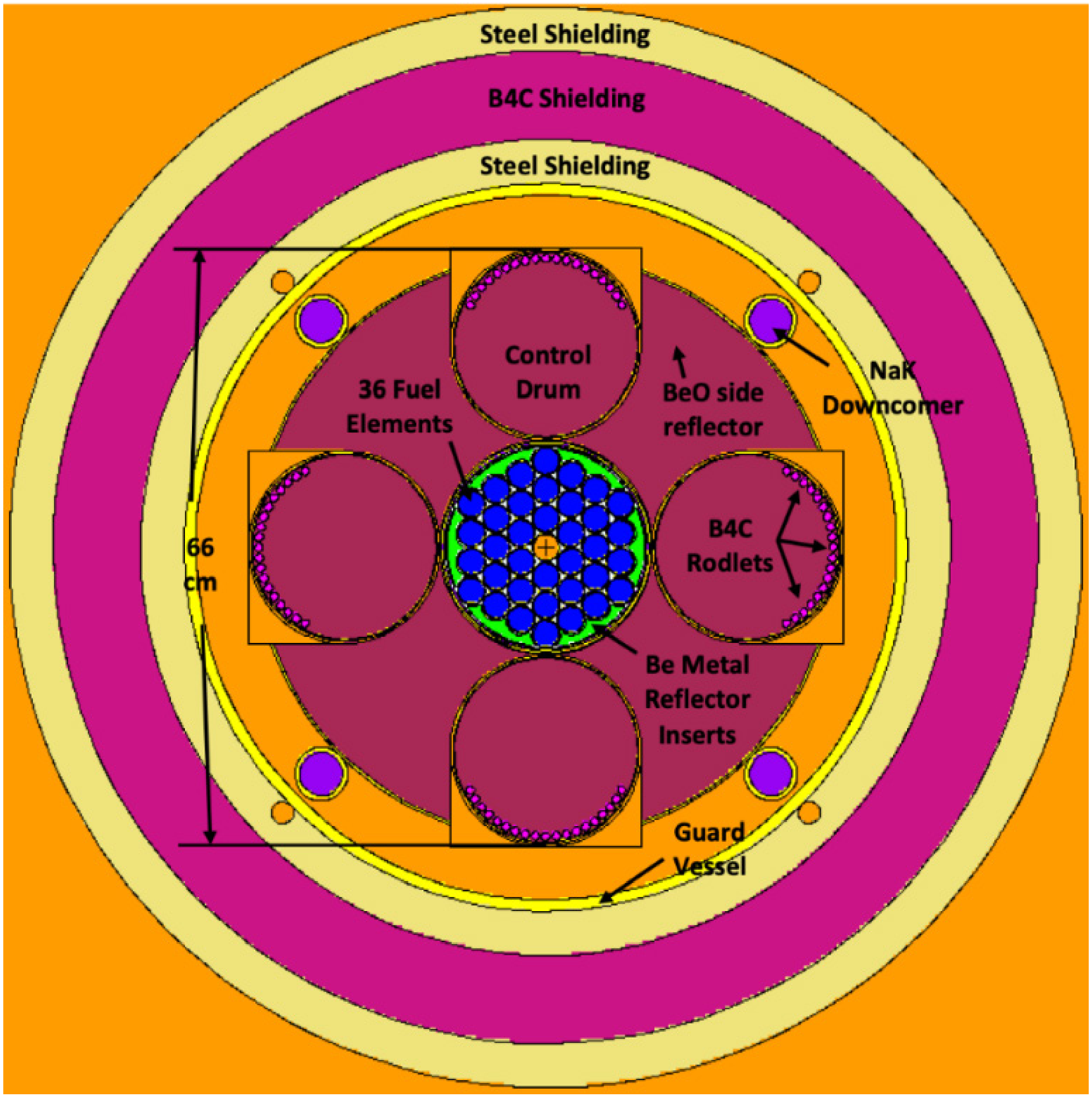

Figure 2. Cross section of the MARVEL microreactor 36-fuel element reactor core.

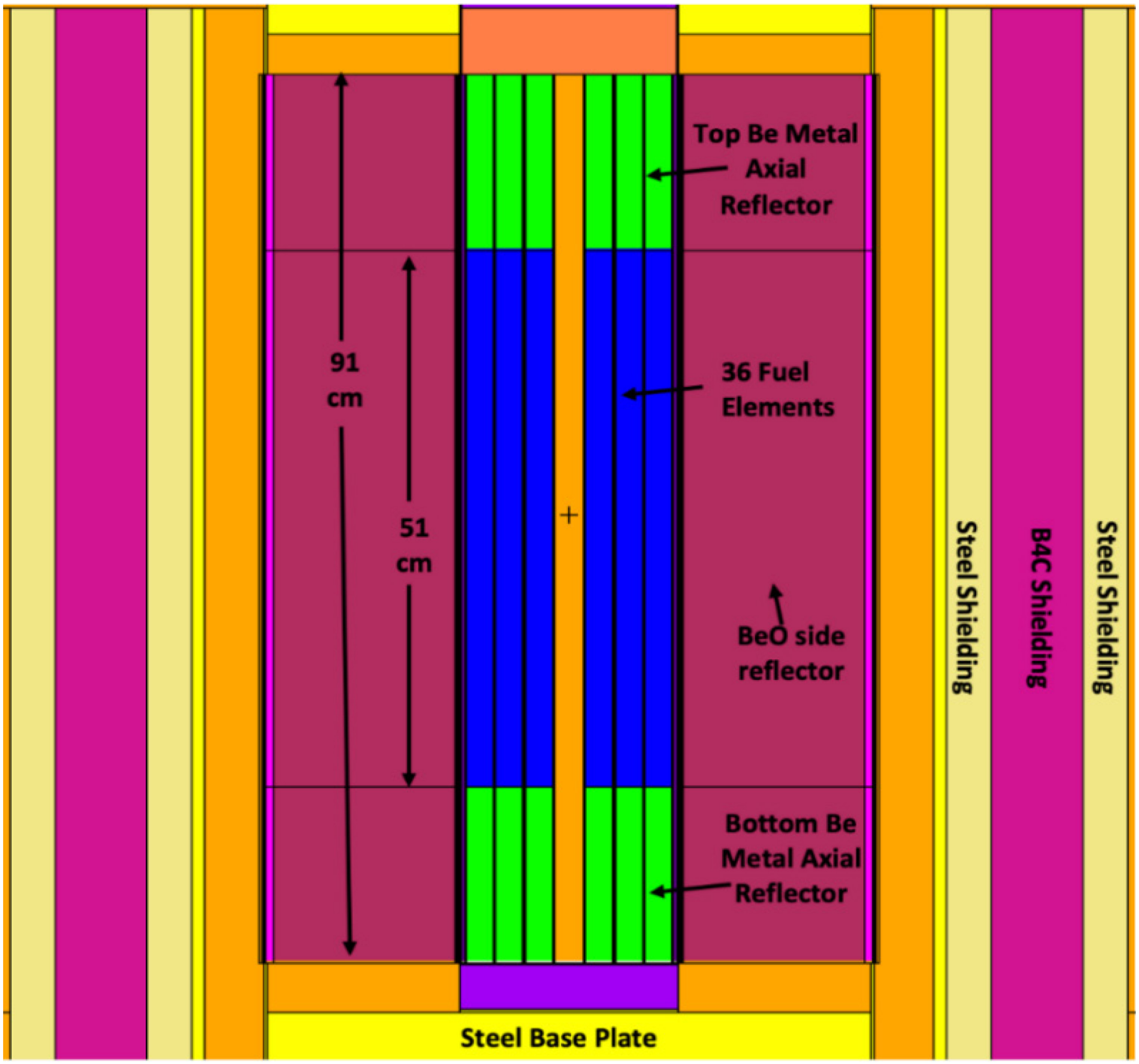

Figure 3. Axial view of the 36-fuel element reactor core system.

The side reflector is a stack of beryllium oxide that moderates and reflects neutrons back into the active core. The beryllium oxide side reflector also houses the four rotating CDs. There are also six in-core inserts that displace and re-direct primary coolant away from the core periphery and through the 36-element array to enhance cooling and natural circulation. These inserts are fabricated out of beryllium metal. The core barrel acts as both the up-flow coolant boundary and the inner wall support for the beryllium side reflector annulus.

2.4 Reactor Coolant System

The primary coolant system (PCS) is a four-loop hydraulic circuit assembled to transport nuclear fission heat from the nuclear fuel to the intermediate heat exchanger (IHX) using natural circulation of the primary coolant. The PCS also transfers decay heat to the ultimate heat sink. The following subsystems comprise the PCS: lower plenum, reactor core, reactor vessel, riser, upper head, IHX region, downcomers, primary coolant, and inert cover gas. The PCS limits radiation effects and integrates instrumentation for relaying system information to the I&C system. Figure 4 depicts the PCS and IHX components.

The lower plenum is a welded shell located below the bottom of the reactor core and consists of the downcomer, pipes nozzles, and outer thermal insulation. The lower plenum is designed to collect flow from the four downcomer pipes and mix and homogenize the primary coolant before it enters the core.

The primary coolant boundary for the MARVEL microreactor design consists of the reactor vessel, cover gas line piping, and reactor vessel head. These SSCs ensure that primary coolant and any leaked fission or activation products remain within the vessel and oxygen remains outside.

About 120 kg sodium potassium eutectic (NaK), a liquid metal at room temperature, serves as the primary coolant. The NaK coolant acts as a radionuclide barrier by retaining fission products by plate-out, chemical solubility, or adsorption mechanisms. Fission heat is generated in the core and removed by natural circulation of NaK. NaK flows upward through the core, rises above the top of the active core, and flows through the upper grid plate and radiation shielding to the four Stirling engine heat exchangers.

The Stirling engine heat exchangers connect to the reactor vessel and interface with the NaK coolant via the IHX. The criteria for the IHX coolant are: (1) fluid must be liquid at operating temperature; (2) fluid has to be unreactive with air and water at elevated temperature; (3) fluid must be able to retain its thermal conductivity properties in a radiation environment without significant degradation; and (4) melting point of the coolant should be less than 300°C to avoid manual engine stall, which can simplify controls of these engines. Therefore, lead-bismuth is selected as the coolant choice for the IHX. The IHX contains about 280 kg of lead-bismuth eutectic in total. An argon gas blanket will be maintained on the IHX to reduce formation of lead and bismuth oxide.

The Stirling engine coils or high-grade heat exchanger, depending on configuration, extract heat from the primary coolant and reduce the NaK temperature. The cooled and denser NaK then flows outward to the periphery of the core, then downward through four downcomer pipes located outside the beryllium oxide side reflector and through in the lower plenum. The NaK then rises back up through the active core under natural circulation forces driven by the heated section of the active core (51 cm active fuel height).

The riser is a welded shell connected to the top part of the vessel. It homogenizes the NaK exiting the core and supplies the fluid a hot column for establishing natural circulation flow. The top of the riser is connected to the bottom of the upper head.

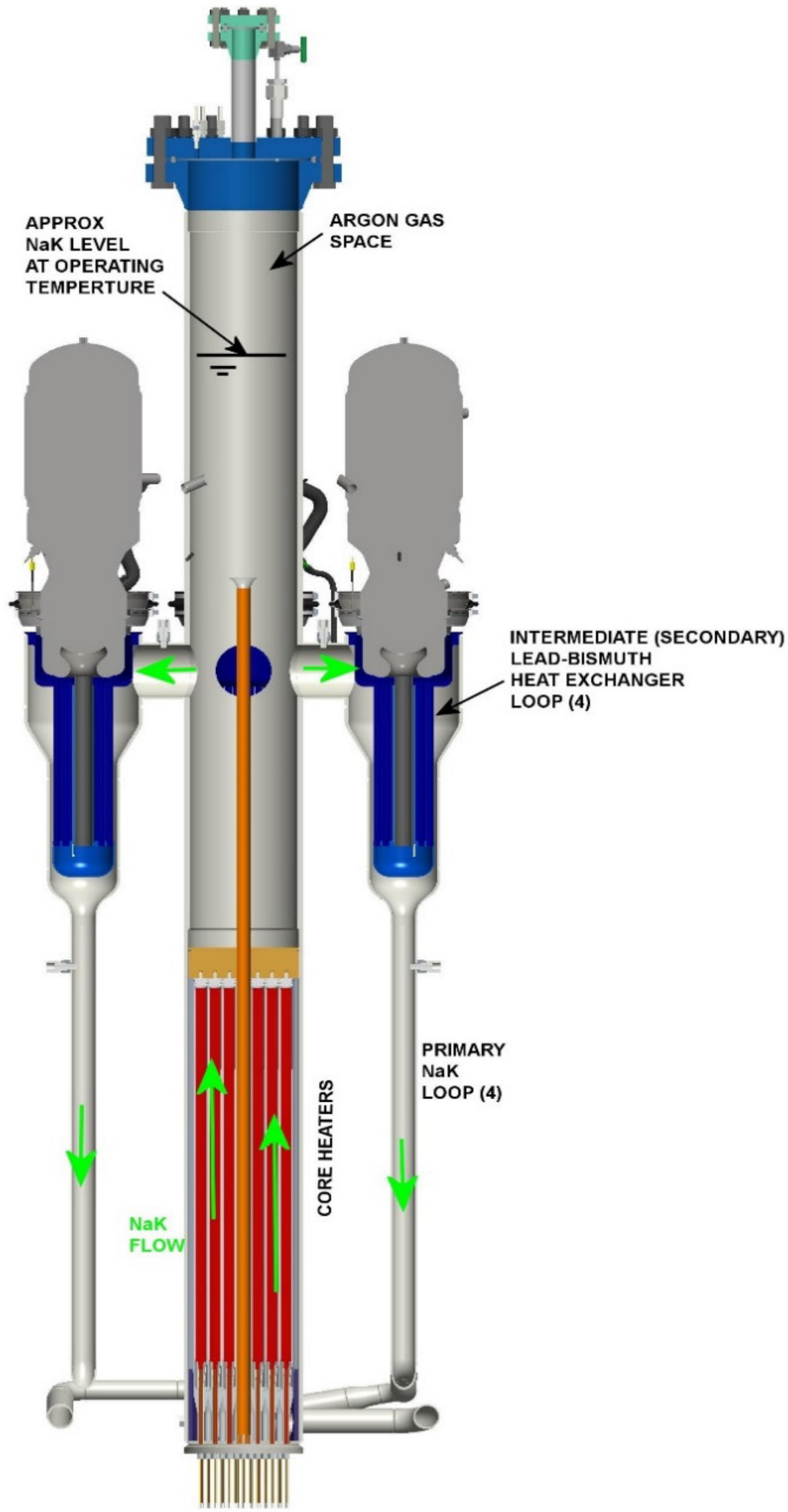

Figure 4. Design of the PCS and IHX.

