OVERVIEW OF GENERATION IV LIQUID METAL-COOLED FAST REACTORS: SODIUM-COOLED FAST REACTOR (SFR) AND LEAD-COOLED FAST REACTOR (LFR)

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I. INTRODUCTION

Sodium-cooled Fast Reactor (SFR) systems and Lead-cooled Fast Reactor (LFR) systems are among the six systems selected for joint development by the Generation IV International Forum (GIF) based on their potential to meet the GIF technology goals.[1] Both reactor types enhance sustainability by means of their fast neutron spectrum and closed fuel cycle, which serve to minimize waste and enhance resource utilization. They also have excellent potential to achieve the goals of safety and reliability, economics, and proliferation resistance and physical protection. The primary missions for both systems are electricity generation and “actinide management” (fissile consumption, conservation or breeding). Further, hydrogen production is feasible with electrolytic processes and thermochemical cycles tailored to the respective coolant temperatures.

Owing to the significant past experience accumulated with SFRs in several countries, the start-up of a prototype Generation IV SFR system is targeted for 2020.[2] The operation of a LFR Technology Pilot Plant (TPP) is also envisioned around 2020.[2]

Liquid metal reactors are designed for high-power density taking advantage of the high heat removal and high heat transport capability of the coolant.

The sodium reactor technology is comparatively mature but remains to be commercialized successfully. Drawbacks of sodium as a coolant include its chemical reactivity and opacity. Lead cooled systems are comparatively less mature but provide advantages stemming from the relative inertness and high boiling temperature of lead coolant. Drawbacks of lead coolant include its high density, corrosive nature, high melting point, and opacity. For both SFR and LFR systems, R&D is required to take advantage of their strengths and minimize their drawbacks. For example, R&D on in-service inspection and repair (ISI&R) technology is needed to assure the safety of reactor operation, in view of the opacity of sodium and lead coolants. The Generation IV International Forum (GIF) provides an effective mechanism for joint R&D in this key area and others. With distilled knowledge, information, experiences, funds and resources in the whole world to one point through GIF cooperation, based on the common Technology Roadmap, the R&D for Generation IV nuclear systems directing a unified aim is accelerated.

This paper provides an overview of the SFR systems which are formally undergoing development through a GIF System Arrangement, and the LFR systems proposed for joint development in the GIF framework; a formal System Arrangement for the LFR remains to be established.

II. SODIUM-COOLED FAST REACTORS (SFR)

II.A. Features and design options of SFRs

In several countries, experimental and prototype SFRs have been constructed and operated for more than 30 years. The SFR system features a fast-neutron spectrum and a closed fuel cycle for efficient conversion of fertile uranium and management of actinides. A full actinide recycle fuel cycle is envisioned. In the Technology Roadmap for Generation IV Nuclear Energy Systems,[1] the SFR was primarily envisioned for missions in electricity and actinide management. Important safety features of the system include a long thermal response time, a large margin to coolant boiling, a primary system that operates near atmospheric pressure, and an intermediate sodium system between the radioactive sodium in the primary system and the power conversion system. Water/steam and carbon-dioxide (CO_2) are considered as working fluids for the power conversion system to achieve high level performance on thermal efficiency, safety and reliability. With innovations to reduce capital cost, the SFR can be competitive in electricity markets.

The three options, shown in Figures 1, 2 and 3 displaying loop-type, pool-type and modular pool-type systems, respectively, are under consideration:

- A medium to large size (600 to 1 500 MWe) loop-type SFR with MA-bearing mixed uranium-plutonium oxide (MOX) fuel, supported by a fuel cycle based upon advanced aqueous processing at a central location serving a number of reactors.[3,4]
- A medium size pool-type SFR with uranium-plutonium-minor-actinide-zirconium metal alloy fuel, supported by a fuel cycle based on pyrometallurgical processing in facilities co-located with the reactor.[5]
- A small size (50 to 150 MWe) modular pool-type SFR with similar metal alloy fuel, supported by a fuel cycle based on pyroprocessing at a central or regional location.[6]

The design and performance parameters of the three options are shown in Table 1.

