Attachment 4

Demonstration Lead-cooled Fast Reactor Details: Westinghouse Lead-cooled Fast Reactor

Westinghouse Electric Company LLC

Contract DE-AC02-06CH11357

Demonstration Lead-cooled Fast Reactor

RT-TR-15-30, Revision 1

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Record of Revisions

Revision	Date	Revision description(1)
0	See EDMS	
1	See EDMS	Revised based on Advanced Test/Demonstration Reactor Point Design Assessment Meeting, held on February 22-24, 2016. The major changes refer to Appendix A, where few scores have been changed based on the discussion during the meeting. Specifically, the scores for metrics 4.1.1, 4.3.1, 4.3.2, 4.4.3 and 5.3.1 have been changed.

Note 1: The main changes are briefly described in this table. In the rest of the document, each row that has changed is marked using a revision bar in the margin of the page.

List of acronyms

AHRS	Auxiliary Heat Removal System	IV	Inner Vessel
AHS	Auxiliary Heating System	LCCS	Lead Chemical Control System
ALFRED	Advanced Lead-cooled Fast Reactor European Demonstrator	LECOR	LEad CORrosion loop
BOC	Beginning Of Cycle	LFR	Lead Fast Reactor
BU	Burnup	LME	Liquid Metal Embrittlement
CGAS	Cover Gas Auxiliary System	LWR	Light Water Reactor
CS	Control System	MC	Main Condenser
CV	Containment Vessel	MSR	Molten Salt Reactor
DHR	Decay Heat Removal	MV	Main Vessel
DHRS	Decay Heat Removal System	NOAK	N-th Of A Kind
DLFR	Demonstration Lead Fast Reactor	RCP	Reactor Coolant Pump
DR	Demonstration Reactor	RS	Regulation System
EFPM	Effective Full Power Month	SFR	Sodium Fast Reactor
ELFR	European Lead Fast Reactor	SG	Steam Generator
EOC	End Of Cycle	SGTR	Steam Generator Tube Rupture
EP	Emergency Preparedness	SS	Safety System bank
EPZ	Emergency Planning Zone	SSTAR	Small Secure Transportable Autonomous Reactor
FAR	Finger Absorber Rod	SV	Safety Vessel
FHR	Fluoride-cooled High Temperature Reactor	TRL	Technology Readiness Level
GIF	Generation IV International Forum	ULOF	Unprotected Loss Of Flow
GFR	Gas Fast Reactor	ULOHS	Unprotected Loss Of Heat Sink
HELENA	Heavy Liquid metal Experimental loop for advanced Nuclear Applications	UN	Uranium Mononitride
HTGR	High Temperature Gas Reactor	USV	Under-Sodium Viewing
IC	Isolation Condenser	UTOP	Unprotected Transient Overpower

Summary

The Westinghouse Demonstration Lead Fast Reactor (DLFR) is a lead-cooled, pool-type fast reactor in pre-conceptual design phase, targeting operation by 2030 and intended for demonstrating feasibility and basic performance of DLFR-based technology for the ensuing *commercial* deployment. Economics and safety are the key elements driving its design. Westinghouse envisions the commercial fleet to become a leading option for carbon-free electricity generation in the U.S. and international energy markets.

The DLFR features a compact, pool-type, primary system, with the main vessel containing all primary components immersed in liquid lead. The power rating is 500 MWt (210 MWe) with a peak fast neutron

flux of about 2×10^{15} n/cm^2 s, but the plant is designed to facilitate power uprates (up to ~700 MWt) once the initial demonstration mission is fulfilled. UO_2 fuel within steel cladding, a well-vetted, commercially-proven and licensing-proof proliferation-resistant fuel technology, is chosen for the DLFR first cores, while subsequent reloads can incorporate higher-performance uranium mononitride (UN) fuel and advanced cladding materials, whose qualification can be performed in the DLFR. In addition to the capability to host non-UO_2 fueled Lead Test Rods/Assemblies, the reactor is provided with ad-hoc regions that can be used for specimen testing, such as the fuel assembly central tube or, for larger specimens, a cavity that can be readily engineered in selected shield assemblies at the core periphery. An average core outlet temperature of 510°C, with a 500°C, 18 MPa superheated steam power conversion system, results in a net plant efficiency of approximately 42%, which can be further increased to near 50% in the follow-on commercial plants through increased operating temperature, enhanced materials, and modifications to the power conversion cycle. An energy storage system allows the plant to provide a variable electricity output, thereby increasing its market attractiveness for complementing electricity generation from non-dispatchable sources.

The DLFR utilizes proven technology that enables licensing certainty and reactor operation by 2030. Since the DLFR shares several thermal-hydraulic, mechanical and fuel aspects with Sodium Fast Reactors (SFRs), it leverages the considerable SFR experience, with the significant advantages of being safer, simpler and less capital intensive. The lead-containing operating environment is exposed to temperatures and lead velocities for which corrosion is managed with currently available materials, as demonstrated from over a decade of lead loop design and operation experience. Refueling operations are simplified relative to previous fast reactor designs through the use of an innovative fuel assembly design that extends above the free surface of the lead pool, thereby eliminating the need for a refueling machine operating under lead, resulting in increased system reliability.

Overall, the proposed LFR technology has a Technology Readiness Level (TRL) of 4, which will increase to 7 through operation of the DLFR. All of DLFR elements are designed to be prototypic of the commercial reactor technology or scalable such that the performance of the commercial product is estimated with confidence. None of the areas identified at a lower TRL level represent a significant showstopper risk and viable engineering solutions have been identified that will be demonstrated in the DLFR.

The key attributes of the reactor technology that the DLFR embodies are inherent safety behavior and high economic competitiveness. The inherent safety derives from innovative system design features combined with favorable lead properties. The integral reactor configuration eliminates the need for primary coolant loop piping and, due to the use of a main and a safety vessel operating at nearly atmospheric pressure, virtually eliminates loss-of-coolant accidents. The lack of exothermic chemical reaction between lead and air/water eliminates a class of abnormal events postulated for other concepts that use more chemically reactive primary coolants. The high boiling point of lead and high density prevent the formation of core voids due to lead boiling and the intrusion of secondary system fluid into the core making for safe, void-free reactor operation. The strong, favorable reactivity feedback guarantees inherent safety protection from a range of postulated accidental conditions such as unprotected events. The high thermal inertia of the primary system results in very slow transients, and less coupling with the balance of plant. The robustness of the safety case simplifies and shortens the licensing process.

Economic competitiveness results from the inherent safety benefits mentioned above, which allow to greatly reduce complexity and number of safety-related systems. In particular, the lack of exothermic chemical reactions of air/water with lead, combined with a small inventory of secondary water, result in a relatively small containment. The resulting compact nuclear island, combined with the high core power density and the high thermodynamic efficiency, are expected to result in construction costs per unit of power generated well below those associated with current LWR designs. Application of modular design features results in a shorter and more efficient construction schedule, with commensurate advantages in terms of construction cost and delivery certainty. Finally, design simplicity, with minimization, and replaceability, of primary system components, enhances reliability and results in cost-effective operation.

Finally, while initially operating on a once-through UO_2 core, the DLFR technology has the typical capability of fast spectrum reactors to support advanced fuel cycles with high uranium utilization and a range of actinide recycle schemes. This is an important strategic consideration for the U.S. to promote long-term fuel supply security and increased public support of nuclear waste policies.

Section 1 : Introduction, objectives and motivations

1.1 Introduction

Westinghouse's goal is the development of an innovative reactor fleet, based on lead fast reactor (LFR) technology, that achieves best-in-class economics, safety and operability and is globally recognized as the preferred option for electricity generation in the U.S. and international energy markets. Westinghouse's strategy is to first demonstrate – and then commercialize − this LFR technology. The demonstration is accomplished with the construction and operation of a Demonstration Lead Fast Reactor (DLFR). A pre-conceptual DLFR design has been developed by Westinghouse and is described in this report. This design features a compact, pool-type, primary system, with the Main Vessel (MV) containing all primary components immersed in liquid lead. The power rating is 500 MWt (210 MWe), with the capability for power uprates (up to ~700 MWt) once the initial demonstration mission is fulfilled. A detailed plant description is presented in Section 4.

1.2 DLFR objective

The objective of the DLFR is to demonstrate feasibility and basic performance parameters of an advanced lead cooled reactor technology for ultimate *commercial* deployment. The knowledge and experience gained through the DLFR construction and operation will enable the development of follow-on, higher performance, commercial units. The increased performance will be achieved by a higher power output (such as from the uprate mentioned in Section 1.1, resulting in economy of scale benefits), increased plant thermodynamic efficiency (through an increase in reactor operating temperature and adoption of a more efficient energy conversion system) and higher fuel burnup and/or power density (by adopting a higher-performance fuel-cladding combination).

1.3 Motivations for selecting LFR technology

Westinghouse selected LFR as the advanced nuclear technology with the best potential for successful *commercial* deployment. Westinghouse's vision for the proposed reactor technology is to achieve widespread deployment, and to this end economics and marketability, beside safety and environmental impact, are paramount considerations. The DLFR is a stepping stone to achieve this vision.

LFR technology has the best potential to simultaneously achieve superior safety and economics, and Table 1 summarizes key advantages relative to other reactor technologies, in the areas of safety, economics and operations. As will be discussed in Section 5, the excellent safety performance results primarily from the properties of lead, particularly the lack of exothermic chemical reactions with water and air, its high boiling point, the favorable heat transfer and excellent neutronics properties which facilitate the use of an open fuel lattice with low core pressure drop and a high degree of natural circulation while maintaining neutron efficiency.

Economic competitiveness is fostered by a compact nuclear island, deriving from the high power density core, the lack of an intermediate flow circuit, and the small containment vessel (CV) associated with reduced containment pressurization in the event of an accident. High operating temperatures, ranging between 510 and 700°C (depending on progress in material development) and suitable to support effective energy storage technologies, are possible, so that the LFR can best complement electricity generation from non-dispatchable sources, which are anticipated to increase their share of electricity production in future energy markets. The LFR operates on a fast spectrum which is suitable to implement advanced fuel cycle strategies with improved uranium utilization and reduced long-lived actinide burden on the repository, a feature which can be of interest in some markets and of future strategic importance for the U.S.

The LFR technology key challenges, addressed through proper engineering, are discussed in Section 5.3.

Table 1: Key Advantages of proposed LFR technology vs. other Reactor Concepts

	LFR Characteristics	SAF	ECON	OPER	Key advantage over
Mostly safety-related	High boiling point	✓	✓		LWR, SFR
	Low chemical reactivity	✓	✓	✓	SFR
	Atmospheric pres. operation	✓	✓	✓	HTGR, GFR, LWR
	Pool configuration	✓			HTGR, GFR, LWR
	Primary system thermal inertia	✓		✓	GFR, HTGR, MSR
	Passive decay heat removal	✓			GFR
Mostly economics- and operations-related	Energy conversion efficiency		✓		LWR, SFR
	High core power density		✓		HTGR, GFR, FHR, LWR
	No intermediate loops		✓	✓	SFR, MSR, FHR
	Low-pressurization containment		✓		LWR, GFR
	Nuclear island compactness		✓		HTGR, SFR, LWR, FHR
	Low pumping power[1]		✓		HTGR, GFR, SFR
	Long-life core potential		✓	✓	HTGR, FHR, LWR
	Modularity		✓		
	High gamma shielding	✓	✓	✓	All
	Maintainability		✓	✓	GFR, MSR
	No need for tritium capturing	✓	✓	✓	FHR, some MSR
	Energy storage capability		✓		LWR
	Fuel usage potential		✓		HTGR, FHR, LWR
	Technology readiness		✓	✓	MSR, GFR, FHR

The current LFR technology readiness level (TRL) provides adequate confidence that the lead technology will be successfully licensed and satisfy the expected performance – key requirements to attract private funding. This confidence derives from:

- Materials research programs, which have demonstrated that lead corrosion protection can be achieved without resorting to a complicated oxygen control strategy (e.g. [1] through [5]).
- Similarities in design, operation, base materials, and fuel cycle with SFR technology, which allow leveraging SFR experience, while taking advantage of lead favorable characteristics.
- Research programs conducted, at great investment, in Europe, which greatly contributed to advancing LFR technology.

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[1] It is common to find statements, particularly in some older publications, that LFR technology is penalized by a high pumping power. However, in an appropriately designed LFR, the pumping power requirements may be lower than, for example, in SFRs. This is because the superior neutronics properties of Pb vs. Na allow the LFR fuel pins to be spaced more widely apart, reducing the coolant velocity in the core and thus the core pressure drop (which is generally the major contributor to the primary circuit pressure drop). Moreover, the elimination of the intermediate loops in the proposed LFR, and of the associated pumps, further contributes to reducing the overall pumping requirement with respect to reactor concepts requiring an intermediate loop [6].

It should be noted that while SFR and HTGR technologies can claim higher TRL than LFRs, they have not attained commercial success due to the lack of economic competitiveness with LWR technology.

1.4 Motivations for selecting this specific DLFR design

The DLFR satisfies Westinghouse's objective of providing a commercially viable reactor technology by enabling:

1. Design features, such as system compactness, design and operation simplicity, and suitability for modular construction conducive to economic competitiveness. These features will be replicated, or scaled-up, in the follow-on commercial units.
2. Materials and technologies compatible with starting reactor operation by 2030.
3. Design of primary system and components optimized for inspectability, maintainability and replaceability.
4. Capability for a 40% power uprate by increasing core power density and the average core outlet temperature, the latter above the initial envisaged 510°C once suitable lead-corrosion resistant materials are developed and qualified.
5. Rapid response to variable electricity output demands by incorporating an energy storage system.
6. Transfer of knowledge and experience accumulated with the DLFR design, licensing, construction, operation and maintenance to the commercial units.

1.5 DLFR capability to satisfy DOE and commercial objectives

The above motivations led to a design which is effective as Demonstration Reactor (DR), attractive as commercial carbon-free electricity source, and economically competitive with the lowest cost electricity sources.

1.5.1 DLFR attractiveness as Demonstration Reactor

The attractiveness of the DLFR to address DOE's strategic objectives "demonstration", "fuel cycle" and "process heat" is discussed in this section.

The DLFR satisfies DOE's "demonstration" objective by enabling to mature the TRL of the proposed technology. Specifically:

- The relatively high power chosen, i.e. 500 MWt (210 MWe) facilitates prototypicality and design scalability and allows addressing licensing issues that will be common with the commercial units.
- The DLFR is designed not only to provide demonstration of the "basic" LFR technology but also to assess and quantify the potential for performance enhancements through operation at higher coolant temperature (provided acceptable corrosion resistance at increased temperature is demonstrated in out-of-pile experiments) and through use of higher performance fuel (e.g. UN). To this end, the core is designed to accommodate an up to 40% power uprate and the primary components are designed to be easily accessible and replaceable.

The DLFR satisfies the "fuel cycle" objective from the standpoint that, by operating in a fast spectrum, it can support advanced fuel cycles with actinide recycle and high uranium utilization similarly to SFRs.

Relative to the "process heat" strategic objective, the DLFR was not designed to provide process heat *per se*, however it supports a reduction in carbon footprint from the industrial sector, which is stated in the TR/DR evaluation criteria document as the underlying motivation for process heat. By means of its energy storage system, the DLFR is capable of providing variable electricity output, thereby replacing gas-fired turbines that otherwise would be used to complement the variability in electricity generation resulting from an anticipated increase in the use of renewable sources.

1.5.2 DLFR attractiveness as commercial product and as baseline for an economically competitive LFR fleet

Elements motivating the commercial attractiveness of the DLFR are discussed as follows.

