Appendix 4.0

Lead-Cooled Fast Reactor

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ACRONYMS

ABR	Advanced Burner Reactor
ANL	Argonne National Laboratory
CO_2	Carbon Dioxide
CRIEPI	Central Research Institute of Electric Power Industry
DOE	Department of Energy
DRACS	Direct Reactor Auxiliary Cooling System
ELSY	European Lead-cooled System
ETD/EFIT	European Transmutation Demonstrator/European Facility for Industrial Transmutation
EURATOM FP6	European Atomic Energy Community 6th Framework Programme
F/M	ferritic/martensitic
FY	fiscal year
GIF	Generation IV International Forum
GNEP	Global Nuclear Energy Partnership
GRID	GNEP Reactors for International Deployment
I-NERI	International Nuclear Energy Research Initiative
IP EUROTRANS	European Integrated Project on transmutation of high-level nuclear waste in an accelerator driven system
IPPE	Institute of Physics and Power Engineering
IRACS	Intermediate Reactor Auxiliary Cooling System
ISTC	International Science & Technology Center
KAERI	Korean Atomic Energy Research Institute
LANL	Los Alamos National Laboratory
LBE	lead-bismuth eutectic
LETF	Lead Engineering Test Facility
LFR	Lead-Cooled Fast Reactor
LWR	light water reactor
MPa	megapascals
MWe	megawatt electric
MWt	megawatt thermal
PCHE	printed circuit heat exchanger
PEACER	Proliferation-resistant, Environment-friendly, Accident-tolerant, Continuable-energy, Economical Reactor
RVACS	Reactor Vessel Auxiliary Cooling System

S-CO_2	supercritical carbon dioxide
SSTAR	Small Secure Transportable Autonomous Reactor
TRU	transuranic

A4.1 INTRODUCTION AND BACKGROUND

The Lead-Cooled Fast Reactor (LFR) has been identified as a technology with great potential to meet the Generation IV mission interests. It is also a candidate for use as a Global Nuclear Energy Partnership (GNEP) reactor for international deployment (GRID), especially in developing countries with limited-capacity power grids. It can also be considered as a backup candidate for the advanced burner reactor (ABR). The LFR is mainly directed toward electricity and hydrogen production, and actinide management. Options for the LFR include a range of plant ratings and sizes from small modular systems to multi-hundred megawatt sized plants.

Two key technical aspects of the LFR that offer the prospect for achieving the Generation IV and GNEP goals of non-proliferation, sustainability, safety and reliability, and economics are (1) the use of lead (Pb) coolant and (2) a long-life, cartridge-core architecture in a small, modular system intended for deployment in areas with limited grid capacity or in remote or isolated locations. Figure A4.1 shows the conceptual LFR system. The Pb coolant exhibits very low parasitic absorption of fast neutrons, and this enables the sustainability and fuel cycle benefits traditionally associated with liquid metal-cooled fast spectrum reactors. Pb does not react readily with air, water/steam, or carbon dioxide, eliminating concerns about vigorous exothermic reactions. It has a high boiling temperature (1,740°C), so the need to operate under high pressure and the prospect of boiling or flashing in case of pressure reduction are eliminated. Two land prototypes and ten submarine reactors using lead-bismuth eutectic (LBE) coolant were operated in Russia, and this provided about eighty reactor years of operating experience. This significant operating experience together with the associated substantial development of coolant technology and approaches for the control of structural material corrosion provide a valuable proof of principle for such heavy-metal cooled systems. The Russians, Europeans, and South Koreans continue to have strong interest in the LFR technology and are therefore candidates for partnering with this technology in GNEP.

The LFR concept currently being studied in the U.S. Generation IV Program is the Small Secure Transportable Autonomous Reactor (SSTAR) concept, which is a small modular fast reactor. The main mission of the 20 MWe (45 MWt) SSTAR is to provide incremental energy generation to match the needs of developing nations and remote communities with small and isolated electrical grids, such as those that exist in Alaska or Hawaii, Ulung Island in the Republic of Korea, island nations of the Pacific Basin (e.g., Indonesia), and elsewhere. This gives early LFR designs a unique niche market for development. In such markets, costs for competing sources of electricity generation are typically higher than in larger markets while large-scale nuclear power plants are not appropriate due to the limited grid capacity. Subsequent evolution of the LFR technology to larger sizes may broaden deployment potential from this niche market to the overall market as the economic benefits of scale combined with the inherent potential of lead-cooled systems for plant simplification are realized.

Design features of the reference SSTAR include a 30-year-lifetime converter core; a natural circulation primary cooling system; autonomous load following; minor control rod adjustability to compensate for the low burnup reactivity swing over the core lifetime; and use of an innovative supercritical carbon dioxide (S-CO_2) energy conversion system. The incorporation of inherent thermo-structural feedbacks imparts walk-away passive safety, while the use of a cartridge core with a 30-year or longer cycle time between refueling imparts strong proliferation resistance. With realization of these technical innovations, the LFR will provide a unique and attractive nuclear energy system that meets Generation IV goals and makes important contributions to GNEP.

