Status Report - W-LFR (United States of America)

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1. Overview

- ☐ **In Operation**
- ☐ **Under Construction**
- ☐ **Described in**

Link to PRIS	--

- ☑ **New Concept**

Number of Units	--
Year	--

Reference Plant

Name of Site	--
Link to PRIS	--
Net Power Output (MWe)	460
Gross Power Output (MWe)	468

1.1 Introduction

The Westinghouse Lead Fast Reactor (LFR) (Ref. P. Ferroni et al., “The Westinghouse Lead Fast Reactor”. International Congress on Advances in Nuclear Power Plants (ICAPP), Juan-les-pins, France, May 12-15, 2019) 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 CO2 (sCO2) 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; MOXfueling 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.

1.2 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

1.3 Design organization or vendor company

ferronp@westinghouse.com

1.4 Links to designer/vendor website

https://www.westinghousenuclear.com/energy-systems/lead-cooled-fast-reactor/

1.5 Design Description

please refer to the individual chapters or to Ref.: P. Ferroni et al., “The Westinghouse Lead Fast Reactor”. International Congress on Advances in Nuclear Power Plants (ICAPP), Juan-les-pins, France, May 12-15, 2019.

1.6 Licensing Application Support Documents

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

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- Phenomena Identification and Ranking Table for safety analysis of the Westinghouse LFR (Ref. WCAP-18392-P. Rev. 0. Westinghouse Lead Fast Reactor Phenomena Identification and Ranking Table. August 2019)
- 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) (Ref. LFR-GW-GER-002, Rev.0. Safety, Security and Environmental Features of the Design. UK-BEIS Advanced Modular Reactor Program. Phase 1 – Feasibility and Development Program. December 2018.)

1.7 Reactor Unit in PRIS

2. Category Fields

Table 1: ARIS Category Fields

ARIS Category	Value	Units of Examples
Current/Intended Purpose	Prototype/FOAK	e.g. Commercial – Electric/Non-electric, Prototype/FOAK, Demonstration, Experimental
Main Intended Application (once commercial)	Baseload, Dispatchable	e.g. Baseload, Dispatchable, Off-grid/Remote, Mobile/Propulsion, Non-electric (specify)
Reference Location	Inland	e.g. On Coast, Inland, Below-Ground, Floating-Fixed, Marine-Mobile, Submerged-Fixed (Other-specify)
Reference Site Design (reactor units per site)	Dual Unit	e.g. Single Unit, Dual Unit, Multiple Unit (# units)
Core Coolant	Pb	H2O, D2O, He, CO2, Na, Pb, PbBi, Molten Salts, (Other-specify)
Reactor Core Size (1 core)	30 MWth <= Thermal power < 1000 MWth	e.g. Thermal Power < 30 MWth, 30 MWth ≤ Thermal power < 1000 MWth, 1000 MWth ≤ Thermal power ≤ 3000 MWth, Thermal power > 3000 MWth
Reactor Type	LFR	e.g. PWR, BWR, HWR, SCWR, GCR, GFR, SFR, LFR, MSR, ADS
Reactor Size	SMR	e.g. PWR, SMR
Neutron Moderator	None	e.g. H2O, D2O, He, CO2, Na, Pb, PbBi, Molten Salts, (Other-specify)
NSSS Layout	Pool-type	e.g. Loop-type (# loops), Direct-cycle, Semi-integral, Integral, Pool-type

Primary Circulation	Forced (6 pumps)	e.g. Forced (# pumps), Natural
Thermodynamic Cycle		e.g. Rankine, Brayton, Combined-Cycle (direct/indirect)
Secondary Side Fluid	CO2	e.g. H2O, He, CO2, Na, Pb, PbBi, Molten Salts, (Other-specify)
Fuel Form	Fuel Assembly/Bundle	e.g. Fuel Assembly/Bundle, Coated Sphere, Plate, Prismatic, Contained Liquid, Liquid Fuel/Coolant
Fuel Lattice Shape	Hexagonal	e.g. Square, Hexagonal, Triangular, Cylindrical, Spherical, Other, n/a
Rods/Pins per Fuel Assembly/Bundle		e.g. #, n/a
Fuel Material Type	Oxide	e.g. Oxide, Nitride, Carbide, Metal, Molten Salt, (Other-specify)
Design Status	Conceptual Design	e.g. Conceptual, Detailed, Final (with secure suppliers)
Licensing Status		e.g. DCR, GDR, PSAR, FSAR, Design Licensed (in Country), Under Construction (# units), In Operation (# units)
Neutron Spectrum	Fast	e.g. Fast, Thermal

