Status Report – Westinghouse Lead Fast Reactor (Westinghouse Electric Company LLC, United States of America)

This reactor design is an evolution from the previous design of the Westinghouse Lead Fast Reactor, which is described in https://aris.iaea.org/Publications/SMR-Book_2018.pdf .

The reference plant has a net power output of >460 MWe.
[*Please note that the list of references for the booklet summaries (denoted as "[S-Ref. No.]") is provided at the end of this document ("References for Booklet Summaries"), while references used for the chapters (denoted as "[Ref. No.]") are listed at the end of each chapter*]

INTRODUCTION

Indicate which booklet(s): [ ] Large WCR [ ] SMR [X] FR

The Westinghouse Lead Fast Reactor (LFR) (Ref. [S-1]) is a medium-output, modular, passively-safe plant harnessing a lead-cooled, fast spectrum core operating at high temperatures in a pool configuration reactor, and coupled with an air-cooled Supercritical CO_2 (sCO_2) Balance of Plant (BoP) system. With the ultimate goal to be competitive even in the most challenging global markets, the Westinghouse LFR has baseload electricity production and load-leveling as the primary design focus. However, it maintains the capability for mission flexibility to address market needs. The plant design seeks to competitively achieve these goals through selected innovations, which make it different from most LFRs developed internationally. Specifically, in addition to adopting a novel design of the primary system and an integrated thermal energy storage system for load-leveling, the Westinghouse LFR pursues innovation in materials in order to increase operating temperature above typical LFR values, as to increase thermodynamic efficiency and ultimately enhance economics. Moreover, high temperature operation and unique configuration of the compact reactor vessel (RV) and guard vessel (GV) present an opportunity for automatically-actuated passive cooling in case of accidents, without the need for instrumentation and control signals or moving parts. Fuel cycle flexibility is embedded in the plant design as the use of a fast-spectrum core permits a wide variety of fueling options and strategies. These range from once-through, high-burnup cores; breed/burn extended life cores; MOX-fueling for most effective plutonium utilization; and actinide burning closed cycle applications to satisfy market demand, customer preference, and nuclear energy policy in the country of deployment.

Development Milestones

2015	Start of downselection process for next-generation reactor technology, and selection of LFR for subsequent development
2017	Pre-conceptual design completed, adopting novel, compact pool design
~2030	Start construction of full-scale prototype, and subsequent operation for techn. demonstration
~2035	Conversion of full-scale prototype to FOAK of commercial unit, and subsequent start of commercial operation

Design organization or vendor company (e-mail contact): ferronp@westinghouse.com

Links (www…) to designer/vendor homepage:

http://www.westinghousenuclear.com/new-plants/lead-cooled-fast-reactor

Detailed Design Description: please refer to the individual chapters or to Ref. [S-1] for a summary.

Most Recent Licensing Application Support Document: although no licensing applications have been pursued yet, some documents have been produced in preparation for such efforts:

- Phenomena Identification and Ranking Table for safety analysis of the Westinghouse LFR ([S-2])
- Safety, Security and Environmental Aspects of the Westinghouse LFR, submitted to the UK Office of Nuclear Regulation (ONR) as part of Phase 1 of the Advanced Modular Reactor program administered by the UK Department for Business, Energy and Industrial Strategy (BEIS) ([S-3])

Reactor Units in PRIS (if applicable): Not Applicable

Table 1: ARIS Category Fields (see also Spreadsheet "Categories") for Booklet

ARIS Category	Input
Current/Intended Purpose	Prototype/FOAK
Main Intended Application (once commercial)	Baseload and Dispatchable (non-reactor based)
Reference Location	Inland (Air-Cooled)
Reference Site Design (reactor units per site)	Dual Unit (each standalone)
Reactor Core Size (1 core)	Small (950 MWth)
Reactor Type	LFR
Core Coolant	Pb
Neutron Moderator	None
NSSS Layout	Pool-type
Primary Circulation	Forced (6 pumps)
Thermodynamic Cycle	"Brankine" (condensing sCO_2)
Secondary Side Fluid	CO_2
Fuel Form	Fuel Assembly/Bundle
Fuel Lattice Shape	Hexagonal
Rods/Pins per Fuel Assembly	
Fuel Material Type	Oxide (prototype); Advanced, high-density fuel (commercial)
Design Status	Conceptual
Licensing Status	Licensing activities not started yet