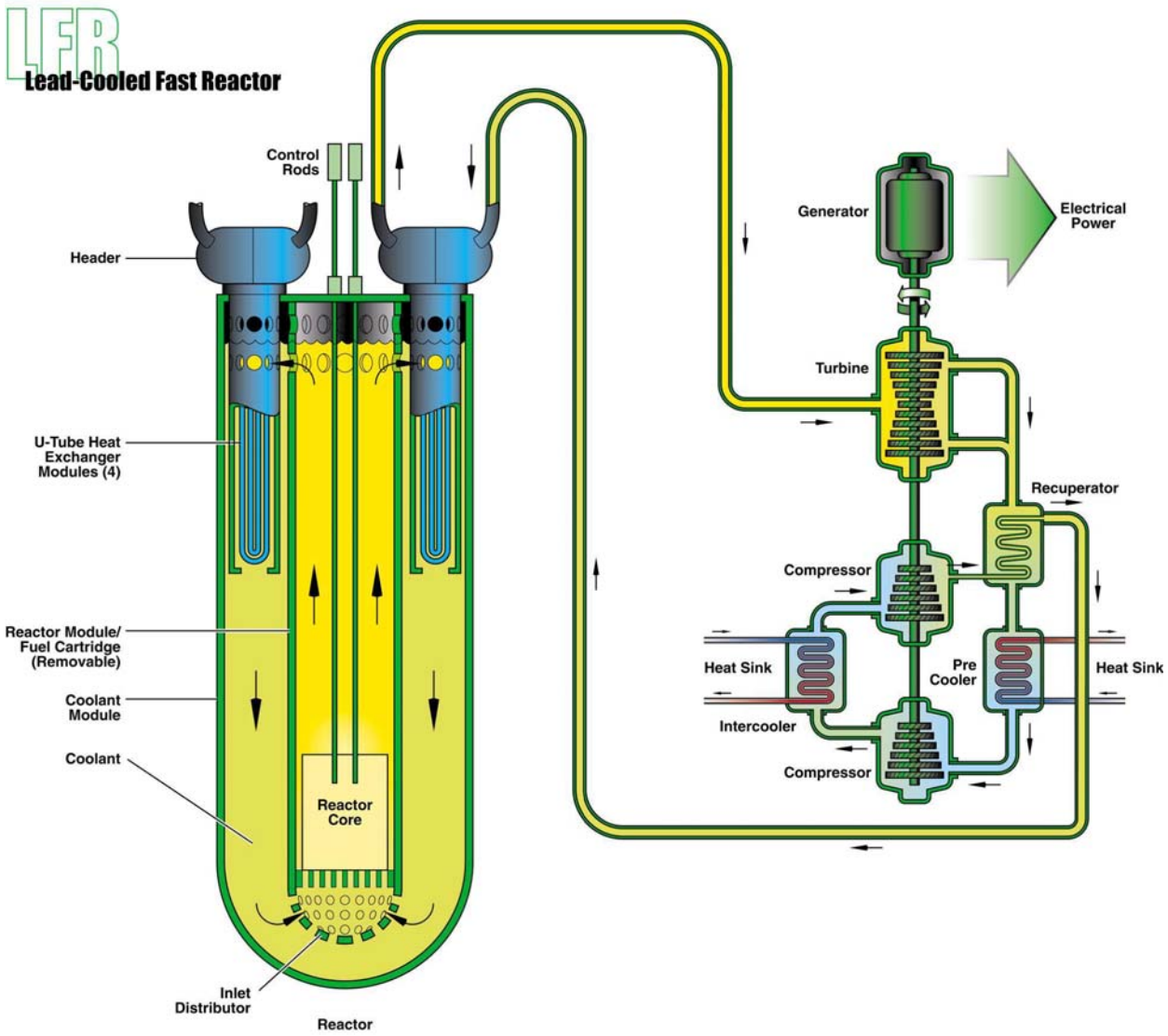

Figure A4.1. Conceptual LFR system.

The SSTAR-type LFR also provides a unique capability for management of actinides. The reactor can be fueled with the plutonium and minor actinide mixture that results from processing Light Water Reactor (LWR) spent fuel (plus some of the separated uranium). With a conversion ratio very near unity to enable the long core life, it serves as neither a breeder nor a burner. It uses the actinides for 30 years and then returns them to be reused upon recycle of the core by the supplier. The fissile material can then be either reformed into more SSTAR fuel for another 30 years of working storage or be made available for other reactors, either thermal or fast spectrum. Early deployment of such reactors could absorb much if not all of the fissile material from LWR recycle and return it at a future time when fissile material supply could be a limiting factor in nuclear energy growth. Alternatively, LFRs could be configured as burner reactors with a shortened fuel cycle and more frequent refueling and have the potential of being more economical than sodium cooled reactors because of the reduction in equipment (no secondary loop) and no need for concern about sodium air/water reaction accidents. The comparatively small size of the S-CO_2 energy conversion system compared to conventional steam systems provides further basis for reduction in building footprints and costs.

A4.1.1 System Description

SSTAR utilizes transuranic (TRU) nitride fuel enriched to nearly 100% in ^{15}N in a compact core. Heat is removed from the core and transported to in-vessel Pb-to-CO_2 heat exchangers by single-phase natural circulation of the Pb coolant; the need for main coolant pumps is eliminated. The fast spectrum core with nitride fuel and Pb coolant has strong reactivity feedbacks that enable autonomous load-following and provide passive power shutdown in the event of loss-of-normal heat removal. The core has a long lifetime/refueling interval of 30 years during which access to the core is restricted, providing proliferation resistance; the TRU fuel is rendered self-protective in the safeguards sense by means of incomplete fission product removal. The Pb coolant and nitride fuel provide for enhanced passive safety whereby the core and in-reactor heat exchangers remain covered by ambient pressure, single-phase, primary coolant inside the reactor vessel, and single-phase natural circulation removes the core power under all operational and postulated accident conditions. The reference SSTAR reactor system is coupled to an S-CO_2 gas turbine Brayton cycle power converter that enables significant improvements and cost savings over the traditional Rankine steam cycle including higher cycle efficiency at temperatures attainable with Pb primary coolant and nitride fuel (650°C peak cladding temperature and 567°C core outlet temperature for a 420°C inlet temperature) as well as remarkably small compressors and turbine, and a smaller plant footprint with simpler secondary side components.

The SSTAR reference reactor core and heat exchangers fit inside a reactor vessel (Figure A4.2) that is about 12 m tall and 3.2 m in diameter—small enough to be transported either by rail, barge, or overland transporter. The compact ~1.22 m diameter/0.98 m height active core (Figure A4.3) is located near the bottom of the vessel. Large diameter (2.5 cm) fuel pins are arranged on a triangular pitch (p/d = 1.185). The core is not composed of individual removable assemblies but is a single proliferation resistant cassette that can be accessed only when refueling equipment is brought to the site at the end of the core lifetime. The fuel pins consist of TRU nitride (enriched to nearly 100% ^{15}N) pellets bonded by molten Pb to the silicon-enhanced ferritic/martensitic (F/M) stainless steel cladding. A tall fission gas plenum (1.75 times the active core height) is provided at the top of each fuel pin. The molten Pb coolant flows upward through the core and the overlying riser region inside of a cylindrical shroud. Near the free surface at the top of the Pb, the coolant enters modular Pb-to-CO_2 heat exchangers located in the annulus between the shroud and reactor vessel to flow downward over the exterior of double-walled tubes containing the upward flowing carbon dioxide (CO_2). The Pb continues through the downcomer region beneath the heat exchangers and enters the lower plenum below the core where a flow distributor tends to equalize the pressure at the core inlet.

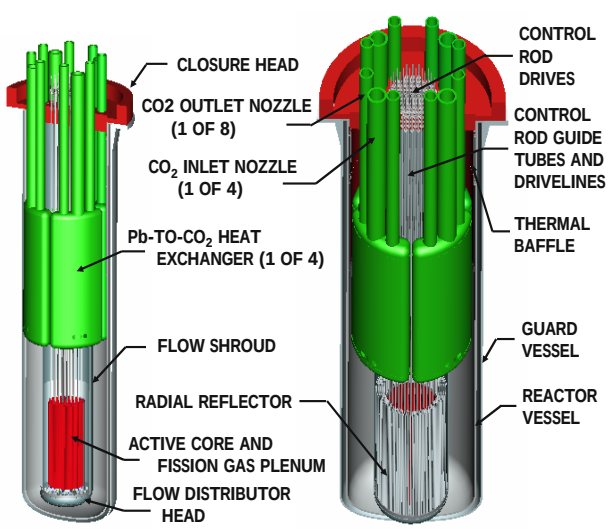

Figure A4.2. Small Secure Transportable Autonomous Reactor (SSTAR).

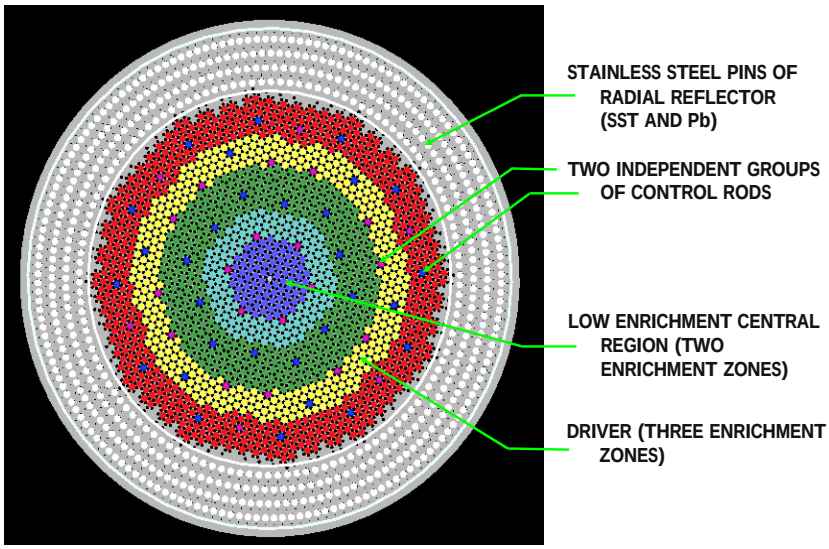

Figure A4.3. SSTAR 30-Year Lifetime Cassette Core (All Fuel Pins Are Shown).

