LEADIR-PS: The Path to a Safe and Economic SMR

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Abstract

Northern Nuclear Industries Incorporated (*N^2 I^2*) is developing a family of Small Modular Reactors (SMRs) called LEADIR-PS, an acronym for LEAD-cooled Integral Reactor-Passively Safe. LEADIR-PS plants under development, focused on process heat applications and the energy demands of Canada, are the LEADIR-PS100 with an output of 100 MWth and LEADIR-PS300 with an output of 300 MWth. A plant consisting of six LEADIR-PS300 reactor modules serving a common turbine-generator, called the LEADIR-PS Six-Pack, is focused on serving areas with higher energy demands.

LEADIR-PS integrates the inherent safety features of the Modular High Temperature Gas Reactor and molten lead coolant in an integral pool type reactor configuration. Molten lead coolant, which boils at 1750 ^{o}C,avoids the cost of a reactor pressure vessel and high pressure/high temperature reactor coolant systems, and the safety concerns regarding pressure vessel and large capacity reactor coolant system piping rupture and precludes evaporation of the coolant. Molten lead does not chemically react with air, water, or graphite.

The Gen IV^{+} LEADIR-PS plants are inherently/passively safe. There are no active systems required for safe shutdown and decay heat removal. Safety is assured without active or stored energy power supply, without a requirement to reposition valves or other devices andoperator intervention or action. The unprecedented safety achieved by LEADIR-PS reactors avoids requirements for a large exclusion radius and demanding evacuation plan requirements.

LEADIR-PS, withsteam conditions of 370 ^{o}C and 12 MPa (more than twice that of water cooled reactors), can serve over 85% of the world's non-transportation process heat demands and is ideally suited to serving Combined Heat and Electricity demands and industrial parks. Energy utilization of over 95% is feasible in process heat and Combined Heat and Electricity applications.

The simple robust design of LEADIR-PS plants in combination with the integration of proven technologies avoids lengthy research and development programmes thereby facilitating near term deployment. With adequate funding, the first LEADIR-PS unit can be operational within eight years.

LEADIR-PS: The Path to a Safe and Economic SMR

1 Introduction

1.1 Background

In defining LEADIR-PS,***N*^{2} *I*^{2}** acknowledged that a new approach that avoids pressure vessels, low boiling point coolants, and complex safety systems was required to achieve both safety and economic requirements. At the same time, the need to employ proven technologies in order to avoid development costs and long development schedules was recognized. Extensive investigation of commercial and demonstrated nuclear technologies resulted in the selection of the technologies summarized in Section 1.2 for LEADIR-PS power plants.

LEADIR-PS is an acronym for **LEAD**-cooled **I**ntegral **R**eactor-**P**assively **S**afe.

1.2 LEADIR-PS Technology

LEADIR-PS technology is a unique integration of technologies developed and proven in nuclear power applications in combination with novel but simple design features and capabilities. This unique integration of technologies facilitates the achievement of unprecedented safety and competitive economics by LEADIR-PS.

The proven technologies employed by LEADIR-PS include:

a) **Graphite moderator and reflector** (used in MAGNOX, AGR, RBMK and HTGR reactors): The negative reactivity temperature coefficient of graphite provides inherent reactor shutdown in the event of elevated temperatures, thereby precluding the potential of a reactivity transient without shutdown. Graphite also provides neutron moderation efficiency and high core structural strength (maximum at 2500 ^{o}C).
b) **TRISO fuel** (used in HTGR reactors in Germany, the US, Japan and China and currently in production in Japan and China): The TRISO Fuel particles are approximately 0.9 mm in diameter and feature an enriched uranium oxide kernel core with four coatings. Refer to Section 2.2. The Silica Carbide coating retains radionuclides at high temperatures, thereby preventing their release to the environment under all postulated accident conditions. No reactor containment is required.
c) **Molten lead reactor coolant** (used by Russia in fast breeder reactors): The 1750 ^{o}C boiling point of lead precludes the evaporation of the lead coolant under all postulated conditions and avoids the requirement for a reactor pressure vessel. The 208 isotope of lead (^{208}PB), which is 54% of naturally occurring lead and has a low thermal neutron capture cross-section, is utilized as coolant in order to achieve high neutron economy. Molten lead does not react chemically with water, graphite or air, and precludes the potential for dissociation of the reactor coolant into hydrogen and oxygen, a safety concern with water cooled reactors.
d) **Pebble Bed core**: Employed by Germany in High Temperature Gas Reactors (HTGRs) and adopted by China for their HTGRs, the Pebble Bed core configuration facilitates

simple on-power refuelling thereby avoiding refuelling outages and providing for global reactivity control.

e) **Integral Pool Type reactor**: The integral pool type reactor, which operates with near atmospheric pressure above the reactor coolant pool, eliminates the need for a reactor pressure vessel. The reactor assembly configuration in combination with the properties of the ^{208}Pb coolant facilitate an integral design with the placement of the steam generators and reactor coolant pumps within the primary reactor coolant pool, thereby avoiding the need for primary reactor coolant system piping and thereby eliminating the potential for reactor coolant pipe failure.

f) **Passive and inherent Shutdown**: The Shutdown Rods in LEADIR-PS, an adaptation of the CANDU Shutdown Rod design, drop by spring assisted gravity when power is removed from electromagnetic clutches by the Safety Shutdown System or by the back-up Passive Initiating Device (see b) below. The negative reactivity temperature coefficient of graphite moderator and reflector assures reactor shutdown in the unlikely event of a complete failure of the Safety Shutdown System.

g) **Passive Decay heat Removal**: In the event that the main and auxiliary core heat removal systems both fail, decay heat is rejected to the passive Reactor Cavity Cooling system which removes decay heat by natural convective air circulation (similar to AP1000). Should this system somehow be become unavailable decay heat from the below grade reactor is rejected to the surroundings (similar to Modular High Temperature Reactors).

