Current status of GIF collaborations on sodium-cooled fast reactor system

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Abstract. The SFR system arrangement Phase II became effective on 16 February 2016 by signatures of CEA, JAEA, KAERI, USDOE, and Rosatom), and was extended for additional 10 years. China signed the SFR SA Phase II on 3th August 2016 and Euratom is expected to sign near future. Collaboration of GIF SFR is growing adding new reactor concepts and related R&Ds. In 2015, a project arrangement on SFR System Integration and Assessment (SI&A) has been signed by 7 members : China, EU, France, Japan, Korea, Russia and US. In the SI&A project, R&D needs from the SFR design will be shown to the R&D project, and R&D results from each R&D project will be integrated into the designs. Presently there are four SFR design concepts as shown in ATFR-2015, 1) JAEA Sodium Fast Reactor (JSFR, loop) Design Track, 2) KALIMER-600 (KAERI, pool) Design Track, 3) European Sodium Fast Reactor (ESFR, pool) Design Track, 4) AFR-100 (DOE, modular) Design Track, are proposed from each signatory. China is going to propose CFR-1200, and Russia is going to propose BN-1200 as new design tracks. After SI&A project started, the GIF-SFR has completed the function of R&Ds and integration of R&D result to the SFR design. This strong collaboration network is expected to provide the promising generation IV SFR concepts. This paper describes SFR design concepts in SFR project and interactions with R&D projects under GIF framework.

Key Words: Generation IV, Sodium-cooled fast reactor

1. Introduction

Uranium resources are finite along with other natural resources and a common goal for the generation IV reactors is to manage this finite resource, since light water reactors (LWR), in service or under construction, exploit very little of the energy potential of uranium. The Generation IV International Forum (GIF) concluded that five fast reactor concepts (sodium-cooled fast reactor (SFR), supercritical water-cooled reactor (SCWR), gas-cooled fast reactor (GFR), lead-cooled reactor (LFR), molten salt reactor (MSR)) have potential to meet the nuclear fuel cycle sustainability goals (very high temperature reactor (VHTR) is selected for hydrogen production) [1]. In those five concepts, SFR has significant pre-existing base technology development and a clear understanding of the remaining challenges to be addressed before industrial deployment.

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10 years. China signed the SFR SA Phase II on 3th August 2016 and Euratom is expected to sign near future. Collaboration of GIF SFR is growing adding new reactor concepts and related R&Ds. In 2015, a project arrangement on SFR System Integration and Assessment (SI&A) has been signed by 7 members : China, EU, France, Japan, Korea, Russia and US. Through systematic review of the Technical Projects and relevant contributions on design options and performance, the SIA Project will help define and refine requirements for Generation IV SFR concept R&D. Results from the technical R&D projects will be evaluated and integrated to assure consistency. The Generation IV SFR system options and design tracks will be identified and assessed with respect to Generation-IV goals and objectives.

2. G-IV SFR systems and candidates under discussion in SIA

When developing a new reactor system, accumulation of experiences on fuel, safety, and material behavior is extremely important and takes a significant amount of time. In the SFR case, those experiences have been successfully accumulated during the past seventy years world-wide. There were and are a lot of experimental and prototype SFRs. Fuel/subassembly specification, safety designs and materials of future SFRs are based on perspectives from those experiences. From the safety point of view, a lot of large demonstration experiments have been conducted and evaluation tools validated by those experiments have been developed. In several reactors, demonstrations of natural convection decay heat removal operation have been successfully conducted. With innovations to reduce capital cost, SFR is aimed to be economically competitive in future electricity markets. The SFR is considered to be the nearest-term deployable Generation IV system. Much of the basic technology for the SFR has been established in former fast reactor programs.