- The DLFR with a base power of 500 MWt (210 MWe) (Phase I), and the capability to accommodate up to 40% power uprate (Phase II), is a commercially viable product for Small Modular Reactor (SMR)-like applications.
- The design features selected result in economic performance superior to other technologies. Specifically:
  - a high power density core combined with a compact nuclear island, mainly resulting from a compact primary system operating at atmospheric pressure with no intermediate circuit
  - a high degree of modularity which facilitates shorter construction and reduces costs.
- The DLFR, and follow-on commercial units, are capable of providing a variable electricity output thanks to the adoption of an energy storage system. This enhances marketability by complementing non-dispatchable energy sources, whose level of penetration in the electricity market is expected to increase.

Section 2 : DLFR technology readiness

2.1 Development history

The initial idea of developing fast reactors cooled with a heavy liquid metal coolant, either pure Pb or Pb-Bi, was considered in the 1950s' [7]. Fast reactors with Pb-Bi coolant were deployed in the Soviet Union, until the 80s', for submarine propulsion, and more recently are being pursued for commercial energy production programs (BREST-OD-300, to be commissioned in 2020-2022, [8]) and the SVBR reactors). LFRs is one of the Generation IV reactor technologies [9] and, currently, members of the GIF-LFR provisional System Steering Committee are EURATOM, Russia, South Korea and Japan, with USA and China as observers [8].

In the U.S. lead-based technology was not pursued because of 1) the anticipated challenges resulting from the corrosive nature of lead coolants and 2) the past emphasis for fast reactors on maximizing fissile breeding performance which could be more effectively satisfied by employing sodium-cooled fast reactors due to their higher breeding potential [10]. However, *the rationale for this generally accepted perception is no longer valid*. The need to maximize breeding performance has dissipated in most of the world, and certainly in the U.S., due to the current and projected abundant uranium resources. Most importantly, over the last 10-15 years material development programs, carried out especially in Europe[2], have demonstrated the ability to achieve lead corrosion protection without excessively penalizing oxygen control strategies. This, together with increased safety benefits from the lack of exothermic chemical reactions between lead and air/water [11], have led to reactor design development programs spanning from test, multi-purpose reactors such as MYRRHA in Belgium, to battery-type reactors such as the Small Secure Transportable Autonomous Reactor (SSTAR), to larger, commercially-oriented designs such as the European Lead-cooled System (ELSY) and, more recently, the European Lead Fast Reactor (ELFR). The ELFR is rated at 1500 MWt (630 MWe) and is developed by a team of 17 partners from 11 European countries; it is supported by demonstration of the technology through the 300 MWt (125 MWe) Advanced Lead-cooled Fast Reactor European Demonstrator (ALFRED), for which a suitable site has been identified in Mioveni, near Pitesti in Southern Romania. The FALCON consortium, formed by

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[2] Approximately €90M in funding have been allocated to support LFR-specific R&D in Europe, in the last few years. This includes ~€58M in the last 5-6 years, and approximately €30M prior to that [12].

Ansaldo Nucleare (Italy), ENEA (Italy), the Nuclear Research Institute (“ICN”, Romania) and the Research Center Řež (“CVR”, Czech Republic), is currently collaborating on design development and programmatic plans for construction, which is anticipated to occur in the 2023-2028 timeframe.

2.2 Technical maturity

The technical readiness of lead-based technology provides adequate confidence that the DLFR will start operation by 2030. This confidence derives from 1) the many similarities with SFR technology and 2) comprehensive research programs on lead technology conducted especially in Europe that advanced significantly the TRL of this technology. Figure 1 compares the expected development timelines forecasted for Generation IV reactor concepts, in 2002 and 2013. The LFR is the only technology for which there has been consistency in the forecasted development phases between 2002 and 2013, with viability already confirmed, and demonstration expected in the early 2020. In contrast, readiness of other technologies had been overestimated in 2002, and realization of an actual, lower readiness resulted from the 2013 GIF evaluation.

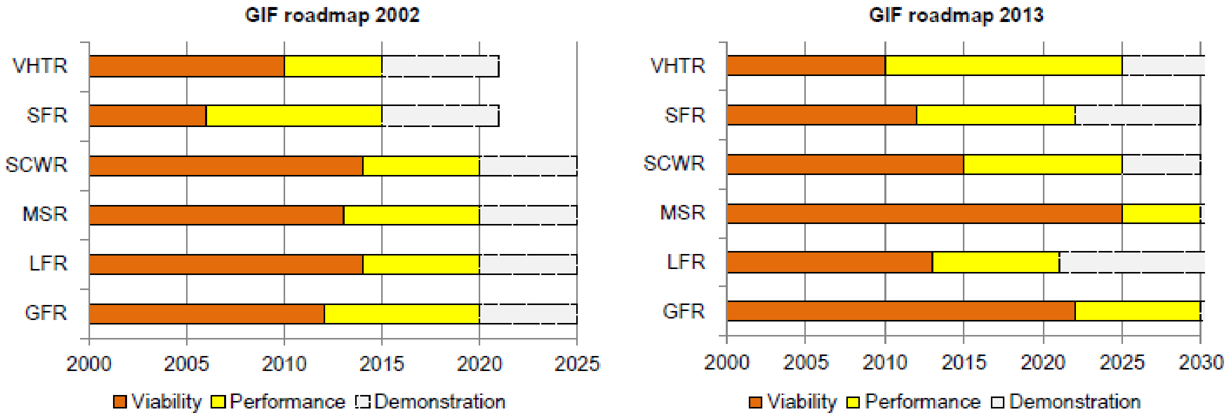

Figure 1: System development timelines as defined in the original GIF 2002 Roadmap (left) and in the 2013 update (right) [13]

2.2.1 Technical readiness of materials and system/components

The DLFR relies on available technology to the maximum extent possible. The DLFR materials and reactor components leverage past in-reactor operating experience, and have been or are currently being tested in lead environments to ensure corrosion resistance. As examples, a bundle of tubes for the ALFRED Steam Generator (SG) [14] is being tested at ENEA’s laboratories in Brasimone, Italy; a prototypical Reactor Coolant Pump (RCP) will also be tested at ENEA’s laboratories in early 2016.

Table 2 shows the material TRL classification for the key reactor components, using the TRL definitions provided by DOE in [15]. The primary system components have a TRL of 5 or higher, with the exception of the pumps, which have presently a TRL equal to 4. Additional details on materials are discussed in Section 4.5.

Table 2: Technology Readiness Level for materials envisaged for key DLFR components

Material	Component	Status	TRL
UO_2	Fuel	Fully tested and qualified for fast reactors	9
D9	Whole assembly structure, including fuel rod cladding	Fully tested and qualified for fast reactors (currently used in the FBTR in India [16])	9
Al_2O_3	Coating[a] (for components exposed to Pb at T>~450°C)	Tested in lead up to 600 °C [1]. Irradiated with heavy ions (up to 150 dpa on D9 [2], up to 450 dpa on 316L [3])	5
AISI 316(L)	Inner Vessel, Lower core plate, Main Vessel, Internals, SG tubes[b]	Tested in lead	8
AISI 400 series	Pump impeller	To be tested – coated – in pool configuration and representative conditions	4

[a] Al_2O_3 is the reference coating material. Other coating options are also being tested (e.g. FeCrAl).

[b] Other material options, such as SS347 or SS304H, are also under consideration for the SG tubes.

2.2.2 Anticipated TRL advancement resulting from DLFR operation

Operation of the DLFR will result in the LFR technology, as a whole, achieving a TRL equal to 7. The components whose TRL will benefit the most from the DLFR operation will be the largest and most complex, such as the integrated SG-RCP unit.

2.2.3 Scalability of technology choices and fabrication options

The DLFR will demonstrate all aspects of the technology: component, system performance, construction and fabrication. The DLFR achieves an effective technology demonstration through the following design principles:

- The choice of a relatively high power output, of about 500 MWt (210 MWe) and justified by the technology readiness associated with DLFR technology, facilitates prototypicality and scalability and addresses licensing issues that will be common with the commercial units.
- DLFR elements are designed to be prototypic of the commercial reactor technology that the DLFR will demonstrate. When not prototypic, the components of the primary systems are designed to be scalable[3].
- The DLFR is designed to be fully modular (mechanical, structural, electrical modules, etc.) and scalable, and its modular construction will be incorporated into the design of the commercial units.

Section 3 : DLFR licensing, development and deployment

3.1 Licensing strategy

Westinghouse envisions a step-by-step licensing path, characterized by progressively increasing the DLFR power levels until the rated power is achieved. Ultimately, the licensing documentation and operating experience for the DLFR will serve as the “benchmark” for the licensing basis for the FOAK/NOAK commercial reactor. With the broad body of knowledge acquired through the operations and licensing activities of the DLFR, essentially a “license-by-test” approach, licensing of the follow-on

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[3] As an example, the design selected for the SGs allows these components to be substantially similar between the DLFR and the commercial units. In the transition from the DLFR to the commercial units, the SGs will only be increased in height (more tubes) and radius (longer tubes) and eventually in number. This will ensure that the benchmarked data and resulting correlations developed through out-of-pile SG testing first, and operation of the DLFR later, are directly applicable to the commercial product.

commercial reactor are more easily achievable. As the regulatory framework evolves, these opportunities will be evaluated and incorporated into the licensing strategy as appropriate.

3.2 Development plan for DLFR and follow-on commercial units

In parallel to the licensing and design process, the development of the DLFR will include extensive testing, some R&D and code qualification, which will be followed by site preparation, construction, plant startup and operation. The next sections briefly describe these activities. Their estimated schedule, including licensing, is shown in Figure 13 in Section 6. The development of the follow-on commercial LFRs will leverage these activities, and will be supported by a business plan aimed at ensuring return on investment and market competitiveness of the commercial fleet.

3.2.1 Testing

Key testing needs for the DLFR development are:

- **Primary components and instrumentation testing** in flowing lead loops and in lead pools. Priority has to be given to the realization of two large-scale facilities, one for full-scale testing of first-of-a-kind components, and one for whole system testing at a properly-reduced scale. Flow loop, pool or mixed configurations will be adopted for these facilities: flow loops will be used to verify thermal performance of the SG, fuel assembly, and dip coolers used in the Decay Heat Removal System (DHRS), as well as to demonstrate the long term performance of the RCPs. A molten lead pool would be used to test refueling equipment, instrumentation, and inspection equipment.
- **Confirmatory testing on lead corrosion resistance of structural materials** at DLFR operating conditions and long exposure times will be required[4].
- **Confirmatory testing of coated cladding corrosion resistance.** UO_2 fuel with D9 steel cladding coated with Al_2O_3 will be adopted for the DLFR first core. The UO_2-D9 combination has been fully qualified in the past for fast reactors and does not require additional qualification for use in the DLFR. Characterization of the cladding-coating combination might require additional testing to confirm the positive behavior observed so far. In particular, coating adherence to the cladding at various stress conditions has been proven, as well as resistance to lead corrosion at the DLFR operational temperature [1] and resistance to radiation damage under ion irradiation (up to 150 dpa on D9 substrate [2], and up to 450 dpa on 316L substrate [3]).
- **Integral and separate effects tests** are included to provide benchmark data required to validate the application of safety analysis codes. An integral effects scale test facility is planned to benchmark safety analysis codes used to predict the plants integral response to thermal transients. This facility, using an electrical heat source to model the reactor core, will predict the combined response of primary and secondary systems to emergency events such as station blackout.
- **High temperature testing**. High temperature test facilities will test components hardened for high temperature service such as instrumentation and inspection equipment.
- **Testing of robotics techniques**. Due to the reliance on automated processes and equipment for inspection and refueling, a robotics lab is required to test remotely controlled inspection and refueling equipment in prototypic conditions.

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[4] This testing will also be extended to the higher temperatures (>510°C) and lead velocities (>2 m/s) envisioned for the commercial units, and combined with R&D on the development of new materials aimed at withstanding these conditions. While existing facilities such as LECOR (LEad CORrosion loop) and HELENA (Heavy Liquid metal Experimental loop for advanced Nuclear Applications) operated by the italian ENEA [17] can be used for the first objective, an uprate of the same facilities or the construction of new ones will be needed for tests at high temperature/velocity.

3.2.2 R&D activities

The key R&D activities for the DLFR are as follows:

- Development/testing of erosion-resistant materials for RCP impellers, at speed of up to ~10 m/s.
- Lead freezing-induced phenomena to: 1) understand the progression of lead freezing in components which could potentially experience rapid cooling, e.g. SGs upon feedwater overcooling, and 2) understand the mechanical stresses on structures generated upon lead freezing/thawing. Insights from these studies will inform component design and safety analysis.
- Lead purification techniques, which will inform the design of the DLFR Chemical Control System. This will include development of coolant chemistry monitoring techniques, for example to assess structure corrosion rates, and confirmatory testing on lead's radioisotope retention capabilities, which will inform safety analyses.
- Technologies for defect detection (including fuel pin leakages), component identification and process monitoring in liquid lead, leveraging technologies already well developed for sodium-cooled reactors such as Under-Sodium Viewing (USV) techniques.

The R&D items specific to the follow-on commercial units (not strictly required but desirable to enhance performance, e.g. by increasing the core operating temperature or the fuel utilization) are:

- Development and qualification of structural materials resistant to corrosion/erosion at lead temperatures higher than those envisioned for the DLFR, i.e. >510°C. Efforts have already been initiated in this direction, e.g. at the Massachusetts Institute of Technology with the development of Functionally Graded Composites [18] and the testing of F91 and Fe-12Cr-2Si alloys which performed well in static lead up to 715°C [19].
- Lead corrosion-resistant fuel cladding materials capable of withstanding high irradiation levels (150-200 dpa) and temperatures (>650°C).

3.2.3 Code qualification

The data collected during the testing campaign discussed in Section 3.2.1 will be used to supplement the code validation database already available from operating existing lead loop/pool facilities. Moreover, by virtue of the similarities between lead and sodium, a significant fraction of the validation efforts already accomplished for SFR modeling codes can be leveraged in LFR development, thereby allowing most of the SFR codes to be applied in LFR development, with minor additions and adjustments.

3.2.4 Site preparation, component fabrication and construction

Site preparation for LFRs should not be significantly different from preparations made for the deployment of today's large LWRs. Westinghouse has significant, relevant and recent experience in the preparation of nuclear reactor sites in the U.S. with the ongoing construction of four PWR units at V.C. Summer and A.W. Vogtle. The only noted exception being the deep excavation required to locate the reactor and its safety systems below grade for protection from postulated external threats. Westinghouse recently performed a detailed investigation concerning deep excavation during the development of its SMR, concluding that deep excavation and dewatering of the site could be performed using modern vertical excavation techniques at reasonable cost and without disruption to the operation of adjacent units.

Construction of the DLFR will be performed in the same manner as the commercial product it is intending to demonstrate. Since reactor economics are dominated by overnight costs and the associated interest, economic competiveness cannot be achieved without significantly shortened construction schedules. It is for these reasons that extensive modularization of the plant's structures, components and systems is a basic requirement for the design. Complete modularization of the plant will facilitate a factory-built and field-assembled delivery model increasing quality while significantly reducing the cost of deployment. Lessons accumulated during the construction of the DLFR will not only help in determining accurate Nth-of-a-kind (NOAK) plants costs but contribute to attaining NOAK delivery performance. WECTEC, the Westinghouse subsidiary formed following the recent acquisition of CB&I Stone & Webster Inc., is capable of constructing the DLFR and is positioned to provide real time feedback to the engineering design organization.

Fabrication of first core, including structural and control elements, will take place in one of the Westinghouse's fuel fabrication facilities[5].

Reactor Vessel Fabrication and the fabrication of other primary components is greatly simplified with lower pressure requirements of the pool type reactor used in the DLFR design and the associated lack of heavy forgings. As a result, sourcing will not require special consideration and extended lead time typically associated with the supply of heavy forgings. Westinghouse's Mangiarotti facility in Italy is capable of providing the majority of the ASME pressure components.

Reactor Vessel Internals Fabrication will be performed by Westinghouse's Newington facility in New Hampshire. This facility is currently supplying reactor internals for the AP1000® construction projects[6]. Westinghouse's parent company, Toshiba, also supplying reactor internals for the AP1000 projects provides an alternate option for supply.