Novel features and capabilities of LEADIR-PSinclude:

a) **Cellular Pebble Bed Core**: The unique LEADIR-PSPebble Bed core incorporates standard Pebble Bed Cells, each with a capacity of 34 $MW_{Th.}$ Pebble Bed Cells are vertical cylindrical cavities in the graphite moderator/reflector that are filled with Fule and Graphite Pebbles (refer to section 2.1.2). Pebble Bed Cells simplify on-power refuelling and allow reactivity devices to be placed in the moderator and reflector rather than within the Pebble Bed Cells. LEADIR-PS reactors with greater or lesser output can be designed by increasing or decreasing the number of standard Pebble Bed Cells.

b) **Passive Initiating Device**: The temperature initiated Passive Initiating Device removes power from the electromagnetic clutches causing the Shutdown Rods to drop into the core in the event that the Safety Shutdown System fails to function when needed.

c) **Secondary Reactor Vessel**: the Primary Reactor Vessel is radially surrounded by the Secondary Reactor Vessel. Refer to Section 2.1.2. Lead within the annulus formed by the Primary Reactor Vessel and Secondary Reactor Vessel, solid during normal operation, provides thermal insulation during normal reactor operation. This lead melts if temperatures in the Primary Reactor Vessel significantly exceed normal values, resulting of circulation the lead in the annulus, and thereby dramatically increasing heat transfer form the core to the Reactor Cavity Cooling System.

d) **Secure control protocol**: The secure control protocol developed facilitates remote unattended operation of up to 30 LEADIR-PS units from one Central Operations

Facility.This system precludes interventions by third parties that could potentially pose a risk to the owner's investment or plant safety while minimizing potential spurious reactor shutdowns caused by the control interface.

e) **Barge Delivery**: The fully modularized LEADIR-PS plant is integrated within a barge, facilitating delivery of largely complete LEADIR-PS units to a wide variety of potential sites, thereby providing short and secure construction schedule under harsh environmental conditions. The Barge can be fitted with skirts and lift fans to facilitate air cushion delivery to inland locations.

Major advances have also been made in other areas including facilitating maintenance from a Central Maintenance Facility. '

The integration of proven technologies with novel design features maximizes the benefits of the technologies incorporated while minimizing research and development cost and schedule. This approach facilitates the design of the economic GEN IV^{+} LEADIR-PS power plants which offer unprecedented safety while being relatively simple, robust and easy to operate. Advances in areas such as remote unattended operation and delivery methods serve to improve LEADIR-PS economics, particularly for single unit stations.

2. Nuclear Design

2.1 Reactor Module Configuration

2.1.1 Overview

An elevation section through the LEADIR-PS Reactor Module Assembly is shown in Figure 2-1 and a plan view of the LEADIR-PS100 reactor core is shown in Figure 2-2. These figures illustrate the principal LEADIR-PS features but may not accurately show the detailed design.

A modified Pebble Bed core configuration, consisting of Pebble Bed Cells is adopted for LEADIR-PS. Pebble Bed Cells are vertical cylindrical cavities located within the graphite moderator/reflector structure. The Pebble Bed in each Pebble Bed Cell consists of Fuel Pebbles and Graphite Pebbles.The LEADIR-PS100reactor core has three Pebble Bed Cells. The LEADIR-PS300 has 9 PBCs. The cylindrical graphite moderator and reflector assembly is surrounded by the cylindrical Reactor Barrel and is supported by the Lower Core Support Structure. The graphite moderator and reflector assembly and Reactor Barrel constitute the Reactor Core Assembly. The Reactor Core Assembly is housed within the ^{208}Pb filled Primary Reactor Vessel. ^{208}Pbhas a relatively low thermal neutron capture cross-section which contributes to excellent fuel utilization. The Fuel Pebbles, Graphite Pebbles and moderator/reflector blocks are buoyant in the ^{208}Pb coolant.

The Primary Reactor Vessel is located within the Secondary Reactor Vessel. The annular space between the Primary Reactor Vessel and the Secondary Reactor Vessel is filled with lead enriched in neutron absorbing lead isotopes. This lead consists of the 'tails' from the ^{208}Pb isotope separation process plus ordinary lead. The lead in the Secondary Reactor Vessel/Primary Reactor Vessel annulus, which is solid during normal operation, provides thermal insulation for the Primary Reactor Vessel, shielding, and sufficient lead inventory to assure that the core remains submerged in lead in the extremely unlikely simultaneous failure of both the Primary Reactor Vessel and Secondary Reactor Vessel structures.

A cylindrical divider within the annulus between the Primary Reactor Vessel and Secondary Reactor Vessel, with openings at the top and bottom, divides the annulus into two annular cylindrical sections. If temperatures in the Primary Reactor Vessel increase significantly above normal operating temperature the lead in the annulus melts and circulation is established, up the channel adjacent to the Primary Reactor Vessel and down the channel adjacent to the Reactor Cavity Cooling System which surrounds the Secondary Reactor Vessel, dramatically increasing heat transfer from the Primary Reactor Vessel to the passive Reactor Cavity Cooling System.

An advantage of utilizing standard Pebble Bed Cells with dedicated refuelling capability is that it facilitates full scale (non-nuclear) testing of a Pebble Bed Cell and all major active Reactor Module Assembly components including the Fuelling Machine Module, Steam Generators, Primary Reactor Coolant System Pumps, and reactivity control mechanisms. .

2.1.2 Reactor Module Assembly

The LEADIR-PS Reactor Module Assembly and the below grade portion of the Reactor Protective Structure are shown in Figure 2.1. The interlocking graphite moderator and reflector blocks form the principal structure of the reactor core and define the cylindrical cavities that are the Pebble Bed Cells. The graphite structure is a vertical cylinder and together with the Reactor Barrel constitutes the Reactor Core Structure. A plan section of the LEADIR-PS100Reactor Core Structure is presented in Figure 2-2. The Reactor Core Structure has passages to allow coolant flow located to assure cooling of the Reactor Core Structure and to provide acceptable coolant pressure loss. The Reactor Core Structure has openings centrally located above each of the Pebble Bed Cells to accommodate the discharge of Pebbles from the PCBs via the Fuelling Modules. The Reactor Core Structure also accommodates the Fuel Transfer Tubes that extend from the Fuelling Machine Module above each of the Pebble Bed Cells to the bottom of the Pebble Bed Cells. Refer to Section 2.7.

Radial support to the graphite core structure is provided by the Reactor Barrel which is centrally located within the Primary Reactor Vessel. The Reactor Barrel is supported from the top plate of the Lower Core Support Structure. Openings around the bottom of the Reactor Barrel allow the reactor coolant to flow into the plenum located below the Reactor Core Structure and into the Pebble Bed Cells immediately above the bottom reflector blocks via openings in the radial reflector.