Table 2: ARIS Parameter Fields (see also Spreadsheet "Data") for Booklet

ARIS Parameter	Value	Units or Examples
	Plant Infrastructure	
Design Life	60	years
Lifetime Capacity Factor	>87% (includes losses from energy storage), >90% baseload	%, defined as Lifetime MWe-yrs delivered / (MWe capacity * Design Life), incl. outages
Major Planned Outages	~10-20 days every 24 months (component maintenance. Upper bound value when refueling is also performed)	# days every # months (specify purpose, including refuelling)
Reference Site Design	2 Units (each standalone)	n Units/Modules
Capacity to Electric Grid	>460	MWe (net to grid)
Non-electric Capacity	Selected non-electric applications on case-by-case basis	e.g. MWth heat at x ºC, m^3/day desalinated water, kg/day H2, etc.
In-House Plant Consumption	~15	MWe
Plant Footprint	~4650	m^2 (rectangular building envelope)

ARIS Parameter	Value	Units or Examples
Site Footprint	~40,500	m^2 (fenced area)
Emergency Planning Zone	Site Boundary	km (radius)
Releases during Normal Operation		TBq/yr (Noble Gases / Tritium Gas / Liquids)
Load Following Range and Speed	~65% – 125+% >10% per minute	x – 100%, % per minute
Seismic Design (SSE)	0.3	g (Safe-Shutdown Earthquake)
NSSS Operating Pressure (primary/secondary)	<0.1 / 30	MPa(abs), i.e. MPa(g)+0.1, at core/secondary outlets
Primary Coolant Inventory (incl. pressurizer)	~3500×10^3	kg
Nominal Coolant Flow Rate (primary/secondary)	~25,300 / ~4000	kg/s
Core Inlet / Outlet Coolant T	390 / 650	ºC / ºC
Available Temperature as Process Heat Source	~630 CO$_2$	ºC
NSSS Largest Component	Core Barrel (vessel and guard vessel are site welded from sections)	e.g. RPV (empty), SG, Core Module (empty/fuelled), etc.
- dimensions	~7.5 / 3.9 / ~35000 kg	m (height) / m (diameter) / kg (transport weight)
Reactor Vessel Material	SS316, possibly protected (e.g. weld-overlay)	e.g. SS304, SS316, SA508, 800H, Hastelloy N
Steam Generator Design	Hybrid microchannel-type Supercritical counter flow	e.g. Vertical/Horizontal, U-Tube/ Straight/Helical, cross/counter flow
Secondary Coolant Inventory	~145,000	kg
Pressurizer Design	N/A (Unpressurized)	e.g. separate vessel, integral, steam or gas pressurized, etc.
Pressurizer Volume	N/A	m^3 / m^3 (total / liquid)
Containment Type and Total Volume	Dry (Guard vessel and filtered vents)	Dry (single/double), Dry/Wet Well, Inerted, etc. / m^3
Spent Fuel Pool Capacity and Total Volume	N/A (Direct loading into casks from Vessel)	years of full-power operation / m^3
	Fuel/Core	
Single Core Thermal Power	950	MWth
Fuel Material	Oxide (UO$_2$ or MOX) (prototype) Advanced fuel(commercial)	
Average Neutron Energy	Fast spectrum	eV
Fuel Cladding Material	Various options being considered	
% of fuel outside core during normal operation	N/A	applicable to online refuelling and molten salt reactors
Core Discharge Burnup	≥100	MWd/kgHM (heavy metal)
Pin Burnup (max.)	<140 (peak, Prototype); <200 (peak, commercial)	MWd/kgHM
Breeding Ratio		
Reprocessing	Possible, but not part of reference design	e.g. None, Batch, Continuous (FP polishing/actinide removal), etc.
Main Reactivity Control	Rods	

ARIS Parameter	Value	Units or Examples
Safety Systems (not including Defense in Depth systems)		
Number of Safety Trains	Active / Passive	% capacity of each train to fulfil safety function
- reactor shutdown	0 / 2	100 / 100
- core injection	0 / 0	N/A
- decay heat removal	0 / 1	100%--> Failure mechanisms in system increase heat removal; i.e. one system with intrinsic redundancy
- cont. isolation and cooling	0 / 0	N/A
- emergency AC supply (e.g. diesels)	0 / 0	N/A
DC Power Capacity (e.g. batteries)	>72 (Post-Accident Monitoring Only)	Hours→ No DC Power needed for safety
Events in which ***Immediate Operator Action*** is required	None	e.g. any internal/external initiating events, none
Limiting (shortest) ***Subsequent Operator Action*** Time		hours (that are assumed when following EOPs)
Severe Accident Core Provisions	No fuel rod failure propagation	e.g. no core melt, IVMR, Core Catcher, Core Dump Tank, MCCI
Core Damage Frequency		
Severe Accident Containment Provisions		e.g. H_2 ignitors, PARs, filtered venting, etc.
Large Release Frequency		
Overall Build Project Costs Estimate or Range (excluding Licensing, based on the Reference Design Site and Location)		
Construction Time (nth of a kind)	<36	months from first concrete to criticality
Material and Equipment Overnight Capital Cost	<\$3000/kW → <\$1380M	Million US\$(2015) [M&E], if built in USA
Cost Breakdown	%[C&C] / %[M&E]	

1. *Plant Layout, Site Environment and Grid Integration*

The Westinghouse LFR, like the AP1000® plant before it, has a number of site characteristics to which it is designed. These have been established to cover a large percentage of the target market, in terms of soil/rock/seismic/weather conditions, without redesign. One key advantage of the LFR, in comparison to most previous nuclear plant designs, is the implementation of standard air cooling for the balance-of-plant. This design only uses small amounts of supplemental water and thus eliminates the need for siting near water bodies. Further, the plant incorporates thermal energy storage as a means to load follow without changing core power; increasing capacity factor and profitability versus traditional load follow methods which perturbate fission power.