The Pb flow is driven solely by natural circulation. The low core pressure drop reflecting a large coolant hydraulic diameter and short fuel pin height is important to this feature. The Pb coolant enters the core at 420°C (providing adequate margin above the Pb freezing temperature of 327°C) and exits the core at a 567°C mixed mean outlet temperature. The maximum temperature at the cladding inner surface is 650°C. Corrosion control is maintained through the formation and maintenance of protective oxide (Fe_3O_4 at lower temperatures) layers upon the steel structural surfaces through maintenance of the dissolved oxygen potential in the Pb coolant. Control rods provide for startup and shutdown while small compensating rod movements offset small reactivity changes during the 30-year core lifetime. Control rods are not needed to effect power changes during autonomous load following due to the strong reactivity feedbacks of the fast spectrum core. The reactor vessel is surrounded by a guard vessel. The exterior of the guard vessel is passively cooled at all times by upward flowing air driven by natural convection; passive air cooling provides for emergency heat removal in the event that neither the normal operational nor shutdown heat removal paths are available. The reactor system is coupled to an S-CO_2 power converter. S-CO_2 at 20 MPa pressure is heated to 552°C in the in-reactor Pb-to-CO_2 heat exchangers (Figure A4.4). It expands to about 7.8 MPa in a remarkably small turbine that drives the generator and then passes through two recuperators (a high temperature recuperator followed by a low temperature recuperator) where a portion of the remaining thermal energy is extracted to preheat the compressed CO_2 that is returned to the in-reactor heat exchangers.

Upon exiting the low temperature recuperator, about 67% of the CO_2 passes through the cooler where heat is rejected from the cycle and the CO_2 is cooled prior to entering a small main compressor at 31.25°C inlet temperature and 7.4 MPa inlet pressure. The CO_2 is compressed to 20 MPa, and preheated in the low temperature recuperator. The remaining 33% of the CO_2 is directly recompressed in a second compact compressor and merged with the other flow stream between the low and high temperature recuperators. This flow split/merge approach is necessitated by the significantly greater specific heat of the higher pressure CO_2 over the temperature range of the low temperature recuperator. The recuperators and cooler incorporate compact diffusion bonded printed circuit heat exchangers (PCHEs), to further reduce component volumes. The plant efficiency of 44% provides 19.8 MWe of electricity for 45 MWt of core thermal power. An expanded description of the most recent SSTAR design is provided in References [1 and 2]. Reference [3] is a preliminary cost study of the SSTAR type reactor power plant and indicates that these plants have the potential for being competitive with power generation costs in many developing and remote regions of the world.

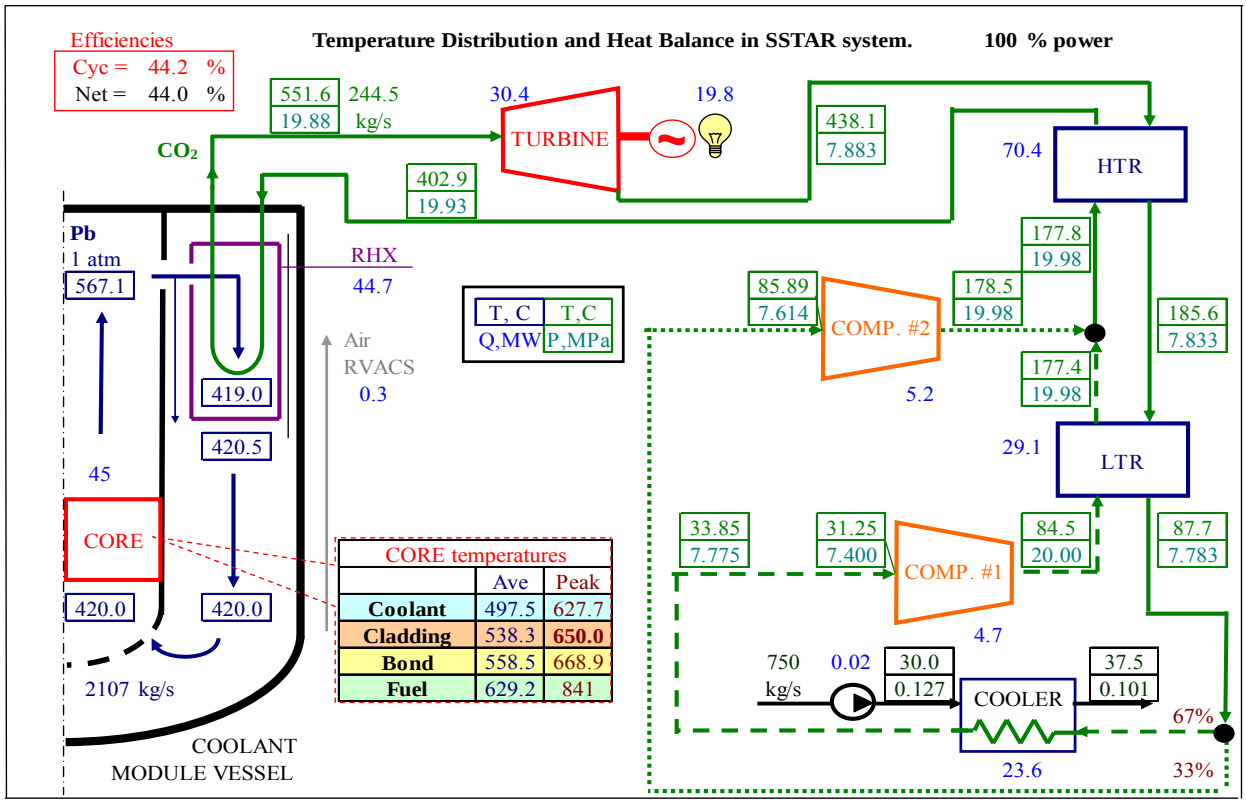

Figure A4.4. Schematic Illustration of SSTAR Reactor and Supercritical Carbon Dioxide Brayton Cycle Energy Converter.

A concept for an early technology demonstration reactor is being developed to provide a shorter, and perhaps less costly, path forward for SSTAR development. The early demonstrator would back off from certain SSTAR design features to permit near-term construction with low technology risk, while demonstrating key SSTAR features and providing a test bed for other SSTAR features. Reduction in operating temperature and core lifetime would enable construction with existing materials, while allowing for advanced material testing. Use of metal or oxide driver fuel might avoid long fuel qualification for nitride fuel, while the facility could be used for nitride fuel testing to qualify future core fuel. Modest increase in neutron flux would reduce test time for fuels and materials. A demonstrator is also an important part of the development of the European Lead-cooled System (ELSY) concept. Development of the concept for a technology demonstrator includes trade studies to identify innovative engineering features that exploit the characteristics of Pb as a coolant and allow the demonstration of the economic potential and industrial attractiveness of lead-cooled systems providing for confirmation of both the SSTAR and ELSY concepts.

