TERRESTRIAL
ENERGY USA

IMSR® Core-unit Definition

Applicable Structures, Systems and Components

Abstract

TEUSA's long term licensing objective for the IMSR® design is to obtain a Standard Design Approval (SDA) for the IMSR® Core-unit. An important component of a 10 CFR Part 52 SDA application for the IMSR® Core-unit is identification and description of the structures, systems and components (SSCs) of the IMSR® Core-unit. This white paper provides a general overview description of the IMSR® design and a more detailed description of IMSR® Core-unit SSCs.

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Non-Proprietary

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I Purpose

The purpose of this white paper is to define the Integral Molten Salt Reactor (IMSR®) Core-unit.

This white paper supports the identification of interface and boundary conditions and requirements necessary to establish the Core-unit as a "major portion" of the overall IMSR® power plant design in an application for a Standard Design Approval (SDA) for the Core-unit under 10 CFR Part 52, Subpart E.

Interface requirements are those requirements related to the interface and boundary conditions associated with the Core-unit. The interfaces will stem from the dependency of the structures, systems and components (SSCs) that are within the scope of the application for a Core-unit SDA as well as on the functional and operational characteristics of SSCs that are not within the scope of the SDA.

Interfaces and boundary conditions can be distinct; however, they can also be used interchangeably. Nonetheless, together, they describe the limitations, constraints, assumptions, and conditions to define the relationship between the Core-unit and the remainder of the power plant.

An interface could include a programmatic requirement or an operational assumption about system performance of the Core-unit. Whereas, a boundary condition could be a physical constraint or an explicit limit on an interfacing system or component, or a similar restraint or limitation associated directly with the Core-unit. Additionally, a boundary condition may be a well-defined physical point of separation, or departure, between an interfacing system and the Core-unit.

The information requirements for a Core-unit SDA application is a subset of the information requirements supporting an application for a construction permit or combined license, thereby supporting the longer-term licensing goals associated with IMSR® deployment. Information that supports an SDA application for the IMSR® Core-unit includes information identifying, defining, or describing:

- the IMSR® Core-unit,
- the associated Core-unit engineering boundary conditions,
- the interfaces between the Core-unit and the remaining portions of the IMSR® power plant,
- the IMSR® Principal Design Criteria (PDC),
- the Core-unit interface requirements & acceptance criteria, and
- other regulatory requirements applicable to the IMSR® Core-unit.

This document provides a general overview description of the IMSR® design. It provides a description of IMSR® Core-unit structures, systems and components (SSC) to support meeting the information requirements in 10 CFR 52.137 related to identifying, defining, and describing the IMSR® Core-unit design basis in an SDA application for the Core-unit. This paper also provides an overview of the main plant buildings, structures, systems and components that make up a single reactor IMSR® Nuclear Power Plant (I-NPP).

II Introduction

Terrestrial Energy USA, Inc. (TEUSA) is developing the Integral Molten Salt Reactor (IMSR®) design to provide electricity or process heat to U.S. industrial heat users. TEUSA is planning for the first commercial deployment of this technology in the late 2020s. The IMSR® is a Generation IV advanced reactor power plant that employs a fluoride molten salt reactor (MSR) design. The IMSR® nuclear power plant, an I-NPP, consists of a nuclear island containing at least one, approximately 440 MWth IMSR® (IMSR400) Core-unit. The IMSR400 has the potential to generate up to 195 MWe of electrical power or to export 600 °C of heat for industrial applications, or some combination of both. The I-NPP includes an adjacent balance-of-plant building that contains non-nuclear-grade, industry-standard power equipment.

The IMSR® design builds upon pioneering work carried out at Oak Ridge National Laboratory (ORNL) from the 1950s to the 1980s, where MSR technology was developed, built, and demonstrated with two experimental MSRs. The first MSR was the Aircraft Reactor Experiment (ARE) and next, the Molten Salt Reactor Experiment (MSRE). Based on the demonstrated feasibility of MSR technology, ORNL commenced a commercial power plant program for MSR technology. This program led to the Denatured Molten Salt Reactor (DMSR) design in the early 1980s.

TEUSA has developed and submitted a Regulatory Engagement Plan (REP) (Reference 2) to the Nuclear Regulatory Commission (NRC). The REP outlines topics and schedules for interaction with the NRC to achieve early resolution of general technical or regulatory matters related to the IMSR® design. More specifically, the REP highlights technical and regulatory topics that directly support the development and submittal of a 10 CFR 52, Subpart E application for a Standard Design Approval (SDA) of the IMSR® Core-unit. This white paper [ ] support the TEUSA SDA application development efforts.

Company Background

TEUSA [ ]. TEUSA is a Delaware C-Corp founded in August 2014 that started active business operations in 2015. TEUSA is a U. S. majority-owned company with corporate offices in New York. [ ].

Canadian Nexus

TEUSA [ ]. TEUSA leverages the ongoing engineering and regulatory work that TEI accomplishes as TEI advances its regulatory activities under Phase 2 of the Vendor Design Review (VDR) process with the Canadian Nuclear Safety Commission (CNSC). Leveraging the efforts of TEI's VDR activities is possible because most of the technical and engineering information used for both regulatory reviews is the same. Leveraging TEI effort eliminates duplicate technical work in the U.S., and the approach also provides substantial cost savings for TEUSA. The figure below provides [ ].