Site Considerations during Operation

Site Requirements/Interface with BoP Systems

The LFR uses a hybrid cooling approach, with a majority of heat being rejected using an air-cooled condenser (ACC) and a small amount of annual rejection being augmented by a wetted surface cooler or ACC spray system. This results in a very small amount of water evaporation relative to conventional water-cooled plants (<<1% annually in most locations). As such, the water usage is estimated to be so minimal that public water is the assumed supply source, thus eliminating the need for significant on-site treatment of raw water. A representative plant layout is shown in Figure 1-1.

The power conversion is designed for operation at a maximum set of ambient conditions, above which water is used to reduce the condensate temperature. Given a system size designed for historic site conditions and adequate water supply, it is not anticipated that conditions will exist such as to limit the plant output relative to the high temperature-rated condition.

The LFR’s output is rated at ISO conditions and, understandably, changes with atmospheric conditions. The plant’s output between ISO conditions and peak temperatures is expected to vary less than 4%. However, the air-cooled condenser is expected to permit a significantly-greater cold-weather output increase in comparison to water-cooled plants. This has the impact of helping to offset the seasonal variation seen with non-dispatchable resources.

Grid Integration

The Westinghouse LFR is designed to load follow using a thermal energy storage system. This will allow variation of power between 65% and 125% of nominal output while maintaining the core at full output. Hour-by-hour modeling of variable grids has shown this approach to have a minimal penalty in capacity factor (~3%), thus representing a minor impact on fuel utilization.

As noted previously, both winter output increase and energy storage will dictate that the grid connection be designed to transmit power in excess of the nominal plant output. It is anticipated that the grid connection should be designed for at least 135% of nominal output (~1250 MWe for a two-unit site). Voltage is expected to be ~20kV, whether a 50Hz or 60Hz market is served. Reactive power support is nominally 0.9pf, although this can be tailored to grid requirements.

While the plant design is still conceptual, it targets the ability to survive a full load rejection without plant trip. Moreover, as the design targets no need for electrical power to support walkaway safety, although not a current design priority technical capabilities are in-place for islanded operation. However, the control systems, non-safety back-up power, and licensing basis to do so would need further exploration.

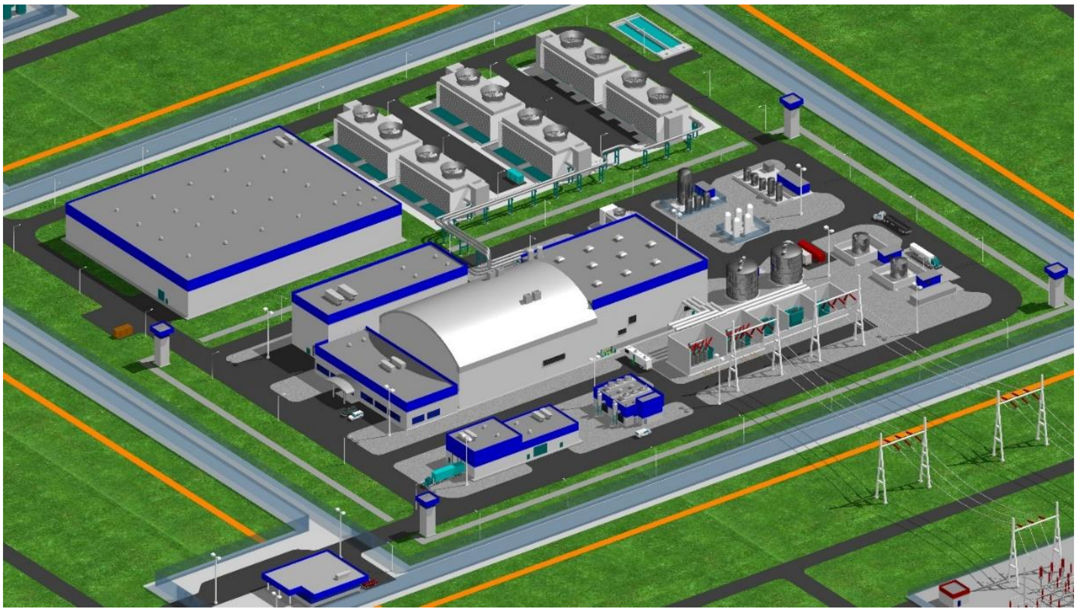

Figure 1-1: Westinghouse LFR representative plant layout

2. *Technical NSSS/Power Conversion System Design*

SUMMARY FOR BOOKLET

The LFR is designed to be a versatile plant, with baseload electricity production and thermal energy storage-based load leveling as the primary design focus, but with the capability (and temperature) to fullfill a range of non-electricity applications according to market demand. Its output is sufficiently small to integrate into lower-capacity grids while also being substantial enough to be used in standard baseload plant applications (Ref. [S-1], [S-4]).