The upper head allows thermal expansion for the primary coolant, contains the PCS inert atmosphere, and is the path for moving the NaK flow from the riser to the IHX region. The upper head is made of 316 SS machined billet. The machined billet furnishes four horizontal flow paths (one for each loop) for the NaK flow. A welded shell, connected to the top of the billet, provides an expansion volume for the NaK during thermal transients and contains the argon gas for the inert atmosphere and enough NaK to maintain the fluid level above the top of the billet in case of a postulated LOCA. A flange is installed on the top head that allows opening the PCS, and a relief valve is located on the flange.

The four IHX regions are welded to the billet of the upper head subsystem and to the four downcomers. The IHX region is a 316 SS cylindrical shell and a 316 SS reducer welded together. The reducer homogenizes and drives the NaK flow from the IHX bottom head to the inlet of the downcomers. The four downcomers are welded to the IHX region and to the lower plenum subsystems. They drive the NaK flow downwards and serve as the cold legs of the PCS to enable natural circulation. The downcomer subsystem is made of 316 SS pipe and thermal insulation.

Bended sections in the downcomers reduce thermal stresses on the vessel and are rounded to minimize pressure drops. In the last part of the downcomers, a dedicated restricted section allows for installing electromagnetic flow meters (one per loop) to relay information regarding flow rate.

The head space in the reactor above the NaK level contains high purity argon gas (about 50 liters in volume). To accommodate thermal expansion and contraction of the NaK without creating excessive pressures in the primary system, a head tank connects to the reactor vessel gas space. The tank is sized to maintain an acceptable pressure in the vessel throughout the full temperature range. The primary vessel cover gas space, head tank, and piping will be sealed and monitored to identify leaks. The inert gas is supplied from one or more standard high purity argon gas cylinders through pipes and a regulator. Supply pressure will be less than 15 psig.

Filling and draining the MARVEL microreactor system are the principal maintenance tasks associated with handling the NaK. Due to the short core life, changing filter elements and installing a purification loop and aerosol filtration and removal system for the argon cover gas system are not required.

2.5 Power Conversion and Heat Rejection System

The power conversion and heat rejection system removes and extracts high-temperature process heat from the IHX, converts that heat into power, and delivers useful electricity to user loads. Alternately, some or all the high-grade heat may be extracted and delivered to a thermal storage medium for integration with heat applications. Figure 5 gives an overview of the power conversion and heat rejection system.

The power conversion and heat rejection system uses Stirling power conversion equipment and associated controls, or a high-grade heat exchanger depending on the configuration, to absorb heat from the reactor and cooling loops. The power convertor absorbs heat from the reactor and uses it to produce electrical energy.

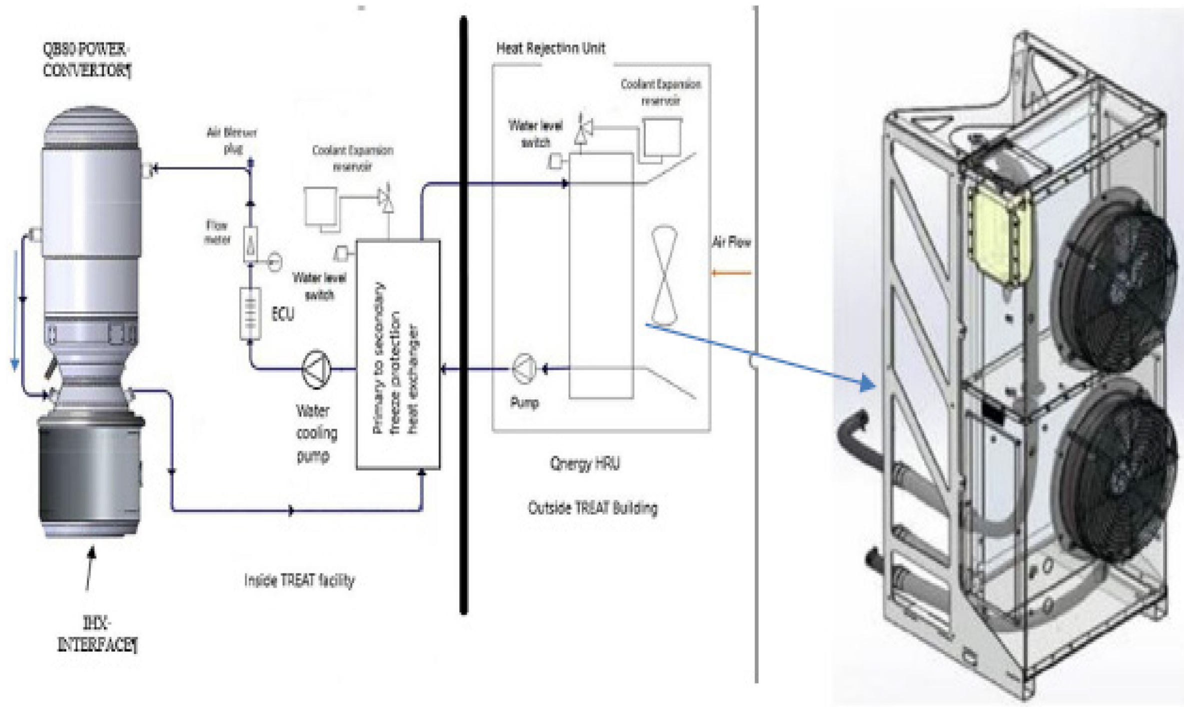

Figure 5. Power conversion and heat rejection equipment.

The four Stirling engines have custom engine control units (ECU). The piston-free Stirling engines can generate about 5 kW of power with a 500°C heat source in their hot end heat exchanger. However, net power production starts at about 250°C with a wide range of thermal input, up to a maximum of 7.1 kW per engine. The hot heat exchanger system of the Stirling engine or the high-grade heat exchanger absorbs heat from the reactor and converts it to mechanical motion. Linear alternators convert this mechanical motion to electrical energy and supply direct current (DC) voltage. The system sends the DC voltage to a bus or to an inverter system that converts it to alternating current (AC). The ECU starts the Stirling engine and receives DC voltage output from the linear alternator. The ECU also monitors system components such as coolant flow, coolant inlet and outlet temperature, and idle mode electrical power dissipation (no electrical load). It also has a shutdown trigger to turn off input heat.

The Stirling engines are closed systems containing helium (110 g per engine) as the power generation coolant. The helium has a maximum allowable working pressure of 73 bar (1,060 psig). Heating and cooling of the helium gas during the Stirling engine cycle is through an external water and propylene glycol, closed loop cooling system. Figure 6 shows the conceptual interface of the Stirling engines to the reactor and the primary coolant circulation path through the Stirling engine heat exchanger.

The low-grade heat rejection system delivers waste heat to the ultimate ambient heat sink (air) through the heat rejection unit located outside the TREAT facility. The low-grade heat rejection system includes a set of pumps and radiators that can be reconfigured for optimized performance.

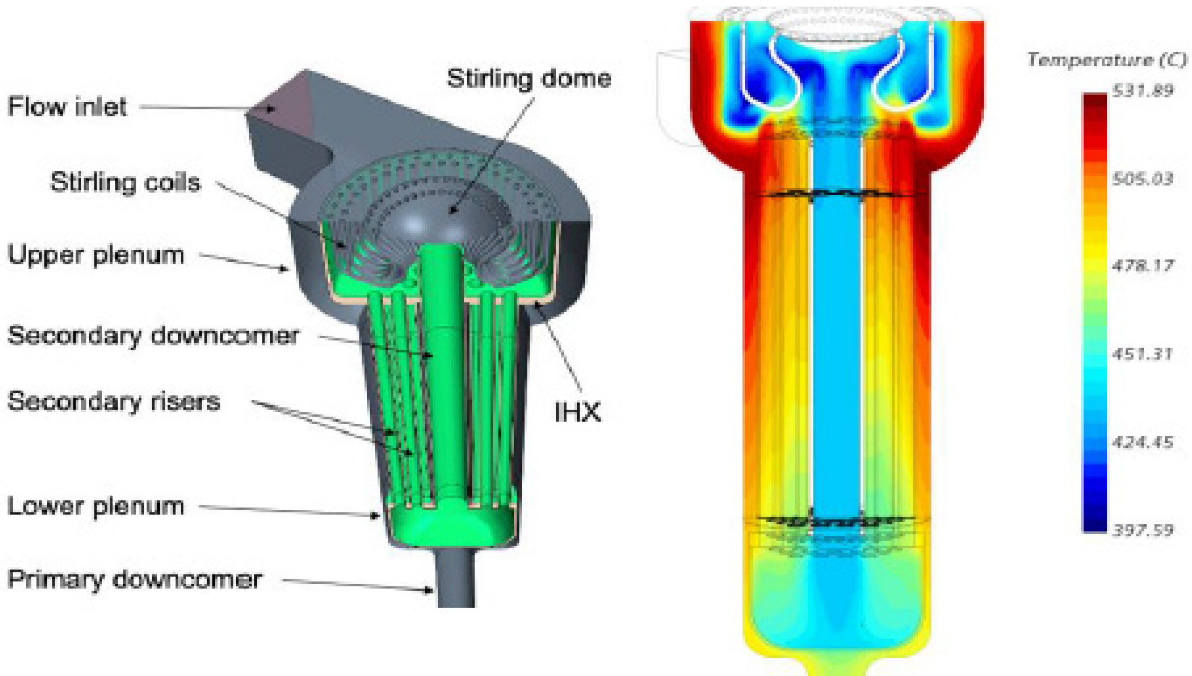

Figure 6. Section schematic of Stirling engine heat exchangers and intermediate lead-bismuth loop.

2.6 Fuel System

The fuel system generates heat through fission reactions and transfers it into the primary coolant via the cladding. The fuel system is designed to contain the fuel and fission products. The MARVEL microreactor fuel is a well-known fuel form that gives significant margin to failure to assure the fuel performs safely over the life of the MARVEL microreactor. The fuel cladding functions as the primary fission product boundary.

The MARVEL microreactor requires INL to assemble and weld a maximum of 70 fuel pins, 22-34 of which will be used to verify the quality assurance (QA) of the fabrication process. The remaining 36 fuel pins will fuel the MARVEL microreactor. The program proposes to store assembled fuel pins at the Materials and Fuels Complex (MFC) Zero Power Physics Reactor (ZPPR) facility until transfer to TREAT for core loading. Transporting the fuel pins to TREAT occurs on roads with access controlled by INL security using an approved transport vehicle. Prior to core loading, the fuel will be temporarily stored in the high-bay of the TREAT facility.

The MARVEL microreactor fuel is a uranium zirconium hydride (U-ZrHx) containing 30-40 weight percent (wt%) U and enriched to 19.75wt%. The MARVEL microreactor fuel is $U\text{-}ZrH_{1.7}$ sodium bonded to type 316 SS cladding. The fuel system is made up of cladding and endcaps, fuel pins, axial neutron reflectors, and gap conductance fluid as shown in Figure 7. The entire fuel system is composed of 36 fuel pins, or about 150 kg of fuel, which includes about 50 kg of fuel required for fuel QA purposes. Each pin measures about 38 in. (96.5 cm) long. The cylindrical U-ZrH fuel pellets are stacked vertically, clad in SS, and sodium-bonded to improve fuel pin heat transfer characteristics. Within each fuel pin clad, a top and bottom beryllium oxide (BeO_2) reflector is located above and below the fuel pellet stack, and a fission gas plenum is located above the top beryllium reflector.