The Graphite blocks that form the bottom of the Reactor Core Structure are attached to the top plate of the Lower Core Support Structure. The Graphite blocks that form the top of the Reactor Core Structure are attached to the Upper Core Support Structure . The design of the Upper Core Support Structure accommodates the thermal expansion of the core graphite over the operating temperature range.

The graphite core structure is designed in accordance with KTA 3232, the design code developed by Germany for graphite reactor components.

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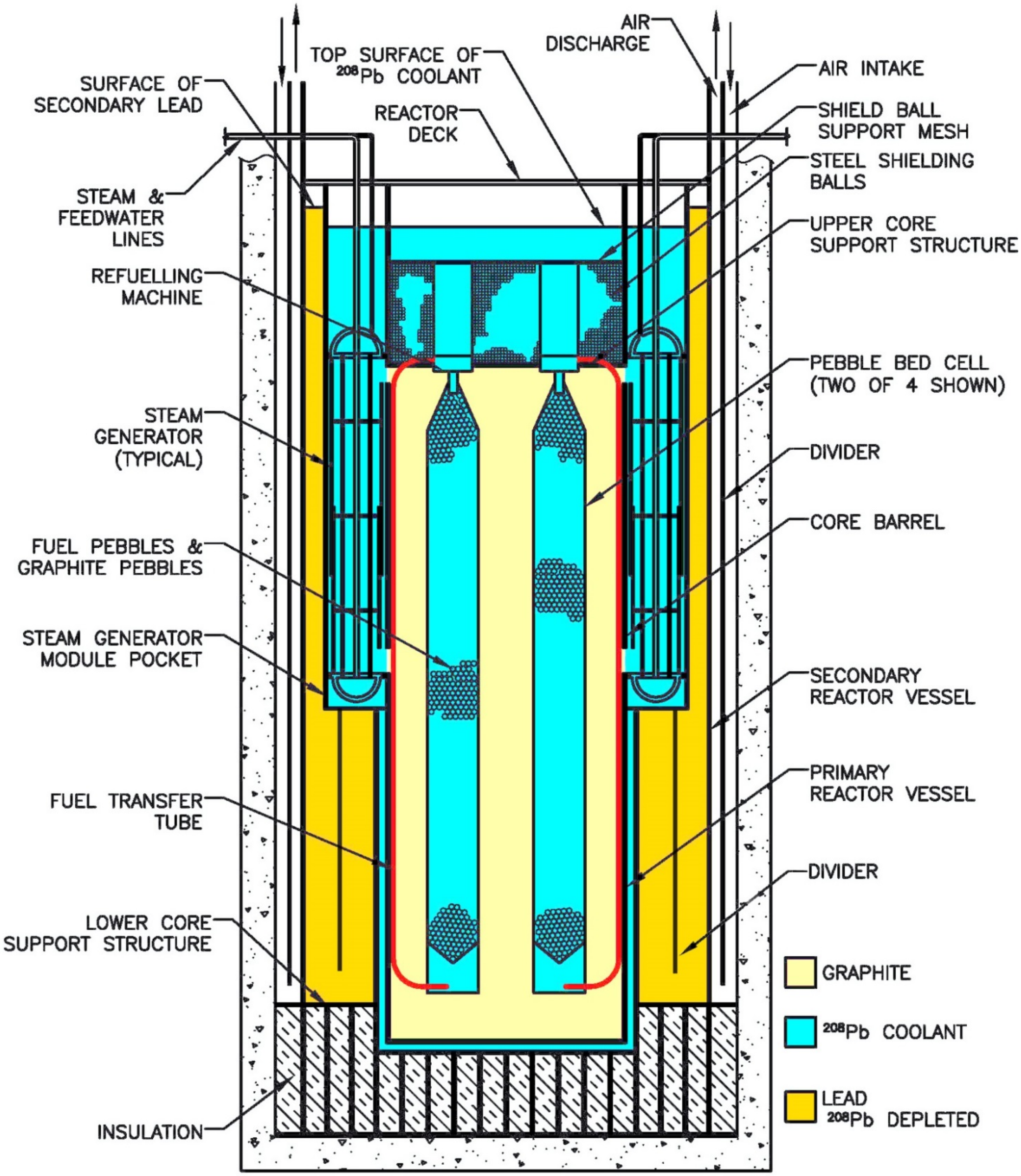