Main Design Features:

***(a).* Primary Circuit**

The Westinghouse LFR, shown in Figure 1, features a novel reactor design configuration with respect to conventional pool-type liquid metal reactors, utilizing high power density hybrid microchannel-type primary heat exchangers (PHE) integral to the upper part of the core barrel, fed radially by the primary coolant as it moves upward in the upper core plenum. The compactness of the microchannel-type design reduces the overall height and volume of the reactor vessel (RV), thus not only making the RV more compact and cheaper, but also alleviating RV support challenges resulting from the otherwise heavier RV should more conventional shell-and-tube heat exchangers be used.

Six of these PHE are located in the RV pool to transfer heat to the secondary side working fluid; S-CO_2 at approximately 30 MPa of pressure. With no welds in the main body, very small CO_2 channels within diffusion bonded plates, and S-CO_2 headers located outside of the RV, a robust structure capable of maintaining extreme pressure differentials is created. When combined with the lack of exothermic reaction between primary lead coolant and S-CO_2, these elements allow PHE's placement into the RV pool to be achieved with reduced risk of PHE failure, i.e., reduced likelihood of a significant RV pressurization resulting from PHE failure. These inherent characteristics of lead coolant and of PHE design strenghten the case for eliminating the need for an intermediate heat transport loop present in other advanced reactor technologies, resulting in a more cost competitive plant.

***(b).* Reactor Core, Fuel and Fuel Handling**

The core employs a conventional fast reactor configuration, featuring hexagonal lattice assemblies with fuel pellets in cylindrical cladding. As a result of the more open lattice that can be realized with lead as opposed to sodium, spacer grids are used as rod supporting mechanism; with negligible neutronic penalty but significantly enhanced natural circulation capability during safety events. Advanced, high-density fuels are being investigated for the commercial fleet, together with higher technology readiness oxide fuels (UO_2 and MOX) which are proposed for the nearer-term, lower temperature prototype plant. Various material options are considered for the fuel rod cladding, currently being downselected based primarily on corrosion, mechanical and irradiation swelling performance. Corrosion testing at 500 and 700°C is currently being performed at partner organizations. Various fuel management and handling schemes are being investigated, with the goal of progressively optimizing the design toward cost-effectiveness, ease of operation and flexibility to address diverse fuel management policies (Ref. [S-5], [S-6], [S-7]).

***(c).* Balance of Plant**

The sCO_2 BoP offers significant efficiency (>48% net efficiency) and size benefits. It ties into an integrated thermal storage system and uses air cooling to greatly ease siting.

***(d).* Containment/confinement**

The Westinghouse LFR adopts a simplified containment design relative to conventional plants. Specifically, no-high-pressure-resistant structure is needed, as a result of the plant leveraging the inherent favorable features of lead coolant; notably primary system operation near atmospheric pressure, lack of boiling concerns and of exothermic reactions with water/air/CO_2, and retention capability of some key radionuclides. Use of filtered vents is envisioned to manage accidental releases from the primary and secondary side, while underground installation of most safety-significant components and effective design of structures/buildings are implemented to ensure protection from external events.

***(e).* Instrumentation and Control Systems**

A design goal for the development of the Westinghouse LFR's plant safety systems is to not rely on signals from the instrumentation and control (I&C) system. As a result, the majority of components, systems, and software used to control the plant will be commercial grade. To support anticipated licensing requirements, a reduced number of "safety-grade" systems will be incorporated, such as post-accident monitoring.