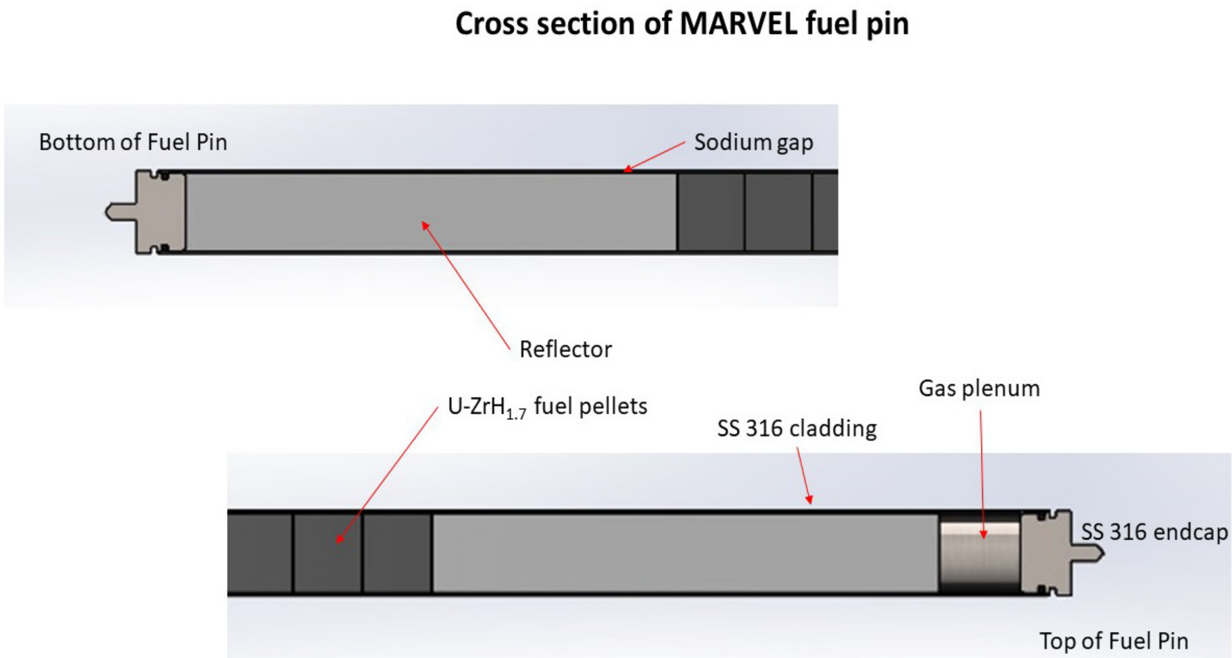

Figure 7. Fuel pin assembly.

Each fuel pellet measures about 1.17 in. (29.72 mm) in diameter by about 1.1 in. long (27.97 mm). Each fuel pin contains 18 fuel pellets. Each fuel pin contains two neutron reflectors made from beryllium oxide, one above the fuel stack and one below the fuel stack, and enough NaK, when liquid, to cover the lower reflector, the fuel stack, and half to three-fourths the length of the top reflector. Each pin also contains a plenum space to accumulate any released fission gases and gaseous hydrogen.

The cladding and endcaps of the fuel pins are made of 316/316 SS (or Incoloy 800). The 316/316 SS cladding has an interior diameter measuring about 1.25 in. (31.8 mm) and a wall thickness of 0.035 in. (0.89 mm). It is possible to use Incoloy 800 cladding. Incoloy 800 is a high temperature alloy with a higher nickel content than 316 SS and has better high temperature mechanical properties. Overall, the neutronic effect of moving from 316 SS to Incoloy 800 with no other design changes is a reduction in reactivity. This reactivity loss can be compensated for with other design choices. For example, reducing fuel pin cladding thickness has a large neutronic effect that could improve the reactivity of the core to offset reactivity losses. Regardless of cladding material, the cladding will be manufactured to a consensus standard and will have margin to failure during MARVEL microreactor operation for both off-normal and anticipated events.

The fuel fabrication method involves mixing about 30-40 wt% U, either in the form of U powder or UH_3 powder, with 60-70 wt% ZrH_2 powder, which is pressed into compacts and densified in a partial pressure of hydrogen to form $ZrH_{1.7\text{-}1.9}$. Depleted uranium and highly enriched uranium feedstock are used to achieve the required pellet enrichment of 19.75wt% U-235. These feedstock materials will be sourced from INL uranium feedstock stores and analyzed for purity prior to use. Surface oxidation is removed via established acid cleaning techniques.

2.7 Reactivity Control Systems

The reactivity control system includes the four MARVEL microreactor CD systems and supporting electrical components (see Figure 8) that control criticality and can shut-down the MARVEL microreactor. Criticality occurs when the nuclear fuel sustains a fission chain reaction, and each fission releases a sufficient number of neutrons to sustain an ongoing series of nuclear reactions. Neutron-absorbing materials disrupt the fission chain reaction by absorbing neutrons to prevent them from causing further fissions. By controlling the number of neutrons available to induce fission, the power of the reactor can be moderated.

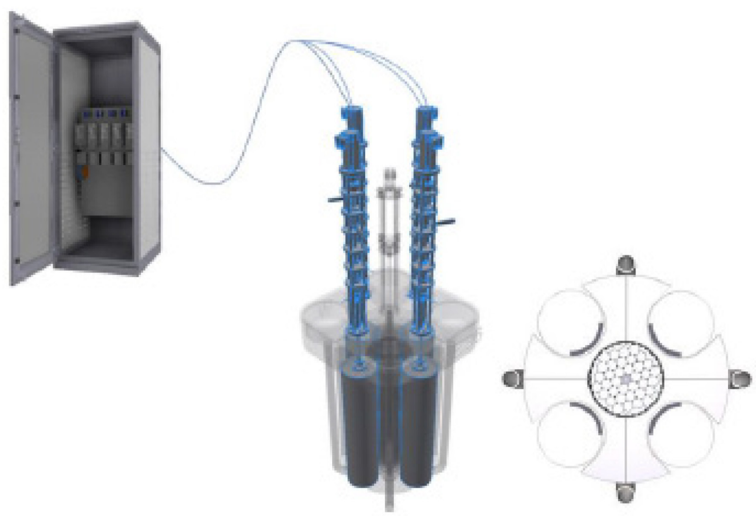

Figure 8. Reactivity control system (showing two of the four CD drive systems).

The supporting electrical components are installed on the CDs or housed in an adjacent control cabinet. The control cabinet houses the instrumentation necessary to drive the CDs and process data from the system. Electrical cables routed between the CDs and the control cabinet send motor driving signals and other information to and from the system instrumentation.

The CD cylinders are made from beryllium oxide and are ~7.2 in. (18.4 cm) in diameter and ~36 in. (91 cm) long. Each drum is supported by a 0.75-in. (1.9 cm) diameter rod through the center, and each drum has a neutron-absorbing plate made of carbon boride that is ~0.4 in. (1 cm) thick. A non-structural, sheet metal cylindrical wrap will be used to house all the beryllium oxide plates. The drums weigh ~110 lb (50 kg).

Rotation of the CDs controls the number of neutrons available in the core to induce fission, which influences target output electrical power. The rotation of the CDs' neutron absorbing material relative to the core is used to achieve and control criticality or shutdown the reactor and maintain it in a subcritical state. A single CD can shut-down the 36-element core during reactor operations. The CD system has drum forcing components (e.g., motor, spring, and damper) that rotate the CDs, and these components are configured and sized to accommodate operational (a motor rotates the drum) and accident modes (a spring drives the CD system when a safety trip is triggered).

For the MARVEL microreactor, criticality is achieved when the CD neutron-absorbing materials are rotated away from the core. When the CD system positions the neutron-absorbing materials directly toward the core, the core is subcritical, or shutdown. As the CDs rotate the neutron-absorbing materials away from the core, there is a point where initial criticality is achieved. Rotating the CDs beyond the initial criticality position controls the number of neutrons available for sustaining the fission chain reaction in the core and the rate at which fissions occur, thus controlling reactor performance. Instrumentation relays information regarding the position and rotation of the CDs.

If a safety related circumstance occurs (e.g., loss of power, seismic event, over temperature, etc.), the reactivity control system rotates the CDs past their initial criticality position to shut-down the reactor automatically. The manual control requires direct activation of the motion control system using manual interfaces linked to the motor driver. The reactor is controlled remotely to allow personnel to be remote from the reactor hazards during reactor startup and operation.

2.8 Radiation Shielding System

The radiation shielding system (RSS) absorbs and reflects radiation to protect the facility, reactor materials, and components, and to protect people and the environment during normal operations and accident conditions. Final shielding design may be adjusted pursuant to additional analysis.

The reactor itself will be located in a concrete pit within the TREAT facility, which gives a means of isolating the reactor within the TREAT facility.

Figure 9 shows shielding locations and materials. Within the reactor, a large square SS plate above the core serves as the main gamma shielding to protect the Stirling engines or high-grade heat exchanger and other components above the core. This plate is about 30 in. (76 cm) thick and includes an about 4-in. (10 cm) thick section of boron carbide neutron shielding. The core and reflector regions are surrounded by SS and boron carbide cylindrical sections to provide gamma and neutron shielding within the reactor assembly. External to the reactor, 6 in. (15 cm) of borated polyethylene sheets line the concrete pit (sides, top, and bottom below the reactor).

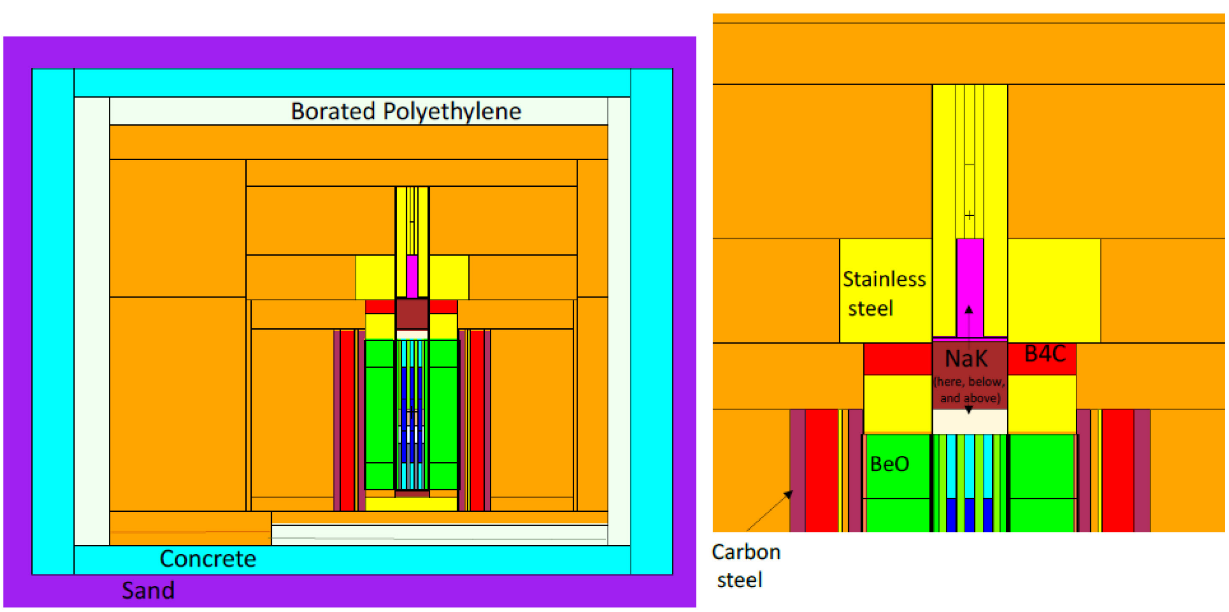

Figure 9. Cross section view of the MARVEL microreactor with shielding.

2.9 Instrumentation & Control System

The I&C system supplies the logic for the reactor and gives indications from sensors. The I&C system has the following main functions: reactor control instrumentation, plant protection, interlocks, drum control, post-accident monitoring, electrical distribution, low-grade heat removal, control system, and human machine interface.

The reactor core instrumentation measures the rate of neutron generation (neutron flux), temperature, flow, and NaK level and senses for leaks. This system uses neutron sensors (source range and steady-state), thermocouples within the primary and secondary loops, flow meters on the primary loop, NaK level probes, and leak detection probes to send the operator key information regarding the state of the reactor core. If a NaK leak is detected by the sensors, the sensors send a scram response to the plant protection system (PPS), which shuts the reactor down. The reactor power can be calculated from the neutron sensors and from the temperature and flow measurements.

The PPS includes components that shutdown the reactor or shutdown the power conversion system. Relays supply power to an electromagnetic clutch, which, if de-energized, allows a spring to move the drums to the shutdown position (i.e., scram). The relays are configured so that a power loss causes a scram. The relays are actuated by a manual scram button in the control room, by a manual scram button local to the reactor, accelerometers for detecting seismic events, computer trips, and reset buttons. There are two relays that are actuated by each scram type for redundancy.

2.10 Siting and Operations

Modifications of the TREAT facility are necessary to support microreactor demonstrations, including MARVEL. These modifications include installing shield blocks and a heating, ventilating, and air conditioning (HVAC) system in the north storage pit, installing industry standard I&C components, electrical power and electronic racks, reactor and control room infrastructure, fire suppression system, and heat rejection and electric load dissipation equipment north of the TREAT reactor building. The proposed modifications to the TREAT reactor building include the following:

- Make penetrations in the fuel storage pit cover(s) for heat rejection fluid loop (i.e., the water-propylene glycol, closed loop)
- Install shielding in the reactor pit
- Route heat rejection ducting from the pit to a condenser unit outside the TREAT facility
- Install a temporary NaK filling station
- Route gas lines and portable gas cylinders to the NaK fill station
- Route conduit and wiring to the condenser unit and the fuel storage pit (power and signal)
- Install fire suppression using an argon gas supply for passivation.