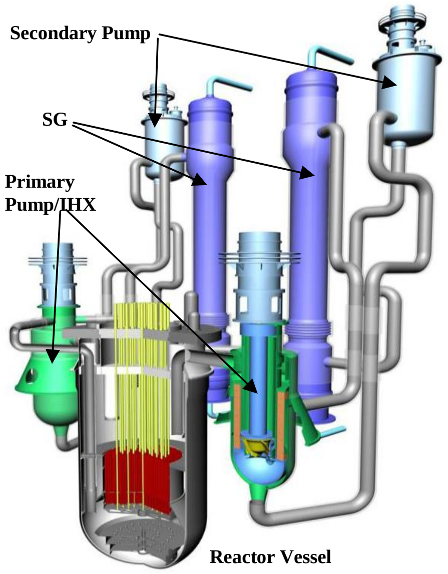

Figure 1: Loop-type SFR

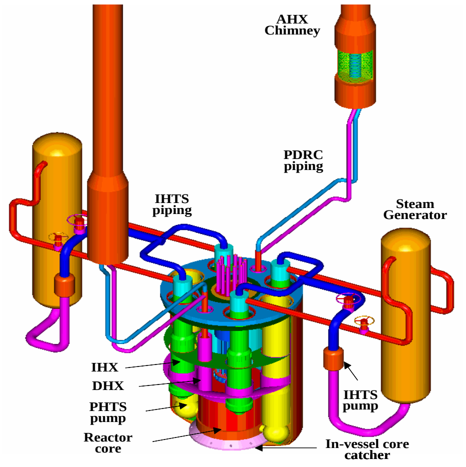

Figure 2: Pool-type SFR

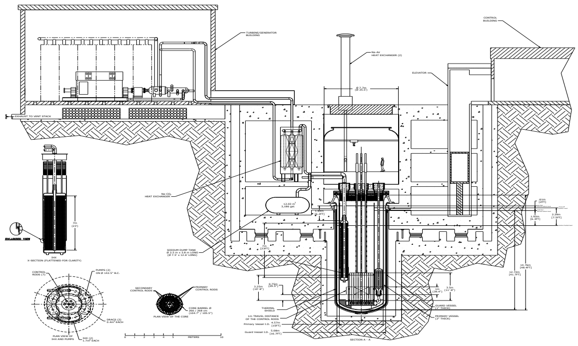

Figure 3: Small Modular pool-type SFR

Table 1: Key Design Parameters of GIF SFR Concepts

SFR Design Parameters	**Loop**	**Pool**	**Small Modular Pool**
Power Rating, MWe	1500	600	50
Thermal Power, MWth	3570	1525	125
Plant Efficiency, %	42	42	~38
Core outlet coolant temperature, ^{o}C	550	545	~510
Core inlet coolant temperature, ^{o}C	395	370	~355
Main steam temperature, ^{o}C	503	495	480
Main steam Pressure, MPa	16.7	16.5	20
Cycle length, years	1.5-2.2	1.5	30
Fuel reload batch, batches	4	4	1
Core Diameter, m	5.1	3.5	1.75
Core Height, m	1.0	0.8	1.0
Fuel Type	MOX (TRU bearing)	Metal (U-TRU-10%Zr Alloy)	Metal (U-TRU-10%Zr Alloy)
Cladding Material	ODS	HT9M	HT9
Pu enrichment (Pu/HM), %	13.8	24.9	15.0
Burn-up, GWd/t	150	79	~87
Breeding ratio	1.0–1.2	1.0	1.0

II.B. SFR Concepts

LOOP-TYPE SFR

To promote favorable economies of scale, many SFR designs have targeted large monolithic plant designs. For this approach, a prominent recent concept is the Japanese Sodium Fast Reactor (JSFR)[3,4] which is an advanced sodium-cooled loop-type reactor evolved from Japanese fast reactor technologies; the conceptual plant design is shown in Figure 1.

The JSFR design employs several advanced technologies to reduce the construction cost: compact design of reactor structure, shortened piping layout, reduction of loop number, integration of components, and simplification of decay heat removal system through enhancement of natural circulation capability. JSFR employs innovative technologies such as modified 9Cr-1Mo steel with high strength, an advanced structural design standard at elevated temperature, two-dimensional seismic isolation, and re-criticality free core to exclude power excursion sequences.

The JSFR design utilizes passive safety features to increase safety assurance. The improvement of the ISI&R technology is a key objective to confirm the integrity of internal structures including core support structure and coolant boundaries. The means of access is taken into account in design, and remote handling and sensor technology for use under sodium as well as a high reliable double-wall-tube SG are being developed.