A4.1.2 System Timeline

The schedule proposed for LFR development is illustrated in Figure A4.5. The plan described in this section reflects 10 years of a 20-year development program leading to startup of a LFR demonstration unit. The key date in the current Ten-Year Program Plan is a decision in 2014 whether to proceed to construction of the LFR demonstration plant.

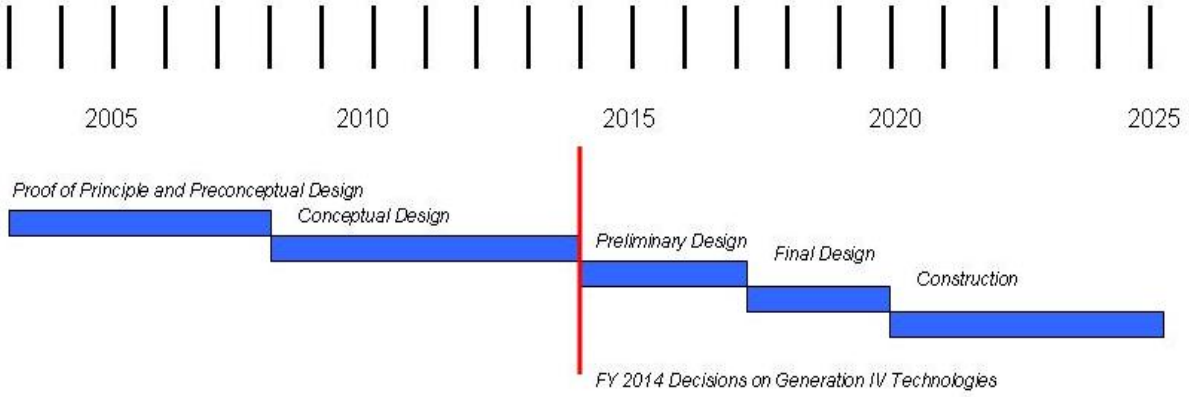

Figure A4.5. Proposed schedule for LFR/SSTAR development.

A4.2 RESEARCH AND DEVELOPMENT STRATEGY

The LFR development strategy incorporates a near-term focus on the technologies needed for the development of a small, simple modular reactor design intended for specialized markets. Targeting this market with a small simple reactor provides the benefit of manageable research and development (R&D) and demonstration costs. If market conditions motivate it, the technology base can be applied later to larger LFR concepts as needed to support a long-term sustainable fuel cycle. Current and near-term R&D is planned to address key viability issues leading to the 2014 decision on construction of an LFR technology demonstrator, while subsequent R&D will address issues leading to alternative plant configurations for the diverse market. The most critical issue needing resolution at this time is the structural and fuel cladding material selection. Much evaluation of the compatibility of heavy metal coolant and structural materials has been completed and Reference [4] provides a summary of the status of material development. Coordination and information sharing with international partners, particularly the mainly European Community team pursuing the ELSY reactor development, are important in assuring that the SSTAR project is efficiently and effectively pursued. The Generation IV International Forum (GIF) Provisional R&D Steering Committee has prepared a draft of the System Research Plan (SRP) for the LFR with molten lead as the reference coolant option and LBE as backup coolant. Figure A4.6 illustrates the basic concept underlying this LFR SRP. It portrays the dual track viability research program leading to a single, combined demonstration facility with the eventual deployment of both types of systems.

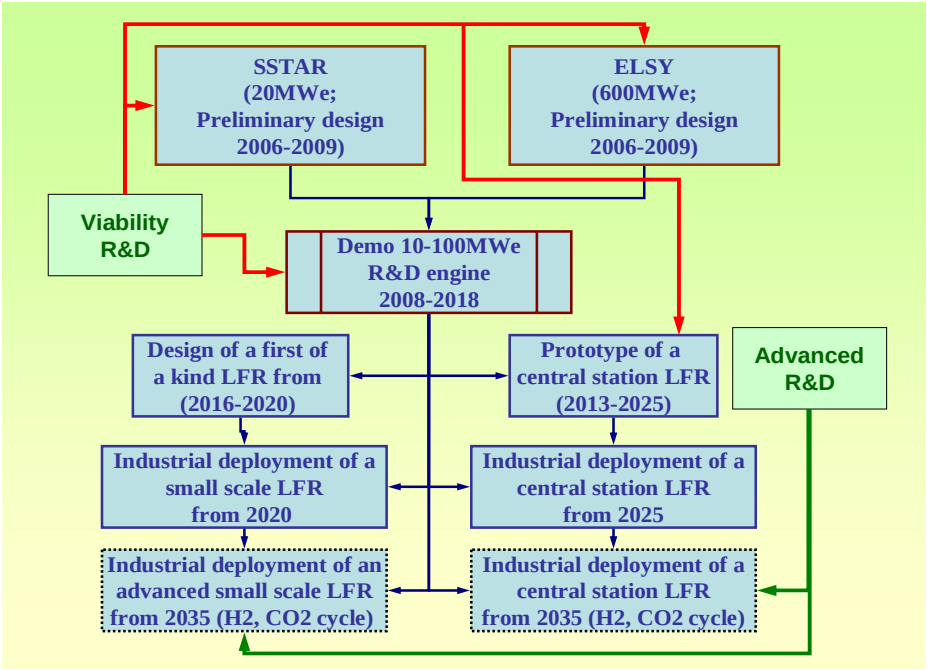

Figure 4A.6. SRP Conceptual Framework.

A4.2.1 Objectives

LFR viability R&D objectives can be grouped according to two purposes:

1. Objectives demonstrating the viability of LFR/SSTAR features to meet all of the Generation IV goals and GNEP goals for GRID type reactors
2. Objectives demonstrating the viability of satisfying requirements for commercial LFR/SSTAR nuclear power plants that serve the diversified nuclear plant market.

Objectives directly related to meeting each of the Generation IV and GRID reactor goals are:

- *Sustainability-1 (S-1) and Sustainability-2 (S-2):* Analyses indicate that the LFR with a fast neutron spectrum core with TRU nitride fuel and Pb coolant is fissile self-sufficient with a core conversion ratio slightly greater than unity. This enables a closed fuel cycle in which there is a fertile feed stream of depleted or natural uranium and a minimal volume waste stream comprised only of fission products. All fissile material including minor actinides can be recycled in the fabrication of new fuel cores and burned as fuel in reactors. Objectives are to confirm the viability of these attributes.
- *Economics-1 (E-1):* Oversight and generation costs have been estimated to be competitive with alternative sources of energy in many areas of the developing world. Objectives are to demonstrate the viability of reducing costs by taking advantage of LFR system attributes that enable savings such as system simplification and enhancement of reliability through elimination of the need for an intermediate heat transport circuit; elimination of main coolant pumps; autonomous load following that simplifies control systems, enhances reliability, and reduces operator requirements; utilization of S-CO_2 Brayton cycle power conversion that offers higher plant efficiency together with smaller, simpler, and fewer balance-of-plant components; and a small plant footprint, factory fabrication, and modular transport and installation at the site that reduce construction time and costs.