3. Parameter Fields

Table 2: ARIS Parameter Fields

ARIS Parameter	Value	Units of Examples
Plant Infrastructure		
Design Life	60	Years
Lifetime Capacity Factor	>87% (ncludes 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)

Operation / Maintenance Human Resources		# Staff in Operation / Maintenance Crew during Normal Operation
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. MW(th) heat at x ºC, m3/day desalinated water, kg/day hydrogen, etc.
In-House Plant Consumption	~15	MWe
Plant Footprint	~4650	m2 (rectangular building envelope)
Site Footprint	~40500	m2 (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 side)	0.1	MPa(abs), i.e. MPa(g)+0.1, at core outlet
NSSS Operating Pressure (secondary side)	30	MPa(abs), i.e. MPa(g)+0.1, at secondary side outlet
Primary Coolant Inventory (incl. pressurizer)	3500000	kg
Nominal Coolant Flow Rate (primary)	25300	kg/s
Nominal Coolant Flow Rate (secondary)	4000	kg/s
Core Inlet Coolant Temperature	390	ºC
Core Outlet Coolant Temperature	650	ºC
Available Tempeature as Process Heat Source	630	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.

- NSSS Largest Component Length	7500	mm
- NSSS Largest Component Diameter	3900	mm
- NSSS Largest Component Thickness		mm
- NSSS Largest Component Weight	35	tonne
Reactor Vessel Material	SS316	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	145000	kg
Pressurizer Design	N/A (unpressurized)	e.g. separate vessel, integral, steam or gas pressurised, etc.
Pressurizer Volume	N/A	m3 / m3 (total / liquid)
Containment Type	Dry	Dry (single/double), Dry/Wet Well, Inerted, etc.
Containment Volume		m3
Spent Fuel Pool Capacity and Total Volume	N/A	Years of full-power operation / m3
Non Electric Application		-
Core Delta Temperature	260	ºC
Fuel/Core		
Single Core Thermal Power	950	MW(th)
Refuelling Cycle	24	months or “continuous”
Fuel Material	Oxide (UO2 or MOX) (prototype) Advanced fuel(commercial)	e.g. UO2, MOX, UF4, UCO
Enrichment (avg./max.)		%
Average Neutron Energy	Fast spectrum	eV
Fuel Cladding Material	Various options being considered	e.g. Zr-4, SS, TRISO, E-110, none
Number of Fuel “Units”		Specify as Assembly, Bundle, Plate, Sphere, or n/a
Weight of one Fuel Unit		kg

Total Fissile Loading (initial)		kg fissile material (specify isotopic and chemical composition)
% of fuel outside core during normal operation	N/A	Applicable to online refuelling and molten salt reactors
Fraction of fresh-fuel fissile material used up at discharge		%
Core Discharge Burnup	≥100	MWd/kgHM (heavy metal, eg U, Pu, Th)
Pin Burnup (max.)		MWd/kgHM
Breeding/Conversion Ratio		Fraction of fissile material bred in-situ over one fuel cycle or at equilibrium core
Reprocessing	Possible, but not part of reference design	e.g. None, Batch, Continuous (FP polishing/actinide removal), etc.
Main Reactivity Control	Rods	e.g. Rods, Boron Solution, Fuel Load, Temperature, Flow Rate, Reflectors
Solid Burnable Absorber		e.g. Gd2O3
Core Volume (active)		m3 (used to calculate power density)
Fast Neutron Flux at Core Pressure Boundary		n/(cm²*s)
Max. Fast Neutron Flux		n/(cm²*s)
Core Control Rod Absorber		-
Core Soluble Neutron Absorber		-
Safety Systems		
Number of Safety Trains	Active / Passive	% capacity of each train to fulfil safety function
- reactor shutdown	Active/Passive	- / - / -
- core injection	N/A	- / - / -
- decay heat removal	Passive	- /100 / -
- containment isolation and cooling	N/A	- / - / -
- emergency AC supply (e.g. diesels)	N/A	- / - / -

DC Power Capacity (e.g. batteries)	>72 (Post-Accident Monitoring Only)	Hours
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 (CDF)		x/reactor-year (based on reference site and location)
Severe Accident Containment Provisions		e.g., H2 ignitors, PARs, filtered venting etc.
Large Release Frequency (LRF)		x/reactor-year (based on reference site and location)
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
Design, Project Mgmt. and Procurement Effort	<$3000/kW → <$1380M	Person-years (PY) [DP&P]
Construction and Commissioning Effort		PY [C&C]
Material and Equipment Overnight Capital Cost		Million US$(2015) [M&E], if built in USA
Cost Breakdown	%[C&C]/%[M&E]	
- Site Development before first concrete		(e.g. 25/10) (30/40) (20/25) (20/10) (5/15) (----------) (to add up to 100/100)
- Nuclear Island (NSSS)		
- Conventional Island (Turbine and Cooling)		
- Balance of Plant (BOP)		
- Commissioning and First Fuel Loading		
Factory / On-Site split in [C&C] effort		%/% of total [C&C] effort in PY (e.g., 60/40)
Nuclear System		
System Steam Flow Rate		kg/s