Figure 2-1: Simplified LEADIR-PS100 Elevation Section

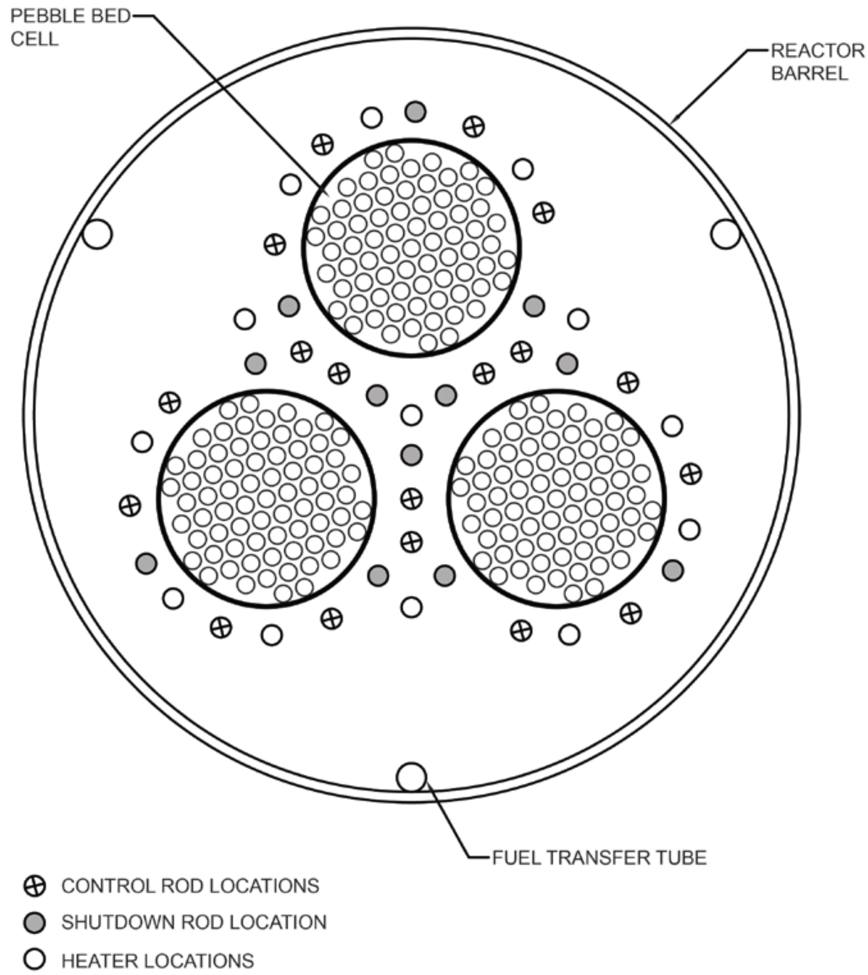

Figure 2.2: LEADIR-PS100 Reactor Core Structure Plan Section

The cylindrical Primary Reactor Vessel is attached to the Lower Core Support Structure. The annulus between the Reactor Barrel and the Primary Reactor Vessel provides passage ways for the reactor coolant discharged from the Reactor Coolant Pumps. The Steam Generation Modules, each of which includes two Steam Generators and one Reactor Coolant Pump, are housed within pockets that are attached to the exterior of the Primary Reactor Vessel. LEADIR-PS100 has two standard Steam Generation Modules located 180 degrees apart. LEADIR-PS300 has six standard Steam Generation Modules. The Primary Reactor Coolant System, incorporated in the Reactor Module Assembly, is described in Section 2.5. The molten ^{208}Pb coolant is an excellent lubricant which minimizes wear on the Fuel and Graphite Pebbles and the Reactor Core Structure

The cylindrical Primary Reactor Vessel is centred within the cylindrical Secondary Reactor Vessel. The Secondary Reactor Vessel is supported from the Lower Core Support Structure. Although there is minimal pressure differential across the walls of the Primary Reactor Vessel during reactor operation, the Primary Reactor Vessel is designed to accommodate the pressure differential that would result if there was no lead in the Secondary Reactor Vessel.

The Lower Core Support Structure consists of top and bottom horizontal structural sections separated by a grid of vertical structural plates. The spaces within the grid are filled with closed cell stainless steel foam insulation. Refer to Figure 2-1

The Upper Core Support Structure which supports the Reactor Core Structure, consists of two independent horizontal sections, the Primary Upper Core Support Structure and the Secondary Upper Cores Support Structure, each capable of independently fully supporting the Reactor Core Structures. The Primary Upper Core Support Structure has a horizontal lower structural support grid to which the upper graphite reflector blocks of the Reactor Core Structures attach and an upper horizontal structural support panel. The upper and lower structural support plates are connected by vertical structures having a variety of shapes. These include lattice tubes for the various reactivity control devices, the electric heaters, and the Fuelling Machine Modules

Vertical webs at 90 degrees to the Primary Reactor Vessel and Secondary Reactor Vessel span the annulus between Primary Reactor Vessel and Secondary Reactor Vessel. These webs are integrated with the cylindrical divider plate to form the primary grid. The primary grid provides support to primary reactor vessel under seismic conditions. Similar support grids are located between the Reactor Barrel and the Primary Reactor Vessel and between the Secondary Reactor Vessel and the External Reactor Support Structure.

The volume between the top of the Upper Core Support Structure and the Services Deck accommodates shutdown rods, control rods, and core heaters when out of the core. Additional shielding is provided in the Services Deck to enable personnel access for maintenance and inspection. A polar crane is provided to allow reactivity mechanisms to be removed and placed in flasks. Reactor Module Assembly data is provided in Table 2-1.

Table 2-1: LEADIR-PS100 Reactor Assembly Module Structures Data

Reactor Barrel Inside Diameter	2900 mm
Reactor Barrel Wall Thickness	35 mm
Reactor Barrel Height from LCSS	9200 mm
PRV Inside Diameter	3200 mm
PRV Wall Thickness	35 mm
PRV Material	17% Cr.SS
PRV Code Class	ASME Section III, Class1
PRV height from the LCSS	10200 mm
SRV Inside Diameter	4200 mm
SRV wall Thickness	35 mm
SRV Material	17% Cr.SS
SRV Code Class	ASME Section III, Class III

2.2 Reactor Fuel

The reactor fuel consists of Fuel Pebbles that contain TRISO fuel particles (Figure 2-3). The Fuel Pebbles have an outside diameter of 60 mm. LEADIR-PS utilizes TRISO particles with approximately 9.8% ^{235}U enriched uranium oxide at reactor equilibrium.