Technical Description

Description of the technology

The Westinghouse LFR harnesses a liquid lead-cooled, fast neutron spectrum core operating at high temperature in a pool configuration. By combining the favourable attributes of liquid lead as primary coolant, selected innovations and modular design, this plant enhances economic and safety performance significantly beyond those of conventional NPPs, and addresses key LFR challenges of the past. The key innovations distinguishing the Westinghouse LFR from other LFR concepts are as follows:

- *Materials that withstand operation in liquid lead at temperatures up to 650°C*. Other LFR design concepts have been limited to ~40% plant efficiency due to lead corrosion concerns with existing materials at operating temperatures above 500°C. The Westinghouse LFR design concept strives to achieve a plant efficiency close to 50% through materials innovations to be validated through testing; dramatically improving the plant's economic performance.
- *Compact, microchannel-type heat exchangers*. These heat exchangers allow the Reactor Vessel (RV) to be reduced in size and weight, thus addressing known concerns resulting from lead's high density, and support capital cost reduction by facilitating safe elimination of the Intermediate Heat Transport System (IHTS) that is instead required in other advanced reactor technologies, such as sodium fast reactors (SFR).
- *A Supercritical CO_2 (sCO_2) Power Conversion System (PCS)* that permits much smaller size turbomachinery, compacted building layout with no in-structure condenser, higher efficiency in the targeted temperature range, and optimally harnesses air as the ultimate heat sink.
- *A thermal energy storage system* providing non-reactor-based load-following capability
- *An advanced, high-density fuel*, supporting enhanced safety and economics.

Reactor Coolant System and Main Associated Systems

The Reactor Coolant System (RCS), shown in Figure 2-1, operates at high temperature (390°C core inlet temperature; 530 and 650°C core outlet temperature in the prototype and commercial phases of operation, respectively) and near atmospheric pressure. As indicated by the colored arrows, the primary lead coolant circulates through the core and then rises through the hot pool, before moving radially into the Primary Heat Exchangers (PHE), where it is cooled. After exiting the PHE, the lead coolant is drawn by the Reactor Coolant Pumps (RCPs) into the upper cold pool and pumped to the lower cold pool, for subsequently turning into the lower core plenum and entering into the core. A cover gas (argon) region, separating the lead pool from the Reactor Lid (RL), is used for multiple purposes. These include accommodating lead pool thermal expansion, preventing outflow leakages by maintaining a negative pressure and monitoring gas composition, and therefore detecting potential fuel rod leaks.

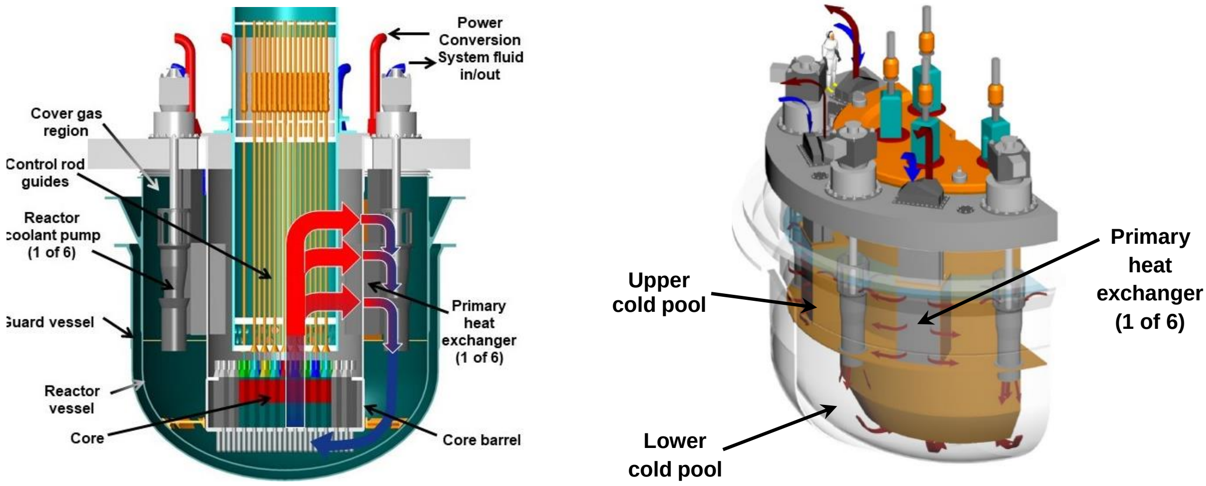

Figure 2-1: Westinghouse LFR RCS: cross section (left); back view with upper/lower cold pools (right)

The RV contains the reactor internals structure which serves to provide mechanical support to the reactor core, through the core barrel shown in Figure 2-1. The RV is manufactured of a clad stainless steel material. The RV retains the lead coolant and also is used to dissipate decay heat in the event that the normal decay heat removal (NDHR) system, which uses the PHE, fails to operate. This safety function is performed through radiation heat transfer to the Guard Vessel (GV), which surrounds the RV, via the Passive Heat Removal System (PHRS). The system composed of the RV and RL is completely enclosed into the Primary Containment (PC), whose lower part coincides with the GV. The gap between the RV and the GV is sized so as to ensure that, in the unlikely event of RV leakage, the resulting drop in lead level inside of the RV does not prevent the core from being adequately cooled.