Figure 1: [ ]

[

]

Licensing Strategy and Objective

The REP provided to the NRC outlines the regulatory strategy for TEUSA activities. [

] to support a commercial operation date for the first U.S. plant in the 2020s. During regulatory reviews, the NRC uses its understanding of the design and operating characteristics as well as the supporting research and engineering work to perform its review responsibilities efficiently. To support the NRC understanding, TEUSA has begun familiarizing the NRC with the IMSR® design as well as the scope of the available and planned analyses, testing, and operational experience in support of the design. By initiating the process of introducing the IMSR® design information to the NRC, TEUSA expects that the NRC can identify any issues that may require further testing or technical analyses. Additionally, the NRC will be more able to estimate the resource and schedule requirements necessary to conduct regulatory activities associated with IMSR® licensing.

TEUSA's long-term licensing objective for the commercial deployment of the IMSR® design in the U.S. is to first obtain an SDA for the IMSR® Core-unit under 10 CFR Part 52, Subpart E. The IMSR® Core-unit represents a significant technical portion of the IMSR® facility and includes many systems that perform important safety function. The systems within the Core-unit are reasonably discernible from systems outside the boundaries of the Core-unit. Subsequent sections of this white paper provide additional details about the design envelope of the IMSR® Core-unit and its safety interfaces.

The arguments supporting TEUSA's long term licensing strategy for seeking an SDA for the Core-unit portion of the IMSR® include:

- [ ],
- [ ], and
- [ ].

This white paper provides a general overview description of the IMSR® design and a more detailed description of IMSR® Core-unit SSCs that would form a 'major portion' of a planned SDA application for the IMSR® Core-unit. The information requirements for an SDA application for the Core-unit is a subset of the information requirements supporting an application for a construction permit or combined license, thereby supporting the longer-term goal of IMSR® deployment by the late 2020s.

If more details about TEUSA licensing activities and objectives are needed, please refer to the Regulatory Engagement Plan previously provided to the NRC (Reference 2).

III IMSR® Power Plant Description – Overview

Historically, there have been primarily two different types of molten salt reactors that have been developed, were considered for development, or are under development. In one type, solid-fueled reactors use molten salt as a coolant. In the second type, the molten salt also contains the nuclear fuel dissolved in the salt, i.e., the nuclear fuel is also a salt, and the molten salt mixture circulates through a region where nuclear fission occurs to produce heat. In this situation, a reactor is considered a "liquid-fuel" MSR, and this liquid-fuel approach is the basis for the IMSR®.

The power plant described in this paper includes the reactor and power conversion process for creating heat in the reactor core and subsequently transferring the heat to produce electricity. Also included is an overview of the site layout and a brief description of the Reactor Auxiliary Building, Turbine Building, Control Building, the Maintenance Building, and other support buildings.

Reactor and Power Conversion Process

The IMSR® is a liquid-fueled, thermal spectrum, burner-type, fluoride molten salt reactor design that uses standard assay low-enriched uranium fuel, with less than 5% enriched ^{235}U. IMSR® design choices permit the use of liquid-fuel MSR technology in an industrial or commercial setting through simplicity and safety of operation. All of the primary reactor components, including the pumps and heat exchangers, are inside a sealed and replaceable Core-unit with the reactor vessel and its closure head forming the primary boundary of the Core-unit. The result is a simplified reactor plant with no external primary system piping loops, no external primary system pumps, and no pressurizer of any kind. The nuclear fuel and coolant circulate entirely within, never exiting, the reactor vessel. The Core-unit operating lifetime is 7-years. After this period, a new Core-unit replaces the spent Core-unit. This approach eliminates any need to open the Core-unit for graphite replacement, maintenance, or repairs, a complex and costly task made hazardous by potential exposure to radioactivity. The design also provides a high degree of safety and unprecedented simplicity of industrial operation, and by extension, materially lower capital and operating costs compared to other power reactor designs in operation today.

The IMSR® fuel salt is a highly stable, fluoride-based, inert liquid with robust coolant properties and intrinsically high radionuclide retention capabilities that operates at a temperature of approximately 700°C. During normal, critical reactor operations, the primary pumps circulate the fuel salt through the reactor moderator and primary heat exchangers. The liquid fuel salt [

]. The fissioning of the fuel raises the temperature of the fuel salt as it passes through the moderator region. The fuel salt, [
] where it is directed
[ ]. Near the top of the reactor vessel, [

---

[1] [

].

].

Heat is transferred from the Core-unit via a secondary coolant system, a system using non-radioactive molten salt as the coolant. The secondary coolant system [ ] secondary heat exchanger. There are [ ]. In the [ ], the secondary coolant [ ]. As the secondary coolant salt passes through the secondary heat exchanger, the heat transfers to a tertiary molten salt coolant loop. After passing through the secondary heat exchanger, the now cooler secondary coolant salt [ ].

The Tertiary Salt Loop utilizes an inexpensive, common molten nitrate solar salt. This loop transfers the heat from the secondary heat exchangers in the Reactor Auxiliary Building, to the balance-of-plant building for electricity production, industrial process-heat uses, or both. The tertiary coolant [ ]. The Tertiary Salt Loop provides the following:

- Adds an additional barrier and inherent heat sink between the non-radioactive Secondary Coolant Loop salt and the non-nuclear steam plant.
- [ ].
- [ ].
- In the event of any tube leakage from the Steam Generator, [ ], unlike fluoride salts, [ ].

The Tertiary Salt Loop is insulated and contains isolation valves on the inlet and outlet pipes for operational and maintenance purposes. The Tertiary Salt Loop design accommodates inspection and maintenance as required, the same as the Secondary Coolant Salt Loop.