Control Rod and Rod Drive will also be fabricated by Westinghouse's Newington facility, where the control rod drive systems for the AP1000 and for the Korean UAE reactor builds are being manufactured.

Fuel Handling Equipment will be designed, manufactured and tested in Westinghouse's crane manufacturing facility located in Shoreview, MN.

3.2.5 DLFR startup, operation and testing

The DLFR startup and commissioning testing will be achieved in stages, with successful completion of each stage being a requirement to proceed to the next level. Failure of any test that results in a design modification will require a restart of various tests at the first phase as determined by the testing review board. The test phases will include startup (functional and performance testing of systems, components and protection logic both before and after fuel loading) and commissioning (low power, power ascension[7] and full power). Feedback from the DLFR operation will be used to inform the design process of the commercial units in order to converge on the best technology before commercialization. The DLFR will be designed with this requirement in mind and include flexibility in areas of the plant that have been identified as first-of-a-kind applications and as such carry more design risk.

Section 4 : DLFR Point Design description

4.1 DLFR general description

The DLFR is a lead-cooled, pool-type fast reactor targeting operation by 2030 to demonstrate feasibility and basic performance of DLFR-based technology for subsequent *commercial* deployment. Economics and safety are the key elements driving its design.

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[5] Although ^{235}U enrichment in these facilities is currently limited to a maximum of 5%, for at least the first core it is anticipated that fuel enriched beyond 5% would be supplied and controlled by the U.S. DOE.

[6] AP1000 is a trademark or registered trademark of Westinghouse Electric Company LLC, its affiliates and/or its subsidiaries in the United States of America and may be registered in other countries throughout the world. All rights reserved. Unauthorized use is strictly prohibited. Other names may be trademarks of their respective owners.

[7] Step-by-step increases in power will also be prescribed by the licensing scheme adopted, as discussed in Section 3.1.

Well-proven UO_2 fuel is selected for the DLFR first cores, while subsequent reloads can incorporate higher-performance uranium mononitride (UN) fuel, whose qualification (in part done through the DLFR) and licensing are required for application in the follow-on commercial LFRs. Similarly, the DLFR will take advantage, to the maximum extent possible, of proven and qualified fuel and structural materials while higher performance, but less developed, materials are envisioned for the commercial units. Table 5 at the end of this chapter summarizes the key features of the DLFR plant.

4.2 Primary system

Figure 2 shows the DLFR pre-conceptual primary system layout. It is a pool-type concept with RCPs integrated into the SGs. The Main Vessel (MV) contains all primary components, fostering the safety benefits of an integral configuration, and emphasizing compactness, thereby enhancing economics. The reactor internals are designed to be extractable from the system to ease maintenance and replacement, which benefits system reliability. The lead coolant, after being heated in the core, is drawn by the RCPs and sent to the SGs, surrounding the core at a higher axial elevation, where it is cooled. The lead then flows down through the downcomer and enters back into the core, from the bottom.

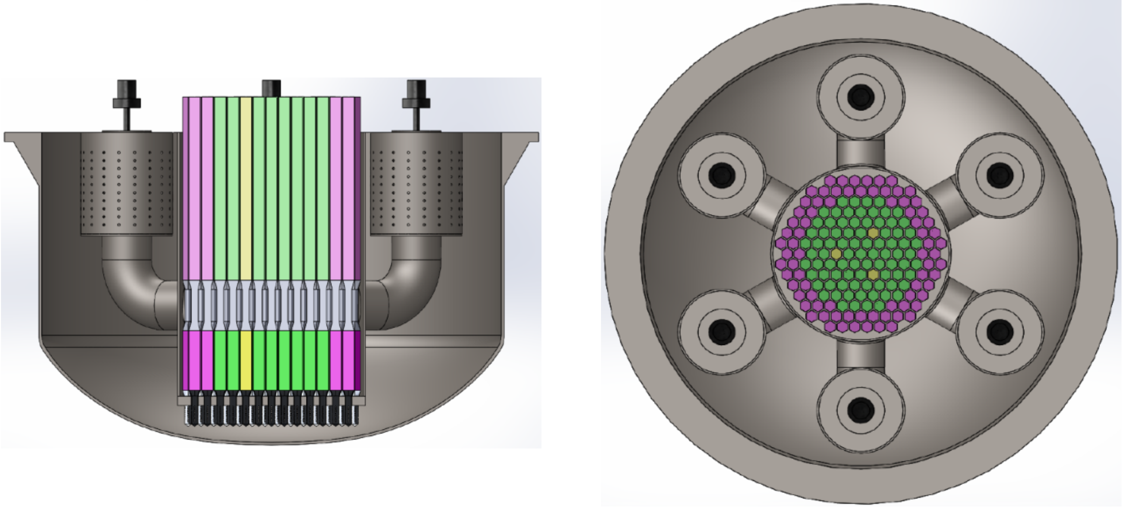

Figure 2: DLFR primary system layout, vertical and horizontal cross sections (pre-conceptual, not in scale, DHRS not shown)

4.2.1 Main Vessel and Safety Vessel

The MV operates at essentially atmospheric pressure and encloses all primary components, thereby representing the second engineering barrier, after the fuel rod cladding, against the potential release of radioactivity. This vessel consists of a cylindrical body welded to a lower toro-spherical head. On the upper part, a flat roof seals the MV through a series of bolts. At the upper end of the cylindrical body, a "Y" junction decouples the stresses due to the differential expansions of the MV and the roof, from the mechanical stresses resulting from hanging the whole system to a concrete support. The entire MV is made of stainless steel class AISI 316L.

The MV is placed into a pit. A second steel vessel (Safety Vessel, SV), made of carbon steel but with a SS316L liner, is foreseen to prevent lead dispersion in the unlikely event of MV failure. The distance between the MV and the SV is dimensioned to facilitate inspection while also ensuring that the drop in coolant level in the primary system, upon MV failure, does not result in insufficient coolant circulation through the SGs and therefore insufficient core cooling. The SV, as well as the concrete reactor pit, are continuously cooled through dedicated systems.

4.2.2 Inner Vessel

The hot and cold legs of the primary circuit are separated by the AISI 316L Inner Vessel (IV). To accomplish its main function, the IV is provided with two ports: i) in the lower part, the IV is connected to the lower core plate (“diagrid”), which supports the fuel and shield assemblies and allows the coolant to enter in the core; ii) a series of openings above the core level to allow lead to flow from the core to the SG-RCP units, with one opening for each unit. At the top of the IV, a second plate ensures proper alignment and positioning of the assemblies.

4.2.3 Steam Generators

Six Steam Generators (SGs), similar to those adopted in the ELSY design [21], are positioned between the IV and the MV, at a higher elevation relative to the core. In this configuration the entire MV is in contact with coolant at the cold leg temperature, which simplifies material requirements and enables the use of the well-known and qualified 316L for this (non-replaceable) component. As shown in Figure 3, each SG consists of a bundle of planar spiral tubes, each representing a layer of the bundle. The inlet and the outlet of each tube are bent to enter/exit vertically in/from the SG and connect with the inlet and outlet collectors, located outside of the primary system, above the MV roof.

The tube bundle is enclosed in an annular space between an inner and an outer perforated cylindrical shell, and bottom and top lids (both solid). The hot lead exiting the core is drawn by the RCP, located inside the inner shell, and sent through the shell to the bundle region where it crosses the bundle, radially, it passes to the outer shell and finally exits the SG through the outer shell orifices. The two lids prevent steam from exiting the bundle region axially during an accidental release due to a SG Tube Rupture (SGTR). In particular, the bottom lid prevents steam from accidentally leaking from a tube to form a downward jet capable of exiting the SG and potentially reaching the core, where it might lead to a reactivity insertion. The bottom-fed DLFR SGs combined with lead cooling occurring as lead moves radially, allows the SGs to perform their function, although progressively less effectively, even in case of reduction of the coolant level in the primary system upon leakage from the MV. This is unlike conventional SGs, especially those fed from the top, in which lead is cooled while moving axially.

The SG-RCP assemblies are designed for inspection and maintenance and to be removable and replaceable. A reduced-scale prototype of planar spiral SG was successfully manufactured and tested in 2013, within the ELSY program, using water/steam on the tube side, hot air on the shell-side [22].

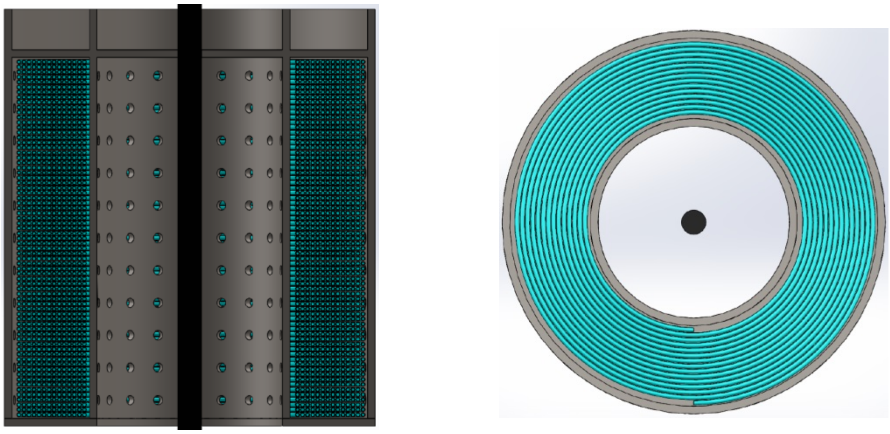

Figure 3: SG vertical (left) and horizontal (right) cross section (pre-conceptual, not in scale, tube connections to secondary inlet and outlet collectors not shown)

4.2.4 Reactor coolant pumps

The DLFR features Reactor Coolant Pumps (RCPs) embedded in the SG structure. Specifically, shaft and impeller of each RCP are immersed in the cylindrical channel at the center of the SG, where the impeller receives hot lead from the mixing plenum above the core and drives it towards the SG inner cylindrical shell. The high density of lead results in adequate suction head with relatively shallow immersion of the RCP impeller, so that the pump shaft connecting the impeller to the motor, located on the reactor roof, can be kept short, and without supporting bearing in lead. The pump impeller, which rotates at high speed (~10 m/s) to generate sufficient pressure head, is made of 400 Series Steel. Ti_3SiC_2 has been identified as one of the most promising coating materials for impellers to withstand lead-induced corrosion/erosion, as it combines the most attractive proprieties of ceramics (refractory, oxidation resistant) with those of metals (thermally and electrically conductive, machinable, resistant to thermal shock, plastic deformations at elevated temperature) [23].

4.2.5 Normal Decay Heat Removal System

The SGs, with steam bypassing the turbine and going directly to the Main Condenser (MC), are used for normal decay heat removal (DHR) and, if they are available, for DHR during off-normal conditions. If the SGs are not available, then two emergency decay heat removal systems, DHRS-1 and DHRS-2, discussed in Section 4.4, will remove decay heat.

4.2.6 Lead Chemical Control System and Cover Gas Auxiliary System

Due to the corrosive nature of the coolant, a dedicated coolant chemistry control system, particularly for oxygen content control, is required. However, to control corrosion of the hottest structures, such as the fuel rod cladding, the DLFR adopts materials/coatings that do not require strict control of oxygen, which is kept at low values ($\sim 10^{-7}$ wt%) to ensure self-protection of the structures exposed to the lowest temperatures, e.g. the MV. This is more practical and safer from the standpoint of minimizing the risks from oxide relocation and accumulation. The Lead Chemical Control System (LCCS) is devoted to the continuous monitoring and control of lead purity and oxygen content. The LCCS is made of sensors and probes immersed in the molten for on-line measurement, and of traps and filters, operating continuously to remove the excess of oxygen and impurities, which might result corrosive or deposit and lead to occlusions.

The Cover Gas Auxiliary System (CGAS) continuously monitors and purifies the argon used as cover gas in the primary system, through a bleed-and-breed gas line. The monitoring function, in particular, provides an indirect indication of the presence of any fuel cladding failure.

4.3 Reactor core

4.3.1 Core description

The DLFR core consists of hexagonal assemblies, with 82 fuel assemblies and 3 safety assemblies arranged in an active core, surrounded by 78 reflector/shield assemblies, for a total of 163 assembly positions, as shown on the left in Figure 4. Assembly dimensions are summarized in Table 5.

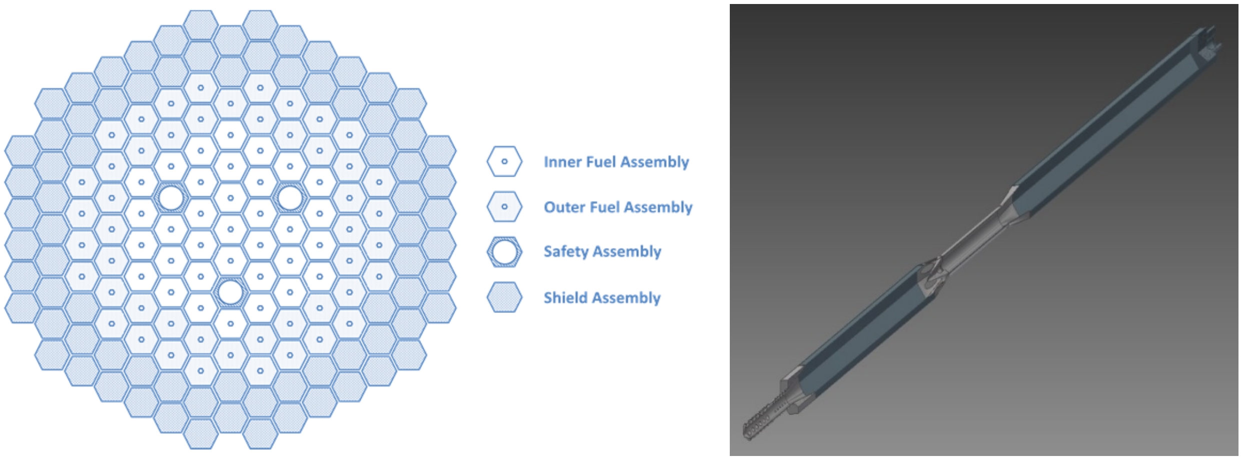

Figure 4. DLFR core layout (left) and assembly (right) (pre-conceptual)

4.3.1.1 Assemblies (fuel, shield, safety)

All assemblies (fuel, shield/reflector, safety) have four main axial sections, described below with reference to to the right picture in Figure 4.

The lower part of the assemblies (leftmost light-gray part in Figure 4) is a cylindrical perforated spike to allow the coolant to enter the assembly. A number of small orifices, as opposed to a single large opening, perforate the spike to allow coolant flow while reducing the likelihood of flow blockage. The spike engages the diagrid thereby defining the positions of the assemblies in the core map. A second set of (smaller) orifices, located on the upper part of the spike, ensures that some flow exits the assembly and feeds the bypass region in between adjacent assemblies, thus contributing to cooling these components from the outside.

The spike is connected to the second section of the assembly, a hexagonal can (“wrapper”) enclosing the pin bundle (gray-blue section on the left in Figure 4). Along its length, the can is provided with pads to ensure that the assemblies remain in contact at different axial locations, to stiffen the core.

At the top of the hexagonal can containing the bundle, a section is foreseen to allow the coolant to exit the assembly and to flow towards the suction port of the RCPs. This section contains thermocouples which provide early detection of any flow reduction potentially impairing the cooling of the fuel elements.

The last section is a stem, dimensioned to allow the assemblies to emerge from the molten lead, above the free surface. This extension provides for simplified fuel handling in the cover gas, in full visibility, thus avoiding the need for a refueling machine operating in lead. In the emerged part of the stem, a ballast can be positioned to address buoyancy and maintain the assemblies weighed down on the lower core plate. The stem extension of the fuel assemblies also permits a continuous, on-line tracking of the core inventory, increasing the safeguardability of the system.