The PC is provided with rupture discs. These devices are used to release secondary fluid (with entrained cover gas and possibly lead droplets in case of PHE rupture inside of the RV) to dedicated areas of the Reactor Building (RB), thus minimizing RV/PC pressurization. Prior to release to the RB, such gas mixture is passed through the Filtered Venting System (FVS). The FVS is connected to the rupture discs through dedicated piping and is aimed at immobilizing radioisotopes, thus preventing their release.

In an innovative departure from typical liquid metal pool-type reactors, the Westinghouse LFR leverages existing cross-cutting innovation originated outside of the nuclear industry, in the form of hybrid microchannel-type PHEs. The favorable attributes of these PHEs include extreme compactness and capability to lower concerns related to the potential for PHE failure and resulting RV pressurization. As shown in Figure 2-1, the PHE are located in an annular region surrounding the hot pool, with their inlet surfaces forming part of the core barrel walls at the periphery of the pool. After flowing from the core to the hot pool (see Figure 2-1), liquid lead moves radially through the PHE's larger channels towards the RCP inlet region, and in the process exchanges its energy to sCO$_2$. This latter fluid flows through U-shape microchannels chemically etched within plates, which are diffusion-bonded to form the vertical plates separating the primary channels, as shown in Figure 2-2. The PHEs use diffusion bonding throughout the entire main body thus eliminating the need for welds, which are often the failure locations in pressurized structures. This, together with the small size of the pressurized sCO$_2$ channels, allows the PHE's main body to withstand pressure differentials notably higher than that existing between the primary and secondary systems (Ref. [1]), thus reducing the likelihood for failure. Moreover, the sCO$_2$ microchannels culminate into plena inlet/outlet headers located *outside* of the PC. The headers' ex-PC location allows limiting RV/PC pressurization sources to that possible from the microchannels only, as the larger break flows potentially resulting from inlet/outlet header failures would discharge outside of the PC. Leaks of < 2 mm size are most-easily addressed with the FVS, especially considering that the relatively clean secondary side fluid would only be contaminated by what it can entrain during escape from the primary lead pool and cover gas region.

The RCPs, of which a sketch is shown in Figure 2-1, are located in the cold pool and their design is currently being developed accounting for the need to withstand corrosion/erosion and to be in line with the overall design philosophy in terms of simplicity, safety and reliability.

Three systems are used to maintain the lead coolant's properties as they pertain to heat transfer, material compatibility, and isotopic purity: the Cover Gas System (CGS), the Lead Volume and Processing System (LPS) and the Lead Heating System (LHS).

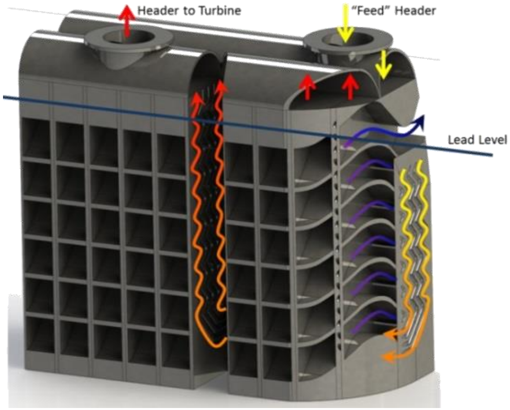

Figure 2-2: Primary Heat Exchanger notional representation.

Fuel system and core design

The core employs a conventional fast reactor configuration, featuring hexagonal lattice assemblies with fuel pellets in cylindrical cladding. Spacer grids are used as rod supporting mechanism, as a result of the more open lattice that can be realized with lead as opposed to sodium, with negligible neutronic penalty but significantly enhanced natural circulation capability during safety events.

The initial core and early reloads will feature oxide (UO_2 or MOX) fuel, which will maximise the use of existing global fuel cycle facilities and thereby minimise investment in new facilities that would be dramatically underutilised during the early years of LFR deployment. The use of oxide fuel, especially UO_2, will also streamline the plant licensing by using well-proven materials during plant startup and early operation while enabling the oxide core to potentially host lead test assemblies with advanced fuel and/or cladding materials. This is because, even though oxide fuel can potentially be used for the commercial fleet, advanced high-density fuels in spite of their lower readiness have the potential not only to improve safety margins and reduce Fuel Cycle Cost (FCC) substantially, but also ease the transition from the lower power (~300 MWe) envisioned in the PLFR to the higher power which was found to be economically optimal for the commercial fleet (~460 MWe), while preserving RV dimensions. Various advanced, high-density fuel options are currently being explored.

Analogously with other RCS structural components, a material evaluation has been performed also for the fuel rod cladding, with the goal of identifying the best candidate material for near-term deployment, as well as lower readiness but potentially higher benefits alternatives for future reactor enhancements. 15-15Ti-based steel has been selected as the primary choice for near-term deployment, in consideration of the abundant irradiation database in fast spectrum for the 15-15Ti base material (Ref. [2]) and the promising corrosion, mechanical and (ion) irradiation performance obtained with Al_2O_3 coating in liquid lead environment (Ref. [3], [4]). As Westinghouse is relentlessly pursuing the most economically competitive and safe form of the LFR for global commercialisation, other cladding materials are of interest for future design evolutions, which are currently being downselected based on their corrosion, mechanical and irradiation swelling performance.