Within the balance of plant, the heat output can be used for power generation or process heat, or any combination of power and process heat. For process heat applications, either a steam cycle or direct use of the solar salt is possible. For power generation applications, the Tertiary Salt Loop heats pressurized feedwater in the steam generator, boiling the feedwater to steam under pressure. [ ] a commercial, standard high-pressure steam turbine. After passing through the HP turbine, the partially expanded steam [ ], the steam enters the intermediate pressure turbine. After exiting the intermediate pressure turbine, the steam flows to low-pressure turbines. After expanding through the low-pressure turbines, the exhaust steam condenses in a condenser. The resulting condensate is sent through feedwater heaters and a deaerator to provide deaerated, [ ] feedwater at the inlet to the steam generator.

The steam turbine drives an electrical generator, generating up to ~195 MWe of turbine island output. The exact net output is site and heat-sink dependent.

Site Overview

The IMSR® site layout includes the buildings required within the site boundary to operate the plant safely and to meet the licensing, safeguards, and security requirements. A typical site has a small footprint (about 7 hectares or 17 acres) and a small security perimeter (approximately 130m x 145m).

An I-NPP site includes a Reactor Auxiliary Building, Turbine Building, Control Building, and Maintenance Building. Also included are the plant support buildings and structures. These include the Administration Building, Simulator and Training Building, Radioactive Waste Building, Coolant Salt Storage Building, Emergency Mitigating Equipment Building, Main Pump House, Water Treatment Building, Fire Water Pump Building, Cooling Water Outlet Building, Sewage Treatment Plant, Electrical Switchyard, and a Security Building.

Figure 2: Typical Site Layout for a Single I-NPP

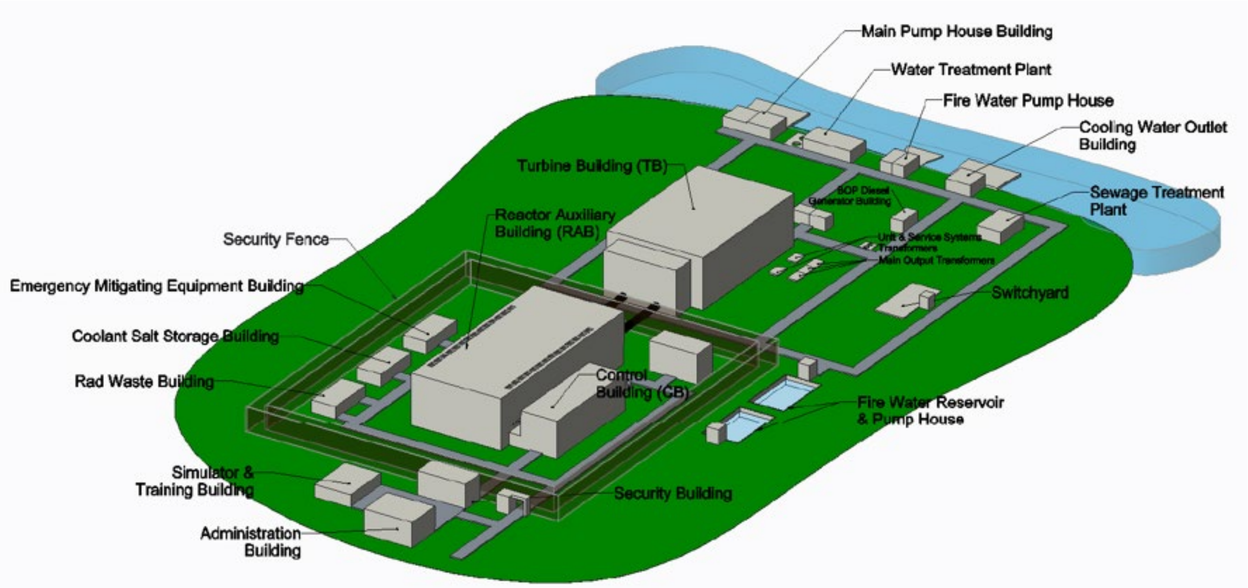


Figure 2 above represents a simplified plant layout identifying the arrangement and configuration of the major buildings, structures, and boundaries of an I-NPP site. A "generic design site envelope," is used to develop the IMSR® site design and encompasses generic site parameters used in Canada, the U.S. and European countries relevant to nuclear plant siting.

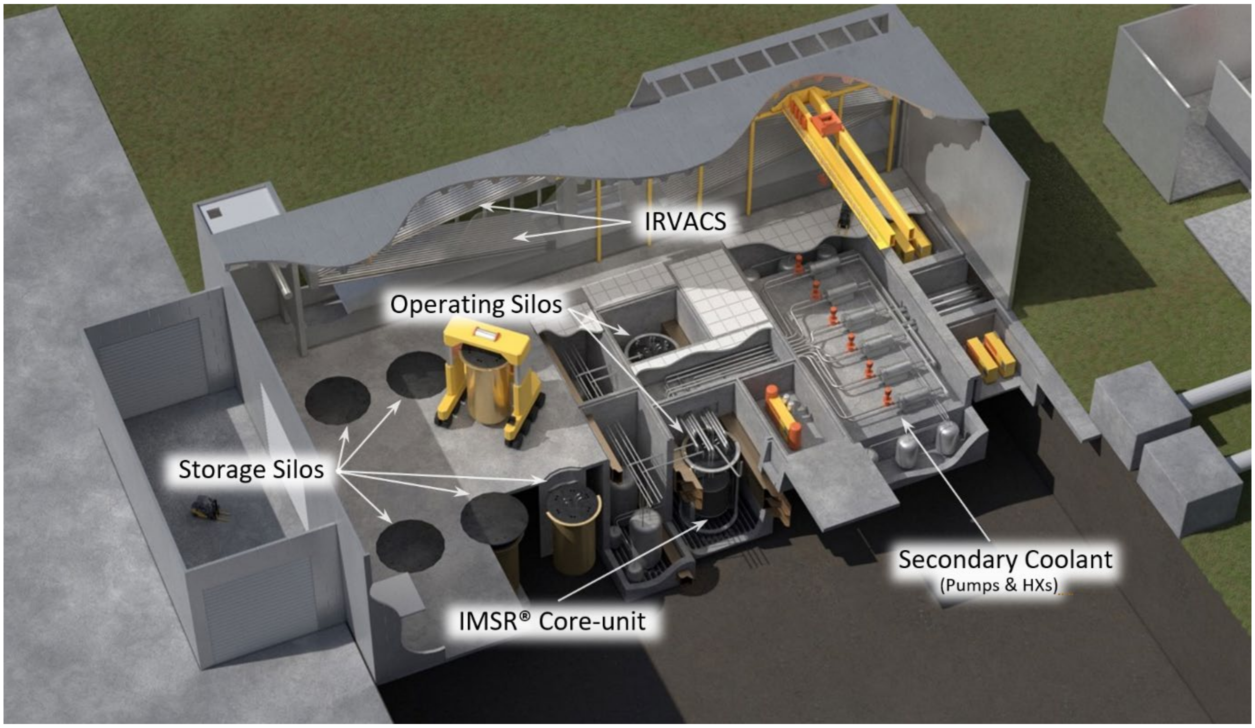
The following section provides, in general terms, a description of the main buildings and structures of a site containing an I-NPP.