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2.1. JSFR

JSFR involves innovative technologies to meet high targets as a future sustainable energy source. Core and fuel design studies with mixed oxide (MOX) fuel for JSFR are going on for a variety of fuel isotopic compositions including minor actinides (MAs). A specific target is to achieve high burnup to reduce fuel cost with fuel cladding of oxide-dispersion-strengthened (ODS) steel, which has the potential to both withstand high neutron dose and possess high-temperature strength. Enhancement of safety is also a key factor to be considered in the core and fuel design. A self-actuated shutdown system (SASS) is provided as a passive safety feature for reactor shutdown to enhance the prevention capability against CDAs. The re-criticality free core concept has the great importance to ensure the in-vessel retention scenario against whole core disruptive accidents. The initiating phase energetics due to exceeding the prompt criticality has to be prevented to restrict the sodium void worth and the core height. The possibility of molten fuel compaction has to be eliminated by enhancing the fuel discharge from the core. For decay heat removal system (DHRS), JSFR originally had 3 reliable systems with full natural convection capability. For measures against loss of heat removal system (LOHRS), recovery of original design base DHRSs and auxiliary core-cooling system (ACS) using air as ultimate heat sink has been added to the original design [1]. From the viewpoint of economic competitiveness, JSFR adopts technologies to reduce construction cost such as two loop cooling system, compact reactor vessel, seismic isolation and so on. And those technologies were evaluated to be suitable for large-scale demonstration experiments [2].

Table 1 JSFR parameters

Items	Values
Output thremal/electric	3530/1500MW
Fuel type	MOX
Fuel contents	LWR UO2 recycle, LWR MOX recycle, FR recycle
Cladding material	ODS steel
Breeding ratio	1.0 to 1.2
Refueling cycle	26month
Burnup	150GWd/t (core average burn-up for driver fuel)
Reactor type	Loop
Primary circuit temperature	550/395deg-C
Number of primary PM/IHX	2/2
Number of secondary PM/HX	2/2
Tertiary system type	Steam turbine
Efficiency	42%
Passive shutdown	Self-Actuated Shutdown System (SASS)
CDA mitiagation	1) Early molten fuel dicharge from subassembly inner duct. 2) Fuel discharge from CRGT in transition phase. 3) Cooling at core catcher.
Configuration of DHRS	DRACS(full NC)+2PRACS(full NC)+ACS
Fuel storage	EVST+water pool

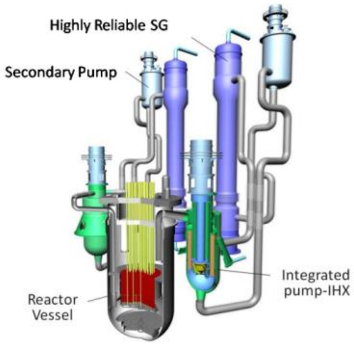

FIG. 1 JSFR Concept

2.2. KALIMER-600

KALIMER-600 is a SFR TRU burner of 600 MWe. The main objective of KALIMER-600 is to demonstrate its TRU burning capability as a commercial SFR burner reactor.

KALIMER-600 is a pool type reactor where the entire Primary Heat Transport System (PHTS) and structure are located inside the vessel. The heat transport system is composed of a PHTS, an Intermediate Heat Transport System (IHTS) and a Steam Generation System as shown in Figure 2. The PHTS is composed of two PHTS pumps, four IHXs and reactor structures. The IHTS consists of two IHTS pumps, two helical tube type steam generators and pipings. There are two independent PDRC loops. Each loop is composed of a Decay Heat eXchanger (DHX) and a natural-draft sodium-to-Air Heat eXchanger (AHX). There are two independent ADRC loops. Each loop is composed of a DHX, a Forced-Draft sodium-to-air Heat eXchanger (FDHX), an electromagnetic pump and an FDHX blower.

The KALIMER-600 conceptual design has been developed by the Korea Atomic Energy Research Institute in 2011. Since 2012, a prototype plant of KALIMER-600 has been being developed with the goal of its construction to be completed by 2028.

Table 2 KALIMER-600 parameters

Items	Values
Output thermal/electric	1500/600 MW
Fuel contents	U-TRU-10%Zr Metal Alloy
Cladding material	Mod.HT9
Conversion ratio	0.74
Cycle length	365 EFPDs
Avg. discharged burnup (MWD/kg)	79.5/81.9 (inner/outer core)
Reactor type	Pool
Primary circuit temperature inlet/outlet	390/545 ℃
Number of primary PM/IHX	2/4
Number of secondary PM/HX	2/2
Tertiary system type	Steam turbine
Efficiency	40 %
Passive shutdown	Passive shutdown system by curie point electromagnet
CDA prevention	1) Inherent reactivity feedback by metal fuel expansion and dispersion into sodium 2) highly reliable safety grade decay heat removal system