Various core designs and fuel handling schemes are being investigated, with the goal of progressively optimizing fuel management toward cost-effectiveness and ease of operation, as well as flexibility to address diverse fuel management policies (Ref. [5], [6], [7]).

Passive Heat Removal System

The Passive Heat Removal System (PHRS) (Ref. [8]) is designed to passively remove decay heat following an accident, should the Normal Decay Heat Removal (NDHR) system fail or be unavailable, by means of (see Figure 2-3):

- Conducting heat through the RV wall
- Transferring heat via radiative and convective heat transfer from the RV wall to the GV wall
- Conducting heat through the GV wall
- Transferring heat via natural convection and boiling to a large volume of water outside of the GV
- Transitioning to natural convection air cooling, circulating outside of the GV when water is depleted

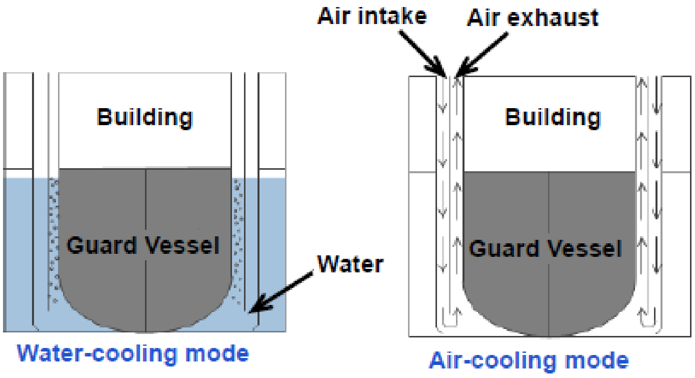

Figure 2-3: Notional representation of Passive Heat Removal System

The PHRS is always on, even during normal reactor operation and shutdown, thus resulting in continuous thermal losses. In these operational modes, however, the temperature of the RV (370-390°C) is not sufficient to promote significant radiative heat transfer, thus limiting these losses to low values (~2-3 MWt). These losses are acceptable and do not pose a challenge to lead freezing as, even in a hypothetical extended shutdown scenario with LHS assumed to fail, lead freezing would occur after a long time. During this time period adequate measures can be taken to ensure the primary pool to remain in liquid state. Instead, when the lead pool temperature increases as a result of an accident, PHRS starts to remove more and more heat, thus increasing its effectiveness just when it is needed.

Power Conversion System and Thermal Energy Storage System

The reference design for the PCS is based on sCO_2 technology. Compacted building layout with no in-structure condenser and increased efficiency at the temperatures of interest represent the main advantages of this PCS relative to water/steam-based PCSs. However, due to the lower TRL of sCO_2 technology, supercritical water PCS is considered in parallel, although with less detail. This will allow adoption of the latter, should the sCO_2's TRL not increase at a pace consistent with the development schedule envisioned for the plant.

Recognising the important role that advanced NPPs have in fulfilling needs of future markets, Westinghouse is currently developing thermal energy storage systems capable of providing load-leveling for thermal power plants. In the Westinghouse LFR the storage system maximises economic advantage by being integrated with the same turbine and generator as would be used for power generation. This approach manages supply fluctuations produced by renewable sources by storing heat energy when electricity demand is low and selling produced electricity from that stored heat when it is high, all while maintaining the core at full-power. This is accomplished through manipulation of PCS flows, increasing or decreasing the mass flow rate through the turbine. Multiple envisioned implementations of this system are under consideration at this time. Common among these concepts is the use of a modular energy storage design, with heat stored in an assemblage of modules consisting of an outer steel case, concrete slabs within this case, and heat transfer oil running between these plates.

The combination of these technologies shows promise in providing a simplified solution which incorporates nuclear base-load, low-cost renewable energy, and variable-output grid support into a single, economic package.

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3. Technology Maturity/Readiness

Currently in conceptual design stage, the Westinghouse LFR is envisioned to be developed through a staged approach that leverages the adequate readiness of LFR's "base technology" and progressively introduces selected innovations to enhance performance and ease some of LFR's existing challenges. This staged approach commences with a lower-power (~300 MWe), nearer-term deployment Prototype LFR (PLFR) that features higher-readiness technology solutions, especially on materials due to the lower operating temperature targeted with this first stage of operation (T_{hot} ~530°C). The PLFR is intended to demonstrate LFR technology's overall safety and performance characteristics, and ability to produce electricity at a cost that is economically competitive in many markets. Following a demonstration phase of a few years, the PLFR plant will be enhanced and uprated to obtain the First of a Kind (FOAK) unit of a higher-power (~460 MWe), higher-temperature commercial fleet. The FOAK plant will maintain the overall configuration and key features of the PLFR, but will incorporate the program's developed innovations, such as materials for higher temperature operation, with the goal of enhancing economics, sustainability and overall performance.