Reactor Auxiliary Building

The seismically qualified Reactor Auxiliary Building (RAB) houses, (i) the IMSR® Core-units and associated nuclear systems, (ii) the various heat removal systems before the Steam Generators and, where required, additional heat transfer equipment to supply process heat to industrial users, and (iii) electrical systems and various auxiliary systems required to operate safely, control, and monitor the plant during all postulated operating conditions. Figure 3 below shows the arrangement of the storage silos, operating silos, a portion of the IRVACS (Internal Reactor Vessel Auxiliary Cooling System), and the location of the secondary coolant system; primarily the pumps and heat exchangers. Importantly, Figure 3 shows the physical relationship between the operating silos, storage silos, and the IMSR® Core-unit.

The Reactor Auxiliary Building [ ].

Figure 3: Reactor Auxiliary Building



Turbine Building

The Turbine Building houses the steam generators, steam and feedwater systems, and cooling systems associated with the turbine generator and the supply of electricity to the grid. The specific design requirements for the Turbine Building layout are dependent on the specific turbine generator and the cooling medium selected for condenser cooling.

The steam plant and the associated buildings have no safety function for the I-NPP and therefore are located outside of the protected area. IMSR® employs a conventional industrial electrical generator system with superheated and reheated steam capabilities as well as multi-stage feedwater heating and a condenser unit.

For power generation, the I-NPP uses standardized superheated steam plant equipment such as the steam generators. The plant's steam generators are based on operating experience from various concentrated thermal solar power plants that use similar liquid nitrate salt-heated steam generators to produce steam for powering turbo-generators. The turbine is a power conversion system designed to change the thermal energy of the steam flowing through the turbine into rotational mechanical work, which rotates a generator to provide electrical power.

The Turbine Building [ ].

Control Building

The Control Building houses the main control center, the security and operations staff, associated change rooms, and facilities required for the operation of the plant. [ ] provide for personnel ingress and egress and, for routing of auxiliary, electrical, instrumentation, and communication conduits between the buildings.

The Control Building [ ]. The Control Building [ ].

Standby Power Buildings

The Standby Power Buildings [ ] safety requirements (i.e., monitoring) [ ] selected equipment. Additional [ ] capability.

The Standby Power Buildings [ ].

Maintenance Building

The Maintenance Building houses the active and non-active shops and facilities associated with the maintenance of equipment removed from the Nuclear Area, as well as the equipment within other buildings and structures.

The Maintenance Building [ ].

IV Structure, System and Component Descriptions

Silos

There are eight silos included in the IMSR® facility. Two silos are for operating Core-units, and six are for Core-unit storage. One of either of these two operational silos houses the operating Core-unit for its 7-year operational life; the second silo houses the previously operated (spent) Core-unit during its radioactivity decay cooldown period. Following cooldown, preparations are made for a new Core-unit by transferring the previously operated Core-unit from the operating silo into a storage silo. The six storage silos only house spent Core-units that have completed the required radioactivity decay cooldown period. The silos interface with the Reactor Vessel and Reactor Support Structure. Figure 3 shows the relationship of the Silo to the Guard Vessel, Core-unit, and other structures, systems and components.

The Silo [ ].

Guard Vessel

The Guard Vessel is a stainless-steel vessel that is fitted around and supports the Reactor vessel. The primary purpose of the Guard Vessel is to catch and retain any fuel salt leakage or radioactive release from the IMSR® Core-unit to protect from any unintended release from the Core-unit. In the event of a Beyond Design Basis failure of the reactor vessel, the Guard Vessel will catch and contain any leaked fuel salt. Unlike the Reactor Vessel, which is a component part of the replaceable Core-unit, the Guard Vessel is a component of the containment boundary. The Guard Vessel is designed to last for the operating life of the plant. Figure 3 shows the relationship of the Guard Vessel, Silo, Core-unit, and other structures, systems and components.

The Guard Vessel [ ].

Reactor Support Structure

The Reactor Support Structure is a steel structure located in the silo. The Reactor Support Structure is used to support and provide alignment of the Guard Vessel inside the Silo. By extension, the Reactor Support Structure also provides support and alignment of the Core-unit. Figure 3 shows the relationship of the Reactor Support Structure, Silo, Guard Vessel, Core-unit, and other structures, systems and components.

The Reactor Support Structure [ ].