The three types of assemblies, i.e. fuel, shield and safety assemblies, are described next.

<u>Fuel Assemblies</u>

The DLFR is fueled with low-enriched uranium in the form of sintered cylindrical pellets. A stack of fuel pellets, along with two insulating pellets at the ends of the rod, a plenum volume for fission gases located below the fuel and a spring for accommodating any differential expansion (thermal, swelling) are enclosed in a cladding tube sealed with plugs at both ends to form the fuel pin. All steel elements of the fuel pin are made of a low-swelling austenitic stainless steel of class “15-15 Ti”, for which (including similar materials) extensive irradiation results are available in Europe, US, Russia and Japan [20]. The preferred candidate is D9 steel, currently used in the Fast Breeder Test Reactor in India [16], to leverage its extensive qualification experience.

The fuel pins are arranged in a triangular lattice and kept in place using grid spacers. The size of the hexagonal can enclosing the fuel bundle is chosen to accommodate a large number of pins which, in addition to reducing the number of assemblies, thereby accelerating refueling, allows replacement of the central lattice positions with a beam tube. This tube can be used as guide tube for a Finger Absorbing Rod (FAR, see Section 4.3.1.2) made of neutron-absorbing material, to accommodate instrumentation or testing capsules.

Shield Assemblies

The shield assemblies protect the IV from neutron damage from the active core neutron flux. These assemblies are of two types. Reflector assemblies are positioned in the first ring around the core to enhance neutron economy. These assemblies are geometrically identical to the fuel assemblies except that the pins contain reflector material solid pellets (yttria-stabilized zirconia). The second type of shield assemblies, positioned on the outermost ring and containing borated steel pins, has neutron absorbing functionality to maximize the protection of the IV.

Safety Assemblies

The safety assemblies are used to shut down the reactor. Each consists of a bundle of absorber pins filled with up to 90% ^{10}B-enriched boron carbide, which can be inserted and withdrawn from the core through the channel located inside of a stiffer “wrapper” serving as a guide “tube”, which has the standard hexagonal shape on the outside, and a cylindrical shape on the inside (see left picture in Figure 4). The bundle of absorber pins is dimensioned and engineered to accommodate moderate deformations of the guide tube to increase the reliability of the insertion mechanism in case of core damage.

4.3.1.2 Finger Absorber Rods

The Finger Absorber Rods (FARs) are relatively large pins containing a stack of boron carbide pellets, which can be inserted in the beam tube at the center of the fuel assemblies, one FAR per assembly. Various ^{10}B enrichments are envisioned to adjust its worth, depending on whether the FAR is for shutdown or for compensating the reactivity swing during the irradiation cycle, as described in Section 4.4.1. The FARs can be designed to enter the core from the bottom or from the top. In the first case, buoyancy ensures passive insertion through the release of an electromagnet that maintains the FARs latched to the respective drive mechanisms. It is worth mentioning that:

- buoyancy-driven acceleration can be higher than gravity[8];
- in order to maintain MV compactness with bottom-inserted FARs, the fuel fission gas plenum is located below the active fuel. This allows the FAR absorber section, of comparable length to the active fuel,, to be aligned with the gas plenum when fully withdrawn.

For FARs entering the core from the top, a ballast to overcome buoyancy as well as to guarantee that the FAR remains in the core after insertion is foreseen.

4.3.1.3 Reactivity control (including shutdown)

Reactivity control is ensured by four banks of neutron absorbing rods, independent from each other and with different functions. These banks, shown in Figure 5, are:

- Regulation System (RS) bank, motor-actuated, top entry (fine reactivity tuning)
- Control System (CS) bank, motor-actuated, bottom entry (broad reactivity tuning and scram)
- Safety System bank 1 (SS-1), ballast-assisted system, top entry (scram)
- Safety System bank 2 (SS-2), buoyancy-assisted, electromagnetic system actuated, bottom entry (scram)

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[8] This requires that the equivalent density of the rod is lower than half the lead density.

RS, CS and SS-1 are composed of FARs, whereas SS-2 is composed of the safety assemblies previously discussed in Section 4.3.1.1.

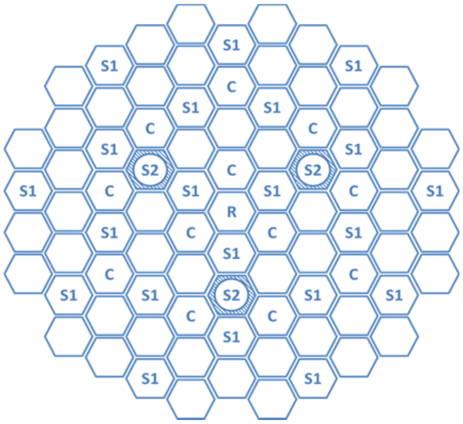

Figure 5. DLFR core layout showing the four absorber rods banks (pre-conceptual design)

The RS bank is a single FAR that can be inserted in the fuel assembly at the center of the core. This FAR contains boron carbide as neutron absorber material, and it is designed to be worth less than 1 $. In this way, it can be used, during operation, to provide fine reactivity tuning to maintain the reactor critical. The FAR of the RS is motor-actuated, entering the core from the top to lower the flux, hence the power, in the hottest part of the core; to ensure that the maximum cladding temperature is maintained within the design limit. The CS bank is applied for broader control of reactivity – e.g. cold-to-hot reactivity compensation during startup, reactivity swing during an irradiation cycle, and power excursions. All FARs of the CS are motor-actuated, entering the core from the bottom. Due to the higher worth required to accomplish its role, this system is composed of a larger number of FARs with boron carbide enriched in ^{10}B up to about 40%.

At startup, the FARs of the CS bank are progressively extracted from the core to approach criticality. Then, their extraction is alternated to that of the RS, both for the ramp-up to full power and for the compensation of the reactivity swing during irradiation. The general strategy is that the RS bank is continuously and slowly extracted from the core; when completely extracted, the CS bank is stepped out to allow the RS bank to enter back into the core. At the end of an irradiation cycle, when the core reactivity reserve is zero, both the CS and the RS banks are in fully extracted position. At the beginning of an irradiation cycle, the CS bank is only partially inserted in the core so that the residual negative reactivity of the bank can be used, if needed, for reactor shut down. This allows the CS bank to be the first system invoked by the reactor protection system for actuating the scram. While the RS and CS banks are intended to be actuated normally during reactor operation, SS-1 and SS-2 are devoted to safety functions, i.e. scram, only. The SS-1 bank is composed of FARs with 90% enriched boron carbide. During operation, these FARs are positioned still atop the core, waiting to be called in by the reactor protection system in case of failure of the CS. To ensure their fast insertion, each SS-1 FAR is equipped with a ballast. The last bank, SS-2, is composed of three safety assemblies occupying three symmetrical positions on the core map. They enter the core by buoyancy, with the absorbing section in a rest position located below the active region but above the lower core plate, taking advantage of the fact that, in the fuel rods, the active region is above the fission gas plenum.

4.3.2 Base-case core configuration

The DLFR reference core configuration has 82 fuel assemblies using UO_2 fuel, for a total thermal power of 500 MWt. Other core configurations (see Section 4.3.3) are envisaged for power up-ratings subsequently to a first period of reactor demonstration.

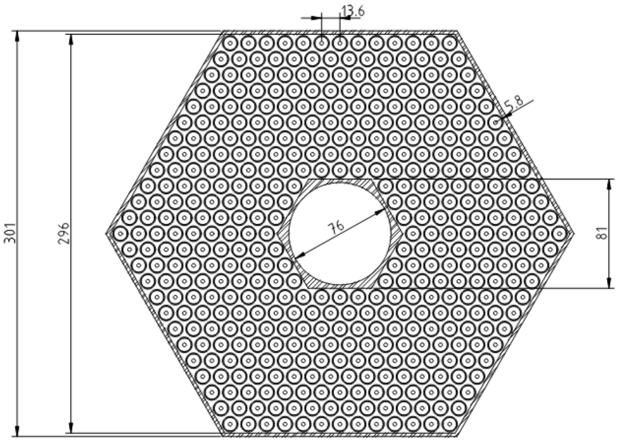

Figure 6. DLFR fuel assembly cross-section

The DLFR achieves a 100 GWd/tU fuel average discharge burn-up (BU). To this end, fuel pellet and fuel pin have been designed to ensure protection of the cladding against internal pressurization, due to gaseous fission products, and pellet-cladding mechanical interaction assuming 125 and 146 GWd/tU peak pin and peak pellet BU values, respectively. The fuel rod bears annular fuel pellets, with the twofold benefit of fuel temperature and gas pressure reductions. A reduced linear power rating (20 kW/m on average, peak of about 30 kW/m) was selected to guarantee a rather large margin from fuel melting. The lattice has ~34% coolant volume fraction, with a fuel active height of 70 cm and a coolant flow velocity of about 1.4 m/s. The fuel assembly, shown in Figure 6, accommodates 469 positions in a triangular lattice, with a pitch of 13.6 mm. The central position of the lattice, along with the three innermost rings, is not occupied by fuel pins, resulting in 432 pins per assembly. Note that the 37 central positions are instead occupied by the beam tube potentially hosting instrumentation, a FAR or a testing capsule.

The fuel bundle is enclosed in a 2.5 mm thick hexagonal can and is supported by several grids distributed along its length to preserve the geometry and prevent or dump vibrations. The first spacer grid is placed upstream the heated region to protect the active part of the bundle from potential flow blockages.

A 9-year in-pile fuel assembly residence time is envisaged for 100 GWd/tU fuel average discharge burnup. A 6-batch refueling strategy was chosen to limit the reactivity swing while maximizing fuel utilization: one sixth (13 or 14) of the fuel elements undergo refueling and are replaced by fresh elements every 18 months.

To ensure criticality throughout the irradiation cycle and flatten the power distribution, the core is divided in two enrichment zones: an inner region composed of 34 fuel assemblies with approximately 17.5% ^{235}U enrichment, and an outer region composed by 48 assemblies with 19.9% ^{235}U enrichment. The reactivity swing along an 18-month cycle is about 2300 pcm, which can be controlled with the CS bank as confirmed in the neutronic analyses performed. These also confirmed the adequate negative reactivity of the remaining banks, as shown in Table 3, leaving room for further optimization to be performed in the future.

Table 3. Required and actual worth of absorber system banks

System	Required worth (pcm)	Actual worth (pcm)
RS	≈300	300
CS	2700	3700
SS-1	1700	4500
SS-2	1700	3000

The peak flux values are achieved in the central fuel element, few centimeters above the core mid-plane, and slightly increase – from Beginning of Cycle (BOC) to End of Cycle (EOC) – from 1.75×10^{15} to 1.81×10^{15} n/cm^2 s. Figure 7 shows the BOC neutron flux radial distribution in the mid-plane of the fueled region of the core (no shield assemblies). The effect on the flux of the three, 2π/3 poloidal symmetric, SS-2 rods can be seen. The right plot in Figure 7 confirms the well behaved, flat, flux (hence power) distribution in the active core with a steep flux decrease only in the reflector and shield assemblies.

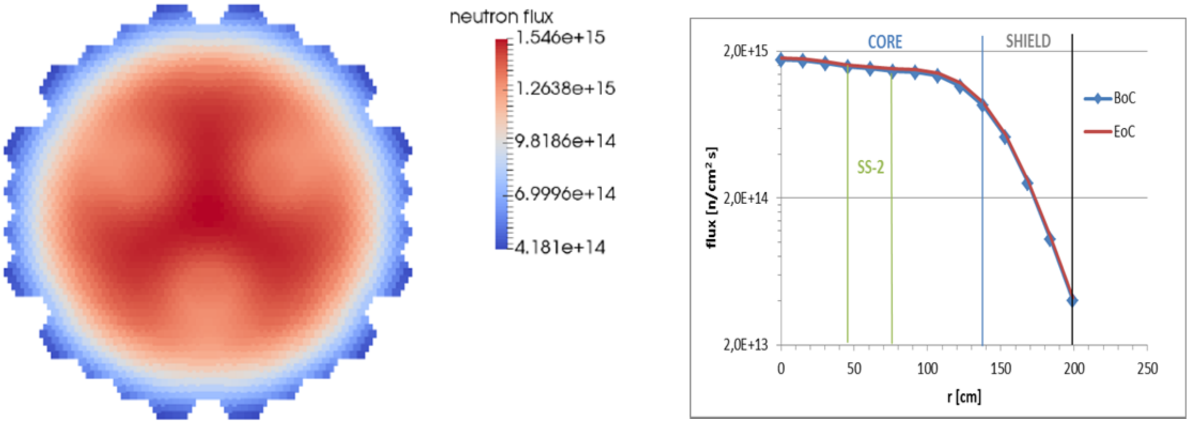

Figure 7. Neutron flux radial distribution (at core mid-plane) at BOC (left, shield assemblies not shown) and comparison between BOC and EOC (right)

4.3.3 Alternative core configurations

The DLFR core has been designed to support a number of alternative core configurations. This flexibility is a key attribute of the DLFR demonstration mission. To this end, the core support plate was sized and positioned (with respect to the SGs) for hosting a variable number of fuel assemblies and the overall design of the assembly was conceived to host different lattices of fuel pins.
The main alternative core configurations considered in the design of the DLFR are:

- a 500 MW(th) core, with low-enriched UO_2 fuel, envisioned as startup configuration (Phase I);
- a 500 MW(th) core, with mixed UO_2-PuO_2 fuel, as an alternative configuration for Pu recycle, e.g. from weapons disposal program (Phase I-A);
- a 700 MW(th) core, with UN fuel, as higher performance and fuel efficient configuration for the follow-on commercial units (Phase II).

4.4 Safety Systems

4.4.1 Shutdown system

The shutdown system was discussed in Section 4.3.1.3 together with the reactivity control system.

4.4.2 Emergency Decay Heat Removal

The first line of defense for DHR is represented by the secondary cooling circuit. During shutdown and off-nominal conditions with scram correctly executed, this heat is removed through the SGs, with steam bypassing the turbine, condensed in the Main Condenser (MC) and sent back to the SGs. However, when the main steam and feedwater lines are isolated, two diversified emergency DHRS are available: DHRS-1 and DHRS-2. DHRS-1 uses the SGs, but is provided with independent loops which connect the cold with the hot collector of each SG tube bundle, and include an Isolation Condenser (IC) immersed in a dedicated pool. The capacity of the pool is designed to ensure several days of grace time in decay heat removal mode. Moreover, the IC can be finned to prolong indefinitely the capacity of DHRS-1 by exchanging heat with air. The operation of each loop is through the opening of a dedicated valve, provided with redundant in-situ energy storage for its actuation. After the valve opens, natural circulation of water kicks-in thereby removing heat from the primary lead circulating across the SG tube bundles. The six loops of DHRS-1 are activated simultaneously during accident management.

DHRS-1 is also used for decay heat removal in case of failure of the reactor protection system: in such case the secondary system only has enough capacity to remove the heat associated with the ensuing, high, power level.

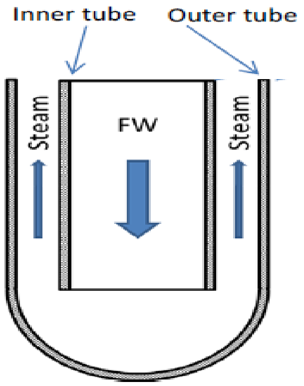

Figure 8. Functional scheme of a bayonet-type tube

Should DHRS-1 fail to actuate, DHRS-2 promptly begins to remove heat from the primary system. For this system a possible design consists of four independent loops operating with pressurized water as cooling fluid, with three out of four loops sufficient to remove decay heat. Each loop comprises a dip cooler immersed in the annulus between the IV and the MV, at an higher elevation with respect to the core, made of a bundle of bayonet-type straight tubes with lead inlet in the upper part of the pool and outlet in the lower part. Figure 8 is a schematic representation of one of such tubes. The tube is immersed in the lead coolant located in the downcomer. Feedwater flows downward inside the inner tube and steam raises in the annulus between the two tubes. The steam is then piped outside the primary system to a heat exchanger, where it is condensed and returned to the dip cooler, closing the loop. The heat exchanger is finned to ensure proper heat transfer with air, thereby providing adequate cooling for an infinite time period. No pumps are required in the loops, as DHRS-2 operates via natural circulation.