- *Economics-2 (E-2):* Financial risk remains to be quantified. The small modular plant requires a smaller outlay of funds and provides a shorter construction time in comparison with a large plant. When the plant goes online it becomes a source of positive cash flow that can be applied to financing the construction of the next module and so on. An objective is to establish the viability of this approach. Another objective of passive safety is to demonstrate the viability of minimizing the threat to investment in the plant due to postulated accidents or sabotage.
- *Safety and Reliability-1 (SR-1):* Objectives are to show the viability of taking advantage of the highly favorable LFR attributes, including properties of Pb coolant (inertness with respect to interactions with CO_2, water/steam, and air, and high boiling temperature), properties of nitride fuel (compatibility with cladding, bond, and coolant; low irradiation-induced swelling and fission gas release; high decomposition temperature; and large thermal conductivity), natural circulation heat transport at power levels exceeding 100% nominal, and large reactivity feedbacks from the fast spectrum core that provide passive power reduction to achieve 'walk-away' passive safety.
- *Safety and Reliability-2 (SR-2):* The SSTAR core and heat exchangers will remain covered by ambient pressure, single-phase, primary coolant inside the reactor vessel, and single-phase natural circulation will remove the core power to either the normal or shutdown heat removal pathways or the Reactor Vessel Auxiliary Cooling System (RVACS) emergency heat removal system under all operational and postulated accident conditions. Objectives are to affirm that this is the nominal behavior and to demonstrate that scenarios that could conceivably result in core damage, such as the simultaneous penetration of both the reactor vessel and guard vessel, have an extraordinarily low probability.
- *Safety and Reliability-3 (SR-3):* Objectives are to develop a viable licensing approach that effectively uses "Walk Away" passive safety and a very low likelihood of core damage to possibly roll back the licensing requirements for offsite emergency response. A specific objective is the acceptance of passive safety as a barrier in the defense-in-depth approach that is a bedrock principle of licensing to argue for reduction of the size of the exclusion and emergency planning zones.
- *Proliferation Resistance and Physical Protection-1 (PR-1):* The TRU fuel with incomplete fission product removal is self-protective in the safeguards sense. In addition, the long core life and transportability features offer a unique approach to proliferation resistance by eliminating the need for an indigenous fuel cycle infrastructure or for the need to handle fresh or spent fuel. Objectives are to establish the viability of achieving a very long core lifetime (which has been shown to be neutronically viable) together with the viability of design measures to restrict access to the fuel or neutrons, to effectively refuel the core and transport it in a coolable and shielded state while maintaining a high resistance to theft, and to provide a plant that is resistant to sabotage or malevolent human-induced acts (e.g., airplane crashes).

Table A4.1 summarizes how specific features of the LFR/SSTAR system can contribute to satisfaction of all of the Generation IV goals. Table A4.2 summarizes how specific requirements for the LFR/SSTAR system can contribute to satisfaction of all of the Generation IV goals. In addition to satisfying GEN-IV goals it is possible that a variation of the LFR may be the most economical system for future Advanced Burner Reactors (ABRs). Larger size LFR plants with cores designed for actinide burning have the potential to achieve the GNEP goals for the ABR at reduced overnight cost.

Table A4.1. Contribution of specific LFR/SSTAR features to meeting of Generation IV goals.

LFR Features	S-1	S-2	E-1	E-2	SR-1	SR-2	SR-3	PR-1
Pb Properties	+	+	+	+	+	+	+	
Nitride Fuel Behavior	+	+			+	+	+	
Fast Spectrum Core—Long Core Lifetime			+	+				+
Fast Spectrum Core—Unity Conversion Ratio	+	+	+	+				+
Fast Spectrum Core—Burn-up Reactivity Swing <$1			+	+	+	+	+	
Fast Spectrum Core—Large Reactivity Feedbacks			+	+	+	+	+	
Simplification—Elimination of Intermediate Heat Transport System			+	+	+	+	+	
Simplification—Natural Circulation Primary Coolant Heat Transport			+	+	+	+	+	
Passive Safety			+	+	+	+	+	
TRU Fuel—Self Protection	+							+
S-CO_2 Brayton Cycle Power Conversion			+	+				
Small Power Level—20 MWe (45 MWt) to 100 MWe			+	+				
Factory Fabricability			+	+				
Full Transportability and Modular Assembly and Installation at Site			+	+				

Table A4.2. Contribution of specific LFR/SSTAR requirements to meeting Generation IV goals.

LFR Requirements	S-1	S-2	E-1	E-2	SR-1	SR-2	SR-3	PR-1
Proliferation Resistance								+
Small Power Level - 20 to 100 MWe			+	+				
Economical Overnight Capital and Generation Costs; Niche Market Conditions			+	+				
'Walk Away' Passive Safety			+	+	+	+	+	
Autonomous Operation			+	+	+	+	+	
Fissile Self-Sufficiency	+	+	+	+				+
Reactor Compatible with Advanced Energy Conversion			+	+				
Small Power Level—20 MWe (45 MWt)			+	+				
Factory Fabrication of All Reactor and Balance-of-Plant Components			+	+				
Full Transportability and Modular Assembly and Installation at Site			+	+				
Efficient Fuel Utilization	+	+	+	+				
60-Year Plant Lifetime			+	+				
Plant Licensable by U.S. Nuclear Regulatory Commission					+	+	+	
Near Worldwide Deployable	+	+	+	+	+	+	+	
In-Service Inspection			+	+	+	+	+	
Flexibility to Generate Other Energy Products—Desalinated Water			+	+				

A4.2.2 Scope

This R&D plan addresses viability issues associated with the LFR leading to a decision in 2014 to proceed with design and construction of the LFR demonstration plant. The plan reflects 10 years of a 20-year development program leading to startup of a LFR demonstration unit. Viability will be established through focused R&D tasks and with formulation of a technically defensible pre-conceptual design. Conceptual design will begin in 2009 and continue, given a decision for pursuing the LFR construction project in 2014. R&D tasks that support conceptual design will be defined in more detail at a later time in the viability R&D program, but will include analysis and experiments intended to reduce design uncertainty and to establish conceptual limiting conditions of operation. Coordination with other international LFR programs remains an important component.

A4.2.3 Viability Issues

Viability issues for the LFR are listed topically as follows and are further described in Section A4.3.

- Core Neutronics
  - Fuel conversion sufficient to sustain a 15- to 30-year-life core
  - Identification of core parameters that provide feedback coefficients, and ensure passive safety and autonomous load following viability
- System Thermal-Hydraulics
  - Natural circulation within core parameter constraints necessary to meet conversion and thermo-structural feedback requirements
  - Thermal response to feedback to ensure passive safety and autonomous load following
  - Feasibility of elimination of an intermediate loop
  - Identification of Pb-S-CO_2 heat-exchanger parameters meeting performance and component design requirements
  - Safety issues arising from S-CO_2 tube rupture and identification of mitigation concepts
  - Concepts for passive decay heat removal.
- Structural Design
  - Stress and temperature conditions for structural materials are compatible with expected materials performance.
- Materials
  - Materials structural reliability in the anticipated service environment (i.e., high-temperature Pb in a fast neutron flux)
  - Materials compatibility with and corrosion behavior in high-temperature Pb
  - Conditions of operation required to ensure materials integrity and compatibility are practically achievable in an operating plant.