The preparation to bring a new reactor online requires a formal plan to assemble and load the reactor and bring the reactor critical. After achieving criticality, some amount of testing is required to validate the assumptions in the safety basis and demonstrate compliance to the TSs for operating the reactor.

The I&C system hardware will be installed near the pit inside the TREAT building. Fluid piping for a closed heat rejection unit connects the power conversion of the reactor to the heat rejection units. Figure 10 shows a conceptual layout of equipment. The location of equipment outside of the reactor pit and outside of the TREAT facility could change, but this configuration is limited to the high-bay area and the area within the fenced TREAT facility perimeter.

Reactor assembly involves assembly of the reactor vessel, nuclear instrumentation and chassis, reactivity control systems, primary plant instruments, reactor trip systems (i.e., safety systems, seismic scram system), manual shutdown system, heat rejection system, and shielding. Following assembly, prior to fuel loading, operability testing is performed on these systems. During this time, the system is also used for operator training and procedure testing.

After operability testing, reactor loading begins. The reactor fuel will be loaded manually using methods standard in the nuclear industry. Fuel pins will be handled under strict criticality control, and subcriticality of the reactor assembly will be ensured throughout by locking control drums in the shutdown positions. After fuel loading, the top grid plate will be installed; the reactor vessel head will be installed; and the vessel will be filled with NaK and sealed. At this point, the final connections to the Stirling engines or high-grade heat exchanger, including loading of the Pb-Bi into the intermediate heat exchanger, load banks, and heat exchangers will be made. Once the final connections are complete and have been tested, the reactor trip systems will be re-tested, which is the final check before the initial approach to critical.

The reactor core starts-up from a cold (room temperature) zero-power condition prior to coming up in power. The four CDs are rotated by the reactor operator in small increments to bring the core to a critical state. The regulating CD puts the core on a slow power period and ramps-up in power in a controlled manner. Relays ensure one CD is rotated at a time to avoid any transient overpower conditions during startup. Similar to commercial reactors, during the initial approach to criticality, the reactor operating parameters will be monitored at predefined hold points to verify the process is proceeding safely and as anticipated. If the reactor operating conditions are not performing as expected, operations will be halted to determine the cause of abnormalities and resumed only when safe operating conditions are again established.

After criticality is achieved, the reactor will be shut down, and the process will be repeated to confirm consistency. After initial criticality, reactor physics parameters will be measured to calculate the shutdown margin and excess reactivity for comparison to TSs. The reactor will then be increased in power to raise temperature enough to complete a heat balance calibration of the nuclear instruments to determine losses and to test the decay heat removal system.

The final stages of startup include testing the power production of the microreactor. The reactor will be raised to a high enough temperature to start the Stirling engines or high-grade heat exchanger, and the power production will be measured at this level. The power will be increased incrementally to test the range of power production up to 100% reactor power. To improve startup efficiency and remove the complications of the secondary Pb-Bi heat transfer medium solidifying, a hot shutdown mode may be defined and employed for the MARVEL microreactor but is not anticipated. Hot shutdown indicates that CDs are rotated fully in and de-latched to prevent inadvertent criticality.

During normal operations, the reactor is stepped-up in power before reaching a desired maximum power level. At each power step, predetermined hold points are evaluated to confirm engine efficiency and proper reactor system performance. Operation at maximum power (100 kW) is referred to as the normal hot operation condition. The MARVEL microreactor will operate in a manual control mode where the reactor operator can manually control the reactor.

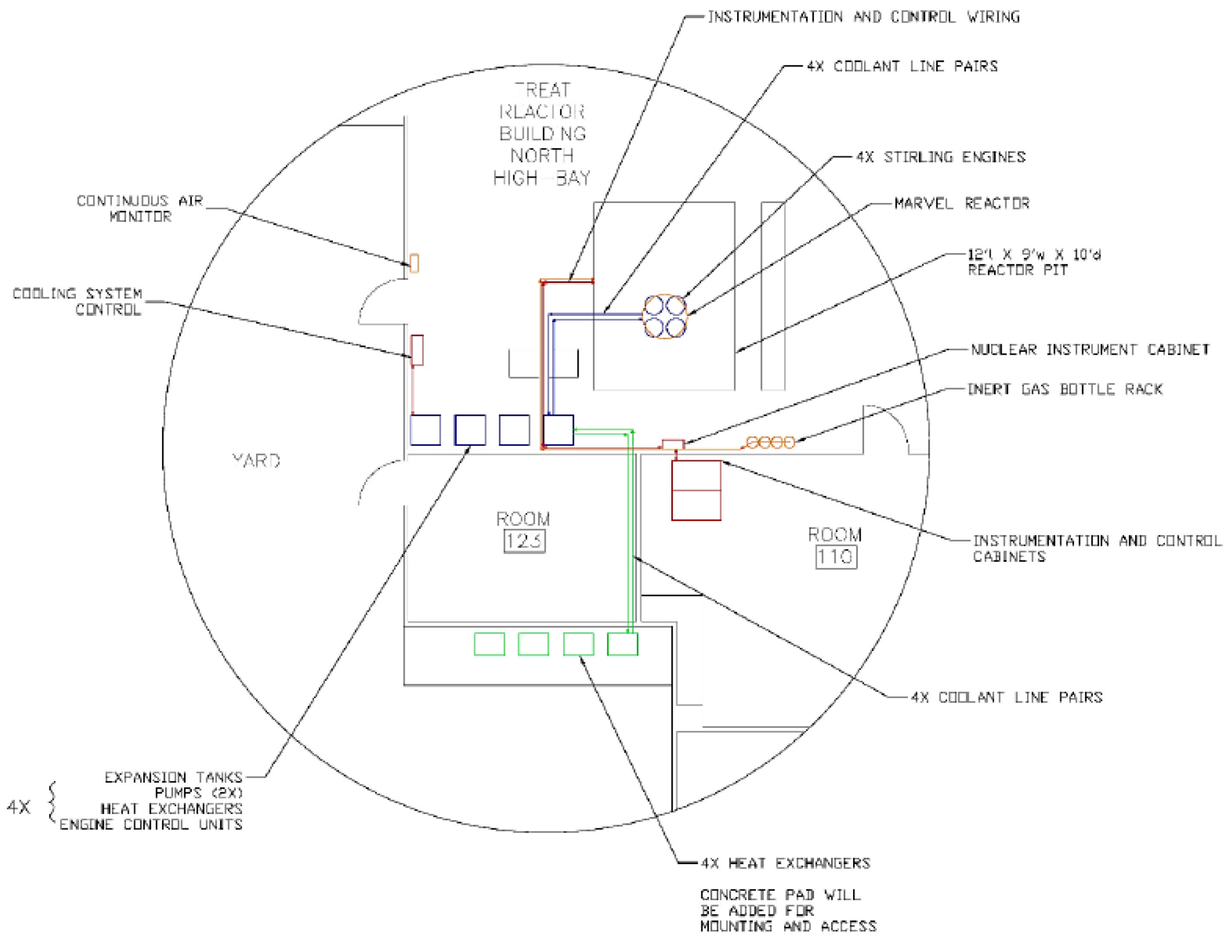

Figure 10. Layout of the MARVEL microreactor in the TREAT facility.

MARVEL will not be operated (i.e., critical) while TREAT personnel are present in the reactor building and simultaneous operations will be administratively controlled. The MARVEL microreactor requires about 10 additional employees (eight employees for construction and two for operations). During normal operation, on-site staff evacuate the TREAT building and control the MARVEL microreactor from building MFC-724. The control room is located more than half of a mile away and also houses the TREAT control console.

3. PROCESS ASSUMPTIONS

The approach to developing the overall project safety basis documentation will follow the guidance of DOE-STD-1189-2016, which is to integrate safety analysis throughout the design process. The standard is intended to implement the safety-in-design philosophies listed in DOE O 413.3B and facility safety criteria listed in DOE O 420.1C. The approach is intended to ensure that hazards are identified early in the project and that a safety design integration team (SDIT) approach is used to design safety into the facility.

The safety basis for MARVEL will be developed in a manner consistent with the maturing of the project design stages. Table 2 summarizes the key safety basis document deliverables and analyses. The MARVEL DSA will be in the form of an addendum to the existing TREAT SAR-420, "Transient Reactor Test (TREAT) Facility FSAR,"[8] and revisions to the TREAT TS-420, "Technical Specifications for the TREAT Facility,"[9] as required. A preliminary DSA (preliminary SAR-420 addendum) and final DSA (final SAR-420 addendum and TS-420 changes) will be developed as shown in Table 2. As the concept matures and greater detail is established, any changes to these assumptions and requirements will be discussed and approved at the appropriate levels and reflected in later revisions to this SDS as well as subsequent safety basis documentation.

The MARVEL configuration management plan and implementation strategy will identify and document the configuration of end products and control changes to configuration during the project lifecycle. For MARVEL, configuration management will include identifying, allocating, and managing requirements; establishing and maintaining facility configuration information; and managing work control and change control.

The MARVEL QA plan and implementation strategy will implement the DOE Idaho Operations Office-approved QA program documented in PDD-13000, "Quality Assurance Program Description."[10] The program complies with DOE O 414.1D, "Quality Assurance,"[11] and 10 CFR 830 Subpart A. The QA program adheres to American Society of Mechanical Engineers (ASME) NQA-1-2008/1a-2009 and 2017 editions, "Quality Assurance Requirements for Nuclear Facilities."[12] All project activities will be performed in conformance with the INL QA Program.

Established implementing procedures and processes will be followed, as written. Consistent with these procedures and processes, a graded approach will be applied for QA through the assignment of quality-level determinations for items and activities at the earliest time, consistent with the application of appropriate controls. The project manager, engineering, and QA engineers supported by the project QA representative will define quality processes that must be in place to comply with the safety basis documentation for the Hazard Category (HC)-2 nuclear facility.

The TREAT Engineering Manager shall be responsible for determining the quality level(s) for project materials, items, and software.

INL QA and MFC Procurement Engineering will aid in developing the required subcontract procurement packages and preparing surveillance plans to monitor subcontractor-performed tests and inspections.

Table 2. MARVEL safety basis deliverables.

	Safety Basis Deliverables		
	Safety Design Strategy (SDS)	Preliminary SAR-420 Addendum (PDSA)	Final SAR-420 Addendum and TS-420 Revisions (Final DSA)
Document Purpose	• Outline and obtain concurrence from DOE on chosen path forward including regulatory standards and other guidance.	• Identify full set of hazards, accidents, and consequences. • Identify full set of necessary safety systems, associated safety functions, and required performance criteria. (This must contain enough detail that procurement specifications and acceptance tests for safety systems can be developed based upon the design criteria identified in the addendum.)	• Allows operation of the reactor once implemented and appropriate startup readiness has been verified. • Provides basis for safe operation of the reactor provided operations are controlled within the described bounds and according to approved controls.
Design Documents	• Design documents sufficient to understand plant layout, general design criteria (GDC), source terms, and general reactor behavior to plant transients, as well as fuel movement and supporting facility strategy.	• Final design documents including system design descriptions, plant design and construction drawings, construction plans, and performance analyses for SR systems.	• As-built plant engineering documents that reflect any site-specific or construction details that modified the final design. • Plant operating documents, such as operations and maintenance procedures.

4. SAFETY SYSTEM SUPPORT INTERFACES

Support and infrastructure systems are at times required for safety system operation. Major facility interfaces between the TREAT facility and MARVEL that are critical to design and the safety design basis have been reviewed, and support and interface system classifications designated consistent with the guidance in Attachment 3 of DOE O 420.1C.

Based on the MARVEL design discussion in Section 2, the following potential facility interfaces have been identified:

1) TREAT building and north high-bay equipment pit structures

2) MARVEL NaK fire prevention and mitigation systems with existing TREAT systems

3) Confinement systems interface with the existing TREAT filtration/cooling system (F/CS)

4) MARVEL and existing TREAT electrical power systems

5) I&Cs, including interface with the use of the TREAT Private Network (TPN), and existing TREAT radiation monitoring system

6) Control room systems including use of existing cabling between the TREAT building and control room

7) MARVEL decay heat removal system losses to ambient using conduction and convection from the vessel to the pit

8) Radiation shielding and protection to workers and equipment from MARVEL on TREAT SSCs, and from TREAT transient operations on MARVEL SSCs

9) Ex-core criticality safety

10) Physical security

11) Hazardous material safety including use of NaK in the TREAT building

12) Decontamination and decommissioning (D&D) activities, including used fuel disposition, core removal, and NaK removal at end of operations.

The TREAT building structure and north high-bay equipment pit structures have been identified as infrastructure systems with the potential to interact with MARVEL systems during a potential seismic event. These potential interactions will be evaluated further and mitigated based on the guidance presented in in Section 6.3.2.4, “System Interaction,” of American National Standards Institute (ANSI)/American Nuclear Society (ANS)-2.26-2004, “Categorization of Nuclear Facility Structures, Systems, and Components for Seismic Design.”[13]

The discussion of the key safety decisions with respect to the other above SSCs and interfaces with the TREAT facility can be found in Section 8.