In the remote event that lead freezing occurred in all SGs, blocking the flow path toward the DHRS-2 dip coolers, the AHRS (Section 4.4.3) is actuated, removing decay heat directly within the IV.

In spite of all proactive safety measures, unpredicted accidents could occur. It is therefore necessary to maintain an ultimate intervention strategy to ensure core cooling, as was done at Fukushima using sea water to cool damaged fuel. Lead is compatible with both air and water and, in extreme conditions, even assuming that all DHR systems have been lost, the use of locally available water applied in the space between the MV and the SV, or even directly on the lead free level[9], is a plausible cooling option to remove decay heat and limit the severity of the event. This is discussed more in detail in Section 5.6.

4.4.3 Auxiliary Heating System and Auxiliary Heat Removal System

The Auxiliary Heating System (AHS) and the Auxiliary Heat Removal System (AHRS) prevent or manage the onset of lead freezing in the primary system which, depending on where the freezing starts, might impair the circulation of the coolant.

The AHS operates during the first fuel loading, when no fission products are present in the fresh fuel core and nuclear heat cannot be credited to maintain the lead molten. A possible design for this system consists of special shield assemblies provided with electric heaters that add to the heating from the RCPs operation to compensate the thermal losses from the primary circuit.

The AHRS function is to remove heat in the eventuality that lead in the SGs becomes frozen, thus blocking the circulation through the normal path[10]. In such a case, even though some cooling may occur through the part of the SGs that is not blocked by freezing, a dedicated auxiliary system is envisioned to ensure that heat is removed from the core. Multiple design options for this system are under consideration.

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[9] Steam explosions are likely in this scenario [11]. However, the severity of the event that would result from a lack of primary pool cooling together with the extremely low likelihood of the simultaneous unavailability of DHRS-1, DHRS-2 and AHRS, justifies including this type of intervention in accident management.

[10] Lead freezing in the SGs might occur in case of feedwater entering the SGs significantly below the melting temperature of the primary coolant – due to a malfunction of the last feedwater pre-heater in the Balance of Plant.

4.5 Structural materials

Table 4 summarizes the structural materials for the DLFR key components. It should be noted that:

- In lead systems, austenitic steels have shown to be preferable to ferritic/martensitic steels to avoid liquid metal-induced embrittlement (LME) ([24], [25]).
- The alumina-forming coating, in addition to providing protection from corrosion and LME, removes the need for impractical coolant oxygen control techniques, e.g. careful management of oxygen concentration which would otherwise be needed to ensure self-passivation of these structures. Pulsed Laser Deposition has been demonstrated to be a promising technique for applying adherent, lead-corrosion protective, Al_2O_3 coating on steels (e.g. D9 and 316L), with encouraging testing results up to 600°C ([1], [26]).
- To the extent possible, the commercial units will use the same classes of materials for the same components of the DLFR. This approach will facilitate downstream qualification of higher temperature materials.

Table 4: Structural materials for the DLFR

	Cladding		Core non-cladding component	Other Internals	SG tubes	Pump impeller	Main Vessel
	Base	Coating					
Max operating temp, °C	600		510	510	510	510	390
Fluence	100-150 dpa			5 dpa	N/A	N/A	0.1dpa
Possible material	D9	Al_2O_3	Same as cladding	SS316	SS316 or SS347, possibly coated	400 Series SS + Ti_3SiC_2	SS316

4.6 Balance of plant

The DLFR utilizes a traditional power conversion system with superheated steam with reheating. A supercritical power conversion cycle is envisaged for the follow-on commercial units to achieve higher thermodynamic efficiency at the higher operating temperature expected, which implies some primary system design modifications, but not to the degree that would require a new demonstration.

Depending on the turbine vendor, this turbine will have either two or three pressure stages. From each of these stages, extractions will be taken to heat feedwater before it re-enters the SGs. One or two stages of reheat will also be used prior to entry into the low pressure stage turbines in order to increase efficiency and preclude turbine blade erosion. A low-pressure stage condenser will remove non-extractable energy from the steam and return it to the condensate. This condenser will be either air or water-cooled depending on the siting requirements of the reactor. A steam turbine bypass system to the condenser will accommodate load rejections and assist with startup and refueling.

Given the small size of the DLFR, electrically-driven feedwater pumps will be used to increase the head of the condensate to the required SG pressures. This reduces complexity compared to the turbine-driven feedwater pumps likely to be used on larger plants. The chemistry of the condensate water is continuously controlled, both to ensure system reliability and validate that no radiologic hazards are present. Considering the operational risk that freezing lead in the SGs poses, the last stage feedwater heater temperature is monitored to ensure feedwater temperature exceeds the lead freezing point. The steam generation system also features a fast depressurization system to empty the SGs and terminate any possible transients following a postulated SG tube rupture event.

The turbine/generator gross efficiency is approximately 44%, with a net efficiency[11] of ~42%.

4.7 Containment

The DLFR Containment Vessel (CV) encloses the reactor system and is the ultimate barrier preventing the release of radioactive products to the environment. Since the DLFR operates with a primary system at nearly atmospheric pressure, the CV is designed for the postulated highest mass and energy release associated with a main feed water or main steam line break. By design, the secondary side water and steam inventory inside the DLFR CV are significantly less, for the same thermal power output, than that of contemporary LWRs. As a result, the CV size addressing the aforementioned functional design requirement is significantly smaller.

Due to the limited amount of stored energy in the secondary side system, the CV physical size is anticipated to be controlled by physical size of the primary system components, equipment associated with its supporting safety systems, and fuel handling systems. Given the compact size of primary system in the DLFR compared to traditional PWRs, the size of the CV is also expected to be considerably smaller than traditional containment vessels.

Limiting the secondary side inventory within the CV also limits the maximum design pressure for the structure. It is for this reason, that the capacity of the structure will likely be dictated by other design or service conditions, such as protection from external events and seismic conditions.

The CV is a modular structural steel concrete composite shell, capable of protecting the reactor from external threats, withstanding the pressurization events and seismic events. Additional security and protection from external events is achieved by locating the CV below grade. The relatively small CV limits the excavation required, while the resulting increase in elevation difference between the reactor core and cooling water sources promotes natural circulation in the passive safety systems designed to remove decay heat during postulated accidents. A redundant means of containment isolation prevents the introduction of additional feed water into the containment following a line break and seal all penetrations, providing the required low-leakage barrier.

In the event of SG tube rupture, MV over-pressurization protection is provided by venting the steam (contaminated due to the contact with the primary coolant) into a collector isolated from the containment atmosphere. Because of this, and since secondary circuit leaks are free from radioactivity, it is anticipated that the level of radioisotopes in the CV during postulated accidents will be minimal. This allows CV venting if required, eventually combined with a containment overpressure protection in the form of a filtered vent system. The lead coolant provides an efficient means of shielding gamma radiation, and structural composite concrete structures will provide the necessary neutron shielding, resulting in reduced radiation levels and man-rem exposures throughout the life of the plant.

The construction and modularization schemes for the DLFR CV are prototypic of the approach that would be required to economically construct the full-scale commercial plant, thus demonstrating the construction and delivery processes. This includes modularization of the reactor building and CV. Lessons learned during the construction of the DLFR will not only facilitate determining accurate NOAK plant costs but also contribute to attaining NOAK delivery performance.

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[11] Despite a power conversion system similar to SFRs, the DLFR has a roughly 2% higher energy conversion efficiency (from about 40% to about 42% net). This is due to the higher feed water temperature, the absence of the intermediate loops (which would degrade the thermal cycle and require power for the associated pumps) and the lower pumping power for the primary coolant circulation (due to the more open fuel assembly lattice).

4.8 Refueling and spent fuel handling

Due to 1) the lack of exothermic chemical reactions of lead with air and water [11], 2) the excellent shielding and fission product retention capabilities of the molten, 3) the continuous purification operated on the coolant and 4) the continuous flushing and cleaning of the cover gas, refueling can be conducted with the MV cover completely removed[12]. This is an important benefit with respect to SFRs, resulting in simplified refueling and enhanced reliability compared to those reactors. Access to the core can occur from the top, taking advantage of the stems extending the assemblies above the free level. These stems permit visual confirmation of engagement and correct fuel placement during fuel movement, thus allowing the refueling machine to be positioned outside of the MV, resulting in increased reliability compared to a fully immersed machine. While not yet fully developed, Westinghouse is confident that viable refueling options exist for the DLFR. Details will be refined in future work. It is worth noting, however, that due to the high temperatures associated with cold shutdown of the LFR and the toxicity of the reactor coolant, it is expected that refueling operations for the LFR will be performed from a remote location[13].

4.9 Decommissioning and waste generation aspects

Lead and the associated impurities become activated under neutron irradiation. The total specific lead activity increases steadily from the first full-power operation and rapidly reaches saturation at about 1.4 Ci/kg. The largest contribution comes from gamma radiation, with alpha and beta decays on the order of $3x10^{-5}$ Ci/kg and 0.3 Ci/kg respectively. This should be taken into account with respect to personnel radioprotection.

For decommissioning purposes, it is noted that after 1 year of cooling, the total specific activity decreases by about 3 orders of magnitude, becoming ~$6.8x10^{-4}$ Ci/kg, almost entirely due to beta decay. Because of the long-lived isotopes, even after 100 years of cooling the specific activity is still above the clearance levels (~$3.5x10^{-6}$ Ci/kg), requiring irradiated lead to be controlled. Contaminated lead can be reused in other LFRs or its radioactive contaminants filtered out if this can be done in a cost-effective manner (the time scale for this need to arise should be considered, e.g. 2100 or later, given the 2030 deployment and assuming a 60-year plant life). As an alternative the contaminated lead, with a foreseen volume of less than 2 m^3 per MWe installed, can be permanently disposed in the nuclear waste repository.

The lead activity is a consideration when addressing the extraction of components from the MV, for inspection, repair or substitution (including refueling). Lead wets surfaces, resulting in contamination of component extracted from the molten. The specific activity, at reactor shutdown, decreases exponentially by about two orders of magnitude in one day, and falling to about $5x10^{-3}$ Ci/kg in one week. This means that all procedures commonly adopted in laboratory for washing the components – by means of acid solutions and water – are to be performed remotely.

4.10 Industrial applications

The DLFR is not intended to test any process heat applications. This is a result of previous Westinghouse investigations that noted a significant number of challenges. In some processes, such as desalination, the use of the heat directly is less-effective than using electricity produced by the plant. In other cases, the customer process heat requirements would likely be incompatible with the outage schedules inherent in a nuclear plant. Furthermore, production stoppages at the customer site would place significant economic hardship on the nuclear plant. Unless a suitably sized cogenerating electrical plant is built to accept the additional power, maintaining a high utilization factor will be difficult.

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[12] All these provisions ensure that, when the reactor is brought to the cold shutdown (set at 380°C), no significant volatiles or vapors can be expected, possibly impairing the removal of the reactor cover.

[13] Although it is not the typical practice, many operating PWRs are actually capable of performing remote refueling operations. Presumably, however, it is not normally done since it does not present a significant advantage for PWR operation.

If in future markets process heat proves to be viable, high-confidence exists that its generation may be accommodated in the follow-on commercial LFR units, given that utilization of the steam for alternative purposes than electricity generation will not necessarily impact the reactor design. However, the plant modifications would be specific to the end user, giving little value to a generic test now.

4.11 Integration with other energy generating options (energy storage)

Nuclear power plants are most economical when running at full power. This is due to the high fixed costs associated with the initial investment and low variable costs associated with fuel and O&M. With this in mind, even if load follow is incorporated, there is an economic incentive in maximizing full-power operation. Due to these realities, the ability to store power when demand is low and sell it when it is high is a significant advantage for any new nuclear design. This would permit the plant to operate on increasingly variable grids resulting from the presence of intermittent renewable sources, and reap the economic rewards of variable operation which currently apply only to natural gas and hydroelectric power.

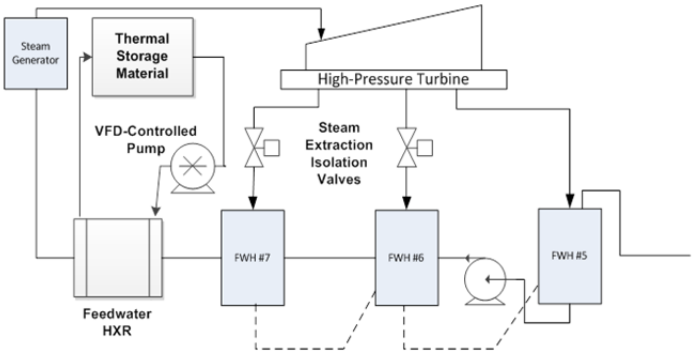

Figure 9: Energy storage: simplified scheme

Westinghouse believes that the most economically effective means to store large amounts of energy in a wide variety of geographic locations is to use thermal storage. Westinghouse has investigated a host of thermal storage materials and has down selected to several, solid-form candidates. This is due to their low cost, availability, favorable thermal bulk storage properties, and wide temperature range capability.

Given the modular nature of the envisioned energy storage system, the DLFR incorporates a small energy storage in order to demonstrate viable operational and technical performance. This system will be designed with a high charge rate, but low capacity in order to allow significant diversion and recovery of energy. This will permit operators to use it as a production system, however for much shorter periods of time.

This system is integrated with the same turbine and generator already installed in the plant, as shown in Figure 9. It manipulates feedwater in order to change the power of the turbine. The charging mode from the steam cycle to the thermal storage is accomplished through removal of heat downstream of the high-temperature feedwaters. This heat is deposited in the solid thermal storage medium and maintained for later use. The discharge mode is accomplished by isolating some or all of the extraction steam to the high-pressure feedwater heaters and, instead, using the stored energy for feedwater heating. The isolation of the extraction steam retains more steam in the turbine and subsequently increases shaft power. A similar arrangement on the reheaters is also under consideration at this time.

4.12 Non-prototypic or non-scalable aspects of the design

Results and knowledge accumulated through the DLFR development and operation will be directly applicable to the follow-on commercial units. Exceptions exist, which are either included in the overall LFR development plan and will be demonstrated through the DLFR and other facilities (fuel and cladding materials), or they are already-demonstrated technologies (balance of plant technologies):

- **Fuel**: unlike for the DLFR, UN fuel is envisioned for the follow-on LFR commercial units. UN fuel qualification will be performed through preliminary testing in the available US test reactors, using provisions to locally reduce thermal flux and increase fast flux, and subsequently using the DLFR to test UN fuel through Lead Test Rods and Lead Test Assemblies.

- **Cladding**: higher discharge burnup and flux levels than in the DLFR, resulting in higher dpa levels on the cladding, are envisioned for the commercial LFR units. Testing of cladding performance, primarily swelling, in these conditions will be performed via ion irradiation first, and subsequently confirmed in the DLFR by placing small cladding samples in the testing regions of the DLFR, i.e. either in the central tube of non-FAR containing assemblies or in some of the shield assembly locations at the periphery of the core. The cladding materials to be tested are those adopted in the DLFR, i.e. D9, some enhancements such as DS4[14], and new materials to be developed through R&D as discussed in Section 3.2.2.
- **Power conversion system**: a supercritical water power conversion system is envisioned for the commercial LFR units, rather than superheated steam, assuming that material testing/development programs conducted in parallel to DLFR development demonstrated the feasibility of increasing lead temperature in the 600-700°C range. Due to the high technology readiness of supercritical water power conversion systems, only minimal re-design efforts will be required.