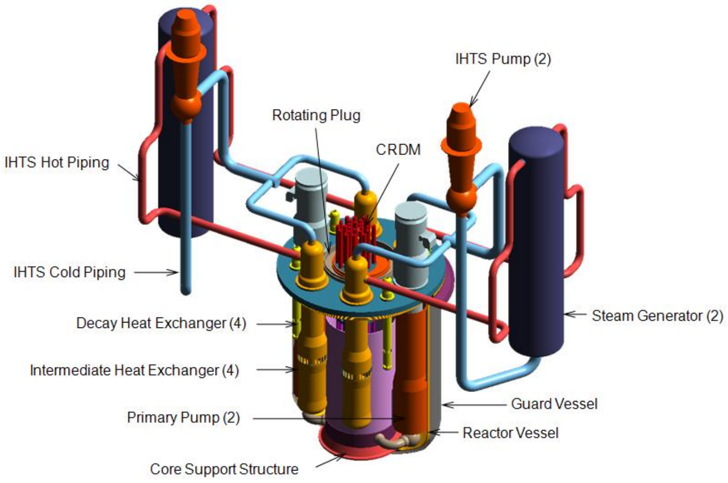

FIG. 2 KALIMER-600 Concept

2.3. ESFR

The European Sodium-cooled Fast Reactor (ESFR) is a large pool type concept of industrial SFR developed within the Collaborative Project on European Sodium Fast Reactor (CP-ESFR) of the 7th Euratom Framework program of the European commission [1]. The ESFR concept aims to achieve economy of scale and to benefit from the generic characteristics of the pool concept including design simplification and compactness. The main objectives guided the ESFR design were: Simplification of structures; Improved In-service Inspection and Repair capabilities; Improved manufacturing conditions for cost reduction and increased quality; Reduction of risks related to sodium fires and to the water/sodium reaction; Improved fuel maintenance, with the capability for a whole core discharge and Improved robustness against external hazards.

The ESFR plant characteristics are given in Table 3. The core design is optimized for the oxide fuel and is composed of two enrichment zones of Inner/Outer core fuel assemblies, and 3 rows of reflector assemblies, of which one row can be used alternatively for fertile blanket or Minor Actinide burning. There are two additional rows of steel blocks dedicated for shielding purpose. There are two independent control rod systems composed of 24 control and shutdown device (CSD) assemblies and 9 diverse shutdown device (DSD) assemblies. The fuel management scheme is based on a fuel residence time of 2050 equivalent full power days with five batches. The maximum fuel burn-up is 155 GWd/tHM for an average power density of 206 W/cm3. Further, the design targets a flexible breeding and minor actinide burning strategy.

Table 3 ESFR parameters

Items	Values
Output thremal/electric	3600/1500MW
Fuel type	MOX
Fuel contents	LWR UO2 recycle, LWR MOX recycle, FR recycle
Cladding material	oxide dispersion strengthened (ODS) steel
Breeding ratio	Flexible (1.0 – 1.2)
Refueling cycle	410 EFPD
Burnup	100/155 GWd/t (core average/maximum burn-up for driver fuel)
Reactor type	Pool
Primary circuit temperature	545/395deg-C
Number of primary PM/IHX	3/6
Number of secondary PM/HX	6/6
Tertiary system type	Steam turbine (steam temperature 490°C @ 185 bars)
Efficiency	42%
Passive shutdown	None
CDA mitiagation	1) Cooling at internal core cather 2) Cooling at external core catcher.
Configuration of DHRS	3DRC(with full NC)+3DRC(with FC)
Fuel storage	EVST

The ESFR primary system is sketched in Figure 3. It is based on options already considered in previous and existing pool sodium fast reactors, with several potential improvements regarding safety, inspection and manufacturing. A particular attention is also given to compactness. The reactor vessel is cooled with sodium (submerged weir) and is surrounded by a hanged safety vessel. Some provisions have been made for internal and external core catchers. The reactor vault can be inspected for maintenance. The strongback is simply lying on the vessel bottom to remove weld spots that are difficult to inspect. The pump-strongback connection is very short and robust compared to solutions used in the past. The inner vessel, with a conical part, is welded directly on the strongback to facilitate manufacturing. An alveolar forged roof structure potentially enhances feasibility, reduces height and weight, and allows cooling. It operates at a temperature of 120°C to avoid sodium aerosol freezing. The components and fuel handling systems are resting on the roof. Large components are based on more classical designs, but all opportunities have been taken during the project to propose innovative concepts such as an Above Core Structure to guide control rods, support instrumentation, and calm sodium above the core.