While focusing on a large monolithic concept, the JSFR design studies consider plant sizes ranging from a modular system composed of medium size reactors to a large monolithic size. The large-scale sodium-cooled reactor utilizes the advantage of “economy of scale” by setting the electricity output of 1 500 MWe. On the other hand, a medium-scale modular reactor would offer advantages of flexibility in meeting power requirements from generating companies and the reduction of investment risk compared with large-scale reactors.

POOL-TYPE SFR

Moderate size SFR designs have also been proposed; in this case, cost reduction relies on design simplification and factory fabrication techniques. A recent example is the KALIMER-600(5) pool-type reactor design, shown in Figure 2, evolved from previous pool-type SFR designs such as the Power Reactor Inherently Safe Module (PRISM), the Super-Phénix (SPX) and the European Fast Reactor (EFR). A pool-type reactor provides many important design advantages in plant economy and safety. The entire Primary Heat Transport System (PHTS) piping and equipment are located inside the vessel completely eliminating the possibility of PHTS piping break outside the reactor vessel. Also the large thermal inertia characteristic of a pool-type reactor enhances passive safety mechanisms. The safety of KALIMER is enhanced further by loading its core with metal fuel which has inherent safety characteristics resulting from large negative power reactivity coefficients and a very low probability of a Core Disruptive Accident (CDA).

For improvement of the plant economy over previous designs, KALIMER reduces the number and/or eliminates equipment by design simplification and novelty, compact design and higher plant efficiency. Its net plant efficiency is designed to reach 39.3% with conventional steam plant. The introduction of the innovative Passive Decay heat Removal Circuit (PDRC) system could enable an increase in the size of the system to 1 000 MWe or more. KALIMER requires neither active-component (equipment) operation nor operator action in managing accidents. Also it does not require a safety grade emergency electricity generator. These safety design features provide very high reliability in the safety management and can accommodate design-basis events (DBE) and beyond-design basis events such as anticipated transients without scram (ATWS) without any operator action or support of active shutdown system operation. The grace period during accidents can be measured in days without violating core protection limits.

SMALL MODULAR POOL-TYPE SFR

The Small Modular Pool-type SFR (SMFR) is aimed at exploiting characteristics inherent to fast reactors for application to small grid applications. In a recent study in the United States,[6] a reactor size of 50 MWe was selected as shown in Figure 3 for a specific niche market where industrial infrastructure is not sufficient for larger systems and the unit cost of electricity generation is very high with conventional technologies.

Innovative design features have been embodied in the SMFR design including a metallic fuel core with high internal conversion ratio, passive safety characteristics, simplified reactor configuration for modular construction and transportability, and supercritical CO_2 Brayton cycle power conversion system. The primary system is configured as a typical pool arrangement and the intermediate sodium exits the vessel and flows to the sodium-to-CO_2 heat exchangers.

A key design feature of the SMFR is its long-lived core – 30 years with no refuelling. This long lifetime improves proliferation resistance by eliminating on-site fuel storage facilities and limiting fuel management to the initial insertion and eventual removal of the core. The SMFR incorporates all the passive safety features developed for SFR applications to avoid plant damage; this includes a passive decay heat removal system directly from the primary coolant pool.

II.C. Status of cooperation

The System Arrangement for the international research and development of the SFR system was signed in November 2006 by EURATOM, France, Japan, the Republic of Korea and the United States. In addition, China signed it in March 2009. Four Project Arrangements on Advanced Fuels (AF), Global Actinide Cycle International Demonstration (GACID), Component Design and Balance Of Plant (CDBOP), and Safety and Operation (SO) have been signed in 2007 for the former three and in 2009 for the SO. The Project Arrangement on System Integration and Assessment (SIA) is expected to be effective in 2009.[2]

By means of the Projects Arrangements mentioned above, the R&D activities currently being conducted are as follows:

AF:	Performance evaluations for oxide, metal, nitride, carbide and nitride/carbide fuels, MA-bearing fuel fabrication technology, and core materials for high burn-up fuels.
CDBOP:	Experimental and analytical evaluation of advanced ISI&R technology including leak-before-break assessment, and alternative energy conversion system with supercritical-CO_2 Brayton cycle.
GACID:	Evaluation of MA-bearing fuel material properties, analysis and evaluation of irradiated fuel data, and program planning for bundle-scale MA-bearing fuel assembly irradiation demonstration in the Monju reactor in Japan.
SO:	Analyses and experiments that support safety approaches and validate specific safety features, development of computational tools useful for such studies, and acquisition of reactor operation technology, as determined largely from experience and testing in operating SFR plants.