4.13 Prototypic and scalable aspects for fuel performance demonstration

The DLFR performance is sub-optimal with current, proven, fuel (UO_2 and D9 cladding) due to limitations in: 1) the achievable discharge BU (limited by irradiation-induced cladding swelling), 2) cladding, and lead operational temperature (limited by corrosion and cladding material properties), and 3) linear heat rate (limited by UO_2 thermal conductivity). Alternatively, there is no reactor, with the proper testing environment, available to test the advanced fuel envisaged for the LFR commercial units, e.g. UN with advanced cladding (advanced double-stabilized austenitic steels or SiC wrapped HT9 are considered for development and testing). To overcome this difficulty, the DLFR will follow a two-step development process. During the first step (Phase I), the DLFR will operate on well-proven UO_2 fuel and D9 cladding at linear heat generation rates and temperatures that do not challenge the fuel. This stage of operation also allows the operational limits of the DLFR to be explored in non-challenging conditions. While in this mode of operation, lead test rods, lead test assemblies, regions and finally (Phase II) full cores of the advanced fuel considered will be introduced in the progression which has been used traditionally by the nuclear industry to introduce new fuels. Also, “new” structural materials will be tested that will be introduced later into the first generation commercial LFR with higher temperature operation and high linear heat generation cores. Samples can be inserted in selected fuel assemblies (in the instrumentation/FAR/test tube at the center of the lattice, see Figure 6) or in testing capsules in some of the shield assemblies. Since the core of the DLFR is relatively large, with height similar to that envisioned for the LFR commercial units, nearly prototypical irradiation conditions can be achieved eliminating any scalability issue. This approach minimizes development costs by minimizing the development time and licensing efforts of new fuel/materials to be introduced in the commercial units.

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[14] DS4 is a double-stabilized advancement of D4. It has already been shown to have good lead corrosion resistance at 550°C and swelling below 0.1% at up to 89 dpa ([4], [5]).

4.14 Summary of DLFR plant characteristics

Table 5: Summary of DLFR plant characteristics[a]

Power- and cycle length-related related characteristics			
Power (thermal/electric)	Phase I	MW	500/210
	Phase II		Up to 700/340
Plant net efficiency	Phase I	%	42.0
	Phase II		46-48
Core average power density		kW/l	102
Peak power density		kW/l	149
Cycle length		mo	18
Fuel residence time		EFPM	108
Peak fast neutron flux		n/cm^2 s	1.81x10^{15}
Primary system operating conditions			
Pressure		MPa	~0.1
Core inlet temperature		°C	390
Core outlet temperature		°C	510
Lead mass flow rate		kg/s	28560
Lead volumetric flow rate		m^3/s	2.74
Average lead velocity in the core		m/s	1.41
Core characteristics			
Core diameter (incl. shield assemblies)		m	4.3
Number of assemblies (fuel+safety+shield)		-	163
Number of fuel assemblies (inner/outer region)		-	82 (34/48)
Number of shield assemblies		-	78
Number of safety assemblies		-	3
Fuel assembly lattice		-	Hex, with duct
Fuel rod support type		-	Grids
Assembly pitch		mm	304
Assembly side-to-side distance (outer/inner)		-	301/296
Central beam tube ID		mm	78
Fuel rods per assembly		-	432
Fuel rod pitch		mm	13.6
Fuel rod OD		mm	11.6
P/D		-	1.17
Fuel rod cladding thickness		mm	0.65
Fuel pellet diameter (outer/inner)		mm	10.0/3.0
Fuel pin total length		mm	1530
Fueled length		mm	700
Plenum length		mm	600
Fuel and materials			
Fuel material		-	UO_2
Fresh fuel enrichment (inner/outer)		%	17.5/19.9
Heavy Metal mass		MT	16.26
Discharge burnup (average/peak)		MWD/kg$_{HM}$	100/140
Feed assemblies per year		-	9.1
Structural materials		-	See Table 4
Secondary system characteristics			
Pressure		MPa	18
Feedwater temperature at SG inlet		°C	340
Steam temperature at SG outlet		°C	500
Number of SGs		-	6

[a] Unless specified otherwise, values shown refer to Phase I of DLFR operation.

Section 5: DLFR Safety Basis

5.1 DLFR safety approach

The DLFR design approach leverages the favorable characteristics of lead not only to obtain a plant with the highest degree of inherent safety but also as a vehicle to enhance economics, operations and maintenance. Table 6 shows this threefold impact of lead properties and system design on safety, economics and operation.

Overall, the DLFR technology significantly enhances post-accident coping periods, provides features and characteristics that minimize the release of radionuclides under severe accident conditions, maximizes resistance to hazards presented by natural phenomena, and presents a credible case to the U.S. NRC to consider the reduction of Emergency Planning Zone (EPZ) requirements.

5.2 Inherent safety features of coolant and fuel

The inherent safety features of lead coolant, whose safety, economic and operational impact is summarized in Table 6, are discussed below:

- The very high boiling point (1745°C) renders the occurrence of a large void region in the DLFR core due to coolant overheating extremely unlikely [27]. This, when combined with the adoption of a pool configuration with main and safety vessels, results in an extremely large margin from coolant boiling and virtually precludes DLFR core uncovery, thus significantly reducing core damage frequency.
- Lead is essentially inert with air or water [11], which is a significant safety advantage relative to SFRs, and operates at atmospheric pressure, which is a key safety advantage relative to LWRs, HTGRs and GFRs. This combination results, in the DLFR, in minimal coolant stored energy, estimated to be about 10 times smaller than in SFRs and approximately 20 times smaller than in PWRs [28]. The selection of the moderator and coolant has proven to be a major factor in global events / accidents at Chernobyl or Fukushima. The catastrophic consequences from dangerous chemical reactions involving moderators or coolants generating large amounts of heat in beyond-design-bases scenarios cannot be over-emphasized in current, and future, reactor designs. The LFR design is not subject to any of these risks or introduce any new risk.
- Even though the local void reactivity coefficient may be positive, the very high boiling point of lead makes void formation upon coolant overheating very unlikely while the high lead density facilitates prevention of accidental void ingress in the core upon SG tube rupture[15]. In addition, even with a global lead temperature increase, e.g. from a transient overpower, the coolant temperature reactivity coefficient is negative due to the prevailing impact on reactivity of enhanced neutron leakages, which provides an effective feedback for the management of the transient. This allows the reactor to be shut down quickly, effectively and passively.
- Lead has been shown to readily absorb and immobilize fission products, notably iodine, cesium and cesium-iodide, thereby reducing the source term in the event of fuel failure, ultimately reducing the radiological exposures to the workers, the public or the environment by a very large degree.

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[15] This is due to inhibition of bubble growth and easier, density-driven separation between the steam/gas phase and the lead. Experimental programs conducted in Europe have demonstrated the feasibility of limiting downward gas penetration following postulated in-vessel SG tube rupture, which results in voids not being able to reach the core [29]. The density effect, together with lead inertness, enables elimination of the intermediate loop in the proposed DLFR technology.

Table 6: Summary of Safety, Economic and Operational Benefits of the proposed LFR Technology

LFR Design Feature	Safety benefits	Economics benefits	Operational benefits
Lead's high boiling point	Low risk of coolant boil off; Intervention and effectiveness of passive safety systems not constrained by coolant boiling	Operation at higher T → higher plant efficiency, potential for sCO_2 power conversion system and energy storage system	Reduced requirements for rapid operator response upon primary coolant overheating
Atmospheric pressure operation in a pool-type reactor configuration	No pressurization-induced stresses on most components; in case of a leak, very low leak rate (from lack of pressure differential)	Use of expensive heavy forgings reduced; No need for multiple, pressurized, safety injection systems	Pb leaks extremely unlikely → "cleaner" containment → lower doses
Lead's low chemical reactivity with H_2O, air	Lower risk of industrial accident; H_2O potentially usable as ultimate coolant fluid in extreme events	No need for intermediate loop and associated systems; no need for provisions for addressing lead-air/ H_2O reaction result in fewer components and higher plant reliability	Easier, safer operation by plant personnel. Reduced requirements for ensuring inert atmosphere during refueling
Lead's high retention capability for fission products (I, Cs, Po, Sr)	Reduced source term in case of fuel damage	Support reduction in EPZ size; Reduced requirements on containment atmosphere filtering system	
Lead's good heat transfer properties	Enhanced decay heat removal during natural circulation	High core power density benefits primary system compactness → lower capital cost per kWe	Reduced requirement for rapid operator response due to high lead thermal inertia and effective natural circulation
Lead's high volumetric thermal capacity	More time for operator response due to high primary system thermal inertia	Lower lead volumetric flow rate → reduced pumping power* → increased net plant efficiency	

* See footnote 1 to Table 1

(Table 6 continues on next page)

Table 6: Summary of Safety, Economic and Operational Benefits of the proposed LFR Technology (cont.)

LFR Design Feature	Safety benefits	Economics benefits	LFR Design Feature
Lead's neutronic characteristic	Open fuel lattice w/o neutron penalty→ enhanced DHR via natural circulation; low core pressure drop allows short RV w/o penalizing natural circulation DHR	Reduced core pressure drop →reduced pumping power *→ increase net plant efficiency.	Reduced reliance on operator action due to passive decay heat removal
	Low reactivity excess to be controlled	Potential for reduced U consumption and increased capacity factor due to fewer refueling outages	Potential for reduced number of refueling outages
Lead's good shielding properties	Lower neutron damage on structures around the core	Reduced need for additional shielding	Lower occupational dose to operators
SG-RCP assembly		Smaller RV resulting in reduced equipment cost	
Compact short spiral tube SG	Reduced lead displacement in case of SG tube rupture	Reduced vessel height resulting in reduced cost of equipment and supports	
RCP in the hot leg feeding SG from the bottom	SG fed from the bottom eliminates risk of cover gas/steam entrainment to the core	Simplified primary coolant flow path results in reduced cost of reactor internal components	
Fuel assemblies with stem extending above lead in cover gas space	Easier refueling enhances system reliability	Elimination of in-vessel refueling machine operating under lead, and of the above-core structure (→ reduced RV diameter); simplification of core supports structures	Easier refueling. Less challenging in-service Inspection and Replacement

* See footnote 1 to Table 1

- The excellent lead neutronics properties for fast spectrum applications (low parasitic absorptions and low neutron moderation) allow a larger fuel pitch, e.g. relative to SFRs, without incurring a significant neutronic penalty. The resulting reduction in pressure loss, coupled with lead heat transport properties, high density and boiling point favor removing a significant fraction of power through natural circulation (e.g. ~23% in the ALFRED design during ULOF [34]), making loss of flow accidents – even unprotected – well tolerated by the plant.

As for the fuel, UO_2 thermal properties (high melting point but low thermal conductivity) result in a rapid increase in temperature for an overpower event. This – combined with the high melting point – results in prompt introduction of a large negative reactivity through the Doppler effect, which is beneficial to mitigate and arrest accidental reactivity insertion transients (e.g. spurious withdrawal of absorber rods, or core compaction, e.g. in case of earthquake). In this way, such accidents can be safely managed even in unprotected conditions.

5.3 Challenging features of the coolant

Lead's main challenges are high corrosiveness, opacity, high melting point and high density. They are addressed through proper material development and system design, as discussed below.

Lead corrosiveness

Lead corrosion can be managed by adequate material choices for the temperature and velocity conditions selected for the DLFR. Moreover, extensive research programs (e.g. [1] through [5]) have demonstrated that proper material choices help relaxing oxygen control requirements, which otherwise would be demanding or impractical to meet in large, commercial, systems. In addition to this, the DLFR copes with lead corrosiveness by:

- Maintaining the lead core outlet temperature below 510°C, where material options with proven resistance to lead corrosion exist (see Table 4).
- Limiting the lead velocity to ~ 2 m/s to limit erosion (with the exception of the pump impeller, where the speed of ~ 10 m/s requires application of a protective coating).
- Designing all the primary system components to be easily inspectable, maintainable and, with the exception of the MV, fully replaceable.
- Keeping the MV, the only non-replaceable component, in contact with the cold leg temperature which does not exceed 400°C[16].

A similar design philosophy to the above will be employed in the follow-on commercial units, with resort to material choices (including coating) suitable to guarantee lead-corrosion protection at the pertinent (higher) operational temperature range.

Lead opacity and high melting point

Proper engineering and system design addresses the challenges in the areas of inspection, maintenance and refueling deriving from the opacity and high melting temperature of lead:

- The DLFR design fully utilizes remote inspection techniques, leveraging the SFR experience and, more generally, the advancements in robotics. For instance, remote refueling operations will be performed in the DLFR to cope with the associated environmental conditions. Although not the typical practice, many operating PWRs already have remote refueling capabilities, and remote refueling has been performed in the SFRs, therefore Westinghouse will devise a viable remote

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[16] The experience accumulated, for example with the SS316 vessel operating in contact with Pb-Bi for about 15 years in the CIRCE facility at ENEA Brasimone in Italy [30], indicates that below about 400°C SS316 can be successfully employed for the MV without manifesting corrosion.

refueling technique for the DLFR. Relative to the SFRs, refueling will be greatly facilitated by 1) the presence of extended stem fuel assemblies extending above the lead-free level and allowing fuel handling in full visibility, and 2) lead inertness with air/water [11], which relaxes the requirements on atmosphere control and facilitates ensuring an acceptable presence of cover gas[17].

- The DLFR is provided with auxiliary and safety systems (see Section 4.2.6) to prevent lead freezing.

Lead density
Lead's high density, about 40% higher than steel, entails a greater weight of the primary system, which complicates seismic requirements compliance. The higher density also introduces some challenges related to the buoyancy of steel structures in lead. For the DLFR, these challenges have been solved through proper engineering and system design, as discussed below:

- Regarding seismic, a very compact primary system is attained in the DLFR design, which maintains the volume of lead, and associated weight and mechanical stresses, to an acceptable level. Seismic isolators are also employed to reduce the mechanical requirements on connections and supports, and lead sloshing, in case of earthquake.
- Challenges introduced by buoyancy are solved through proper engineering of supports, links and mechanical structures in general. For instance, the fuel assemblies can be designed to sink in lead by devising the extended stem such that its weight above the lead free level can compensate the buoyancy. Control rods, as discussed in Section 4.3.1.3, are provided with ballasts which allow them to be inserted from the top and fall by gravity. Alternatively, buoyancy is turned into an advantage; for instance bottom-inserted control rods, which rise in the core by buoyancy, are adopted for the DLFR Control System bank and the Safety System bank #2.

5.4 Barriers against release of radioactive materials

In the DLFR the traditional barriers to fission product and actinide release that are the safety foundations of commercial nuclear power are maintained and enhanced, as discussed below.

First barrier: fuel and fuel cladding. The fuel pellet is the first physical fission product barrier. The cladding tube, sealed and coated, represents the first engineering barrier to the dispersion of solid radioactive material and especially to the release of gaseous/volatile elements. It is noted that the coating, protecting the cladding against lead corrosion and self-healing, has proven impermeable to tritium generated by ternary fissions in the fuel and by ^{10}B neutron capture in the B_4C absorber rods. Hence, the entire radioactive inventory is maintained inside the fuel rod in normal conditions.

Second barrier: lead coolant. In the event that the first engineering barrier fails, lead coolant through its excellent retention properties provides a very effective means to protect the environment from radioactivity release. Overall, lead's retention capabilities result in a reduction in the release of all the main radio-toxic isotopes from the melt to the cover gas by a factor of 30,000 at least, relative to the radioactivity level potentially released from the fuel [31].

Third barrier: Main Vessel. The MV, together with all the volumes defined by the systems penetrating its roof (which are in turn enclosed in sealed barriers), are sealed thus preventing radioactivity in the primary system to reach the containment.