5. SAFETY STRATEGY

The safety goals in nuclear facility design and operation are to ensure adequate protection of the public, workers, and environment. Traditionally, these goals have been fulfilled by an approach that applies DID by applying various layers (or levels) of protection to prevent the release of radioactive and hazardous materials.

NOTE: *For MARVEL, some passive systems may contribute to multiple levels of DID as documented in the DSA.*

DOE-STD-1189-2016 requires that a design upgrade analysis shall be performed to evaluate the application of nuclear safety design criteria and requirements to the major modification project and to the existing facility. That analysis is provided in Section 2.10, "Siting and Operations."

The DOE philosophy for DID is best summarized in DOE G 420.1-1A, "Nonreactor Nuclear Safety Design Guide for use with DOE O 420.1C, Facility Safety."[14] The MARVEL safety design approach will implement the DID strategy by adapting the five layers of DID from the DOE G 420.1-1A guidance. Although the DID descriptions in that guide are for nonreactor nuclear facilities, the principles are adaptable to reactor facilities and applied to MARVEL as outlined in the following sections.

5.1 DID Layer 1: Prevention of Abnormal Operation and Failures

Accident prevention is the first priority. The first layer of defense treats events of the lowest severity. This level focuses on reliable normal operation and accident prevention through features of the plant design, construction, availability, operation, and maintainability, and includes reliability enhancement through redundancy, QA, testability, inspectability, and simplified fail-safe system design. This DID principle ensures that sufficient operating design margin exists to avoid accident initiators in normal operations.

The objective for provisions of Layer 1 is to control small plant disturbances and transients. Success in this objective entails prevention of off-normal operation and anticipated operational occurrences through design selection and SSC quality and mitigation of events through design choices that provide robust accommodation of reactor conditions.

This will be achieved for MARVEL by proper selection of fuel, cladding, coolant, and structural materials that are stable and compatible, and by following high quality practices in construction and operation. The MARVEL reactor will take advantage of well-established U-ZrH fuel, NaK coolant, and structural materials that are compatible. The MARVEL design will consider the proposed operational ranges for systems and components and ensure that material selection provides for reliable operations during normal operations.

Thermal and operational cycles will be considered in this analysis to ensure that fatigue failures and aging degradations are both understood and minimized. Plant control systems will be designed as high reliability industrial systems to keep high plant availability. Additionally, adequate instrumentation to ensure reliable plant control and early recognition of abnormal conditions will be provided. Plant control systems will be designed to ensure that: 1) stable plant states are maintained and 2) changes resulting in abnormal operations are minimal.

The arrangement of components will be designed that allows monitoring, inspection, and testing for performance changes or degradation. Finally, the MARVEL design will provide for repair and replacement of components, as necessary, to ensure that operation and safety margins are not degraded.

5.2 DID Layer 2: Control of Abnormal Operation and Detection of Failures

Recognizing that SSC failures may occur despite the care taken in design, construction, and operation associated with Layer 1 of DID, the second layer of safety prevents propagation of failures when they occur. The second layer of defense treats events that fall into the anticipated frequency category. The objective of DID Layer 2 is to detect and control (or mitigate effects of) anticipated events, by plant indications that operators can use to identify the cause of events and take corrective actions. Success in meeting the objectives in this layer result in the return to normal operation.

Plant I&C systems will provide the initial protection for ensuring that abnormal operations and deviations are detected and minimized and that conditions can be appropriately corrected when failures occur. Plant control systems will contain provisions to detect and provide alarms associated with equipment failures and inform operators to take other precautionary or response actions. I&C systems will be designed to perform their associated functions in a reliable manner such that plant transients and abnormal conditions are minimized, either by automatic response or by operator action, if equipment failures do occur.

This layer of DID for MARVEL will be ensured in part by selection of fuel, cladding, coolant, structural materials, and coolant configuration that provide large safety margins between normal operating conditions and limiting failure conditions. Fuel failure consequences will be mitigated by the compatibility of fuel and cladding with the coolant (reducing or eliminating post-failure fuel degradation that could otherwise lead to other fuel failures). Operating margins will include margin for uncertainties in performance of humans and SSCs and uncertainties in the analyses. Non-nuclear testing will be used to further reduce uncertainties in analyses.

In addition, the MARVEL design benefits from favorable reactivity feedbacks that, together with the low-pressure NaK coolant and U-ZrH fuel, provide passive shutdown and passive safety behavior under various reactor upset conditions.

5.3 DID Layer 3: Control of Accidents Within the Design Basis

The objective of the third layer of defense is to prevent and mitigate unlikely and extremely unlikely event plant conditions within the design basis. This will be accomplished by engineered safety features (ESFs) that are capable of returning the facility to a safe controlled state. This will be achieved in MARVEL by conservative design and engineered safety systems for reactor shutdown and decay heat removal. Success in meeting the objectives in this layer occurs when required safety functions have been performed for the design basis accidents (DBAs).

Successive, multiple physical barriers (cladding, coolant, reactor vessel) will be in place for protection against release of radioactivity and hazardous materials. Multiple, diverse, and independent means will be provided to accomplish safety functions. Reactor shutdown systems and shutdown heat removal systems provide high-reliability protection functions.

The selection of liquid NaK coolant and U-ZrH fuel with a pool-type primary system arrangement provides a highly reliable reactor system with large operational safety margins and instill passive response characteristics that prevent or mitigate consequences of DBAs. The coolant thermophysical properties provide superior heat removal and transport characteristics at low operating pressure. The U-ZrH fuel operates at a relatively low temperature, below the coolant boiling point, due to its high thermal conductivity.

The primary system confines all significantly radioactive materials within a single vessel and allows for shutdown heat removal by natural circulation.

5.4 DID Layer 4: Control of Severe Facility Conditions

This layer's objective is to control severe plant conditions and mitigate beyond extremely unlikely event consequences. The proposed MARVEL design will be capable of accommodating various beyond extremely unlikely basis accident initiators without producing conditions that might lead to a severe accident. The inherent and passive features of the system are responsible for bringing the system to a stable state at safe temperatures. Successful operation of Layer 4 also involves maintaining fundamental safety functions for the retention of radioactive or hazardous material.

The passive performance mechanisms for ensuring reactivity control and cooling generally provide stronger feedbacks as temperatures increase. These design features help to control the level of severity of facility upsets. Additionally, the various levels of confinement barriers (cladding, coolant, reactor vessel, and TREAT building structure) provide thresholds that serve to control the release of radioactive material if facility conditions are severe enough to result in fuel failures and releases.

5.5 DID Layer 5: Mitigation of Radiological Consequences

The fifth layer of defense applies to severe accidents where significant releases of radiological or hazardous material occur. The objective of Layer 5 is to mitigate accident doses to workers and the public by employing anticipatory emergency planning and off-site accident management. It serves to ensure that even in the extremely unlikely event of a severe accident, adverse impacts on health and safety are still avoided. Successful operation of this layer prevents adverse health and safety impacts.

Significant adverse consequences from significant releases of radioactive or hazardous materials are limited by the MARVEL limited core size and fission product inventory. Consequences are also mitigated by emergency procedures and emergency response (sheltering, evacuation, etc.). As required for emergency response, means are provided to monitor accident releases. Additionally, emergency management planning provides a mechanism for taking appropriate actions to protect the public and workers should all other barriers fail.

DOE requirements for emergency planning in DOE O 151.1D, "Comprehensive Emergency Management System,"[15] and the large distance to the INL site boundaries from the TREAT building, as well as additional safety management programs (SMPs), provide capability to mitigate consequences from these extremely low probability events.

The MARVEL control room will be collocated with the TREAT control room. Radiological consequences to MARVEL workers will be limited by the distance from the TREAT building to the TREAT control room, and evacuation of the TREAT building during transient and MARVEL operations. Consequences to MFC collocated workers will also be analyzed.

6. SAFETY GUIDANCE AND REQUIREMENTS

There are numerous sections of the CFR, DOE Orders, and other policy requirements that are applicable to the design, construction, and operation of MARVEL. Safety analysis documentation will meet the requirements of 10 CFR 830 Subpart B, “Safety Basis Requirements.”

Most specifically, 10 CFR 830 Subpart B requires the development of a DSA for DOE nuclear facilities to ensure that hazard controls are established to provide for the adequate protection of workers, the public, and the environment from the hazards associated with the work in the facility. MARVEL will follow all applicable DOE requirements, including DOE O 420.1C.

Additionally, a Code of Record will be developed which identifies and documents appropriate requirements for the design and construction of MARVEL. Specific requirements from individual design disciplines or interface issues will be appropriately documented in the facility and system design requirements.

6.1 General Design Criteria

As stated in Section 3.1 of SAR-420, TREAT facility-specific general design criteria (GDC) were developed based on 10 CFR 50, Appendix A, “General Design Criteria for Nuclear Power Plants.”[16]

However, the guidance in Nuclear Regulatory Commission (NRC) regulatory guide (RG) 1.232, “Guidance for Developing Principal Design Criteria for Non-Light-Water Reactors,”[17] describes the NRC’s proposed guidance for adapting the 10 CFR 50 Appendix A GDC to develop principal design criteria (PDC) for non-light-water reactor (LWR) designs. RG 1.232 addresses two specific non-LWR design concepts: sodium-cooled fast reactors (SFRs) and modular high temperature gas-cooled reactors. Although MARVEL is not an SFR, the RG 1.232 Appendix B SFR design criteria will be used as the guidance to develop PDC for the MARVEL project’s unique design as applicable and appropriate.

In addition, DOE O 420.1C requires that for any new DOE nuclear reactor, a set of reactor-specific safety design criteria and a set of reactor design codes and standards must be established in accordance with the SDS required by DOE-STD-1189-2016. RG 1.232 guidance will be used to meet the DOE O 420.1C reactor-specific safety design criteria requirement.

Existing industry codes and standards will be used to the extent possible. MARVEL SSCs designated as SR based on meeting the criteria in Section 10.2.3 will be considered for application of the requirements in DOE O 420.1C for safety-class (SC) SSCs.

7. HAZARD IDENTIFICATION

10 CFR 830 Subpart B paragraph 202(b)(3), requires that the hazard categorization for a DOE nuclear facility be performed consistent with DOE-STD-1027-92, “Hazard Categorization and Accident Analysis Techniques for Compliance with DOE Order 5480.23, Nuclear Safety Analysis Reports,”[18] which has been superseded with DOE-STD-1027-2018, “Hazard Categorization of DOE Nuclear Facilties.”[19] DOE-STD-1027-2018 is an update of DOE-STD-1027-92. Both are still applicable and consistent for MARVEL.

DOE-STD-1027-2018, deemed an appropriate mechanism for meeting and implementing the requirements of DOE-STD-1027-92, identifies that reactors with steady-state powers 20 MWth and greater are considered Category A reactors and that Category B reactors are those otherwise not classified as Category A reactors. Category B reactors are considered to be HC-2 facilities.

TREAT is a Category B reactor and is classified as a HC-2 nuclear reactor facility. Given the anticipated MARVEL thermal power as <100 kWt, MARVEL is also a Category B reactor. Consistent with the hazard category interpretations in DOE-STD-1027-2018, given that TREAT and MARVEL are both Category B reactors, the TREAT facility remains overall a HC-2 facility. They are considered separately because each is anticipated to only run when the other is not; however, even if their steady-state powers were added, they would still fall within the Category B thresholds. As required by DOE-STD-1027-2018, hazard analysis will be performed as part of final hazard categorization to determine the effects of available energy sources and radioactive material release mechanisms.

Hazards that are normally associated with a small reactor facility can result from postulated failure conditions in one or more of the reactor systems or from operational errors. The principal safety functions to protect against potential hazards are adequate cooling, reactivity control, and continued integrity of radioactive material confinement boundaries. All three may be related to a degree, depending upon the details of a given accident.

Hazards to workers include exposure to direct radiation or airborne radioactive material. SSCs serving a safety function in protecting the facility worker from radiological hazards include shielding and monitoring systems.

In addition to nuclear hazards, the possibility of sodium and potassium chemical reactions or fires also exists. Hazardous materials (radiological and chemical) shall be minimized to those necessary to accomplish the mission.

8. KEY SAFETY DECISIONS

Decisions will be made during the initial project life cycle that will affect the eventual design and construction of MARVEL. This section discusses important considerations specific to MARVEL to enable clarity in safety expectations.

8.1 Passive Safety in Design

The fuel form was chosen because of its high reactivity, due to the homogenization of uranium atoms (fuel) and hydrogen atoms (moderator). The bound hydrogen atoms in the U-ZrH crystalline lattice also provide a strong negative temperature coefficient of reactivity. As the fuel temperature rises, the thermal neutron peak shifts upward in energy and reduces the U-235 fission rate. This passive negative feedback mechanism from the fuel and thermal expansion of various in-core components, can reliably mitigate reactivity changes to assure that acceptable (non-dangerous) steady-state conditions are reached, and the specified acceptable fuel design and bulk coolant limits are not exceeded during accident conditions.

The design also incorporates natural circulation of liquid NaK as a passive and reliable primary coolant heat rejection mechanism. The passive heat rejection system provides for passive heat transfer from the core to the ambient air through the vessel wall and other structures without actuation devices (i.e., valves or actuators). The passive system design will maintain heat rejection geometry and features and natural circulation ability during all normal operations and shutdown conditions and accident conditions.