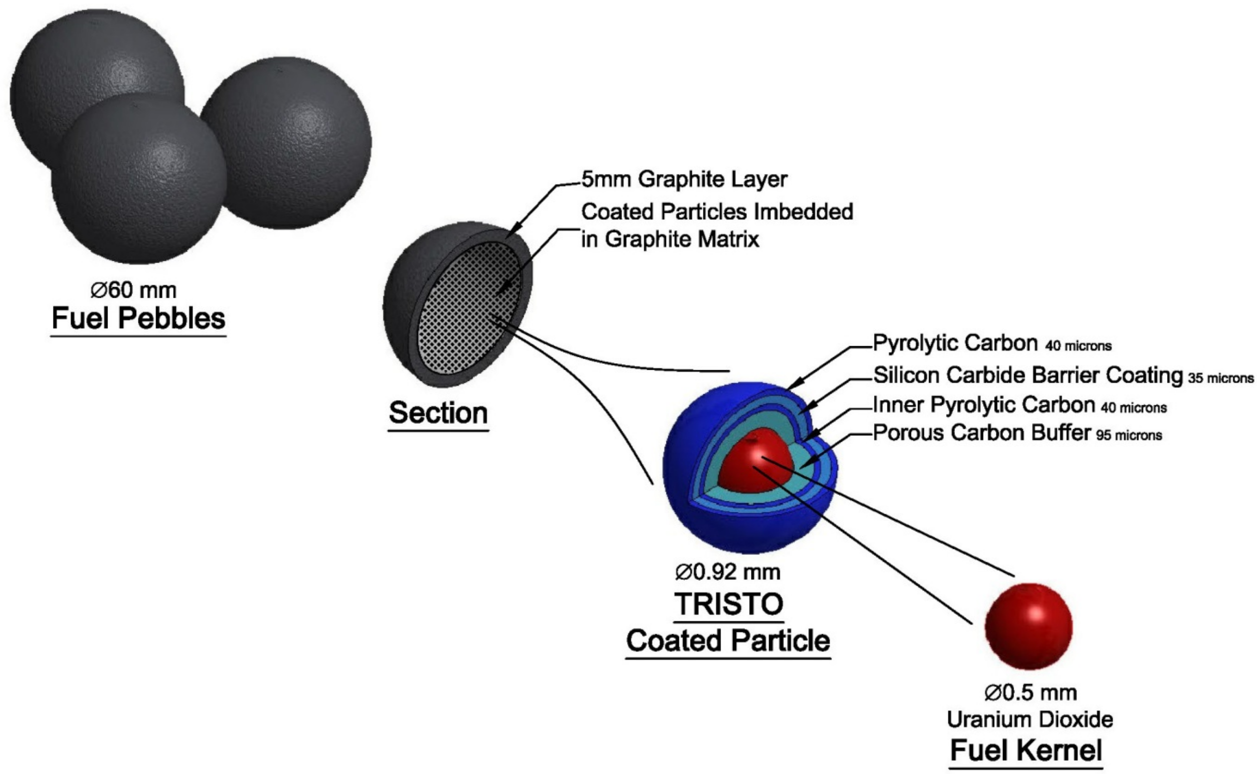

Figure 2-3: TRISO and Fuel Pebble Configuration

The relatively high enrichment level is required in order to obtain the required uranium loading in the core, as less than 0.6% of a Fuel Pebble consists of ^{235}Uand is not as the result of neutron inefficiency.

The nominal dimensions of the Fuel Pebbles and the Fuel Kennel are summarized in Table 2-2 Pebble Bed Cell data is provided in Table 2-3. The initial load of Fuel Pebbles has TRISO kernels with approximately 5.0% ^{235}U enriched uranium oxide.

In the future TRISO particles containing Thorium can be incorporated without reactor modification. The use of Thorium serves to reduce the required refuelling rate and to dramatically reduce the quantity and toxicity of spent fuel. A dominant factor in not using Thorium initially is the absence of commercial sources of reactor grade Thorium.

The fuel kernels are coated by pyrocarbon and layers of silicon carbide, the main purpose of which is to prevent fission product release under all postulated conditions. The coatings consist of low density pyrocarbon (PyC), silicon carbide, (SiC) and high density PyC. The low density PyC accommodates fission product accumulation and reduces the structural load on the subsequent layer of PyC. The SiC coating between the layers of PyC confines the volatile fusion products at temperatures up to 1800 ^{o}C.

New fuel Pebbles contain TRISO particles with a burnable neutron absorber that to serves to limit the heat generated in the Pebble during their initial period in the reactor core.

Table 2-2: Nominal Characterisitcis of LEADIR-PS100 Fuel		
Parameter	**Unit**	**Value**
Fuel Pebbles		
Pebble Dieamter	mm	60
Fuel Region Diameter	mm	50
Exterior fuel free region thickness	mm	5
Heavy metal loading	gm/Fuel Sphere	9.0
Uranium enrichment	% U-235	9.8 (Equalibriumcore)
Coated Particle		
Kernel Diameter	mm	0.50
Buffer layer thickness	mm	0.095
Inner Isotropic layer thickness	mm	0.040
SiC layer thickness	mm	0.035
Outer Isotropic layer thickness	mm	0.040
Particle outside diameter	mm	0.92

Table 2-3: Pebble Bed Cell Data	
Number of Pebble Bed Cells	3
Pebble Bed Cell inside diameter	990 mm
Number of Fuel Spheres (each cell)	10,000
Uranium load per Sphere	9 grams
Uranium enrichment, equilibrium core	9.8%
Uranium enrichment new core	5%
Number of Graphite Spheres	26,000

2.3 Reactor Control

The Pebble Bed Cells (three in LEADIR-PS100 and 9 in LEADIR-PS300) are neutronically closely coupled and the small LEADIR-PS core is stable in all modes. Reactor control takes advantage of the strong negative reactivity temperature coefficient of the graphite reflector/moderator and the high heat capacity of the core.

The on-power refuelling system is the primary mechanism for reactor reactivity control. The Fuelling Control System records the activity level of all Fuel Pebbles that enter each of the Pebble Bed Cells and thereby enables monitoring of the reactivity level and distribution in each of the Pebble Bed Cells. Based on this information and information provided by the in-core flux detectors, the fuelling rate of each of the Pebble Bed Cells is adjusted and/or the number of spent Fuel Pebbles discharged to spent fuel is increased or decreased. A new Fuel Pebble replaces every spent Fuel Pebble discharged.

Operational reactor control is provided by the Reactor Control System. The Reactor Control System monitors and controls all functions that are related to reactivity control, including the on-power refuelling system, but excluding except for the Safety Shutdown System. The fully automatic Reactor Control System utilizes dual redundant computers that incorporate numerous checks and safeguards.

Fine adjustment of reactivity in the core is provided by the Control Rods that operate in the reflector/moderator regions adjacent to the Pebble Bed Cells. Refer to figure 2-2. The control rods are individually driven into/out of the moderator/reflector via electrically powered stepping motors. Flux detectors distributed throughout the reflector/moderator provide an accurate indication of reactor power distribution. The location of the control rods and flux detectors in the moderator/reflector region of the core avoids loads being imposed on these devices by the circulating Pebble and Graphite Beds.

The Reactor Control System also controls all operating parameters in both the nuclear plant and the conventional plant. High level control and monitoring is provided by the Central Operating Facility which is designed to facilitate the operation of up to 30 LEADIR-PSunits. The Central Operations Facility has the capability to automatically or manually put any of the LEADIR-PS units under its jurisdiction into a secure shutdown mode.

The Reactor Control System shutdown capability is backed up by the Secondary Control System which is located in the Auxiliary Services Building remote from The Electrical & Control Building.

2.4 Safety Shutdown System

The Safety Shutdown System incorporating dual redundant computers is independent from the Reactor Control System. The Safety Shutdown System utilizes vertical Shutdown Rods that operate in the moderator/reflector regions of the core. The circular shutdown rods have a depleted uranium core that increases their density sufficiently above that of the lead coolant to facilitate insertion by spring assisted gravity. Boron provides the required neutron absorption capability.