Fourth barrier: Containment Vessel. The CV is composed of a sealed armed concrete structure, leak-tightened by a steel liner on its inside. The building is maintained in a controlled atmosphere, and continuously in a slight vacuum with respect to the outer environment. The same is true for the MV

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[17] Refueling has been historically difficult in SFRs due to the strict cover gas chemistry requirements which prevent the MV roof to be opened.

atmosphere, which is maintained in slight vacuum with respect to the containment. In this way, in the event that any leak occur from one of these engineering boundaries, the leak flow would be inward, preventing release to the environment and the public.

5.5 Inherent radionuclide retention capability of lead

Lead readily absorbs and immobilizes fission products, most notably iodine, cesium and cesium-iodide, (i.e. fission products with low melting and boiling points), thereby reducing the source term in the event of fuel rod failure ([20], [11]). As mentioned in Section 5.4, this benefits defense-in-depth since it greatly reduces the potential radiological exposures to the workers, the public and the environment. Not only have these retention capabilities been experimentally demonstrated around the world using medium- and large-scale facilities, but also the release behavior of volatile radionuclides is fairly well understood [11], which is important to reduce uncertainties and therefore avoid applying unnecessary conservativisms in the safety analyses.

5.6 Beyond Design Basis Accident mitigation

Decay heat removal during shutdown and design basis accidents was discussed in Sections 4.2.5 and 4.4.1, respectively. In the event of extreme, unforeseen, events leading to failure of all DHR systems, the use of locally available water as emergency coolant is plausible due to the lack of significant chemical reactions between lead and air/water [11]. Two approaches have been considered relative to mitigating these unlikely scenarios.

The first approach, which protects the integrity of the MV, consists of spraying water on the primary system. This line of defense relies on two separate and diverse systems, spraying water inside and outside the MV, respectively. Water is sprayed directly on the free surface of the lead[18] using a dedicated line entering the MV, and drawing water from the pools where the DHRs heat exchangers are immersed. These pools are connected – through dedicated lines – with the storage tanks distributed outside the containment building, accessible to emergency squads for continual refilling as required in the event of prolonged DHRs operation. The second system uses the containment building fire protection lines, and sprays water outside the MV, ultimately flooding the gap between the MV and the SV. This system draws water from the same storage tanks outside the containment building mentioned above.

Both types of spray systems require voluntary actuation by the emergency squads, either inside (for in-vessel spray) or outside (for ex-vessel spray) the containment building, so that the latter system can be actuated regardless of the conditions inside the containment building.

The second approach relies on the passive cooling system immersed in the concrete of the reactor cavity. This system is designed to operate effectively in the ultimate condition of failure of the MV, with leaked primary lead filling the gap between MV and SV. This provision ensures indefinite long-term, stable and reliable DHR operation eventually resulting in the solidification of the lead leaked from the MV. In this extreme scenario, the primary system would be sealed to maintain the fuel and the main inventory of radioactivity within the plant.

5.7 Maximum hypothetical accident

Possible accident initiators for the DLFR were identified using the approach followed by other LFR projects [32]. A Master Logic Diagram top-down approach provided the reference list of initiating events,

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[18] Steam explosions are likely in this scenario. However, the severity of the event that would result from an otherwise lack of primary pool cooling together with the extremely low likelihood of simultaneous unavailability of DHRS-1, DHRS-2 and AHRS, justifies including this type of intervention in accident management.

which was then complemented with their categorization according to the associated probability of occurrence.

The DLFR leverages the favorable properties of lead and, through a robust design, achieves a very high safety in the largest number of accident conditions. All protected transients, regardless of the condition or combination of initiators, are easily managed [33]. Concerning unprotected conditions, safety criteria embedded in the design of the DLFR assure the plant is capable of withstanding potentially severe conditions with long grace times. A number of publications in literature support the conclusion that, due to the features of the lead coolant and provided that a proper design approach is adopted, a LFR is robust enough to not incur in generalized nor even extended core degradation. Safety analyses supported by integral experiments validating the simulation tools, indicate that [34]:

- no coolant boiling nor loss of coolant (outside of the SV) can occur in any accidental scenario;
- fuel melting – occurring only in case of extreme reactivity insertions – never propagates beyond a ~1 mm thick layer of fuel around the pellet central hole in the few, central pellets in the hottest fuel pins;
- no generalized failure of the fuel pins can occur, the most severe condition that can be hypothesized being the breaching of the cladding of all the pins in a single fuel assembly;
- failure of the MV can occur in case of loss of main heat sink, but only after a grace time that is acknowledged to be sufficiently long for operators to intervene and prevent MV failure to actually occur. Moreover, the cooling of the SV and of the lead as soon as it leaks from the MV is expected to induce freezing of the leak, thereby self-sealing the MV crack.

Each of the consequences mentioned above (fuel melting, fuel pin failure, MV failure) are associated with various beyond design basis events (extreme unprotected reactivity insertion, unprotected loss of flow and unprotected loss of heat sink, respectively). Consistent with WANO recommendations of a 30 minute grace time for manual reactor shutdown in the event of failure of the automatic reactor protection control system, all these consequences initiate far beyond this minimum grace time, and often even several days into the regular and proper operation of the safety systems.

5.8 Size of Emergency Planning Zone

Commercial deployment of LFR technology will introduce a level of inherent safety that has not been realized by any previous nuclear power generating technology. The absence of postulated severe accident scenarios associated with this technology will ultimately eliminate the requirement for EPZs that extend beyond the plant’s site boundary. Since the current emergency preparedness (EP) regulations are based on a framework developed for large LWRs, it is anticipated that a Nuclear Energy Institute lead working group would develop technology-specific recommendations for LFR to the NRC to create EP regulations that are commensurate with the significantly reduced risk to the public. As recently recommended by the NRC for SMRs, it is expected that the EP for LFRs will be scaled to be commensurate with the accident source term, fission product release and associated characteristics specific to the plant’s design.

Several design features and attributes associated with LFR technology would contribute to reduced risk of severe accident and potential fission product release:

- Lead’s high boiling point significantly reduces the risk of core voiding and thus fuel pin failure upon reactivity insertion. It also provides a marked advantage in coping with severe accident initiators, including unprotected events [35].
- Atmospheric pool reactor with MV-SV configuration combined with very high boiling point precludes core uncovery.
- Inherent safety behavior from markedly negative temperature reactivity feedback.
- Open, low pressure loss fuel lattice, combined with the heat transfer properties of the coolant, facilitate heat removal from the core through natural circulation.

- Lead's favorable retention capabilities, especially in regard to iodine, cesium and cesium-iodide, result in a significant reduction in source terms in case of extensive core damage.

5.9 DLFR safety performance

Because of the limited consequences that postulated protected events have in the DLFR (see Section 5.7), the safety performance for the DLFR is qualitatively discussed below for (unprotected) Beyond Design Basis Events. Quantitative results referred to the ALFRED reactor are presented as an example of reactor behavior that is anticipated for the DLFR, with the main purpose of identifying the long grace times available before maximum allowed core and vessel wall temperatures are reached, or the risk of lead freezing is attained in the primary system [34]. Unprotected flow blockage, Unprotected Loss Of Flow (ULOF), Unprotected Transient Overpower (UTOP) and Unprotected Loss Of Heat Sink (ULOHS) are discussed.

Unprotected flow blockage

Even though unlikely due to assembly design provisions[19], this scenario assumes that a progressive reduction of coolant flow in a fuel assembly, undetected by failed thermocouples at the outlet of the fuel assembly, occurs. Without intervention of the reactor protection system, the coolant flow continues to decrease until the assembly structures heats up, deforms and precludes cooling. Fuel cladding initiates failure under the inner pressure of gaseous fission products. In addition to the assembly coolant temperature increase, detection of these fission products in the cover gas provides another, alternative means for detecting the accident and commanding reactor scram. Should this fail, the increased temperature in the blocked fuel assembly triggers a negative Doppler response in the fuel, with a consequent local depression of the power that is detected by the neutron flux monitoring system. Due to the large margin between fuel operation and melting temperatures, and to the power reduction due to local Doppler response, no fuel melting occurs; nonetheless, fuel dispersion in the primary system – upon washout of the fuel pins on the inside by lead penetrating the cladding breach – is considered, so that the most severe scenario is equivalent to the complete de-cladding of all the fuel pins in the affected assembly. No propagation of the core degradation occurs, the accident being inherently arrested by Doppler and by cross-flow of colder coolant from the by-pass region upon heating-induced failure of the assembly duct.

Unprotected Loss of Flow

ULOF can occur if all RCPs simultaneously trip and the reactor protection system fails to scram the reactor. The sudden reduction in coolant flow causes lead in the active region to overheat and rise by buoyancy: this, along with the sinking of the cold lead in the downcomer, enhances heat removal through natural circulation from the core. Due to the core low pressure loss, mainly due the DLFR open fuel lattice, the pressure head required to initiate natural circulation flow rate is achieved when the temperature of the cladding is still sufficiently low, thereby allowing the fuel pins to withstand creep for several days without the need for any operators' intervention.

A typical LFR response during an ULOF transient is shown in Figure 10. This response is for the ALFRED reactor [34], for which the low pressure loss core resulting from the open fuel lattice, similar to that adopted for the DLFR, results in a natural circulation providing ~23% of the nominal flow rate.

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[19] The design of the fuel assembly has a perforated foot reducing the likelihood of complete and sudden occlusion.

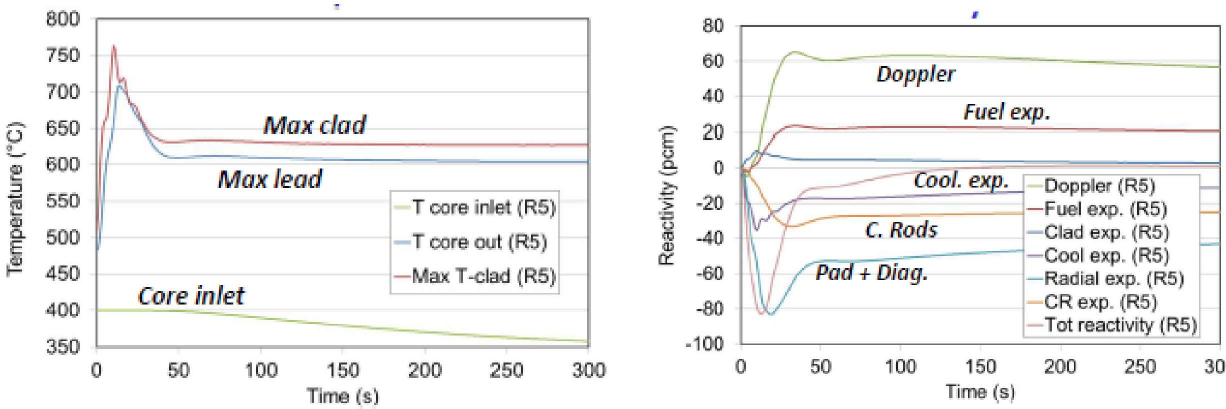

Figure 10. Coolant and cladding temperature (left) and reactivity contributions (right) during ULOF (results referred to the ALFRED reactor [34])

Unprotected Transient Overpower

UTOP occurs when reactivity is inserted in the core and the reactor protection system fails to actuate to compensate the excess reactivity and also to shut the reactor down. The increased neutron multiplication due to the reactivity insertion quickly causes the power to increase. Although the RCPs and the SGs operate normally, a core overheating occurs, with a prompt effect on the fuel and then on the coolant and the structures. The increase in fuel temperature quickly triggers a large negative Doppler feedback – increasing with the core power – significantly dumps the reactivity excursion which is then terminated by the other negative feedbacks (mainly fuel expansion and core flowering). For an UTOP, the largest concern is fuel which, in the early phases of the transient, might approach or even exceed the melting temperature. For this reason, the DLFR core has been designed with a peak linear power in nominal conditions sufficiently low to ensure that fuel melting does not occur in the most severe reactivity insertion event. Figure 11 shows the behavior of the ALFRED reactor during an UTOP transient.

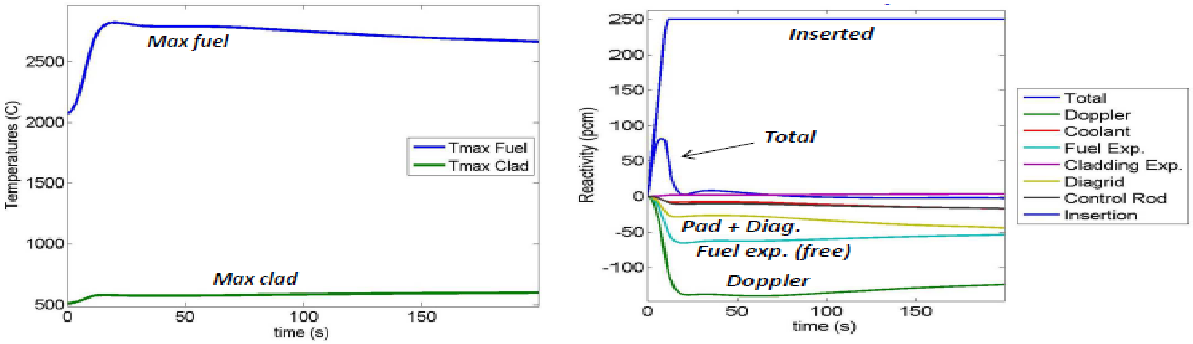

Figure 11. Coolant, cladding and fuel temperature (left) and reactivity contributions (right) during UTOP (ALFRED reactor, with 250 pcm of reactivity insertion in 10 seconds [34])

Unprotected Loss of Heat Sink

An ULOHS occurs in the event of the loss of the SGs as main heat exchangers and failure of the reactor protection system. In this event, the heat removal is through the DHRSs only, which are sized for a much lower power than the nominal value of the plant. In these conditions, all system temperatures increase, triggering a large negative reactivity feedback which passively reduces the core power to a level manageable by the DHRSs. The systems, without approaching any condition potentially leading to fuel melting, stabilize at conditions that pose no concern to the fuel or integrity of the cladding, for very long grace times (on the order of days). The only concern might regard the MV, if no countermeasures are taken to cool down its walls. This is because lead temperature will stabilize at a level which leads to accelerated vessel creep and shorter, time-to-failure. Still, the grace time before MV failure occurs is sufficiently long to support intervention by emergency squads and actuation of dedicated cooling procedures, including, as a last resort, direct water cooling of the MV outer surface and primary system structures.

Typical reactor behavior during an ULOHS event, again referred to the ALFRED reactor, is shown in Figure 12 [34]. It can be seen that cladding failure time exceeds 10^6 seconds (>10 days).