III. LEAD-COOLED FAST REACTORS (LFR)

III.A. Features and design options of LFRs

The LFR features a fast-neutron spectrum and a closed fuel cycle for efficient conversion of fertile uranium. It can also be used as a burner of minor actinides from reprocessed spent fuel. An important feature of the LFR is the enhanced safety that results from the choice of a relatively inert coolant. In the Roadmap, the LFR was primarily envisioned for missions in electricity and hydrogen production, and actinide management.

To acquire a larger experience in handling lead and resolve corrosion issues of structural material during the high-temperature operation of LFR, particularly by means of more effective and reliable oxidized surfaces, the international R&D collaboration in GIF is expected to be formalized in the future by means of a System Arrangement.

The designs that are currently proposed as candidates for international cooperation and joint development in the GIF framework are two pool-type reactors shown in Figures 4 and 5:

- the Small Secure Transportable Autonomous Reactor (SSTAR) with mixed uranium-plutonium nitride (MN) fuel.[7]
- the European Lead-cooled System (ELSY) with MOX fuel.[8]

Key design data of SSTAR and ELSY are presented in Table 2.

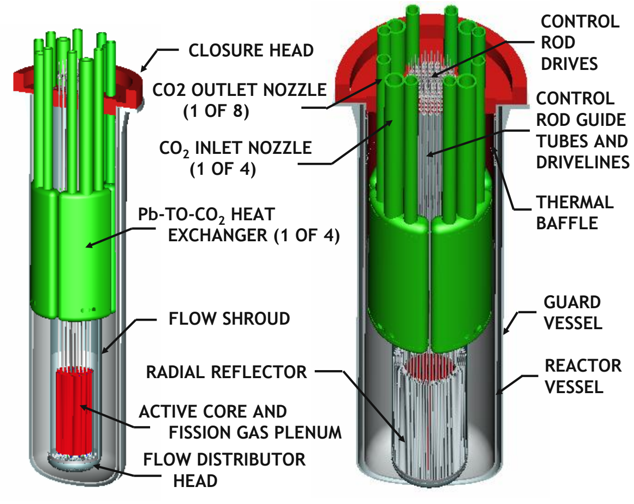

Figure 4: Small Secure Transportable Autonomous Reactor (SSTAR).

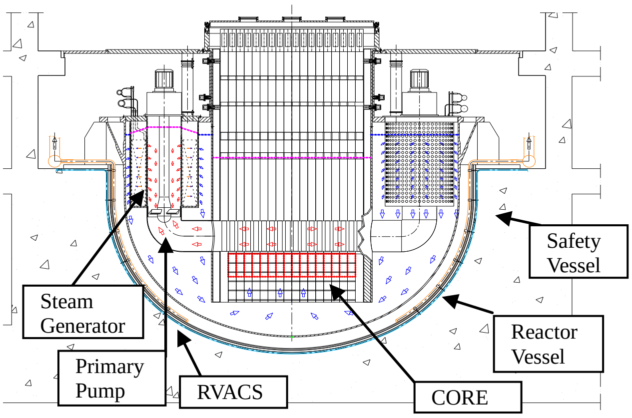

Figure 5: ELSY Primary system configuration.

Parameters/System	**SSTAR**	**ELSY**
Power (MWe)	19.8	600
Conversion Ratio	~1	~1
Thermal efficiency (%)	44	42
Primary coolant	Lead	Lead
Primary coolant circulation (at power)	Natural	Forced
Primary coolant circulation for DHR	Natural	Natural
Core inlet temperature (°C)	420	400
Core outlet temperature (°C)	567	480
Fuel	Nitrides	MOX, (Nitrides)
Fuel cladding material	Si-Enhanced F/M Stainless Steel	T91 (aluminized)
Peak cladding temperature (°C)	650	550
Fuel pin diameter (mm)	25	10.5
Active core Height/ equivalent diameter (m)	0.976/1.22	0.9/4.32
Primary pumps	-	No. 8, mechanical, integrated in the SG
Working fluid	Supercritical CO_2 at 20MPa, 552°C	Water-superheated steam at 18 MPa, 450°C
Primary/secondary heat transfer system	No. 4 Pb-to-CO_2 HXs	No. 8 Pb-to-H_2O SGs
Safety grade DHR	Reactor Vessel Air Cooling System + Multiple Direct Reactor Cooling Systems	Reactor Vessel Air Cooling System + Four Direct Reactor Cooling Systems + Four Secondary Loops Systems

TABLE 2: Key Design Parameters of GIF LFR Concepts

III.B. LFR concepts

SMALL SECURE TRANSPORTABLE AUTONOMOUS REACTOR (SSTAR)

The current reference concept for the SSTAR[7] in the United States is a 20 MWe natural circulation reactor concept with a small shippable reactor vessel, as shown in Figure 4.