Containment

The Containment system forms a sealed, low-leakage envelope to house all systems that may contain highly radioactive material, specifically the Core-unit (active reactor), the off-gas lines/storage, irradiated fuel tanks, and any pipe transferring irradiated liquid fuel. In the event of a leak in any of these systems, the containment prevents the release of any radioactive materials to the Reactor Auxiliary Building. The Containment system also minimizes releases in the unlikely event of a severe accident. The Containment system includes the Guard Vessel and a common containment boundary that encloses the top plate of the Reactor Vessel, the off-gas and fuel transfer lines, and the irradiated fuel storage tanks.

The main functions of Containment are to:

- Provide a passive barrier for high activity sources within the plant to protect workers and the public from radiation doses during normal operations and accidents. The main sources of

radioactive materials in the plant are the reactor core, off-gas storage, and irradiated fuel systems.
- Control personnel access into Containment to protect plant personnel from radiation. [ ].
- Shield plant personnel working above the Reactor Vessel in the RAB from ionizing radiation.
- Minimize leakage to assure that normal operation release limits are met, and AOOs and DBAs do not result in exceeding dose acceptance criteria defined in TEI Design Guides.

The Containment system follows the passive safety design principles of the IMSR400 in that it does not require [ ] to carry out its functions. The Containment is continuously sealed when the reactor contains fuel. The Containment environment is conditioned prior to the initial start-up of a Core-unit and then sealed. It does not require [ ] for the time period between Core-unit replacements.

The Containment [ ].

Internal Reactor Vessel Auxiliary Cooling System (IRVACS)

Under normal conditions for reactor heat removal, the fuel salt mixes convectively in the Core-unit and transfers heat out through the primary heat exchangers to the secondary heat exchangers as described above in the Reactor and Power Conversion Process section. The IRVACS functions as an alternate emergency heat sink to remove heat generated within the Core-unit during transients, accidents, or whenever the normal heat removal paths are lost.

IRVACS [ ] system that operates [ ] to transfer heat from the Core-unit to the atmosphere. IRVACS is always operating and does not require any AC or DC electrical power. The system functions continuously irrespective of Core-unit status or plant state. The system has no actuation devices, no flow control mechanisms, nor any other type of control device. The heat removal capacity is sized to remove the maximum postulated decay-heat load, including after an accident where normal heat removal might not be available.

IRVACS is seismically qualified, highly robust, and fail-safe. It provides a passive, [ ] to transfer heat from the hot, uninsulated silo to the atmosphere. During all plant operations, the hot Reactor Vessel [ ] Reactor Auxiliary Building. [ ] to the atmosphere. [ ] the process is repeated. Figure 3 shows the relationship of IRVACS, Reactor Support Structure, Silo, Guard Vessel, Core-unit, and other structures, systems and components.

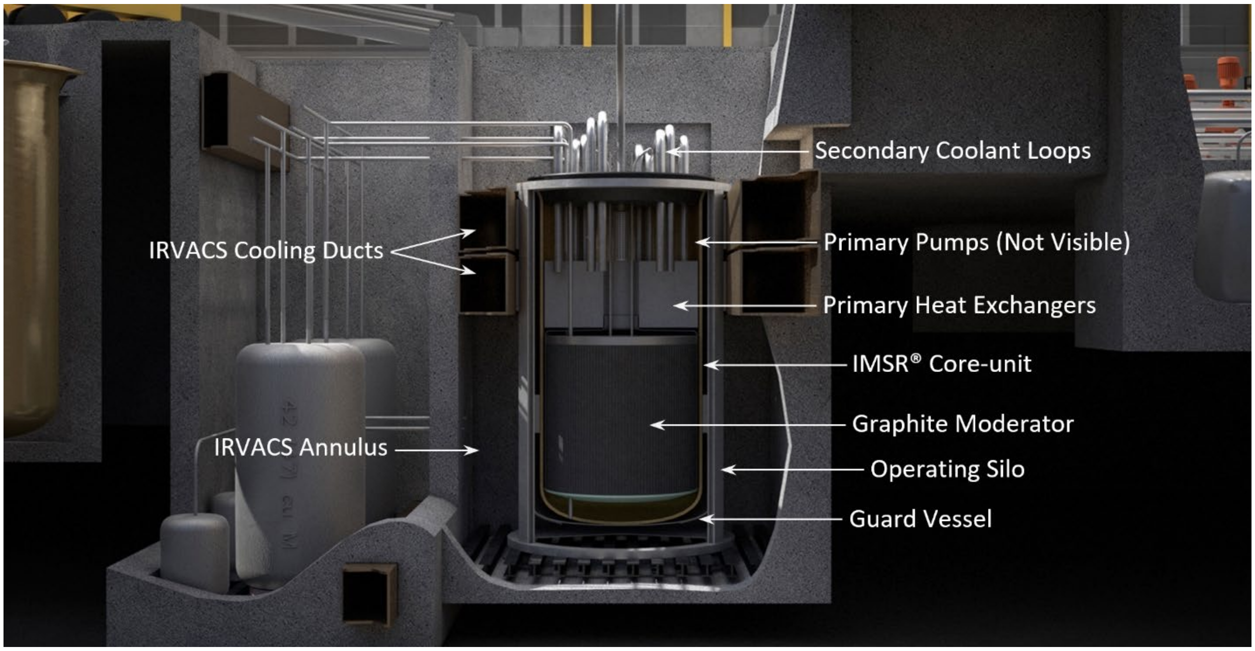
The IRVACS [ ].

Irradiated Fuel Cooling System (IFCS)

The IFCS removes the decay heat generated by the stored irradiated fuel. The system is like the IRVACS in operation in that it is entirely passive, [ ], and is cooled by the atmosphere. However, the IFCS [ ].