Decay heat removal function is provided by the Direct Reactor Cooling (DRC) System which comprises six sodium loops. All loops extract heat from the primary sodium of the hot pool by means of immersed sodium/sodium dip coolers (DHX) removing each 50% of total residual power, and reject the heat to the environment using sodium/air heat exchangers situated on the periphery of the reactor building roof within air stacks. In this concept, diversity (operational and structural) and redundancy of the 6 DRC loops is ensured by 3 natural convection and 3 forced convection loops (i.e. with pumps in sodium and air to increase efficiency of the exchangers and with different component designs).The secondary system comprises six 600 MWth parallel and independent sodium loops, each connected to an IHX located in the reactor vessel. Each loop includes one Mechanical Secondary Pump (MSP), modular Steam Generators (SG) and one Sodium Dump Vessel (SDV).Each secondary loop hosts 6 modular Steam Generators of 100 MWth each made out of modified 9Cr1Mo (ASME grade 91). The modularity is aimed at reducing the impact on the IHX of a Sodium/Water reaction and at improving overall plant capacity factor.

The design of the ESFR nuclear Island layout considers the twinning of two reactors with a shared fuel handling building and a shared component maintenance building. The aim is to reduce the weight related to these two heavy investment cost items by sharing it for two production units. For the whole nuclear island, it is intended to achieve seismic resistance criteria, which leads to a single seismic raft based on seismic bearing pads. Further considerations concern heavy commercial aircraft crash resistance criteria for safety related buildings using specific reinforced Aircraft Crash Protection concrete shells.

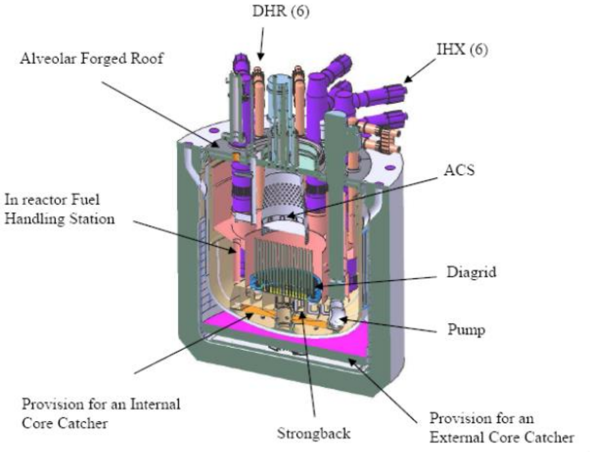

FIG. 3 ESFR Concept

2.4. AFR-100

An Advanced Fast Reactor with 100 MWe power rating (AFR-100) was developed at Argonne National Laboratory to target emerging markets where a clean, secure and stable electricity resource is required, but a large-scale plant cannot be accommodated. The AFR-100 is targeted for small local grids, transportable from pre-licensed factories to remote plant sites for affordable supply, and operated for a long period without refueling. To achieve these strategic goals, several design requirements were proposed for the AFR core development; i.e., a power rating of 100 MWe that is equivalent to 250 MWth for a target thermal efficiency of at least 40%, a long refueling interval (30 years or more) with small burnup reactivity swing, a core barrel diameter of less than 3.0 m, and an active core height of less than 1.5 m.

Under the US-DOE programs, several options and innovative fast reactor technologies have been investigated or are being developed for improving overall core performance, achieving capital cost reductions, and increasing inherent safety. These features include the following:

- a compact long-lived core design with fission-gas vented (and non-vented) fuel
- advanced shielding material
- advanced structural materials that reduce commodities
- advanced cladding materials that allow higher burnup levels to be achieved beyond the current range of existing cladding performance
- compact intermediate heat exchangers
- compact fuel handling system
- self-cooled electromagnetic pumps
- advanced supercritical carbon dioxide power conversion system with superheated steam backup
- increased core outlet temperatures that increase the overall plant thermal efficiency

These innovative fast reactor technologies are not currently available, but it is expected that they will be available when the AFR-100 is deployed. Thus, the AFR-100 concept developed herein incorporated these technologies in order to investigate the effect on overall primary plant compactness which directly impacts economics while maintaining an inherent safety approach. Some of these technologies are also applicable to other fast reactor designs with the same expected benefit. Table 1 provides some of the parameters for the AFR-100.