- Nitride Fuel
  - Uranium nature and TRU nitride compatibility with Pb at elevated temperatures
  - High-burnup potential of nitride fuel during an extended core life is not yet established
  - Transient behavior must be shown to not exacerbate off-normal events
  - Repeated recycling of high actinide content fuel.
- Passive Safety Characteristics
  - Thermo-structural feedback coefficients required to ensure passively safe response must be practically achievable
  - Decay heat removal after accidents must be sufficient to prevent core damage
  - Pb-S-CO_2 heat exchanger tube rupture must not prevent heat removal from the core or introduce positive reactivity insertion
  - Relief of reactor system overpressure following Pb-S-CO_2 heat exchanger tube rupture.
- In-service Inspection
  - Reactor vessel and safety system integrity in the vessel sealed for 30 years must be verified using a viable and practical means.
- Cost Impacts
  - Design features to achieve necessary safety and proliferation resistance must not impact capital costs to render the LFR uneconomical for the envisioned deployments
  - Operating strategy must be compatible with requirements to ensure operating costs are acceptable for the envisioned deployments
  - Cost-essential design features must be identified to ensure compatibility with design for performance.
- Whole-core Refueling
  - Concepts for safe and secure refueling must be identified and must be practical
  - Shielding and cooling of a spent core cassette must be practically achievable
  - Design features to allow refueling must not add significantly to capital cost and must not compromise safety of containment.
- S-CO_2 Brayton Cycle Energy Conversion
  - The energy conversion system must be developed and demonstrated
  - The smaller, innovative conversion plant components must be developed and demonstrated.

A4.2.4 Research Interfaces

The LFR R&D program interfaces with a number of domestic and international partners, as described below. In addition, the current LFR concept calls for use of an S-CO_2 energy conversion system, and this plan assumes that the U.S. Generation IV Energy Conversion R&D will address development needs of that technology. However, the LFR program will identify and address aspects of S-CO_2 energy conversion that are specific to the LFR.

A4.2.4.1 Relationship to Generation IV International Forum Research and Development Projects and Other International Cooperation

A GIF LFR Provisional System Steering Committee has been formed with members from the European Community (EC), Japan, Republic of Korea, and the U.S. The Russian Federation has also recently joined the GIF with experts from the Institute of Physics and Power Engineering (IPPE) and the Russian Research Center "Kurchatov Institute" (RRC KI) being designated to represent Russian interests. There has been a long history of cooperation with Russian Pb-Bi and Pb reactor technology experts, in particular from IPPE which has been the leading research and development laboratory for Pb-Bi and Pb technology in the Russian Federation. Several on-going International Science and Technology Center (ISTC) projects support further development of coolant technology and materials.

In the bilateral action plan to enhance global and bilateral nuclear energy cooperation developed by the US-Russian Civilian Nuclear Energy Working Group, one of the principal areas of cooperation is the development of exportable small- and medium-yield reactors, sustainable in terms of safety and nonproliferation. The leading Russian developers of LBE/Pb cooled fast reactors will be well represented in the subgroup on this topic.

Since they have substantial prior experience with LBE cooled reactors, interactions with the Russians through the GIF could further benefit LFR development. A working draft of an LFR System Research Plan (SRP) has been developed that describes the research interests of each participant and identifies opportunities for collaborative studies. The SRP includes tracks toward both small (SSTAR-type) and medium-large-sized LFRs (ELSY-type), with potential for a joint demonstration reactor of intermediate size.

Lead coolant R&D activities in Europe are well established based on active past and ongoing research efforts in the development of accelerator-driven systems. In 2005, a group of 29 organizations and many universities initiated the European Integrated Project on transmutation of high-level nuclear waste in an accelerator driven system (IP EUROTRANS) project to develop a preliminary design for a European Transmutation Demonstrator/European Facility for Industrial Transmutation (ETD/EFIT). More recently, in September of 2006, renewed European interest in reactor R&D led to the initiation of the ELSY project , sponsored by the EURATOM 6th Framework Programme (EURATOM FP6) to design and evaluate a medium-size (600 MWe) lead-cooled, forced convection fast reactor. U.S. organizations have been updated periodically on the ELSY project, and it has become a central element of the Generation IV International Forum LFR System Research Plan, along with SSTAR. Continued sharing of project status information is anticipated.

Work with Japan includes cooperation on topics common to small modular fast reactors, with focus on lead coolant in the U.S. and sodium coolant in Japan. Periodic coordination meetings are held with the Central Research Institute of Electric Power Industry (CRIEPI) and Toshiba. In addition, technical collaborations and information exchanges exist with the Japan Atomic Energy Agency (JAEA) and Tokyo Institute of Technology. Finally, communication with organizations conducting LFR research in South Korea as well as Japan is an ongoing part of participation in the GIF.

A4.2.4.2 University Collaborations

The University of California-Berkeley has been a long-standing member of the LFR R&D community with contributions in innovative core and component design and analysis.

Partnership in material science topics includes work with Massachusetts Institute of Technology, University of Nevada-Las Vegas, University of Illinois at Urbana-Champaign, and University of Wisconsin at Madison.

A4.2.4.3 Industry Interactions

In addition to working with Toshiba via CRIEPI, discussions on potential cooperation have been held with General Electric and Westinghouse. Further industry participation is expected when funding permits.

A4.2.4.4 International Nuclear Energy Research Initiatives/Nuclear Energy Research Initiatives

A U.S. Department of Energy (DOE)/EURATOM Joint International Nuclear Energy Research Initiative (I-NERI), "Lead Fast Reactor Engineering and Analysis," is in progress between Argonne National Laboratory (ANL) and the Joint Research Center of the European Commission, Institute for Energy in Petten, the Netherlands.

There is an on-going I-NERI between Los Alamos National Laboratory (LANL) and the Korean Atomic Energy Research Institute (KAERI) and Seoul National University in the Republic of Korea on fuel cladding materials development and testing as well as improved oxygen sensors. The Republic of Korea program, Proliferation-resistant, Environment-friendly, Accident-tolerant, Continuable-energy, Economical Reactor (PEACER), is developing a LBE-cooled transmutation reactor.

There is an ongoing I-NERI between ANL and the KAERI on "Supercritical Carbon Dioxide Brayton Cycle Energy Conversion." Seoul National University is also a contributor to that collaboration through a subcontract from KAERI.

A proposed cooperation with the Japan Atomic Energy Agency would examine oxide dispersion strengthening (ODS) steel irradiation performance and compatibility with Pb-alloys. Another proposed cooperation with CRIEPI would involve participation in retrieval and examination of archived Fast Flux Test Facility material irradiation specimens.

A new U.S./EURATOM I-NERI project has been proposed, "Lead-Cooled Fast Reactor Concept Design and Evaluation," between Argonne National Laboratory, the European Nuclear Energy Agency, Lawrence Livermore National Laboratory, and Del Fungo Giera Energia S.p.A for trade studies for a near-term deployable LFR demonstrator.

A4.3 HIGHLIGHTS OF RESEARCH AND DEVELOPMENT

A4.3.1 Core Neutronics

Motivation:

Core design is essential in establishing the necessary features of a 30-year-life core, and determining core parameters that impact feedback coefficients, which are essential inputs for establishing passive safety and autonomous load-following viability.

Tasks:

- Further optimize the core configuration
  - Determine the size of the central low enrichment zone and configurations of the active core enrichment zones to reduce radial power peaking and improve time-dependent conversion behavior for the long-life core strategy.
- Establish startup/shutdown rod and control rod strategy
  - Assess number and location of rods
  - Satisfy diversity and redundancy requirements
  - Confirm low excess reactivity requirements for each control rod.
- Calculate reactivity feedback coefficients
  - Support autonomous load following evaluation
  - Support passive safety evaluation.