The IFCS [ ].

Figure 4: The IMSR® Core-unit, Guard Vessel, Reactor Support Structure, and IRVACS ducting in an Operating Silo. Also shown is the Secondary Coolant system piping configuration and interface to the Core-unit as well as the IRVACS annulus surrounding the Silo.



Secondary Coolant System

The purpose of the Secondary Coolant System is to deliver heat from the Primary Heat Exchanger to the Secondary Heat Exchanger, where the heat is transferred to the Tertiary Salt Loop. Figure 4 shows the relationship of Secondary Coolant System piping to the Core-unit and other structures, systems and components.

The Secondary Coolant System [ ].

Cover Gas & Off Gas Management System

[It also accommodates [ ] over its 7-year operational life. A separate portion of the Cover Gas System provides [ ].

The Cover Gas System [ ]. During critical power operation, the Cover Gas System [ ].

The Core-unit [

].

Cover Gas and Off Gas Management System
].

Makeup Fuel System (MFS)

The purpose of the MFS is to provide the initial fuel load for new Core-units and to periodically add fuel to the reactor during operation to maintain the reactivity of the core and maintain the fuel temperature in the core at the desired value.

Initial fuel load is “start-up” fuel; fuel added during operations is “make-up” fuel. The system has a safety function to limit the rate and amount of reactivity that can be added to the core to ensure the fuel temperature does not increase in an uncontrolled manner. The system also ensures that fuel outside the Core-unit cannot go critical and meets regulations for safeguards.

The system operates intermittently, is normally isolated from the Core-unit, and kept at, or near, atmospheric pressure.

The MFS [ ].

Irradiated Fuel System (IFS)

The primary purpose of the IFS is to remove the fuel from the Core-unit and transfer the fuel to storage tanks for long term on-site storage. This system
]. The system can store all of the irradiated fuel generated over the 60-year life of the plant. At [ ], the system [
].

Below are the main functions of the Irradiated Fuel System:

- [
].
- [
].
- [
].
- [
].
- [
].

The Irradiated Fuel System [ ].

Instrumentation and Control

In general, the control functions are not challenging in terms of complexity and performance due to the passive and inherent safety design features of the IMSR®. The I&C system’s main functions deal fundamentally with integrated control of production, interlocks for safety coordination, and monitoring system status. Compared to conventional nuclear technology, some of the in-core instrumentation and process equipment for the salt systems operate in a higher temperature environment, [
].

The I&C architecture is designed for high reliability and robustness against internal failures and external events to ensure that the control functions are available. The use of [ ] achieves high reliability. The [ ]. Critical equipment is also qualified to ensure credited safety functions are available for common-mode events such as earthquakes or extreme environmental conditions that may be caused by postulated initiating events. The Secondary Control Area (SCA) [ ]. The SCA and Main Control Room (MCR) [ ] are also provided.

The system design employs redundancy in systems performing safety or important power production functions to achieve high reliability and fault tolerance in the system. This approach is most effective if the redundant systems and equipment are independent of each other such that failures do not propagate to affect the backup system/equipment, nor do common-mode events (e.g., fire) cause failure of the redundant system/equipment at the same time.

For the IMSR® I&C, [ ]. The design of the I&C architecture ensures [ ]. There are [ ].

Main Control Room and Secondary Control Area

The Main Control Room (MCR) is located in the Control Building and is the center for all plant operations. The Control Building is seismically qualified and is designed to withstand the effects of all postulated natural phenomena so that control room operators should not need to leave the control room during plant transients and postulated accidents. From the MCR, the operator can perform all control, monitoring, and safety functions of the plant. In case of unavailability of the MCR, operators relocate to the Secondary Control Area (SCA) to monitor and ensure that the plant remains in a safe state. Local instrument rooms, which may also contain local monitoring and control capability, are distributed throughout the plant as needed.

V Core-unit Description

The critical feature of IMSR400 innovation is the integration of the primary reactor components into a sealed and replaceable reactor vessel called the Core-unit. The replaceable IMSR400 Core-unit ensures that the materials' lifetime requirements of all reactor core components are not limiting factors, which has been a challenge for the immediate commercialization of MSRs.

The Core-unit is comprised of the following items:

- Reactor Vessel,
- Fuel Salt,
- Primary Pumps,
- Graphite Moderator,
- Shutdown Rods,
- Primary Heat Exchangers, and
- Connections to other systems.

[

]. Piping connections associated with the Core-unit are provided for the:

- Secondary Coolant System,
- Cover Gas & Off Gas Management System,
- Fuel System, and
- Irradiated Fuel System.

Reactor Vessel

The Reactor Vessel is an upright, [ ] cylinder. It contains the full inventory of liquid fuel salt and there are no external fuel salt piping loops associated with the Reactor Vessel. All the nuclear heat fission energy is generated within the Reactor Vessel. [ ], the Reactor Vessel forms the primary, nuclear boundary during normal operation, anticipated events, and Design-Basis-Accidents (DBAs).

The Reactor Vessel boundary performs the following functions:

- Contains the fuel salt,
- Provides a flow circulation path for the fuel salt, and
- Provides a support (anchor point) for the core internals.

[

].

The Reactor Vessel is monitored and inspected [

]. The Reactor Vessel also sees significant neutron flux. The flux must be below the alloy embrittlement limit, and the limit [

].

The Reactor Vessel itself is a passive boundary. However, instrumentation is used in the Reactor Vessel to measure:

- Temperature,
- Pressure,
- Neutron flux, and
- Fuel salt level.