8.2 Siting

DOE O 420.1C requires that nuclear facilities be sited in a manner that gives adequate protection for health and safety of the public, on-site workers, and collocated workers at adjacent facilities in accordance with uniform standards, guides, and codes which are consistent with those applied to comparable licensed nuclear facilities and the non-nuclear industry. MARVEL is proposed to be located at the INL TREAT facility in the north high-bay equipment pit.

Application of the safety-in-design principles identified in DOE-STD-1189-2016, as well as the evaluations to ensure adequate protection of facility and collocated workers in the safety basis, will provide assurance that the design is capable of meeting the requirements outlined in DOE O 420.1C and 10 CFR 830 for the TREAT facility location.

8.3 Seismic and Other Natural Phenomena Design Categorization

DOE O 420.1C Chapter IV provides the specific requirements for DOE facility design, construction, and operation to protect the public, workers, and environment from the impact of natural phenomenon hazard (NPH) events (e.g., earthquake, wind, flood, lightning, snow, and volcanic eruption).

As required by DOE O 420.1C, MARVEL will satisfy the applicable requirements and criteria contained in DOE-STD-1020-2016, "Natural Phenomena Hazards Analysis and Design Criteria for DOE Facilities."[20] Specifically, the facility and systems will be classified, as defined in DOE-STD-1020-2016, according to the risks of their failure, and designed to perform in accordance with the necessary NPH criteria for that classification.

Based on the evaluation in ECAR-5127, "Evaluation of the MARVEL Reactor Inhalation Dose Consequences,"[21] and on the criteria in DOE-STD-1020-2016, the MARVEL reactor and support safety systems are categorized as NPH design category (NDC)-2, and the other facility handling systems are categorized as NDC-2 or less, per the criteria in DOE-STD-1020-2016.

8.4 Fuel Acceptance Strategy

The first layer of DID in Section 5 will be achieved for MARVEL by proper selection of fuel, cladding, coolant, and structural materials that are stable and compatible, and by following high quality practices in construction and operation. The second layer of DID for MARVEL is ensured in part by selection of fuel, cladding, coolant, structural materials, and coolant configuration that provide large margins between normal operating conditions and limiting failure conditions.

A fuel acceptance plan will be prepared which outlines criteria for identifying appropriate fuel service conditions under normal and accident conditions as well as criteria for evaluation and demonstration of ability of the fuel to perform the identified safety functions. The objective of the fuel design process will be to ensure the fuel design can perform its safety functions during design basis conditions. The design basis conditions will be identified in the Functional and Operating Requirements for the fuel system and will encompass fuel in-service conditions through normal and accident operating conditions. The design validation will demonstrate through analysis that fuel will perform its functions through those conditions A fuel monitoring program will be established to verify that fuel behavior meets expectations.

8.5 Fire Prevention and Mitigation Strategy

The MARVEL design will provide systems for protection against internal fires. Fire protection systems will be designed to applicable National Fire Protection Association (NFPA) requirements and DOE-STD-1066-2016, “Fire Protection.”[22] A fire hazards analysis will be performed as part of the design process to identify the potential fire hazards and determine the need for design of fire detection and suppression systems, as well as appropriate fire area segmentation.

Compliance with DOE-STD-1066-2016 and the requirements for hazards evaluation and mitigation in the safety basis will ensure that the risks of all types of fires are adequately mitigated for MARVEL, including external fires.

8.6 Confinement Strategy

The MARVEL confinement strategy will be performance-based in that the confinement performance requirements will be derived from the accident analysis and not prescriptively identified. It is anticipated that a robust fuel structure will serve as the first confinement barrier with the reactor vessel and PCS to meet the performance requirements of the accident analysis, and the TREAT reactor building providing the final confinement structure.

Though not anticipated additional reactor confinement barriers may be required if uncertainty in reactor behavior is high, to protect the building investment. The accident analysis will determine the necessary safety classification and the specific required minimum performance criteria (e.g., allowed leakage rate or pressure retention requirements) for each of these systems.

8.7 Electrical Power

The MARVEL system will be able to shut down without the need of normal (site commercial) power. Normal power is site commercial power, supplied to TREAT over a pole line from the MFC-768 Power Plant 13.8-kV system. MARVEL systems will be designed to be fail safe in the event of loss of normal power, and it is anticipated that sufficient margin will be available in the design to assure safe plant shutdown upon loss of normal power, without needing a separate electrical power source. Any electrical power production systems will be designed to applicable codes and standards.

8.8 Instrumentation and Controls

Instrumentation will be provided to monitor variables and systems over their anticipated ranges for normal operation, for anticipated operational occurrences, and for accident and post-accident conditions, as appropriate, to assure adequate safety, including those variables and systems that can affect the fission process, the integrity of the reactor fuel and core, the primary coolant boundary, and the confinement boundaries and associated systems. Appropriate controls will be provided to maintain these variables and systems within prescribed operating ranges. Adequate instrumentation will be incorporated to provide:

1. Continuous monitoring of the neutron flux and reactivity status of the reactor with fuel in the reactor vessel.

2. Continuous monitoring of the reactor control variables (e.g., actuators and resolvers for CD position) such that adequate operating margins are maintained.

3. Continuous monitoring of essential reactor and process variables (e.g., temperature and pressure of the reactive vessel), including confinement status.

4. Diagnostic systems for detecting off-normal conditions.

I&Cs will be designed to perform their associated functions in a reliable manner such that plant transients and abnormal conditions are minimized if equipment failures do occur. Safety classification of I&Cs will be limited to only those components and functions necessary to prevent or mitigate accidents capable of exceeding evaluation guidelines (EGs) as identified in the safety analysis.

8.9 Control Room

The MARVEL control room will be collocated with the TREAT control room, including use of existing cabling between the TREAT building and control room. MARVEL will apply a graded approach to this requirement in that the TREAT control room provides the existing provisions from which actions can be taken to operate the MARVEL reactor safely under normal conditions and to ensure the ability to perform any credited operator actions under accident conditions.

Equipment at appropriate locations outside the control room will be provided (1) with a design capability for prompt shutdown of the reactor, including necessary I&Cs to maintain and monitor the unit in a safe condition following shutdown, and (2) with a capability for subsequent management of long-term temperature control of the reactor through the use of suitable procedures.

8.10 Reactor Protection

MARVEL will be provided with a reactor protection system (RPS) to ensure reactor shutdown under off-normal and accident conditions within the design basis. The design will be such as to minimize the likelihood that an operator action can prevent the RPS from performing its safety functions or inhibit the functioning of any inherent and passive safety feature.

The RPS will provide adequate capability of reactor shutdown with the most reactive CD stuck at its critical position under any projected operating condition. It will contain the ability to send appropriate trip and protection signals to other support systems, as necessary, to protect the reactor within the analyzed design basis. Design and performance requirements for the RPS will be developed to meet the requirements for safety systems from associated standards based upon the safety functions identified in the hazard and accident analysis. The use of standards cited by and referenced in DOE O 420.1C will be used on a graded basis, based on the function of the SSC and importance in the accident analysis.

8.11 Decay Heat Removal

A system to remove residual heat will be provided. MARVEL will be designed to provide for emergency decay heat removal to an ultimate heat sink. It will provide for passive, continuous operation and will be considered as a safety system.

8.12 Ex-Core Nuclear Criticality Safety

Provisions for evaluating and ensuring the reactor remains subcritical when shutdown, core assembly fueling, and defueling will be considered as part of the reactor safety reviews of the design. Additionally, designs that ensure criticality safety during fuel handling and fuel storage within the facility, will be implemented through application of a criticality safety program consistent with DOE requirements and the ANSI/ANS 8 series of standards.

8.13 Physical Security/Safeguards

The MARVEL design will include consideration of physical protection of the facility against malicious acts, in accordance with DOE requirements, as part of the design. As part of the conceptual and final design activities, vulnerability analyses will be performed. Protection of the facility will be accomplished by design, as much as practical, with safety and security being considered in an integrated fashion such that design and operational decisions are made in consideration of the impact each has on the other.

8.14 Source Term

The source term of primary interest is the MARVEL inventory of radionuclides that could be released in the event of an accident to the site and beyond the site boundary. To assess the adequacy of the plant design and control strategy, the safety analysis process also will define a source term released in bounding accident scenarios and evaluate the potential leakage of radionuclides to and transport within the environment. Determination of the source term (identifying the quantity of material involved in the accident and progression through confinement layers) will be done in a manner consistent with available technical information.

The mechanisms of release and transport will be considered and modeled as appropriate. The parameters utilized in the source term and consequence assessments will be documented within a modeling protocol or individual analysis documents and appropriately summarized in safety basis documents.

8.15 Hazardous Material/Industrial Safety

Hazardous materials (radiological and chemical) shall be minimized to those necessary during normal operations to accomplish the mission. The MARVEL will follow site-wide procedures for handling and storing hazardous materials generated during normal operations.

Disposition of beryllium and NaK at project end is discussed in Section 8.17.

8.16 Used Fuel Disposition

As discussed in DOE/EA-2146, "Draft Environmental Assessment for the Microreactor Applications Research, Validation and Evaluation (MARVEL) Project at Idaho National Laboratory,"[23] at project end, the fuel pins will be removed from the reactor and surveyed for radiation and contamination. After inspection, the assemblies will be placed in designated shipping or storage containers following criticality control protocols. Containers may be dry stored at TREAT or shipped to MFC for storage or treatment in accordance with legal, regulatory, operations, and scheduling requirements for the transfer and storage of these fuels. Refer to DOE/EA-2146 (Reference 23) for a detailed discussion on used fuel disposition.

8.17 Decontamination and Decommissioning

As discussed in DOE/EA-2146, at project end, the reactor fuel, reactor vessel, and associated activated metal components will be disassembled and analyzed using existing MFC facilities and processes. Alternately, MARVEL could be disassembled in the TREAT facility. The resulting waste from this analysis will be dispositioned using existing waste disposition paths (i.e., transuranic, remote-handled low-level waste (LLW) waste, contact-handled LLW, and mixed LLW).

Waste characterization and disposal concerns regarding the disposition of beryllium and NaK will be addressed in accordance with DOE O 435.1, “Radioactive Waste Management.”[24]

Given the small size of the reactor and associated components and systems, the waste volumes generated in this phase will a small impact on plans in place for the INL waste management program and disposition vendors. Cumulative radiological and waste generating impacts would be minimal. Radiological releases during normal waste management operations would not be expected to result in adverse health impacts. Additional waste volumes would be small compared to current waste volumes at INL. These small volumes would be nearly indiscernible from current operations when combined with past, present, and reasonably foreseeable future actions. Cumulative impacts from waste generation, management, and disposal would be small.[23]

As discussed in DOE/EA-2146, for D&D of the MARVEL microreactor, an initial activation analysis and modeling of the MARVEL microreactor beryllium oxide side reflectors reveals that these components will be DOE LLW or NRC Class A LLW and can be dispositioned through existing disposition paths, either DOE or commercial sites. It is assumed that this analysis would be bounding for other components and wastes that may be generated. Given this, it is concluded that all radioactive waste, other than the reactor fuel, generated in this phase will be NRC Class A LLW or mixed LLW and has current disposition paths in DOE or commercial facilities.[23]

The disposition of the primary coolant, NaK, will be one of the major waste-generating operations. NaK used as the primary coolant can become activated in a neutron flux with predominate activation products being short-lived. A minor amount of coolant activation products will be present due to activation of impurities in the coolant. The approximately 61 gallons of NaK primary coolant can be packaged in a manner that can be treated and dispositioned by existing vendors. NaK will be packaged to meet DOT and vendor waste acceptance criteria.[23]

The preliminary documented safety analysis (PDSA) hazard and accident analysis will evaluate related accident scenarios, including those associated with defueling, and identify required preventive and mitigative SSCs and controls. Appendix A identifies that the PDSA Chapter 13 will discuss the overall MARVEL D&D plan, including used fuel disposition.

Refer to DOE/EA-2146 (Reference 23) for further detailed discussion on beryllium and NaK disposition.

9. RISKS AND OPPORTUNITIES – PROJECT SAFETY DECISIONS

A risk management plan will be prepared for the project. The plan will define the scope, responsibilities, and methodology for identifying, assessing the impacts of, and managing risks that could affect successful and timely completion of the project, including an evaluation of safety-in-design risks and opportunities.

10. SAFETY ANALYSIS APPROACH AND PLAN

The purpose of this section is to provide the overall framework for demonstrating compliance with safety basis requirements in 10 CFR 830 Subpart B. Authority to approve the design, fabrication, construction, operation, and testing of MARVEL falls within the purview of DOE.

10 CFR 830 Subpart B requires the development of a DSA for DOE nuclear facilities to ensure that hazard controls are established to provide for the adequate protection of workers, the public, and the environment from the hazards associated with the work in the facility. This section outlines the core regulatory requirements and summary of key decision criteria that will be utilized in order to meet the expectations associated with safety basis documents.