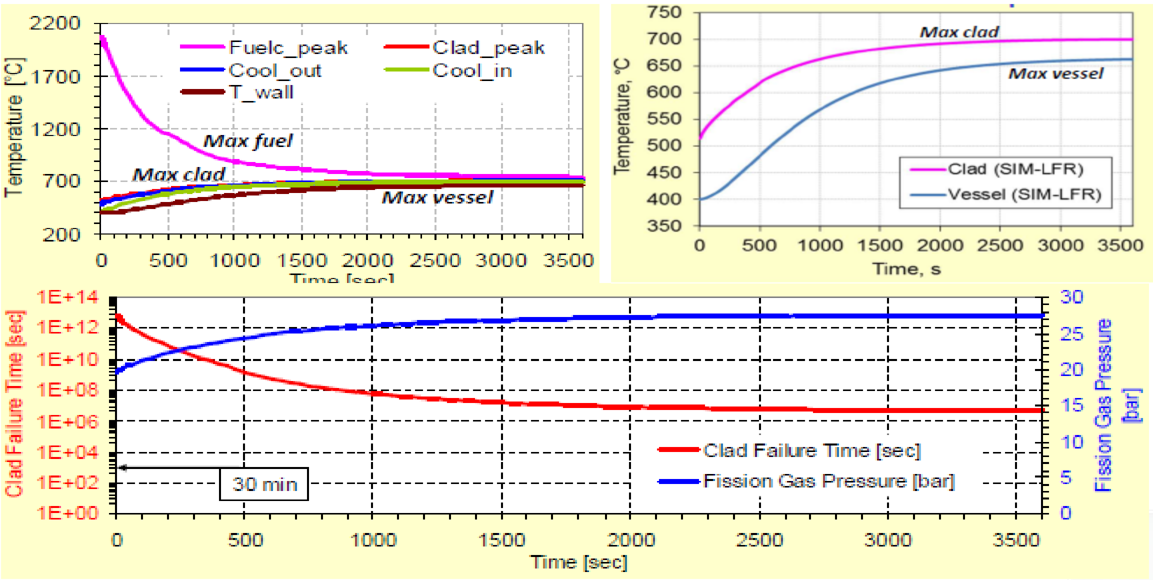

Figure 12. Evolution of main temperatures (above) and cladding time-to-failure (below) during ULOHS (results referred to the ALFRED reactor, [34])

Section 6 : Economics and schedule

Due to the pre-conceptual stage of the design, quantitative evaluations on project cost and plant economics are premature. However, various DLFR characteristics are conducive to reduced project cost and enhanced economics, relative to LWR and other technologies:

- Reduced capital cost per unit of electricity and shorter construction schedule resulting from a high Nuclear Island power density (extremely compact primary system and containment, combined with a high power density core), a ~42% plant efficiency, design simplicity, reduced number of safety systems, and use of advanced modular design and construction techniques.
- Reduced R&D costs result from using, to a large extent, proven and qualified reactor technology, building on well-developed SFR experience and leveraging ongoing, extensive research programs[20] that are fulfilling lead specific technology gaps.
- Reduced licensing challenges, compared to less developed technologies, as a result of the above-mentioned considerations and the exceptional safety case
- An appropriate electric power output which combined with thermal energy storage will ensure revenues from electricity generation that abundantly exceed operational costs.

Figure 13 shows the project schedule, with the various activities discussed in Section 3.2.

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[20] See footnote 2 on page 8.

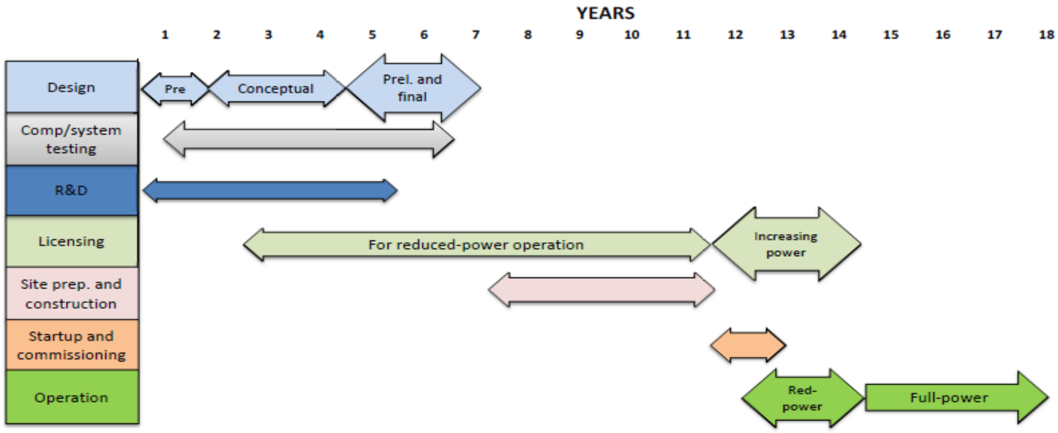

Figure 13: Estimated schedule for DLFR development, assuming availability of funding

Section 7 : Conclusions

Westinghouse believes that an advanced reactor technology must enable, first and foremost, significant economic savings compared to current LWRs to allow large-scale commercial deployment and satisfy global demand for clean and safe energy. Westinghouse has recognized LFR technology as the next generation reactor with the best economics *and* safety potential, and is committed to bring this technology to commercial fruition. As a first step, Westinghouse has developed a point design DLFR for demonstration of the LFR technology by 2030, which was described in this report.

The Westinghouse DLFR features a compact, pool-type, primary system, with the main vessel containing all primary components immersed in liquid lead. The power rating is 500 MWt (210 MWe) however the plant is designed to facilitate power uprates (up to ~700 MWt) once the initial demonstration mission is fulfilled. An average core outlet temperature of 510°C, with a superheated steam power conversion system, results in a net plant efficiency of approximately 42%.

In the DLFR design emphasis is given to proven technology that enables licensing certainty and reactor operation by 2030. Since the DLFR shares several thermal-hydraulic, mechanical and fuel aspects with SFRs, it leverages the considerable SFR experience, with the significant advantage of being safer, simpler and less expensive to build and operate. UO_2 fuel in steel cladding is chosen for the DLFR first cores, however subsequent reloads will incorporate higher-performance UN fuel for qualification and licensing. The lead-containing operating environment is exposed to temperatures and lead velocities where corrosion is managed with currently available materials, as demonstrated from over a decade of lead loops operating experience, and without resorting impractical oxygen management techniques. Refueling operations are simplified over previous fast reactors through the use of an innovative fuel assembly design that extends above the free surface of the lead pool, eliminating the need for a refueling machine operating under lead.

Overall, the proposed LFR technology has a Technology Readiness Level (TRL) equal to 4, which will increase to 7 through the DLFR operation. None of the areas identified at lower TRL represents a potential showstopper, and suitable engineering solutions have already been identified and will be successfully demonstrated in the DLFR.

The key attributes of the Westinghouse LFR technology are inherent safety behavior and best-in-class economics. The integral reactor configuration eliminates primary coolant loop piping and, due to the use of a main and a safety vessel operating at nearly atmospheric pressure, virtually eliminates loss-of-coolant accidents. The lack of exothermic chemical reaction of lead with air and water [11] eliminates several accident scenarios postulated for other reactor concepts using chemically highly reactive primary coolants. The high boiling point of lead, and high density, prevent reactivity insertion from voids formation, or intrusion, into the core. The strong, favorable reactivity feedback ensures inherent safety protection in a range of postulated accidental conditions. The high thermal inertia of the primary system results in benign transients and decoupling from the balance of plant. The robustness of the safety case, and the solid fuel form which preserves the cladding as defense-in-depth barrier for spatial confinement of the radioactive inventory, greatly simplifies licensing. Overall, the DLFR technology significantly improves post-accident coping periods, provides features and characteristics that minimize the release of radionuclides under severe accident conditions, maximizes resistance to hazards presented by natural phenomena, and presents a credible case to the U.S. NRC to consider the reduction of Emergency Planning Zone (EPZ) requirements.

The DLFR design features are either prototypic or scalable, so that the performance of the commercial product will be predicted with confidence. The compact nuclear island, combined with the high core power density and the high thermodynamic efficiency, will lower construction costs per unit of power well below those of current LWRs. Design simplicity, with minimization, and replaceability, of primary system components will improve reliability and allow cost-effective operation. Higher operating temperatures with targeted thermodynamic efficiencies close to 50%, supported by progress in materials and modifications to the power conversion cycle, are envisaged for the commercial units following the DLFR. An energy storage system will allow the plant to provide a variable electricity output, thereby increasing its market attractiveness for complementing electricity generation from non-dispatchable sources. Complete modularization of the plant will facilitate a factory-built and field-assembled delivery model increasing quality while significantly reducing the cost of deployment.

Westinghouse and its subsidiaries, with their demonstrated capabilities to design, license, build and supply worldwide nuclear reactors, are uniquely positioned to bring the LFR technology to the market.

Acknowledgment

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Appendix A: Self-assessment against Demonstration Reactor Metrics

The table below shows the Demonstration Reactor evaluation criteria. The answer for each metric is indicated by red text within a thick border cell. Comments on some of the criteria are as follows.

2.1.1 Westinghouse is confident that the DLFR total project cost will be less than $4B. This confidence results from:

- design elements conducive to capital cost reduction and to shorten construction schedule (e.g. primary system and containment compactness, design simplicity, reduced number of safety systems, use of modular construction);
- reduced R&D needs due to the rather "conventional" technology, i.e. solid, pin-type fuel cooled by a liquid coolant, to extensive research programs, especially on materials, already conducted in the past (~$100M in R&D funding in Europe[21]), and to the similarities with the well-developed SFR technology.
- the company's experience in plant design, licensing and construction, particularly the lessons learned from the ongoing construction of AP1000 plants in US and China.

2.1.2 Based on the TRL of the technology, Westinghouse is confident that between 10 and 15 years are needed for the DLFR to be developed and become operational.

2.2.1 Because of the relatively large power rating selected for the DLFR, i.e. 210 MWe, revenues from electricity generation are expected to exceed operating costs (the latter defined as O&M cost+fuel cost). Assuming a 90% availability factor, the DLFR will generate 210x365x24x0.9= 1,655,640 MWhr-e/yr. Therefore:

- Gross revenues from electricity sale: they can be estimated by multiplying the electricity produced by the electricity spot price. Since the latter varies significantly throughout the year and across the country, a representative value of 37.2 $/MWhr-e is used[22]. Hence, revenues are 1,655,640x37.2 = 61,589,808 $/yr.

- O&M cost: the average O&M cost for US nuclear power plants, in 2014, was 19.08 $/MWhr-e [37], which for the DLFR would translate into an annual cost equal to 1,655,640x19.08 = 31,589,611 $/yr.

- Fuel cost: the fuel cost for the DLFR operating in once-through has been calculated to be 13 $/MWhr-e. The resulting annual cost is 1,655,640x13 = 21,523,320 $/yr.

Hence, the net annual revenues estimated for the DLFR are: 61,589,808- (31,589,611+21,523,320) ~ $8.5 M/yr.

2.3.1 An assumed 30-day refueling outage, combined with the 1.5 year fuel cycle length, result in a 94% availability factor. Additional 24 days of downtime would be needed to reduce this factor to 90%. This, together with the relatively "conventional" technology used, justifies an anticipated capacity factor ≥ 90%.

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[21] Approximately €90M in funding have been allocated to support LFR-specific R&D in Europe, in the last few years. This includes ~€58M in the last 5-6 years, and approximately €30M prior to that [12].

[22] This value was calculated as average between the spot prices, averaged over 2015, in New England (55.03 $/MWhr-e), Pennsylvania-New Jersey-Maryland interconnection (PJM, 46.91 $/MWhr-e), Midwest (37.05 $/MWhr-e), Texas (27.98 $/MWhr-e), Northwest (26.27 $/MWhr-e), Northern California (40.66 $/MWhr-e), Southwest (28.25 $/MWhr-e) and Southern California (35.71 $/MWhr-e) [36].

3.1.2 An EPZ limited to the plant boundary is anticipated for the DLFR. This would be in line with recent proposals to reduce the size of the EPZ for nuclear plants, and for the DLFR would be motivated by the small source term expected, resulting primarily from:

- the use of "conventional" solid fuel configuration, which preserves fuel and cladding as one of the four Defense-in-Depth barriers against fission product release;
- the fission product retention capabilities of lead;
- the reduced sources for containment pressurization (extremely low likelihood of lead boiling, atmospheric pressure operation of the primary system, lack of exothermic chemical reactions between lead and air/water [11], small inventory of secondary water).

4.2.1 As fast reactor, the DLFR has the ability to demonstrate multiple core configurations and fuel management schemes.

4.2.2 The DLFR will operate with UO_2 fuel and will then test and transition to a higher performance fuel. UN is the preferred choice, but also metal fuel can be accommodated.

4.3.1 and 4.3.2. R&D activities, including testing, are anticipated to require 5-10 years and between $250-500M. As mentioned for Metric 2.1.1, it should be noted that significant funding for LFR R&D, of the order of $100M in Europe for example, has already been allocated and partly used to support development of LFR technology.

4.4.3 Testing regions can extend beyond the 70 cm-tall active fuel, since an appreciable fast neutron flux will characterize axial elevations higher than the active core. As for the volume, when considering the active core height only, these regions are between about 2 liters in high-flux areas (beam tube at the center of each fuel assembly) to 40-50 liters which can be engineered within selected shield assemblies.

5.1.1 The DLFR is a fast reactor and as such it has the ability to use recycled fuel and therefore to support a closed fuel cycle.

5.3.1 The fuel performance is scalable since commercial units are expected to operate with higher fuel duty, in terms of linear power and/or discharge burnup with respect to the DLFR, using either UO_2 or UN fuel.

Metric	**Description**	**Scores and Criteria**		
		9	**5**	**1**
1.1.1	Does the DLFR have safety characteristics and systems/components expected in the commercial plant?	**Demo replicates the passive and inherent safety characteristics and has prototypic systems/ components**	Demo has some of the passive and inherent safety characteristics and the resultant safety behavior of demo can be confidently scaled to the commercial system	Safety behavior of demo has important non-scalable aspects
1.1.2	Does the design have adequate instrumentation and will it gather appropriate data for code validation tests?	**High fidelity instrumentation and data to validate performance and safety models**	Some instrumentation and data to validate performance and safety models	Limited instrumentation and data to validate performance and safety models
1.1.3	Does the design implement technology selections that are prototypic or scalable to commercial unit?	Prototypic	**Scalable**	Neither
1.1.4	Does the design have maintenance approaches that are prototypic or scalable to commercial unit?	**Prototypic**	Scalable	Neither
1.1.5	Does the design use prototypic or scalable technologies in the fabrication of important systems and components?	**Prototypic**	Scalable	Neither
2.1.1	Project cost (including R&D, design and licensing)	**< 4 B$**	4-8 B$	>8 B$
2.1.2	Project schedule (from today to start of operation)	<10 years	**10-15 years**	>15 years
2.2.1	Annual net operating costs (operation+maintenance+fuel - revenues)	**< $0/MWt-h**	$0-10/MWt-h	>$10/MWt-h
2.3.1	Availability factor	**>90%**	70-90%	<70%
3.1.1	Ability to address key licensing issues for follow-on commercial units	**Demonstration unit can address most of the key licensing issues for follow-on commercial units**	Demonstration unit can address some of key licensing issues for follow-on commercial units	Demonstration unit can address few number of key licensing issues for follow-on commercial units
3.1.2	Size of emergency planning zone	**< 400 m**	0.4-16 km	16 km
4.1.1	Does the system facilitate component demonstration of that expected in follow-on commercial units?	**Prototypic**	Scalable	Neither
4.2.1	Number of alternative core configurations (e.g. seed blanket and core, or breed and burn)	**More than 2**	1-2	None

Metric	**Description**	**Scores and Criteria**		
		9	**5**	**1**
4.2.2	Number of alternative fuel types	**More than 2**	1-2	None
4.3.1	R&D Time	<5 years	**5-10 years**	> 10 years
4.3.2	R&D Cost	< 250 M$	**250-500 M$**	>500 M$
4.4.1	Fast flux conditions	>5E15 n/cm2-s	**5E14 to 5E15 n/cm2-s**	<5E14 n/cm2-s
4.4.2	Thermal flux conditions (<0.625 eV)	>5E14 n/cm2-s	1E14 to 5E14 n/cm2-s	**<1E14 n/cm2-s**
4.4.3	Irradiation volume and length	**Vol > 10 l, length > 2 m**	Vol = 5-10 l, length = 0.5-2.0 m	Vol < 5 l, length < 0.5 m
5.1.1	Use of fuel natural resources	**<20 MT/GWe-yr**	20-150 MT/GWe-yr	>150 MT/GWe-yr
5.2.1	Is the fuel fabrication approach prototypic or scalable to commercial unit?	**Prototypic**	Scalable	Neither
5.3.1	Is the anticipated fuel performance prototypic or scalable to commercial unit?	Prototypic	**Scalable**	Neither
5.4.1	Is the spent fuel handling prototypic or scalable to commercial unit?	**Prototypic**	Scalable	Neither
6.1.1	Number of energy conversion systems or industrial applications (for the actual design, not the potential of the technology)	More than 3	**1-3**	None
6.2.1	Coolant outlet temperature	>700 °C	**400-700 °C**	<400 °C