The Reactor Vessel [ ]. In addition, the vessel operates at low pressure and is conservatively designed and made of [ ]. Due to these factors, preliminary safety analysis has demonstrated that vessel failure does not occur in any DBA.

A Guard Vessel surrounds the Reactor Vessel in the event of a Beyond Design Basis failure of the vessel, to catch and contain any leaked fuel salt. The Guard Vessel, however, [ ].

The Reactor Vessel is designed to not require maintenance over its 7-year nominal lifetime.

Liquid Fuel Salt

The IMSR® operates by fissions of low-assay low enriched uranium (LEU) [ ] dissolved in a molten primary coolant comprised of a fluoride salt-mixture. The primary purpose of the fuel salt-mixture is delivery of the low-enriched fissile uranium into the IMSR® graphite core for heat generation through a sustained fission chain reaction and subsequent transportation of the heated salt to the Primary Heat Exchangers. The [ ] over the 7-year lifetime. The lower melting temperature of the fuel salt-mixture relative to the operational temperature range implies that the fuel salt-mixture will be molten during normal operation ensuring uniform distribution of the fuel and fission products. Fluoride fuel salt-mixtures offer high potential for nuclear applications as they generally have the following essential characteristics:

a) High boiling temperatures;
b) Low vapor pressures;
c) High heat capacities;
d) Low chemical reactivity; and
e) High solubility of fission products.

In any potential emergency involving a sudden temperature increase, the core negative temperature reactivity coefficient will inherently stabilize the reactor such that the IRVACS can passively remove the heat it produces.

The uranium fuel in the form of uranium [ ], is dissolved in a eutectic mixture of [ ]. The fuel salt is thus an integral system – nuclear fuel, coolant, and heat transfer medium. An integral system provides the basis for a less complicated reactor configuration and enhanced positive safety attributes. Using a liquid fuel eliminates the need for fuel cladding operating under high pressure and in a highly radioactive environment. The fuel salt is impervious to radiation and maintains a homogeneous mixture of the fuel and coolant.

Primary Pumping System

The Primary Pumping System performs the essential function to circulate the fuel salt through the Core-unit. Its purpose is to provide enough flow through the Primary Heat Exchangers and Moderator to facilitate full power operation without exceeding the material temperature limits of the Core-unit components.

The system [ ] system. It directly [ ], Containment, and [ ]Primary Heat Exchangers, Secondary Coolant Salt Loop, Graphite Core, Reactor Vessel, reactivity control devices, and [ ].

The [ ] is part of the [ ]. As a result, the design has:

- high integrity and leak-tightness,
- high temperature and radiation resistance,
- ability to accommodate thermal expansion, and
- monitoring provisions to detect leaks.

The primary pumping system is wholly contained within the sealed Core-unit.

Graphite Moderator

The purpose of the Graphite Moderator is to provide the medium for slowing down neutrons to promote the nuclear chain reaction. The Graphite Moderator core design [ ], to the Primary Heat Exchangers. The graphite [ ].

Shutdown Rods

IMSR® reactor shutdown (i.e., sub-criticality) is not required to reach a safe end-state for any Anticipated Operation Occurrence (AOO) or DBA (a safe end-state for IMSR® is defined to be the reactor at low power, the reactor vessel temperature within acceptable limits, and no fuel boiling). However, as a defense-in-depth safety measure, and for operational purposes, the IMSR® design includes the Shutdown Mechanism (SDM) as an independent means of shutting down the reactor.

The purpose of the Shutdown Mechanism (SDM) is to bring the reactor to a sub-critical state. The SDM makes use of Shutdown Rods to bring the reactor to a shutdown sub-critical state, which would eventually result in cooldown to a cold condition as decay heat subsides. The safe shutdown state for the IMSR® will employ the Canadian definition of a guaranteed shutdown state. The guaranteed shutdown state is defined as a reactor state with sufficient negative reactivity to ensure subcriticality in the event of any process failure and for which administrative safeguards are in place to prevent net removal of negative reactivity. After the reactor is shutdown [ ].

The Shutdown Rods [ ]. When power is lost, the rods drop under the force of gravity. The I&C systems [ ].

Primary Heat Exchangers (PHX)

The PHXs provide heat transfer between the circulating fuel salt and a separate closed-loop secondary coolant salt. The PHXs [ ]. The PHXs [ ] and transfers the heat to the secondary coolant salt and then [ ] the fuel salt [ ]. The fuel salt then [ ].

The secondary coolant salt [ ]. This coolant salt transfers the heat away from the reactor core while being isolated from the highly radioactive primary fuel salt liquid. The secondary coolant salt [ ].

The PHXs design transfers the total core heat load, which is equal to the thermal power produced in the reactor core, plus the additional heat load from the decay heat of internally delayed fission off-gases.

[ ]. The heat exchanger tube size and arrangement [ ].

Connections to Other Systems

Other reactor piping systems connected to the Core-unit include the:

- Makeup Fuel System,
- Secondary Coolant System, and
- Off Gas Management System.

VI Core-unit Operations

The IMSR® Core-unit is sealed during operation. The sealed Core-unit concept has both safety and economic advantages. This configuration restricts even minute amounts of volatile fission products from escaping to the environment. The Core-unit is replaced every 7 years [ ]. The IMSR400 plant design sustains eight Core-unit replacement cycles giving it a 56-year operational lifetime. At the end of each 7-year cycle, the fuel salt is discharged to storage in containment, and the used Core-unit is similarly placed in a storage silo within the plant. The stored Core-unit remains in storage for the remaining plant life. The IMSR® power plant design incorporates two Core-unit Silos; this accommodates switching to a new Core-unit every seven years. One Silo is for the operating Core-unit, and one Silo is for storage of either a standby Core-unit or a spent Core-unit, depending on the life-cycle stage of the plant. This is explained in the following table:

Life-cycle Stage	Silo A	Silo B
Years 1 through ~7	Operating Core-unit	Standby (unfueled) Core-unit
Years 8 through ~14	Defueled Core-unit cools and radioactively decays	Operating Core-unit
Years ~15 through 21	At the beginning of year ~15, the defueled Core-unit is moved to storage. A new Core-unit is inserted and begins operation.	Defueled Core-unit cools and radioactively decays

This process of alternating between operating and storage/standby continues through the plant life which is planned to be 8 cycles or 56 years.