10.1 MARVEL Safety Analysis Report Format and Content

The MARVEL DSA format and content strategy will be to develop an addendum to the existing TREAT SAR-420. SAR-420 Chapter 10, "Experimental Facilities and Utilization," will need to be replaced with a new power generation chapter in the addendum. Therefore, the LWR edition of NRC RG 1.70, "Standard Format and Content of Safety Analysis Reports for Nuclear Power Plants,"[25] and NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants,"[26] will be used as the guide to format and content for this chapter. RG 1.70 is designated in the CFRs (10 CFR 830) as a safe harbor for DOE reactor SARs. Appendix A of this SDS provides an outline of the format and content for the SAR-420 addendum.

TS-420 will be revised to add controls derived from the SAR-420 addendum. Additional controls as derived from the addendum accident analysis will also be added.

10.2 MARVEL Safety Analysis Process

The overall objective of this section is to describe a systematic and reproducible framework for selection of accidents, classification of SSCs, and determination of the adequacy of the MARVEL DID strategy outlined in Section 5 of this document.

The safety analysis process for the MARVEL project for compliance with 10 CFR 830 will follow a process consistent with the Licensing Modernization Process (LMP) as outlined in Nuclear Energy Institute (NEI)-18-04, "Risk-Informed Performance-Based Guidance for Non-Light Water Reactor Licensing Basis Development,"[27] and supporting documents.

The process in Figure 11 has been adapted to fit DOE regulatory requirements as applicable and appropriate. (Note that the nomenclature in NEI-18-04 uses the term licensing basis event [LBE] instead of safety basis event [SBE] as used in this document.) This approach provides reasonable assurance of meeting the requirements of 10 CFR 830 for protection of the public and worker. The process for event identification and subsequent control selection is outlined below.

The initial qualitative hazards analysis and final Chapter 15 accident analyses will evaluate the impacts of MARVEL operations, hazards, and accidents on the TREAT facility and transient testing operations, and likewise, the impacts of TREAT hazards and accidents currently evaluated in SAR-420 will be evaluated for impact on MARVEL.

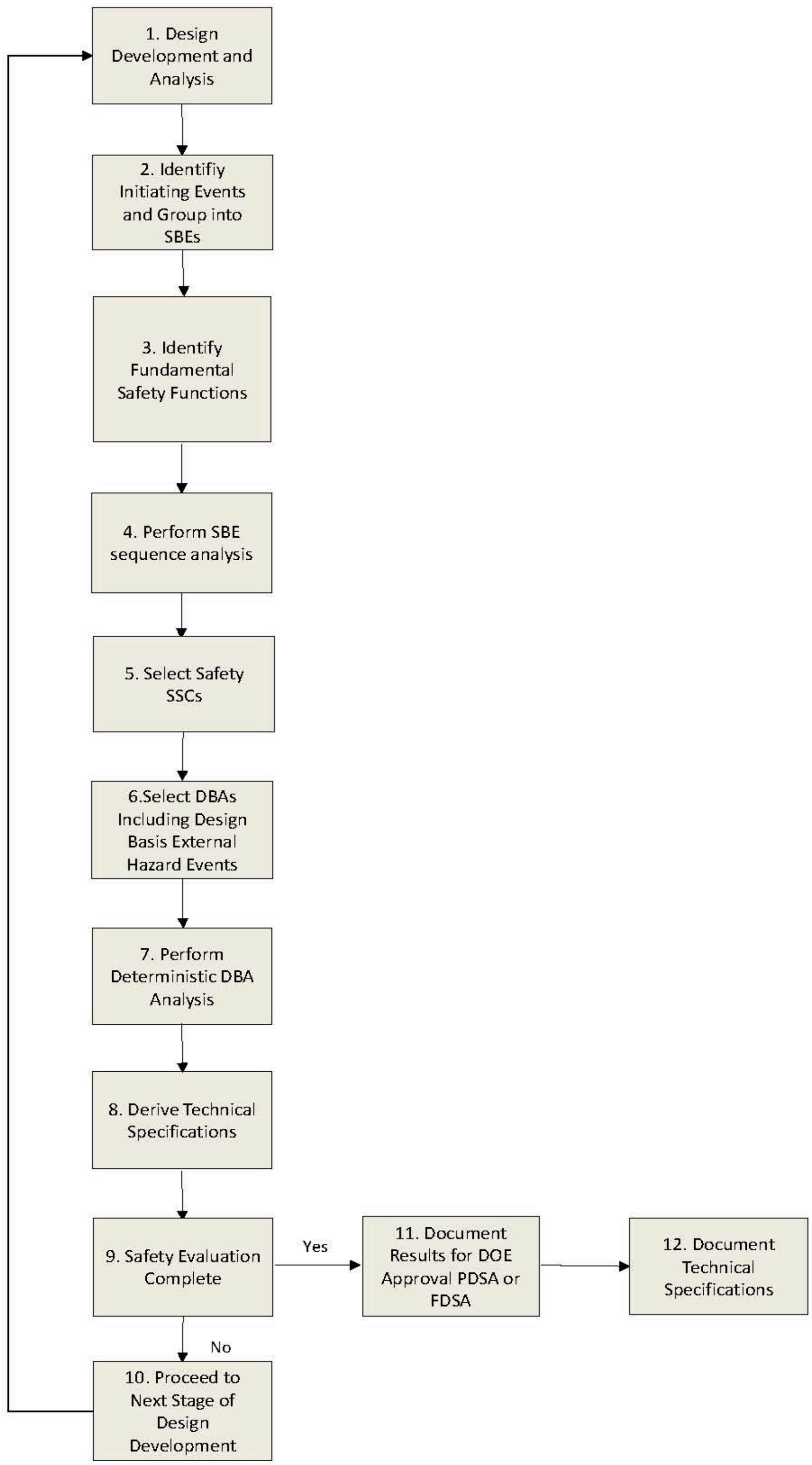

Figure 11. MARVEL hazards evaluation and accident analysis general flow (adapted from NEI-18-04).

The following briefly summarizes the implementation of the major tasks in the MARVEL hazards evaluation and accident analysis general flow in Figure 11:

Task 1: Includes defining each element of the safety-in-design approach to develop sufficient understanding to perform the deterministic safety analyses.

Task 2: A systematic approach is used to identify initiating events (IEs) that challenge at-power MARVEL plant operation and require successful mitigation to prevent radionuclide release. IEs are grouped into SBE categories according to similar attributes, such as plant response and system end states. (Note that the nomenclature in NEI-18-04 uses the term LBE instead of SBE as used in this document and explained in later sections.)

Task 3: Identifies the fundamental safety functions (FSFs) necessary to keep the IEs identified in Task 2 from progressing to end states that could result in core damage and release of radioactive or hazardous material.

Task 4: Event sequences are modeled to obtain an understanding of accident progression; response of SSCs performing the FSFs; and sequence end states.

Task 5: The full set of SBEs are examined to identify that the safety functions necessary and sufficient to ensure that the EGs are met. For each of these required safety functions, a decision is made on which SSCs: 1) perform the required safety functions, 2) are available on all the SBEs, and 3) should be classified as safety SSCs.

Task 6: For each SBE identified, a DBA is defined that includes the required safety function challenges represented in the SBE but assumes that the required safety functions are performed exclusively by SR SSCs, and all non-safety SSCs that perform these same functions are assumed to be unavailable. These DBAs will be used for performing the conservative deterministic transient safety analysis.

Tasks 7-8: For each defined DBA, a deterministic transient safety analysis is performed to demonstrate compliance with EGs, establish safety margins, and define SSC performance requirements and operational limits (TSs). Derivation of the MARVEL TSs will be in Chapter 16 of the MARVEL SAR-420 addendum.

Tasks 9, 11, 12: Documentation of the results of the analyses in the DSA for approval by DOE, and development of the MARVEL TS document.

Task 10: The process in Figure 11 is iterative and will be repeated as necessary as the MARVEL design matures from interim to final design.

10.2.1 Hazards and Accident Evaluation

A qualitative hazard evaluation will provide (a) an assessment of the facility hazards associated with the full scope of planned operations covered by the SAR and (b) the identification of controls that can prevent or mitigate these hazards or hazardous conditions. The hazard evaluation shall analyze normal operations (e.g., startup, facility activities, shutdown, and testing and maintenance configurations) as well as abnormal and accident conditions. In addition to the process-related hazards identified during the hazard identification process, the hazard evaluation shall also address natural phenomena and man-made external events that can affect the facility. The qualitative accident analysis provides the formal characterization of a limited subset of accidents and the determination of consequences and hazard controls associated with these events.

The hazards and accidents identified in the MARVEL evaluation will be analyzed for their effect on TREAT operations and safety. MARVEL operations will not be conducted while TREAT personnel are present in the reactor building, and simultaneous operations will be administratively controlled. In addition, the hazards and accidents analyzed in SAR-420 Chapter 15 will be analyzed for their effect on MARVEL operations and safety.

10.2.2 Evaluation Guidelines

EGs consistent with SAR-420 Chapter 15 Table 15-2 (see Table 3) shall be used.

10.2.3 Safety SSC Classification

MARVEL SSCs will be classified as SR, non-safety-related (NSR), or NSR with augmented requirements (NSR-AR) consistent with the SSC classifications in SAR-420 Chapter 3 Section 3.2. Appendix B of this SDS provides an initial MARVEL SSC classification based on SAR-420 SR and NSR-AR SSC criteria below.

MARVEL SSCs that meet the following criteria shall be classified as SR SSCs:

1. Is the SSC required to shut down the reactor and maintain it in a safe shutdown condition or ensure integrity of the primary coolant boundary?

2. Is the SSC required to ensure capability to prevent or mitigate the consequences of accidents that could result in potential consequences greater than the consequence guidelines in Chapter 15 Table 15-2?

3. Does the SSC contain an item required to establish an SR/NSR interface such that an SR system is isolated from an NSR system?

4. Could failure of the SSC prevent reactor shutdown or inhibit an SR SSC function?

MARVEL SSCs that meet the following criteria shall be classified as NSR-AR SSCs:

1. Is the NSR SSC assumed in the accident analyses in Chapter 15 to provide an additional layer of protection to (1) shut down the reactor and maintain it in a safe shutdown condition, (2) monitor the status of the reactor, or (3) monitor and filter reactor effluent?

2. Does the NSR SSC prevent or mitigate the consequences relative to the safety or protection of the facility or collocated worker?

3. Is the NSR SSC otherwise designated by TREAT management to support operational commitments or key assumptions in the SAR?

Table 3. MARVEL evaluation guidelines.

SBE Frequency Category[a]	Typical Frequency of Occurrence (F), (yr^{-1})[a]	Reactor Shutdown Fuel/Cladding Guidelines	Non-Fuel Shutdown Heat Removal Guidelines	Radiological Consequence Guidelines[a] (TED)		
				Off-site	On-site	Worker
Anticipated (TREAT Plant Condition 2)	$F \geq 10^{-2}$	• No additional barrier damage or failure occurs beyond the IE. • No fuel damage occurs beyond the IE, nor is there impact on fuel integrity or lifetime.	• No loss of reactor shutdown and decay heat removal functions occurs.	<5 rem	<5 rem	No distinguishable threshold
Unlikely (TREAT Plant Condition 3)	$10^{-2} > F \geq 10^{-4}$	• A coolable geometry is maintained for the fuel. • No fuel melting or other condition, such as excessive fuel temperature, occurs that could result in the uncontrolled movement of fission products and/or fuel from their intended location.	• At least one means of reactor shutdown and decay heat removal remains functional. • Confinement functional capability is maintained to control the release of fission products or other radioactive material to the environment.	<5 rem	<25 rem	<25 rem
Extremely unlikely (TREAT Plant Condition 4)	$10^{-4} > F \geq 10^{-6}$	• Assess design capability with respect to the accident prevention and mitigation safety objectives.	• Assess design capability with respect to the accident prevention and mitigation safety objectives.	<25 rem	<100 rem	<100 rem
Beyond extremely unlikely	$F < 10^{-6}$	• No criteria	• No criteria	• No criteria	• No criteria	• No criteria

a. TREAT FSAR Chapter 15 Table 15-2.

10.2.4 Defense-in-Depth Adequacy

The evaluation of the DID strategy in Section 5 is integrated with the hazard and accident analysis and is an integral part of the SSC classification and performance requirement determination. The evaluation of the DID strategy ensures that the specific design-related DID requirements of DOE O 420.1C Attachment 2 Chapter I are met in the MARVEL design.

Outcomes of this task include possible changes to the design to enhance the plant capabilities for DID, formulation of conservative assumptions for the transient safety analysis and consequence analyses, and input to defining and enhancing programmatic elements of DID.

11. SAFETY DESIGN INTEGRATION TEAM – INTERFACES AND INTEGRATION

The SDIT ensures the integration of safety into the design process. The composition of this team in Table 4 is adjusted as necessary to ensure the proper technical representation, including traditional worker safety disciplines, emergency management, and safeguards and security commensurate with the analyzed hazards and the specific project phase.

The SDIT ultimately supports decisions to be made by the Federal Project Director. Core members of the SDIT, responsible for implementation of safety-in-design for the project, and their corresponding responsibilities will be identified in the SDIT charter.

Table 4. MARVEL SDIT core team members.