The above approach has been conceived to reduce uncertainties through initial use of higher-maturity design solutions in the PLFR (as to demonstrate several aspects of LFR's "base technology"), but also to simultaneously assess viability of lower-maturity but higher performance innovative materials envisioned for subsequent use. It is worth noting that, because of significant out-of-pile operational experience with lead-based facilities accumulated internationally over the past two decades (Ref. [S-8]), the technology readiness level (TRL) of LFR's base technology is sufficient to provide reasonable confidence in technical viability without the need for extensive campaigns of basic R&D. Rather, work in applied R&D as well as separate and integral effect testing (including on materials) is most-typical of the anticipated project needs, and it is informed by outcomes of development activities such as the Phenomena Identification and Ranking Table (PIRT) performed on the safety analysis of the Westinghouse LFR (Ref. [S-2]). Westinghouse leverages domestic and international collaborations to most effectively advance the design, benefitting from knowledge and expertise specific to lead technology and fast reactor design accumulated by various organizations worldwide.

4. *Safety Concept*

SUMMARY FOR BOOKLET

The overarching objective of the Westinghouse LFR is to achieve the highest standards of safety while ensuring capital cost affordability and competitive electricity generation. This safety objective can be illustrated in a set of high-level goals which accompany the development of the Westinghouse LFR regardless of the specific target market:

- The LFR should be a passive safety plant
- The LFR design should lead to practical elimination of core melt accidents which would lead to early or large releases
- The LFR should be able to achieve and maintain safe shutdown conditions for an extended period of time; at least 72 hours (with strong preference for unlimited cooling) following defined design basis accidents, without requiring either operator action or coolant inventory supply
- The LFR should have simple/reduced emergency preparedness (EP) requirements relative to existing plants, so that only limited protective measures in area and time are needed for the public (no permanent relocation, no need for emergency evacuation outside the immediate vicinity of the plant, limited sheltering, no long-term restrictions in food consumption) and that sufficient time is available to implement these measures.
- The LFR design solutions should be augmented by appropriate DiD functionality that is demonstrated to reduce plant risks. This is achieved by incorporating relevant good practice, evaluating alternatives via optioneering assessments, quantifying risks, as well as a balanced cost-benefit analysis.

The fundamental principles used to achieve the overarching goal mentioned above, which also represent distinguishing safety enhancements of the Westinghouse LFR design over existing NPP technology, are the full exploitation of the inherent favorable properties of liquid lead as a primary coolant and the adoption of passive protective safety measures designed to function during fault sequences in the event that normal duty systems have failed. Specifically, passive safety is targeted through a plant adhering to IAEA Category B2 principles with the potential for limited Category C features, such as rupture discs (classified as a safety-grade moving mechanical part) (Ref. [S-9]).

The most relevant passive system is the Passive Heat Removal System (PHRS), which is designed to passively remove decay heat following an accident, should the Normal Decay Heat Removal (NDHR) system fail or be unavailable, by means of:

- Conducting heat through the RV wall
- Transferring heat via radiative and convective heat transfer from the RV wall to the GV wall
- Conducting heat through the GV wall
- Transferring heat via natural convection and boiling to a large volume of water outside of the GV
- Transitioning to natural convection air cooling, circulating outside of the GV when water is depleted

The PHRS is always on, even during normal reactor operation and shutdown, thus resulting in continuous thermal losses. In these operational modes, however, the temperature of the RV is not sufficient to promote significant radiative heat transfer, thus limiting these losses to low values. These losses are acceptable from the plant's efficiency standpoint and have been demonstrated not to pose a challenge to lead freezing as, even in a hypothetical extended shutdown scenario with an assumed failure of the supplemental lead heating system, lead freezing would not occur for a long time from such failure. During this time adequate measures can be taken to ensure the primary pool remains in liquid state. Conversely, when the lead pool temperature increases because of an accident, PHRS starts to remove exponentially more and more heat, thus increasing its effectiveness just when it is needed.

In addition to passive safety systems, safety features that are inherent in the design and materials used are:

- High thermal capacity inherent in the primary lead pool
- Negative reactivity feedback from Doppler coefficient and thermal expansion of core structures
- Lead's retention capability for certain radionuclides.

The operation of the above-mentioned passive systems is being assessed using highly developed computer codes, such as SAS4A/SASSYS-1 (Ref. [S-10]). Validation and verification of these codes is progressing using experimental data collected in the past and will continue as new data are collected using existing and to-be-built facilities; characterized by a progressively increasing level of prototypicality with respect to reactor's conditions.

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