Table 4 – AFR-100 Parameters

	Parameter
Electrical/Thermal Power	100MWe/250MWt
Thermal efficiency	41.9%
Reference Fuel	UZr metal fueled core, 30 year life
Core, Diameter/Height	118” (300 cm)/ 167.3” (425 cm)
Core, No. of Drivers	150
Primary Sodium Coolant Temperature, Inlet/Outlet	743F/1,022F (395C/550C)
Total Primary Sodium Mass Flow Rate	2,802 lb/s (1,271 kg/s)
Primary Sodium Volumetric Flow Rate	5,864 gpm (0.37 m^3/s)
Primary Pumps	Electromagnetic
PHTS Configuration	Core Cover – Cold Pool
Core Support	Top Supported with redundant support rods
Intermediate Heat Exchanger Configuration	Kidney-shaped Removable IHX – Straight twisted tubes®
Reactor Vessel Support	Conical Ring – Top

	Support
Emergency Decay Heat Removal	Direct Reactor Auxiliary Heat Exchanger in cold pool – Twisted Tube® HX
Primary Purification System	Integrated cold trap within reactor vessel
Power Conversion System	S-CO_2 Brayton Cycle with superheated steam backup
Containment	Steel Containment with separate plane impact shield
In-Vessel Fuel Handling Mechanism	Single Rotatable Plug with pantograph FHM

AFR-100 is a concept as a small modular reactor as shown in Figure 4.

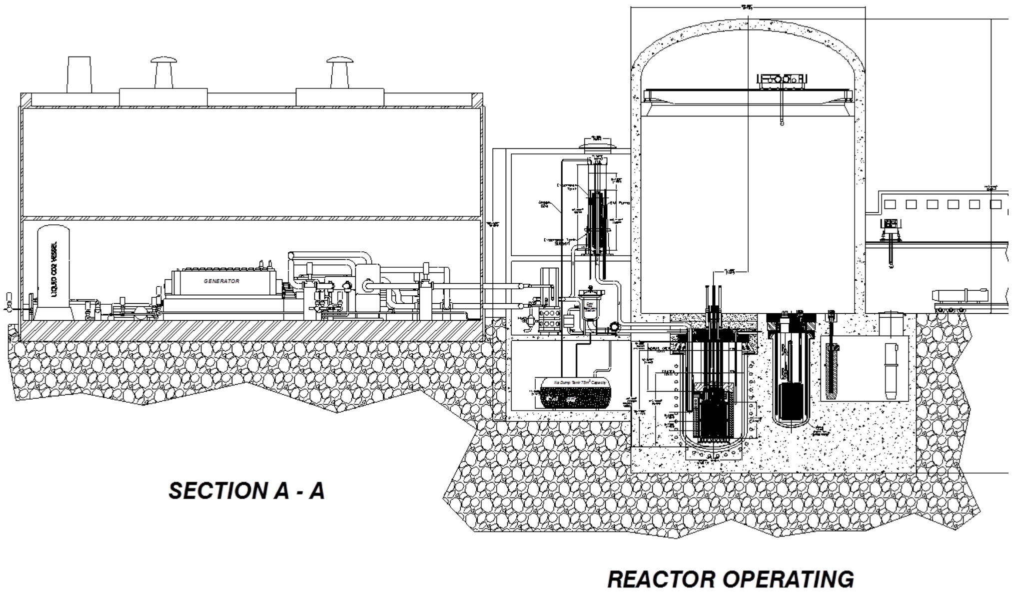

Figure 4 – AFR-100 – Elevation View in Reactor Operating Mode

2.5. BN-1200 (candidate)

The BN-1200 is designed as a commercial large size nuclear power unit with pool-type sodium-cooled fast reactor using a traditional steam-water tertiary circuit.

BN-1200 has enhanced safety based on maximal application of inherent safety features and passive safety systems that allows to meet safety requirements set for the 4th generation reactors.

Application of some innovative decisions, in particular integral steam generators, simple refuelling system etc, decreases strongly cost of the power unit making it competitive with other energy sources.