The Shutdown Rods are supported by cables that wind onto cylindrical grooved drums. The shutdown rods are normally fully withdrawn form the core. The Shutdown Rods drop by gravity with initial spring assist when power is removed from the electro-magnetic clutches that connect the drums to the drive motors (CANDU technology). The Shutdown Rods drop into vertical ‘U’ shaped circular channels that extend to near the bottom of the Reactor Core Structure. This configuration allows the ^{208}Pb coolant in the Shutdown Rod channel to flow out of the channel as the Shutdown Rod drops. The reapplication of power to the electro-mechanical clutches allows the Shutdown Rods to be withdrawn from the core by the Shutdown Rod drive motors.

Shutdown Safety System initiation of Shutdown Rod deployment is controlled by redundant safety system computers based on triplicated (2 of 3 logic) neutronic and process system parameters. In addition, Passive Initiating Device is provided that removes power from the electro-magnetic clutches and causes the Shutdown Rods to drop into the core when a specified core outlet temperature is reached. This system provides passive backup to the Safety Shutdown System and significantly increases the reliability of shutdown by the Shutdown Rods. Each Shutdown Rod is tested on power via a partial drop every 30 days to confirm functionality and capability. The Safety Shutdown System parameters are also routinely tested on-power.

Unlike water cooled reactors, very fast Shutdown Safety System action is not required in LEADIR-PS due to the high heat capacity and negative temperature reactivity coefficient of the graphite moderator/reflector.

Shutdown via the graphite negative reactivity temperature coefficient precludes TRISO fuel damage under all postulated events including the failure of the both active and passive shutdown initiation.

2.5 Primary Reactor Cooling System

2.5.1 Overview

The Reactor Cooling System is contained within the Reactor Module Assembly (refer to Figure 2-1). The Primary Reactor Cooling System utilizes molten ^{208}Pb coolant which solidifies at 327 ^{o}C and has a boiling point of 1750 ^{o}C. LEADIR-PS coolant is obtained by the separation of the ^{208}Pb isotope from commercially available pure lead. The ^{208}Pb is ‘conditioned’ prior to being placed in the reactor. Conditioning includes the removal of oxygen and the addition of small quantities of particulate graphite.

The LEADIR-PS100 Primary Reactor Cooling System includes two standard Steam Generation Modules, each consisting of two once through Steam Generators and one variable speed Reactor Coolant Pump. Refer to Figure 2-4.LEADIR-PS300 has six Steam Generation Modules. The Steam Generator shell comprises two overlapping concentric cylinders, the Steam Generator upper shell and the Steam Generator lower shell, that result in a ‘floating’ lower Steam Generator feedwater tubesheet. The feedwater tubesheet is free to move vertically within the Steam Generator Module supports structure. This configuration prevents stress in the Steam Generator tubes due to thermal expansion/contraction. Molten ^{208}Pb has excellent lubrication qualities.

The ^{208}Pb coolant flows downward through the Steam Generators where the heat of fission is transferred to ordinary water to generate superheated steam. On exiting the Steam Generators, the ^{208}Pb coolant enters the suction of a Reactor Coolant Pump. On being discharged from the Reactor Coolant Pump the ^{208}Pb flows downward. Most of the ^{208}Pb coolant enters the Pebble Bed Cells through horizontal passages in the Reactor Barrel and radial reflector near the top of the bottom reflector into the Pebble Bed Cells while the remainder of the reactor coolant enters the distribution plenum located below the bottom graphite reflector. This ^{208}Pb coolant then flows upwards through coolant passages in the bottom reflector to provide cooling to the moderator and reflector. The ^{208}Pb then flows through coolant passages in the top reflector and into the upper distribution chamber which connects to the Steam Generation Modules. The distribution chamber is filled with Steel Shielding Balls that provide radiation shielding to the Services Deck. The ^{208}Pb coolant flow through the distribution chamber provides cooling to the Steel Shielding Balls and Upper Core Support Structure.

Rupture of a Steam Generator tube is accommodated in LEADIR-PS as water/steam does not react with the molten ^{208}Pb coolant. Water escaping from a Steam Generator tube rupture tends to solidify the ^{208}Pb in the vicinity of the rupture thereby reducing the rate of water discharge from the rupture. As the Steam Generators are located outside of the Primary Reactor Vessel escaping steam does not enter the Primary Reactor Vessel.