Organization	Responsibility	Member
DOE-ID	DOE-ID Program Interface	Jihad Aljayoushi
	Nuclear Safety	Charlie Maggart
MARVEL	MARVEL Project and Design Lead	Yasir Arafat
	MARVEL Project Manager	Steve Martinson
	Nuclear Safety Manager	Jason Andrus
	Nuclear Safety Engineer	Doug Gerstner
	TREAT Plant Operations Manager	JR Biggs
	TREAT Engineering Manager	Brandon Moon
	TREAT Lead Scientist/Nuclear Facility Manager	Jim Parry

12. REFERENCES

1. DOE-STD-1189-2016, "Integration of Safety into the Design Process," U.S. Department of Energy, December 2016.

2. MMD-119, "10 CFR 830 Major Modification Determination for Microreactor Applications Testbed," Rev. 0, May 2020.

3. LWP-18113, "Integration of Safety into the Design Process," Rev. 2, September 2020.

4. 10 CFR 830, "Nuclear Safety Management," Subpart B, "Safety Basis Requirements," *Code of Federal Regulations*, Office of the Federal Register, January 2001.

5. DOE O 413.3B, "Program and Project Management for the Acquisition of Capital Assets," Change 4, U.S. Department of Energy, October 2017.

6. DOE O 420.1C, "Facility Safety," Change 3, U.S. Department of Energy, November 2019.

7. INL/LTD-20-57892, "An Initial Microreactor Design for Near-Term Demonstration," Rev. 0, April 2020.

8. SAR-420, "Transient Reactor Test (TREAT) Facility FSAR," current revision.

9. TS-420, "Technical Specifications for the TREAT Facility," current revision.

10. PDD-13000, "Quality Assurance Program Description," current revision.

11. DOE O 414.1D, "Quality Assurance," Change 1, U.S. Department of Energy, May 2103.

12. ASME NQA-1-2008/1a-2009 and 2017 editions, "Quality Assurance Requirements for Nuclear Facilities.".

13. ANSI/ANS 2.26-2004, "Categorization of Nuclear Facility Structures, Systems, and Components for Seismic Design," American National Standards Institute/American Nuclear Society, December 2004.

14. DOE G 420.1-1A, "Nonreactor Nuclear Safety Design Guide for use with DOE O 420.1C, Facility Safety," U.S. Department of Energy, December 2012.

15. DOE O 151.1D, "Comprehensive Emergency Management System," Change 1 (MinChg) U.S. Department of Energy, October 2019.

16. 10 CFR 50 Appendix A, "General Design Criteria for Nuclear Power Plants," *Code of Federal Regulations*, Office of the Federal Register, January 2001.

17. NRC RG 1.232, "Guidance for Developing Principal Design Criteria for Non-Light-Water Reactors," U.S. Nuclear Regulatory Commission, April 2018.

18. DOE-STD-1027-92, "Hazard Categorization and Accident Analysis Techniques for Compliance with DOE Order 5480.23, Nuclear Safety Analysis Reports," Change 1, U.S. Department of Energy, 1997.

19. DOE-STD-1027-2018, "Hazard Categorization of DOE Nuclear Facilities," U.S. Department of Energy, November 2018.

20. DOE-STD-1020-2016, "Natural Phenomena Hazards Analysis and Design Criteria for DOE Facilities," U.S. Department of Energy, December 2016.

21. ECAR-5127, "Evaluation of the MARVEL Reactor Inhalation Dose Consequences," Rev. 0, August 2020.

22. DOE-STD-1066-2016, "Fire Protection," U.S. Department of Energy, December 2016.

23. DOE/EA-2146, "Draft Environmental Assessment for the Microreactor Applications Research, Validation and Evaluation (MARVEL) Project at Idaho National Laboratory," Idaho National laboratory, January 2021.

24. DOE O 435.1, "Radioactive Waste Management," Change 1 (Pg Chg) U.S. Department of Energy, August 2001.

25. "Standard Format and Content of Safety Analysis Reports for Nuclear Power Plants," Regulatory Guide 1.70, Rev. 3, U.S. Nuclear Regulatory Commission.

26. "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants," NUREG-0800, U.S. Nuclear Regulatory Commission.

27. NEI-18-04, "Risk-Informed Performance-Based Guidance for Non-Light Water Reactor Licensing Basis Development," Nuclear Energy Institute, Revision 1, August 2019.

28. DOE O 422.1, "Conduct of Operations," Change 2, U.S. Department of Energy, December 2014.

Appendix A

Microreactor Applications Testbed
TREAT SAR-420 Addendum Format and Content

Chapter 1: Introduction and General Description of Facility

Chapter 1 will summarize the principal MARVEL design bases and considerations, general descriptions of the reactor facility that illustrate the anticipated operations, and the design safety considerations, including the limiting potential accidents. This chapter will summarize the detailed information found in subsequent chapters of the SAR addendum.

Chapter 2: Site Characteristics

No changes expected.

Chapter 3: Design of Structures, Components, Equipment, and Systems

Chapter 3 will describe the MARVEL design bases and facility SSCs, and the responses to environmental factors on the reactor site (e.g., floods).

Chapter 4: Reactor

Chapter 4 will describe the design bases and the functional characteristics of the MARVEL core and its components. In this chapter, the safety considerations and features of the reactor are discussed.

Chapter 5: Reactor Coolant Systems

Chapter 5 will describe the design bases and the functional characteristics of the MARVEL coolant and associated systems at the facility, including the primary and intermediate systems, as applicable, and coolant makeup and purification systems. The chapter also describes provisions for adequate heat removal while the reactor is operating and while it is shutdown.

Chapter 6: Engineered Safety Features

Chapter 6 will describe the design bases and the functional characteristics of the MARVEL ESFs that may be required to mitigate consequences of postulated accidents at the facility. This includes DBAs.

Chapter 7: Instrumentation and Control Systems

Chapter 7 will describe the design bases and the functional characteristics of the MARVEL I&C systems and subsystems at the facility, placing emphasis on SR systems and safe reactor shutdown.

Chapter 8: Electrical Power Systems

Chapter 8 will describe the design bases and the functional characteristics of the MARVEL electrical power systems that provide power to SR SSCs.

Chapter 9: Auxiliary Systems

Chapter 9 will describe the design bases and the functional characteristics of the MARVEL auxiliary SSCs not described elsewhere.

Chapter 10: Power Generation System

Chapter 10 will describe the design bases and the functional characteristics of the MARVEL power generation and process heat systems.

Chapter 11: Radiation Protection Program and Waste Management

Chapter 11 will describe the design bases and the functional characteristics of the radioactive waste management programs for MARVEL.

Chapter 12: Radiation Protection

Chapter 12 will describe the design bases and the functional characteristics of the radiation protection program for MARVEL. The description of the radiation protection program should include health physics procedures, monitoring programs for personnel exposures and effluent releases, and assessment and control of radiation doses, both to workers and the public. The program to maintain radiation exposures and releases as-low-as-is-reasonably-achievable (ALARA) includes the control and disposal of radiological waste from reactor operations.

Chapter 13: Conduct of Operations

Chapter 13 will describe the bases and describes the functions of plans and procedures for the MARVEL conduct of facility operations. These include discussions of the management structure, personnel training and evaluation, provisions for safety review and auditing of operations by the safety committees, QA and reliability assurance, and other required functions, such as: 1) reporting, 2) security planning, 3) emergency planning, and 4) criticality safety. This chapter will describe the MARVEL D&D plan, including used fuel disposition. This chapter will conform to DOE O 422.1, "Conduct of Operations."[28] Approval of the SAR-420 addendum will constitute DSA approval of the Conduct of Operations Conformance Matrix required by DOE O 422.1.

Chapter 14: Test Programs

Chapter 14 will identify the necessary tests, inspections, analyses, and acceptance criteria that must be verified to ensure adequate construction and operation upon initial MARVEL startup after construction. This will include the results of the primary coolant apparatus test (PCAT).

Chapter 15: Accident Analyses

Chapter 15 will describe the scenarios and analyses of accidents for operation of MARVEL, as well as the technical basis from which they were derived. These accidents may include a fission product release and radiological consequences to the operational staff reactor users, the public, and the environment. The function of ESFs is discussed in the accident analysis, as applicable.

Chapter 16: Derivation of Technical Specifications

Chapter 16 will present the MARVEL TSs, which state the operating limits and conditions and other requirements for the facility to acceptably ensure protection of the health and safety of the public. Additionally, the SMPs established as programmatic requirements in the accident analysis are also described. SMPs will include emergency management, fire protection, criticality safety, and radiation protection program commitments. Specific administrative controls will not be called out separately and may be in limiting condition for operation (LCO) format.

Chapter 17: Quality and Reliability Assurance

Chapter 17 will describe the quality and reliability assurance programs for MARVEL.

Appendix B

Preliminary MARVEL Safety SSC Classification Summary

Table B-1. Preliminary MARVEL SSC classification summary.

Fundamental Safety Function	Sub-Functions	Recommended Classification	Safety Classification Criterion	Safety Function(s)
Reactivity control	PPS (other than manual scram and seismic trip)	NSR-AR	NSR-AR-1	– Receive input signal and initiate a reactor shutdown by passive insertion of the CDs. – Upon loss of off-site power (LOOP), initiate a reactor shutdown by passive insertion of the CDs.
	Seismic early warning trip	SR	SR-1	– Sense a seismic event and provide PPS actuation signal to shutdown reactor by passive insertion of the CDs.
	Manual scram	SR	SR-1	– Shut down the reactor and maintain it in a safe shutdown condition by manual operator scram.
	CD passive insertion capability	SR	SR-1	– Release CD following signal from PPS manual scram and seismic early warning trip. – Provide passive insertion of negative reactivity to shut down the reactor and maintain in shutdown condition. – Structural performance of CDs, guide structures, and core under operating and transient conditions to ensure unobstructed insertion path and reactor shutdown.
	CD relays	SR	SR-1	– Prevent simultaneous uncontrolled withdrawal of more than one CD as a result of equipment or operator error.
	CD stops	SR	SR-1	– Limit CD movement to ensure that available excess reactivity insertion does not challenge fuel and temperature limits when inserted instantaneously.
	IRF	SR	SR-1	– Provide system performance related to geometric and physics changes in order to provide negative reactivity insertion as a function of temperature increase such that the resulting reactor power is reduced to passive heat rejection levels before fuel and vessel temperature limits are challenged and core damage occurs.
	Power conversion	NSR	N/A	– N/A

Fundamental Safety Function	Sub-Functions	Recommended Classification	Safety Classification Criterion	Safety Function(s)
Core flow/heat removal	Primary NaK circulation flowpath and core coolable geometry	SR	SR-1	– Structural, mechanical, and geographic spacing to ensure natural circulation through fuel assemblies at reactor operating and elevated transient temperatures and to ensure conduction heat transfer to the passive ambient air heat rejection system is possible. – Design provisions to ensure major core flow blockages are not credible. – Maintain core coolable geometry in a seismic event.
	Passive heat rejection	SR	SR-1	– Maintain heat rejection geometry and features and natural circulation ability during all normal operations and shutdown conditions and SBEs.
Confinement of radioactive material	Fission product barriers including fuel matrix and cladding	SR	SR-1	– The fuel retains many radionuclides within its matrix. – The cladding around the fuel provides a barrier for gaseous fission products. – Fuel and cladding structure design to remain within temperature limits to maintain core coolable geometry.
	Primary coolant boundary including reactor vessel and downcomers	SR	SR-1, 4	– Confinement barrier to ensure primary NaK and any leaked fission or activation products remain within vessel and oxygen remains outside. – Reduce probability of large NaK leaks due to pipe design under normal and transient operating conditions.
	Guard vessel	NSR-AR	NSR-AR-2	– Prevent NaK-air, NaK-water, NaK-concrete, and NaK-organics interactions. – Prevent the core from being uncovered during a postulated LOCA by controlling the void space inside the guard vessel
	TREAT building F/CS	NSR-AR	NSR-AR-2	– Not credited in the SBE and accident analysis. Existing safety functions for TREAT operations in SAR-420 are adequate as DID for any MARVEL release.

Fundamental Safety Function	Sub-Functions	Recommended Classification	Safety Classification Criterion	Safety Function(s)
Auxiliary/ supporting systems for key safety functions	Instrumentation power	NSR-AR	NSR-AR-1	– Provide power to instruments and monitoring panels for monitoring safe plant shutdown from the control room and under accident conditions.
	Post-accident monitoring	NSR-AR	NSR-AR-1	– Ensure ability for operators to verify reactor shutdown, initiate a manual scram if required, and monitor post shutdown conditions from the control room and under accident conditions.
	Large NaK fire prevention	NSR-AR	NSR-AR-1	– MARVEL vessel and external piping passive design shall prevent release of NaK and limit NaK-air interaction and resultant fire in the event of failure. Must be able to withstand system NaK temperatures and pressures and thermal stress/strain for an extended period of time. Minimize potential chemical consequences from large NaK fire.
	NaK fire detection and suppression	NSR-AR	NSR-AR-2	– Minimize potential chemical consequences from large NaK fire.
	Shielding	NSR-AR	NSR-AR-2	– Ensure that large shielding components are designed such that the design shielding rates are met under normal operations and potential accident conditions, which might otherwise result in significant loss of shielding.
	Criticality prevention	NSR-AR	NSR-AR-2	– Provide a subcritical configuration in support of material movements under normal and accident conditions.
	Backup power	NSR	N/A	– N/A
	TREAT building crane(s)	NSR-AR	NSR-AR-2	– Prevent drops of heavy loads onto the reactor during initial fueling or D&D.