Table 5 BN-1200 parameters

Items	Values

Output thermal/electric	2800/1220 MW
Fuel type	Mixed uranium-plutonium nitride fuel / MOX-fuel
Fuel contents	LWR UO2 recycle, LWR MOX recycle, FR recycle
Cladding material	austenitic EK164/ferritic-martensitic EK181
Breeding ratio	1.1 to 1.4 / 1.2
Refueling cycle	920 to 1320 / 1060 to 1320 eff. days
Burnup	7.6 to 10.9 / 11.8 to 14.5 % h.a.
Reactor type	Pool
Primary circuit temperature	550 / 410 deg-C
Number of primary PM/IHX	4/4
Number of secondary PM/HX	4/4
Tertiary system type	Steam turbine
Efficiency	43.5 (gross) / 40.7 (net) %
Passive shutdown	Self-Actuated Shutdown Systems (SASS)
CDA mitigation	1) Upper sodium cavity, 2) Cooling in core catcher
Configuration of DHRS	DRACS (full NC)
Fuel storage	EVST + water pool

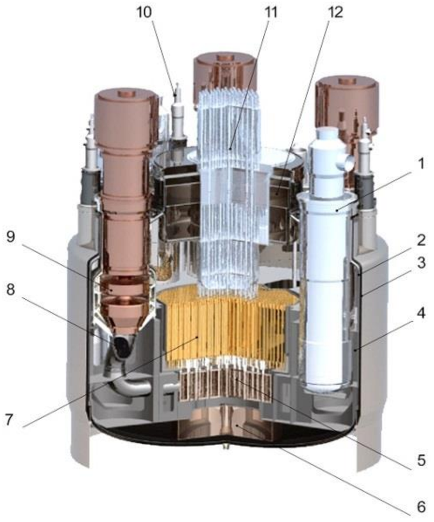

FIG. 5 BN-1200 *Concept*

1 – IHX; 2,3 – main and guard vessel; 4 – supporting structure; 5 – inlet plenum; 6 – core catcher; 7 – core; 8 – pressure pipeline; 9 – MCP-1; 10 – refueling mechanism; 11 – CRDM; 12 – rotating plugs

2.6. CFR-1200 (candidate)

The CFR-1200, which is the commercial type fast reactor in China, is designed to explore the important role of fast reactor in the nuclear energy development and the whole fuel cycle. The design of CFR-1200 will meet the objectives for generation IV nuclear energy systems.

CFR-1200 is a 1200MWe pool type sodium-cooled fast reactor. MOX fuel and ODS cladding material will be used based on the design goals. Passive features, including passive shutdowm and passive heat removal, will both be considered for safety. For the power conversion system, some R&D of Super-CO2 conversion will also be carried out in spite of water-steam conversion as the first choice.

According to the rough schecule of CFR-1200, The pre-concept design is from the year 2015 to 2020. The concept design may last at least 5 years from 2020, and then followed by at least 5 years preliminary design.

Table 6 CFR-1200 parameters

Items	Values
Output thremal/electric	2900MW/1200MW
Fuel type	MOX
Fuel contents	LWR UO2 recycle, LWR MOX recycle, FR recycle
Cladding material	ODS
Breeding ratio	~1.2
Refueling cycle	300
Burnup	150MWd/kgHM
Reactor type	Pool
Primary circuit temperature	395/545
Number of primary PM/IHX	4/8
Number of secondary PM/HX	4/32
Tertiary system type	Water-steam/Super-CO_2
Efficiency	41%
Passive shutdown	Thermal-hydraulic and Curie point
CDA mitiagation	Core catcher
Configuration of DHRS	Primary circuit/Secondary circuit/Vessel
Fuel storage	Burnup fuel tank and water pool

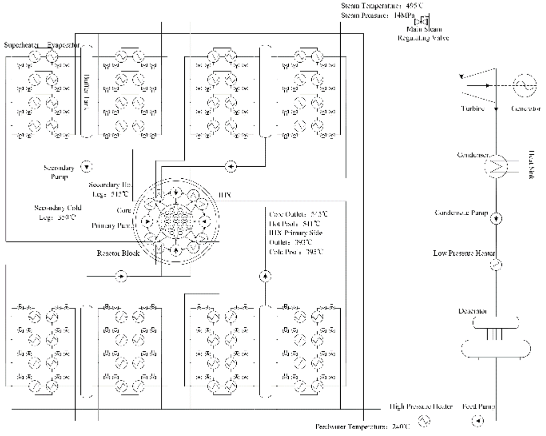

FIG. 6 CFR-1200 *Concept*

3. Status of Project Management Boards

3.1. Safety and Operation (SO)

The SO project is arranged into three Work Packages (WPs) which consist of WP SO 1 “Methods, models and codes” for safety technology and evaluation, WP SO 2 “Experimental programmes and operational experience” including the operation, maintenance and testing experience in the experimental facilities and existing SFRs (e.g. Monju, Phenix, BN-600 and CEFR), and WP SO 3 “Studies of innovative design and safety systems” related to the safety technology for the Gen IV reactors such as passive safety systems. For common projects, following four items have been defined.