Primary means of cooling and decay heat

In the IMSR® design, the primary means of reactor cooling occurs when the fuel salt flows convectively, and its heat is transferred out through the PHXs under normal conditions. The Core-unit is also passively cooled by the IRVACS, [ ] that transfers heat to the atmosphere. The IRVACS is continuously in operation and is sized to remove decay-heat, including after an accident where the normal heat removal means might not be available.

Low pressure, high temperature operation

The IMSR® operates at near-atmospheric pressure rather than 70-160 atmospheres of pressure, as is the case with conventional nuclear. Furthermore, the IMSR® design removes the possibility of a system overpressure condition resulting from chemical reactions since all materials inside the IMSR® Core-unit have high intrinsic chemical compatibility. Furthermore, there is very little stored energy in the primary loop (i.e., no mechanism for the generation of high-enthalpy steam), during and after transients, or system upsets. Therefore, the IMSR® does not require expensive high-pressure reactor vessels, high-pressure containment, or active safety systems.

Reactor physics and reactivity control

There are three ways to control reactivity when the IMSR® is critical. These are 1) the negative temperature reactivity coefficient, 2) make-up or fresh fuel addition, and 3) the SDM to terminate the fission reaction and shut down the reactor.

The IMSR® controls reactor power inherently without the automatic manipulation of a reactivity control device. The inherent feature that controls reactivity in the short term is the highly responsive negative core temperature coefficient of reactivity.

Negative temperature reactivity coefficient

The IMSR® design has a strong negative reactivity coefficient of temperature. This inherent feature provides a self-governing and stable temperature regime that establishes the inherently safe operating profile of the IMSR®. The rapid response characteristic and [ ] also allow for load-following capability, which enables an IMSR® to back up variable wind and solar power generation. Along with this fast-acting stability, is long term stability for load-following [ ].

Furthermore, the IMSR® design ensures that in an accident which increases reactor power (e.g., fueling error) or fuel salt temperature (e.g., loss of normal heat removal), the core negative temperature reactivity coefficient inherently stabilizes the reactor such that the IRVACS can passively remove the heat it produces.

Makeup fuel addition, reactivity control, and reactor shutdown

Both start-up and makeup fuel are [ ], the enrichment for the initial fuel load and makeup fuel [ ].

A typical operation would be [ ].

Periodic makeup fuel additions over Core-unit life accounts for reactivity changes due to fuel burnup. This is analogous to rod withdrawal in a light water reactor. Short term power transients are controlled by the inherent response of the negative temperature/power reactivity coefficient of the design.

IMSR® reactor shutdown [ ], as discussed earlier. The safe end-state for IMSR® is defined above. However, as a defense-in-depth safety measure, and for operational purposes, the IMSR® design includes the Shutdown Mechanism (SDM) as an independent means of shutting down the reactor.

VII Conclusion

In accordance with TEUSA's Regulatory Engagement Plan (REP), the Company intends to submit an application for an SDA of the IMSR® Core-unit consistent with the requirements established in 10 CFR 52, Subpart E. To help establish the basis for the SDA application, TEUSA has defined the IMSR® Core-unit in this white paper by providing an overview of the major SSCs that make up the overall IMSR® plant, [ ].

This white paper supports the IMSR® Core-unit SDA application development efforts. As outlined in the REP, [ ]. By summarizing the SCC's included and excluded from the Core-unit, this white paper establishes the basis for the content of future IMSR® pre-licensing documents.

Abbreviations & Acronyms

AOO – Anticipated Operational Occurrence

ARE – Aircraft Reactor Experiment

BeF_2 – Beryllium Fluoride

CFR – Code of Federal Regulations

CNSC – Canadian Nuclear Safety Commission

Cs - Cesium

DBA – Design Basis Accident

DMSR – Denatured Molten Salt Reactor

I&C – Instrumentation and Control

IFS – Irradiated Fuel System

I-NPP – IMSR Nuclear Power Plant

IMSR® – Integral Molten Salt Reactor

IRVACS – Internal Reactor Vessel Auxiliary Cooling System

KF – Potassium Fluoride

LIF – Lithium Fluoride

MCR – Main Control Room

MFS – Makeup Fuel System

MW – Megawatt

MWe – Megawatt Electric

MWth – Megawatt Thermal

MSR – Molten Salt Reactor

MSRE – Molten Salt Reactor Experiment

NaF – Sodium Fluoride

ORNL – Oak Ridge National Laboratory

PDC – Principal Design Criteria

PHX – Primary Heat Exchanger

PSA – Probabilistic Safety Assessment

R&D – Research and Development

RAB – Reactor Auxiliary Building

REP – Regulatory Engagement Plan

SCA – Secondary Control Area

SDA – Standard Design Approval

SDM – Shutdown Mechanism

SHX – Secondary Heat Exchanger

Sr - Strontium

SS – Stainless Steel

TEI – Terrestrial Energy, Inc.

TEUSA – Terrestrial Energy USA, Inc.

U.S. – United States

VDR – Vendor Design Review

Xe - Xenon

References

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