A4.3.2 System Thermal-Hydraulics

Motivation:

Studies of system thermal-hydraulics are essential for establishing the parameters for potential natural circulation cooling in the primary system, identifying any safety issues to be addressed in subsequent design, and establishing parameters for ensuring passively-safe response.

Tasks:

- Conduct autonomous load following evaluation for reactor using the calculated reactivity feedback coefficients
  - Determine need for any enhancement of core radial expansion feedback
  - Develop and evaluate control strategy for S-CO_2 Brayton cycle to match the heat removal from the reactor to the load demand from the electrical grid over power levels from near zero to above nominal.
- Determine viability of elimination of intermediate heat transport system
  - Evaluate effect of tube rupture in Pb-to-CO_2 heat exchanger and blow-down of CO_2 into reactor system
  - Develop pressure relief strategy for reactor coolant system

- Evaluate need to contain CO_2 and entrained radionuclides released from reactor coolant system
- Assess impact upon containment configuration, size, capability, and other requirements
- Determine viability of failure-resistant heat exchanger concepts.

- Ensure viability of startup using natural circulation
  - Evaluate possible need for small flow assist during startup or shutdown
  - Assess options for startup flow: mechanical, electromagnetic, lift (non-condensable gas injection), or jet pumps
  - Assess options for melting the Pb and heating the primary coolant system to maintain the Pb in a molten state prior to and during initial neutronic startup.
- Establish viability of emergency heat removal concept
  - Evaluate reliability and safety grade system requirements
  - Assess performance of passive air cooling of outside of guard vessel
  - Assess effects of coolant chemistry on heat transfer
  - Compare relative merits of alternate in-reactor cooling systems (e.g., Direct Reactor Auxiliary Cooling System [DRACS] or Intermediate Reactor Auxiliary Cooling System [IRACS]) versus RVACS approach – performance, reliability, cost, resistance to attack or sabotage
  - Determine final selection of emergency heat removal approach.
- Determine approaches for accidental and deliberate freezing and thawing of Pb coolant
  - Assess stresses resulting from accidental freezing incidents and potential for damage to fuel pins structures
  - Develop procedure for deliberate freezing of coolant
  - Assess stresses resulting from thawing of frozen coolant
  - Develop procedure for thawing of frozen coolant to minimize potential for damage to fuel pins and structures.

A4.3.3 Structural Design

Motivation:

Viability of the long-life core and passive safety under all abnormal conditions (including seismic events that might unacceptably reconfigure a core) requires materials that can withstand stresses at high temperatures and, for some components, contact with liquid lead. The range of expected stresses and temperatures, and the potential materials must be identified. Establishing actual materials and conditions of operation are design functions to be accomplished later in a development program. However, ranges of conditions must be identified to provide requirements for materials and to determine that such material performance can be achieved within an engineering development program.

Tasks:

- Evaluate pre-conceptual structural design to ensure viability at projected system temperatures up to 650°C peak cladding
  - Identify suitable structural materials for core, in-vessel structures, reactor, and guard vessels using the materials at projected system temperatures
  - Evaluate concepts for core support, core clamping, and restraint
  - Evaluate effect of seismic requirements on structures including reactor and guard vessel thicknesses
  - Evaluate effects of accidental freezing and thawing events upon structures.

A4.3.4 Materials

Motivation:

Prior experience with heavy liquid metals and with fast reactors indicates that construction materials will be challenged in the envisioned LFR environments. Viability of long core lifetime, passive safety, and economic performance (both capital and operating costs) will depend upon identifying materials with the potential to meet service requirements.

Tasks:

- Identify candidate silicon-enhanced F/M steels, oxide dispersion strengthened F/M steels, austenitic steels, silicon carbides, functionally graded materials, and other candidate materials
- Conduct compatibility and corrosion testing of candidate materials with heavy liquid-metal coolants
- Demonstrate control of corrosion to ensure adequate thickness of cladding and structural elements at operating temperatures over long core and reactor lifetimes
- Conduct mechanical property tests to ensure elimination of liquid metal embrittlement at operating temperatures, and substantial retention of strength and structural stability over the long service life
- Develop and test suitable welding and other joining methods
- Prepare code cases for selected cladding and structural materials throughout the operating temperature range.

A4.3.5 Nitride Fuel

Motivation:

Achieving long core life, walk-away passive safety, and reliable operation will require robust and predictable fuel performance for long durations under service conditions. Nitride fuel has many properties and characteristics that render it well suited for LFR application. However, there is very little data on nitride fuel performance to confirm the current design assumptions regarding this fuel type for TRU nitride fuel or for transient fuel performance. In addition, although operation with failed fuel must be a low-probability circumstance, it must be accommodated, so sufficient compatibility of irradiated nitride fuel with lead at high temperatures must be demonstrated.

Tasks:

- Perform irradiation testing and demonstration to projected burnup (>13 atomic weight %) under operating conditions
  - Include TRU nitride with volatile minor actinide constituents.
- Perform transient testing including accident conditions to verify acceptable fuel behavior.

A4.3.6 Passive Safety Evaluation

Motivation:

Passively-safe response can be designed into the reactor core and plant based on current experience and passive safety design principles. However, the magnitudes of feedback coefficients for a given design and integral behavior of a reactor plant must be verified through further analysis. It is anticipated that some coefficients may require enhancement through design modification, and those design impacts must be determined acceptable at the preconceptual level through follow-on analysis. Eventually, inherent response of components (i.e., the magnitude of the coefficients for certain design configuration) must be verified with single-effect experiments and through integral testing and demonstration with a reactor plant. These experimental tasks, however, are not necessary for the viability phase.

Tasks:

- Evaluate operational transients and postulated accidents
  - Apply coupled LFR thermal-hydraulics, neutron-kinetics, S-CO_2 Brayton cycle energy converter plant dynamics analysis code
  - Model both reactor system and S-CO_2 Brayton cycle.
- Evaluate potential for flow instability
- Evaluate potential for flow reversal
- Use calculations to demonstrate that core and Pb-to-CO_2 heat exchangers remain covered by ambient pressure, single-phase, primary coolant inside the reactor vessel and single-phase natural circulation removes the core power under all operational and postulated accident conditions with the exception of postulated beyond design basis accidents having an extraordinarily low probability
- Evaluate removal of afterheat during postulated accidents
- Consider industrial health aspects of operation with Pb and CO_2
  - Pb vapor and aerosols following leaks/spills
  - CO_2 release
  - Po-210 radiotoxicity in case of LBE coolant option.
- Identify decontamination and decommissioning issues that would impact design.

A4.3.7 In-Service Inspection

Motivation:

Fifteen- to thirty-year operation of a plant with a sealed core will require a means of inspection and verification of key safety structures and boundaries. If such integrity cannot be verified, then the LFR concept is not likely to be licensed. Therefore, concepts for inspection and verification (in-service inspection) must be identified during the viability R&D phase for subsequent engineering development.

Tasks:

- Identify in-service inspection approaches for operation over long core lifetimes of 30 years or more or propose and evaluate approaches (e.g., robust core support) that significantly reduce or minimize the requirements for in-service inspection
- Assess capability to operate with failed cladding over long core lifetime.

A4.3.8 Assessing Cost Impacts

Motivation:

Because the envisioned LFR concept will not have the benefit of economy of scale, the identified opportunities to reduce capital and operating costs below those of larger, base-load plants must be evaluated. In particular, additional design features with strong cost impacts must be identified and considered for subsequent changes to design requirements.