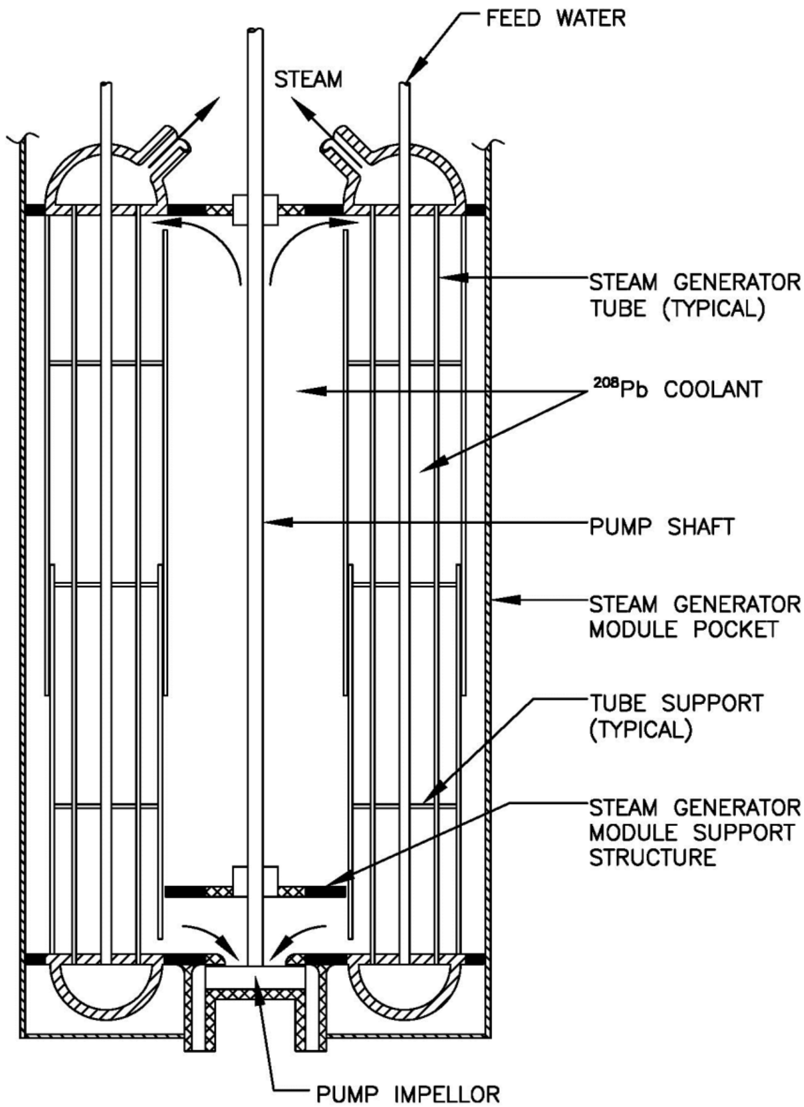

Figure 2-4: Steam Generation Module Section – View 90^o to the PRV

2.5.2 Primary Reactor Coolant System Operation

The variable speed Reactor Coolant Pumps provide coolant flow to the Steam generators as a function of reactor power. The core outlet temperature of 560 ^oC is thereby maintained above 20% power. The core inlet temperature reduces as power drops below 20% full power, to a minimum of 345 ^oC.   Feedwater flow to the Steam Generators, delivered by the Main Feedwater System, is varied as a function of reactor power. The steam temperature at the discharge of the Steam Generators reduces with reducing reactor power below 20% full power.

The ^{208}Pb coolant circulation in the Primary Reactor Vessel by natural convection is capable of removing up to approximately 20% of full power with half of the Steam Generators out of service.

The Auxiliary Feedwater System (AFWS), located in the Auxiliary Systems Building provides a backup supply of feedwater to remove decay power in the event that the Main Feed Water System is unavailable.

Cooling of the reactor core to below 340 ^{o}C is an uncommon occurrence as the combination of decay heat and heat provided by the heaters are capable of maintaining the ^{208}Pb temperatures above this temperature. All major maintenance activities can be completed with the ^{208}Pb coolant temperature at or above 340 ^{o}C including exchange of steam generators, Reactor Coolant Pump impellorand bearing assemblies, and reactivity mechanisms.

In the event that the ^{208}Pb temperatures do fall to below 340 ^{o}C, increasing the reactor temperature to above 340^{o}C is required in order permit operation of the Reactor Coolant Pumps. Diverse mechanisms are provided for heating the Reactor Core Structure and the^{208}Pb coolant. These are:

a) Steam from the Auxiliary Steam System which is supplied by the small electric Services is provided to the Steam Generators.
b) Electrical heating elements, inserted into the leg of the U-shaped shutdown rod channels in the graphite reflector columns that are not used by the Shutdown Rods prior to reactor cooldown.
c) Heating coils in the reactor inlet plenum

Melting of the ^{208}Pb in the Primary Reactor Vessel and forced circulation can be achieved from a 100 ^{o}C core temperature in approximately 120 hours utilizing the steam supply to the steam generators and the electric heaters. Steam supply to the steam generators facilitates warm-up of the reactor in the event that a cooldown occurs without the electric heaters having been inserted, although the time required increases significantly.

2.6 Core Heat Removal

Heat removal is via the Steam Generators utilizing the Main Feedwater System and Main Condensor System during most periods. Turbine steam bypass to the condensers enables continued reactor operation at 100% full power for up to 5 minutes and indefinite operation at powers of 60% or below in the event that the Turbine-Generator is unavailable.

Backup heat removal capability and Shutdown Cooling capability is provided via the Auxiliary Feedwater System in conjunction with the Passive Auxiliary Condensor. Fast action is not required due to the high heat capacity of the graphite and reflector.

In the event that all active heat removal systems fail, elevated temperature in the Primary Reactor Vessel causes the lead in the Secondary Reactor Vessel to melt, establishing a circulation flow in the Secondary Reactor Vessel and decay heat is transferred to the Reactor Cavity Cooing System via a combination of convection, conduction, and radiation. Up to 20% full power heat can be removed by natural convection circulation of the ^{208}Pb coolant. In the unlikely event that the cavity cooling system is unavailable, decay heat is transferred to the surroundings, primarily via radiation. The temperatures within the reactor core are maintained within operating design limits assuring that the fuel and core are not damaged. Th reactor cavity cooling system serves an owner’s investment protection function and is not required for safety.

2.7 Fuelling and Fuel Management

The LEADIR-PSFuelling System recirculates the fuel and graphite Pebbles in each of the Pebble Bed Cells, discharges depleted Fuel Pebbles to Spent Fuel Storage, delivers new Fuel Pebbles to the Pebble Bed Cells and returns graphite Pebbles to the Pebble Bed Cells. Each Fuel Pebble makes an average of seven passes through between the time it first enters the core and the time it is discharged to the Spent Fuel Storage.

Each of the Pebble Bed Cells is provided with a Fuelling Machine Module located above the Reactor Core Structure. The Fuelling Machine Modules operate with minimal pressure differentials and have generous clearances. All Fuelling Machine Module drives are located above the operating deck. Pebbles are delivered to the Fuelling Machine Modules by the buoyancy of the Pebbles in the molten ^{208}Pb coolant and are returned to the bottom of the Pebble Bed Cells utilizing coolant pressure differential.

The Fuelling Control System records the activity level of all Pebbles that enter each Pebble Bed Cell and thereby monitors the reactivity level in each of the Pebble Bed Cells. Based on this information and information provided by the in-core flux detectors, the fuelling rate of the Pebble Bed Cells is adjusted and/or the number of Fuel Pebbles discharged to spent fuel and the number of New Fuel Pebbles increased/decreased.

3. Maintenance

LEADIR-PS is designed to operate for periods of three or more years without maintenance. Major maintenance is accomplished by “change-out” as much as possible. Plant simplifications, for example, the utilization of only electric operated valves, which eliminates the need for and the maintenance of pneumatic systems, reduce the number of maintenance procedures and spare parts requirements.

Extensive condition monitors at the LEADIR-PS units provide information to the Central Operating Facility which is utilized when scheduling maintenance outages and to manage spare parts inventory. The warehouse at the LEADIR-PS unit maintains a small inventory of spare parts and consumables but most spares are maintained at the Central Maintenance Facility.