The lead coolant is contained inside a reactor vessel surrounded by a guard vessel. Lead is chosen as the coolant rather than lead-bismuth eutectic (LBE) to avoid generation of alpha-emitting ^{210}Po via neutron interactions with bismuth, and to eliminate dependency upon bismuth which might be a limited or expensive resource. The lead flows upward through the core and a chimney above the core formed by a cylindrical shroud. The coolant enters four modular lead-to-CO_2 heat exchangers located in the annulus between the reactor vessel and the cylindrical shroud.

Physical properties of the lead coolant, the nitride fuel containing transuranic elements, the fast spectrum core, and the small size combine to promote a unique approach to achieve proliferation resistance, while also enabling fissile self-sufficiency, autonomous load following, simplicity of operation, reliability, transportability, as well as a high degree of passive safety. Conversion of the core thermal power into electricity at a high plant efficiency of 44% is accomplished utilizing a supercritical CO_2 Brayton cycle power converter.

EUROPEAN LEAD-COOLED SYSTEM (ELSY)

The ELSY[8] reference design is a 600 MWe reactor cooled by lead, shown in Figure 5. ELSY has been under development since September 2006, and is funded also by EURATOM within the Sixth Framework Programme. The ELSY project is being performed by a large consortium of European organizations to demonstrate the possibility of designing a competitive and safe fast critical reactor using simple engineered features, while satisfying Generation IV goals, including waste minimization and effective waste management through minor actinide consump–tion (burning).

Simplicity and reduced footprint would be possible due to the elimination of the intermediate cooling system and the identify-cation of innovative solutions to reduce the primary system volume and the complexity of the reactor internals.

ELSY features a cylindrical inner vessel, axial-flow primary pumps located inside the inner shell of the spiral-tube bundle SGs, and safety decay heat removal system with lead-water dip coolers. Because fuel assemblies are largely sustained by buoyancy and kept in the vertical position by support beams in gas space, the hitherto classical core support plate has become needless, and the refuelling machine can operate in gas instead of in lead.

All reactor internal structures are removable; particularly the SG Unit can be lifted off by radial and vertical displacements which disengage the unit from the reactor roof. Above-mentioned technologies would contribute greatly to reducing necessity of ISI&R in molten lead.

The core consists of an array of open (wrapperless) fuel assemblies (FAs) of square pitch surrounded by reflector-assemblies, a configuration that presents reduced risk of coolant flow blockage. An alternative solution with closed hexagonal FAs has been retained as a fall-back option.

III.C. Status of cooperation

Preparation of a System Arrangement for approval by participating GIF members has been considered, but formal agreements are still pending. The LFR System Research Plan (SRP) is under preparation by the Provisional System Steering Committee (LFR-PSSC) with the participation of the Representatives from EURATOM, Japan, the United States and experts from the Republic of Korea. In addition, informal meetings were held with the participation of the representatives of the nuclear industry, research organizations and universities involved in LFR development.[2]

VI. CONCLUSION

Some candidate concepts of SFR and LFR systems, which take advantages of respective features, are proposed. GIF participants are going to conduct cooperative R&D concluding project arrangements around common techniques to each system.

Profiting from the experience of the R&D and operation of the experimental and prototype SFRs acquired over many years, the international collaborative R&D activities for the SFR system within GIF are being successfully conducted; start-up of a prototype system is targeted for 2020.

The LFR system is proposed for joint development within GIF. The draft LFR SRP describes a dual track viability research program with convergence to a single, combined Technology Pilot Plant (TPP) leading eventually to the deployment of both types of systems (SSTAR and ELSY). Following the successful operation of the TPP around the year 2020, an independent development of two prototypes is expected to lead to a subsequent industrial deployment of the central station LFR and the SSTAR, respectively.

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