System Steam Pressure		MPa
System Steam Temperature		ºC
System Feedwater Flow Rate		kg/s
System Feedwater Temperature		ºC
Reactor Core		
Active Core Height		m
Equivalent Core Diameter		m
Average Linear Heat Rate		kW/m
Average Fuel Power Density		kW/kgU
Average Core Power Density		MW/m3
Outer Diameter Of Fuel Rods		mm

4. Plant Layout, Site Environment and Grid Integration

SUMMARY FOR BOOKLET

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.

4.1 Site Requirements during Construction
4.2 Site Considerations during Operation

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 onsite treatment of raw water. A representative plant layout is shown in Figure 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.

4.3 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: Westinghouse LFR representative plant layout

5. Technical NSSS/Power Conversion System Designn

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 nonelectricity 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 (Refs. P. Ferroni et al., “The Westinghouse Lead Fast Reactor”. International Congress on Advances in Nuclear Power Plants (ICAPP), Juan-les-pins, France, May 12-15, 2019, and C. Stansbury, M. Smith, P. Ferroni, A. Harkness, “Westinghouse Lead Fast Reactor Development: Safety and Economics Can Coexist”. International Congress on Advances in Nuclear Power Plants (ICAPP), Charlotte, NC, USA, April 8-11, 2018).

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-CO2 at approximately 30 MPa of pressure. With no welds in the main body, very small CO2 channels within diffusion bonded plates, and S-CO2 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-CO2, 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 (UO2 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 (Refs. G. Grasso, A. Levinsky, F. Franceschini, P. Ferroni, A MOX-fuel core configuration for the Westinghouse Lead Fast Reactor. International Congress on Advances in Nuclear

Power Plants (ICAPP), Juan-les-pins, France, May 12-15, 2019, and F. Franceschini, G. Grasso and P. Ferroni, “Advanced fuel cost performance assessment for the Westinghouse LFR”. International Congress on Advances in Nuclear Power Plants (ICAPP), Charlotte, NC, USA, April 8-11, 2018, and T. K. Kim, N. Stauff, C. Stansbury, A. Levinsky, F. Franceschini, “Long core life design options for the Westinghouse LFR”. International Nuclear Fuel Cycle conference (GLOBAL). Seattle, WA, USA, September 22-26, 2019).

(c). Balance of Plant

The sCO2 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, nohigh-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/CO2, 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 safetysignificant 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.

5.1 Primary Circuit
5.2 Reactor Core and Fuel
5.3 Fuel Handling
5.4 Reactor Protection
5.5 Secondary Side
5.6 Containment/Confinement
5.7 Electrical, I&C and Human Interface
5.8 Unique Technical Design Features (if any)

6. Technology Readiness

SUMMARY FOR BOOKLET

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 (Thot ~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. Overview of experimental facilities in support of lead/LBE-cooled fast reactors. Available at: https://nucleus.iaea.org/sites/lmfns/Pages/overviewlfr.aspx), 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 mosttypical 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. WCAP-18392-P. Rev. 0. Westinghouse Lead Fast Reactor Phenomena Identification and Ranking Table. August 2019). 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.

6.1 Deployed Reactors
6.2 Reactors under Licensing Review
6.3 Reactors in the Design Stage

7. Safety Concepts

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. IAEA-TECDOC-626, “Safety related terms for advanced nuclear plant,” September 1991).

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.T. H. Fanning, ed., The SAS4A/SASSYS-1 Safety Analysis Code System, ANL/NE-12/4, Nuclear Engineering Division, Argonne National Laboratory, 2012). 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.

7.1 Safety Philosophy and Implementation
7.2 Transient/Accident Behaviour

8. Fuel and Fuel Cycle

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8.1 Fuel Cycle Options
8.2 Resource Use Optimization
8.3 Unique Fuel/Fuel Cycle Design Features

9. Safeguard & Physical Security

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9.1 Safeguards
9.2 Security
9.3 Unique Safeguards and/or Security Features

10. Project Delivery & Economics

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10.1 Project Preparation and Negotiation

10.2 Construction and Commissioning
10.3 Operation and Maintenance