If required, the Steam Generators and the coolant pump impellor and bearing assemblies are easily removed and exchanged from the Services Deck. Reactivity mechanisms, the Fuelling Machine Module Indexing Modules and the Fuelling Machine Module Rotors are also replaceable from the Services Deck

In the case of distributed LEADIR-PS units, scheduled maintenance is completed by a dedicated Maintenance Team that, together with the necessary equipment spare parts and tools, travels from one LEADIR-PS plant to another to complete the maintenance outages. Based on a two week maintenance outage, a single Maintenance Team can service approximately 20 LEADIR-PS units. Equipment overhaul and major services are provided at the Central Maintenance Facility. An Advanced Maintenance Team generally consisting of four persons arrives at the unit three days in advance of the balance of the Maintenance Team to put the Service Water System and Service Air System into operation and otherwise ready the unit and Accommodations Building (provided at remote locations) for the planned activities.

LEADIR-PS has provisions for unscheduled maintenance, should component failures or deterioration occur. The Central Maintenance Facility will provide unscheduled maintenance of the LEADIR-PS plants. A single crew will provide both scheduled and unscheduled maintenance when the LEADIR-PS fleet is small. Separate crews for scheduled and unscheduled maintenance will be provided when the LEADIR-PS fleet is sufficiently large.

The approach to maintenance of LEADIR-PS Six-Pack stations, depending on the number of LEADIR-PS Six-Packs at the site, is similar to that employed at current large nuclear power plants.

4. LEADIR-PS100 Operating Characteristic and Unit Data

4.1 Operating Characteristics

LEADIR-PS100 operating characteristics are summarized below.

a. ‘Black Start’ capability independent of the electrical grid. A connection to the electrical grid is not necessary for reactor operation or safety.
b. 100% power operation without an electricity grid connection for pure process heat applications.
c. Operation at up to 100% power as the only electricity supply to the electricity grid.
d. The unit can maintain sustained operation at any power level between 10% and 100% of full power.
e. Reactor control is normally in the reactor following load (electricity and/or process heat) mode.
f. The power design increase rate for the reactor and reactor systems is 0.2 percent of full power per second between 10% and 100% power.
g. The power reduction design rate for the reactor systems is 0.2 percent of full power from 100% power to 60% power and 0.05 percent per second below 60% power. More rapid load reductions results in steam bypass to the condensor.
h. The design basis load following capability is a daily cycle 100% to 60% to 100% at rates that do not exceed 0.1 percent per second.
i. In the event of a loss of line to the grid, the unit can supply the unit loads and continue operating indefinitely. The turbine steam bypass to the condenser accepts steam flow following a loss of line or turbine trip thereby reducing the rate of reactor power reduction and reducing the severity or thermal transients.

4.2 LEADIR-PS100 Unit Data

LEADIR-PS100 unit data is provided in Table 4-1. Except for capacity specific data provided under reactor, the data in Table 4-1 is applicable to LEADIR-PS300

Table 4.1: LEADIR-PS100 Unit Data

Reactor	
Type	Cellular Pebble Bed
Number of Pebble Bed Cells	3
Pebble Bed Cell Diameter	990 mm
Moderator & Reflector	Graphite
Reactor Barrel Inside Diameter	2900 mm
Effective Pebble Bed Depth	8000 mm
Number of Fuel Pebbles in core (total)	30,000
Number of Graphite Pebbles in Core (total)	78,000
Fuel and Graphite Pebble Diameter	60 mm
Reactor Core Structures	
Materials for components in ^{208}Pb contact	17%CR SS
Primary Reactor Coolant System	
Coolant	^{208}Pb
Pressure at top of Primary ^{208}Pb Pool	0.05 MPa
Average core outlet temperature	560 ^{o}C
Average Core inlet temperature	360 ^{o}C
Total Coolant Flow (total)	3500 kg/sec
Number of Steam Generation Modules	2
Number of Steam Generators	4
Steam Generator Characteristics	Once Through, counter flow
Steam Generator Tube Material	17% Cr SS
Total Steam flow rate	43.5 kg/sec
Steam Pressure at Discharge Nozzle	12 MPa
Steam Temperature at Discharge Nozzle	370 ^{o}C
Number of Reactor Coolant Pumps	2
Reactor Coolant Pump Type	Vertical Centrifugal
Reactor Coolant Pump Speed	0 to 3600 rpm
Turbine Generator System	
Turbine Speed	3600 rpm
Net Heat to Turbine	100 MWTh
Steam Conditions to Turbine	
Pressure	12 MPa
Temperature	370 ^{o}C
Net Electrical Output	38 MW (site dependant)
Main Condensor Type	Water or Air Cooled (Site dependant)
Turbine Bypass Steam Discharge Capacity	100% for 5 min., 60% continuous

5. LEADIR-PS Safety Overview

The Gen IV$^+$ LEADIR-PS reactors, unlike water-cooled reactors are inherently/passively safe. , Safety of the below grade LEADIR-PS reactor is maintained even if all above grade structures are lost, and in the event of a substantial fire above the Reactor. Specifically, to assure safety, there is:

- No requirement for operator action.
- No requirement for valve repositioning.
- No requirement for any of the plant operating systems.
- No requirement for any type of electrical, pneumatic, or other power source.

The inherent characteristics and design features of LEADIR-PS assure that there is:

- No potential for a Loss OfCoolant Accident (LOCA).
- No potential for a reactivity transient without shutdown/scram.
- No potential for a loss of decay heat sink.
- No potential for containment failure (containment not required).
- No potential for pressure vessel or high pressure reactor coolant system pipe failure (do not exist).
- No potential for dissociation of reactor coolant into hydrogen and oxygen.

The Gen IV$^+$ LEADIR-PS provides unprecedented safety through the unique integration of proven technologies and novel design features. There are no active systems required for safe shutdown and decay heat removal. No active or stored energy power supply is required, there is no requirement to reposition valves or other devices and there is no requirement for operator intervention or action to assure safety.

6. Summary

LEADIR-PS100, a unique integration of established and proven technologies with simple, robust, but novel design features, meets the identified small reactor requirements and can serve a broad spectrum of energy demands. These include process heat applications covering a wide range of pressures and temperatures, district heating, and electricity production. LEADIR-PS can be utilized in situations as diverse as areas of high population density, remote islands and isolated areas.Energy utilization of over 95% is feasible in process heat and Combined Heat and Electricity applications.

Modularization, factory assembly and barge delivery assure short and secure construction schedules, even in remote areas with harsh environments.

The relatively simple, economic and robust LEADIR-PS designs assure reliable long term operation. Features such as central control of up to 30 LEADIR-PS units from a Central Control Facility, and maintenance by a Central Maintenance Facility serve to enhance economics,.