Tasks:

- Determine basis for credible estimate of plant costs
  - Estimate plant capital and generation cost factors, with consideration of LFR-specific attributes (e.g., experience with factory construction of modules, etc.)
  - Account for benefits of design simplification, enhanced reliability, passive safety, factory fabrication, modular assembly, reduced construction time at site, and reduced staffing
  - Account for the significantly higher efficiency and other potential benefits of S-CO_2 Brayton cycle power conversion.
- Evaluate economic conditions for niche market applications and develop suitable economic models for LFR deployment.

A4.3.9 Whole-Core Cassette Refueling

Motivation:

If the proliferation-resistant LFR system is to be viable as envisioned, with refueling occurring only at 30-year intervals and with equipment that is brought onsite temporarily rather than maintained onsite, credible concepts for emplacing and exchanging fueled core cartridges must be proposed and considered. Preconceptual designs for such systems and identification of the requirements those systems would place on the reactor primary system as well as the containment and buildings must be evaluated.

Tasks:

- Determine viability of cooling spent cassette during retrieval and shipment following short cooldown period
- Identify spent-fuel-cassette shielding concepts
- Evaluate in-cask cassette cooling concepts
- Evaluate safeguards considerations
- Determine impact on plant containment and building structures.

A4.3.10 Supercritical-Carbon Dioxide Brayton Cycle

Motivation:

Use of an S-CO_2 Brayton cycle for energy conversion offers the prospect of significantly higher efficiencies at the reference LFR core outlet temperature and acceptable efficiencies with lower Pb coolant outlet temperatures, which reduces the challenges for materials in a near-term demonstration. Higher plant efficiency enhances the revenue from the sale of electricity over the plant lifetime. Furthermore, the economic viability of the LFR may depend on reduction of capital cost achieved by incorporation of an S-CO_2 Brayton cycle rather than a steam Rankine cycle. Therefore, several R&D tasks associated with S-CO_2 Brayton cycle conversion are identified as viability tasks. Some of these tasks are expected to be addressed as part of Generation IV Sodium-Cooled Fast Reactor (SFR) R&D, but LFR-specific issues involving impact on reactor operation and design and heat exchange with lead coolant will be considered as part of the LFR scope.

Tasks:

- Evaluate innovative design concepts for compressors, turbines, PCHEs (by Heatric, a subsidiary of Meggitt (UK), Ltd.), and other components
- Design, test, and demonstrate performance of compressors and turbine under prototypical conditions
- Demonstrate performance of recuperators and cooler with small channels (e.g., PCHEs) under prototypical conditions without fouling or corrosion
- Demonstrate operation of an integral S-CO_2 Brayton cycle at sufficiently large scale
- Demonstrate control system strategy for an integral S-CO_2 Brayton cycle at sufficiently large scale.

A4.4 PROJECT COST AND SCHEDULE

The time and resources to conduct the planned R&D to prepare the LFR technology and design for 2014 decision to proceed with a prototype construction is shown below with a known budget for fiscal year (FY) 2007.

A4.4.1 Fiscal Year 2007 Project Budget

The FY 2007 budget for LFR R&D activities is provided in Table A4.3.

Table A4.3. FY 2007 budget profile for LFR activities ($K).

Task	FY-07[a]
System Design and Evaluation	481
Materials	50
Total	531

a. FY 2007 budget includes FY 2006 carryover funds.

A4.4.2 Ten-Year Project Schedule

The schedule proposed for LFR development is illustrated in Figure A4.7. If there is sufficient interest in an earlier demonstration than that identified in the current Generation IV schedule, then a critical decision-driven schedule for a demonstration project can be prepared. However, the plan described in this appendix reflects a ten-year development of the technical basis for a Generation IV down-selection and decision whether to proceed to construction of a LFR demonstration.

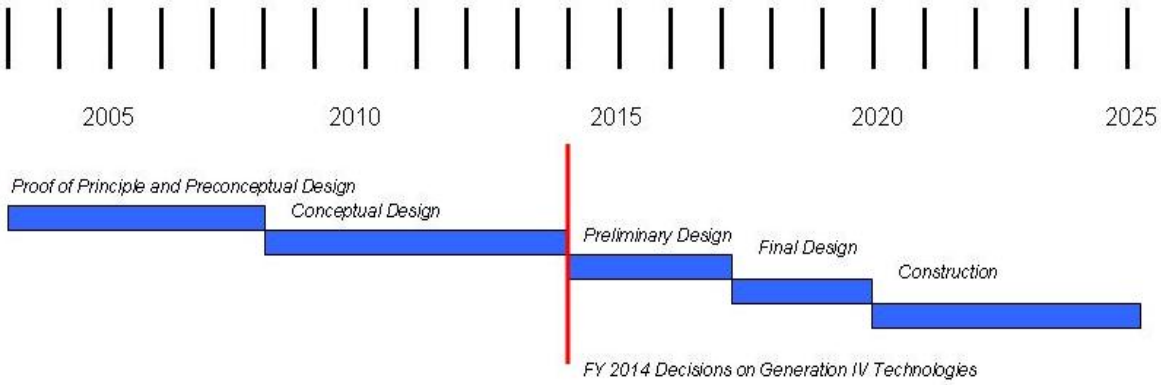

Figure A4.7. Proposed Schedule for LFR Development.

A4.4.3 Ten-Year Project Milestones

FY 2007

- Complete initial assessment of mechanical and corrosion properties of primary candidate LFR materials in as-received condition
- Complete preliminary selection of primary candidate materials for LFR system
- Issue status report on preconceptual viability studies and evaluations including structural viability assessment, initiation of plant transient analyses and safety evaluation, and initiation of evaluation of core refueling and transport options.

FY 2008

- Establish reference cladding design and material specifications
- Complete facility design for Lead Engineering Test Facility (LETF)
- Issue status report on preconceptual viability studies and evaluations including plant transient analyses and safety evaluation, viability of core refueling and transport approach, and plan for utilization of LETF and other LFR experiment facilities.

FY 2009

- Complete initial aging and irradiation resistance assessment of candidate materials
- Begin LETF construction
- Issue status report on preconceptual viability studies and evaluations including plant transient analyses and evaluations, initial analyses of available experiment data to calibrate analysis methods, and reduction of effects of assumptions and uncertainties in analyses.

FY 2010

- Establish initial design database for short-term mechanical and corrosion properties of primary candidate LFR materials in as-received condition
- Issue initial report on preconceptual design
- Begin LETF testing.

FY 2011

- Issue initial LFR Materials Handbook
- Issue status report on experiments performed in LETF and other LFR facilities
- Issue final report on preconceptual viability studies and overall viability assessment.

FY 2012

- Report qualification testing and modeling status
- Issue status report on experiments performed in LETF and other LFR facilities
- Begin fuel testing
- Issue interim status report on conceptual design.

FY 2013

- Report qualification testing and modeling status
- Issue status report on experiments performed in LETF and other LFR facilities
- Issue interim report on fuel testing
- Issue interim status report on conceptual design.

FY 2014

- Issue interim status report on conceptual design
- Issue interim report on fuel testing
- Issue interim status report on licensing basis and approach.

FY 2015

- Issue interim status report on conceptual design
- Issue interim report on fuel testing
- Issue interim status report on licensing basis and approach.

FY 2016

- Issue final status report on conceptual design
- Issue report on LFR/SSTAR licensing basis and approach.

A4.5 REFERENCES

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