- Natural circulation in sodium systems (first priority)

  - Design issues: thermal stratification, flow redistribution or reversal, freezing, thermal stress
  - Evaluation methods: PIRT, model selection, plant-scale validation, uncertainty quantification
  - Fundamental models: heat capacity, pressure loss, and property correlations; experimental measurement techniques

- Reactivity control systems and passive shutdown options
  - Hydraulic devices, Curie-point, GEMs, ARC, etc.
- Ex-vessel cooling system options
  - RVACS (air NC), forced oil convection, modeling approaches, etc.
- Sodium boiling experience
  - Timing and location, stability, codes and methods, experiments

3.2. Advanced Fuel (AF)

The SFR-AF project aims towards developing high burn-up minor-actinide bearing fuels as well as claddings and wrappers capable of withstanding high neutron doses and temperatures. It includes research on remote fuel fabrication & material manufacturing techniques as well as performance under irradiation. The related long term research is enhanced and accelerated gaining knowledge and solving issues thanks to a fruitful cooperation: 15 deliverables for 2015 have been distributed and 22 for 2016 is going to be distributed. Degrees of technical progress are not uniform: metal &oxide fuels have been identified as candidates for 1st generation transmutation fuels whereas carbide & nitride fuels are long term options. A membership extension to get Russia (ROSATOM) and China (CIAE) on-board was completed in October 2015. Project Arrangement (PA) will be extended till 2027 and New Project Plan till 2027 is under preparation involving following three items.

- SFR non MA-bearing Driver Fuel Evaluation, Optimization & Demonstration
- MA-bearing Transmutation Fuel Evaluation, Optimization & Demonstration
- High-burnup Fuel Evaluation, Optimization & Demonstration

3.3. Global Actinide Cycle International Demonstration (GACID)

Research on component design and balance-of-plant covers experimental and analytical evaluation of advanced in-service inspection and repair technologies including leak-before-break assessment, steam generators and development of alternative energy conversion systems, e.g. using Brayton cycles. Such a system, if shown to be viable, would reduce the cost of electricity generation significantly. The primary R&D activities related to the development of advanced BOP systems are intended to improve the capital and operating costs of an advanced SFR. The main activities in energy conversion system include: (1)

development of advanced, high reliability steam generators and related instrumentation; and (2) the development of advanced energy conversion systems based on Brayton cycles with supercritical carbon dioxide as the working fluid. In addition, the significance of the experience that has been gained from SFR operation and upgrading is recognised. New Project Plan from 2017 to 2021 is under preparation involving new two members: Russia (ROSATOM) and China (CIAE).

3.4. Component Design and Balance of plant (CDBOP)

The GACID project aims at conducting collaborative R&D activities with a view to demonstrate, at a significant scale, that fast neutron reactors can indeed manage the actinide inventory to satisfy the Generation IV criteria of safety, economy, sustainability and proliferation resistance and physical protection. The project consists of MA bearing test fuel fabrication, material properties measurements, irradiation behaviour modelling, irradiations in Joyo, licensing and pin scale irradiations in Monju, and post-irradiation examinations, as well as transportation of MA raw materials and MA bearing test fuels.

4. Conclusions

In 2015, a project arrangement on SFR System Integration and Assessment (SI&A) has been signed by 7 members : China, EU, France, Japan, Korea, Russia and US. In the SI&A project, R&D needs from the SFR design will be shown to the R&D project, and R&D results from each R&D project will be integrated into the designs. Presently there are four SFR design concepts. China is going to propose CFR-1200, and Russia is going to propose BN-1200 as new design tracks. After SI&A project started, the GIF-SFR has completed the function of R&Ds and integration of R&D result to the SFR design. These strong collaboration network is expected to provide the promising generation IV SFR concepts. This paper describes SFR design concepts in SFR project and interactions with R&D projects under GIF framework.

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[1] The US DOE Nuclear Energy Research Advisory Committee and the Generation IV International Forum, “A technology roadmap for Generation IV Nuclear Energy Systems”, December 2002, GIF-002-00