# Appendix 5.0
# Sodium-Cooled Fast Reactor

# Contents

# A5.1 INTRODUCTION AND BACKGROUND

## A5.1.1 System Description

The sodium-cooled fast reactor (SFR) system features a fast-spectrum reactor and closed fuel recycle system. The primary mission for the SFR is the management of high-level wastes and, in particular, management of plutonium and other actinides. With innovations to reduce capital cost, the mission can extend to electricity production, given the proven capability of sodium reactors to utilize almost all of the energy in the natural uranium.

A range of plant size options is available for the SFR, ranging from modular systems of a few hundred MWe to large monolithic reactors of about 1500 MWe. Sodium core-outlet temperatures are typically 550ºC. The basic system reference values for the SFR are shown in Table A5.1. Table A5.2 shows the range of values for the design parameters of the two main concepts being pursued under the Generation IV International Forum (GIF), the Japan Nuclear Cycle Development Institute SFR (JSFR), and the Korean KALIMER concepts.

Table A5.1. Reference parameters for the SFR

| System Parameters | Reference Value |
|---|---|
| Outlet Temperature (°C) | 510 - 550 |
| Pressure (atmospheres) | ~ 1 |
| Power Rating (MWe) | 150 - 1500 |
| Fuel | Oxide or metal alloy |
| Cladding | Ferritic or ODS ferritic |
| Average Burnup (MWd/KgHM) | ~ 70 – 200 |
| Conversion Ratio | 0.5 – 1.3 |
| Average Power Density (MWth/m$^3$) | ~ 350 |

Table A5.2. Basic design parameters for the current GIF SFR designs, JSFR and KALIMER.

| Design Parameters | Reference Values |
|---|---|
| Plant Power, MWe | 600 - 1,500 (Middle-Large) |
| Thermal Power, MWt | 1,589 - 3,570 (Middle-Large) |
| Plant Efficiency, % | 38 - 42 |
| Outlet coolant temperature, $^{o}$C | 510 - 550 |
| Inlet coolant temperature, $^{o}$C | 366 - 395 |
| Cycle length, months | 18 |
| Fuel reload batch, batches | 3 – 4 |
| Fuel Type | Metal(U-TRU-10%Zr Alloy), MOX(TRU bearing) |
| Cladding Material | HT9 , ODS |
| Burn-up, GWd/t | 66 - 150 |
| Breeding ratio | 1.0 - 1.2 |

The primary coolant system in a SFR can either be arranged in a pool layout (a common approach, where all primary system components are housed in a single vessel), or in a compact loop layout favored in Japan. For both options, there is a relatively large thermal inertia of the primary coolant. The two conceptual configurations are shown in Figure A5.1. A large margin to coolant boiling is achieved by design and is an important safety feature of these systems. Another major safety feature is that the primary system operates at essentially atmospheric pressure. A secondary sodium system acts as a buffer between the radioactive sodium in the primary system and the energy conversion system in the power plant.

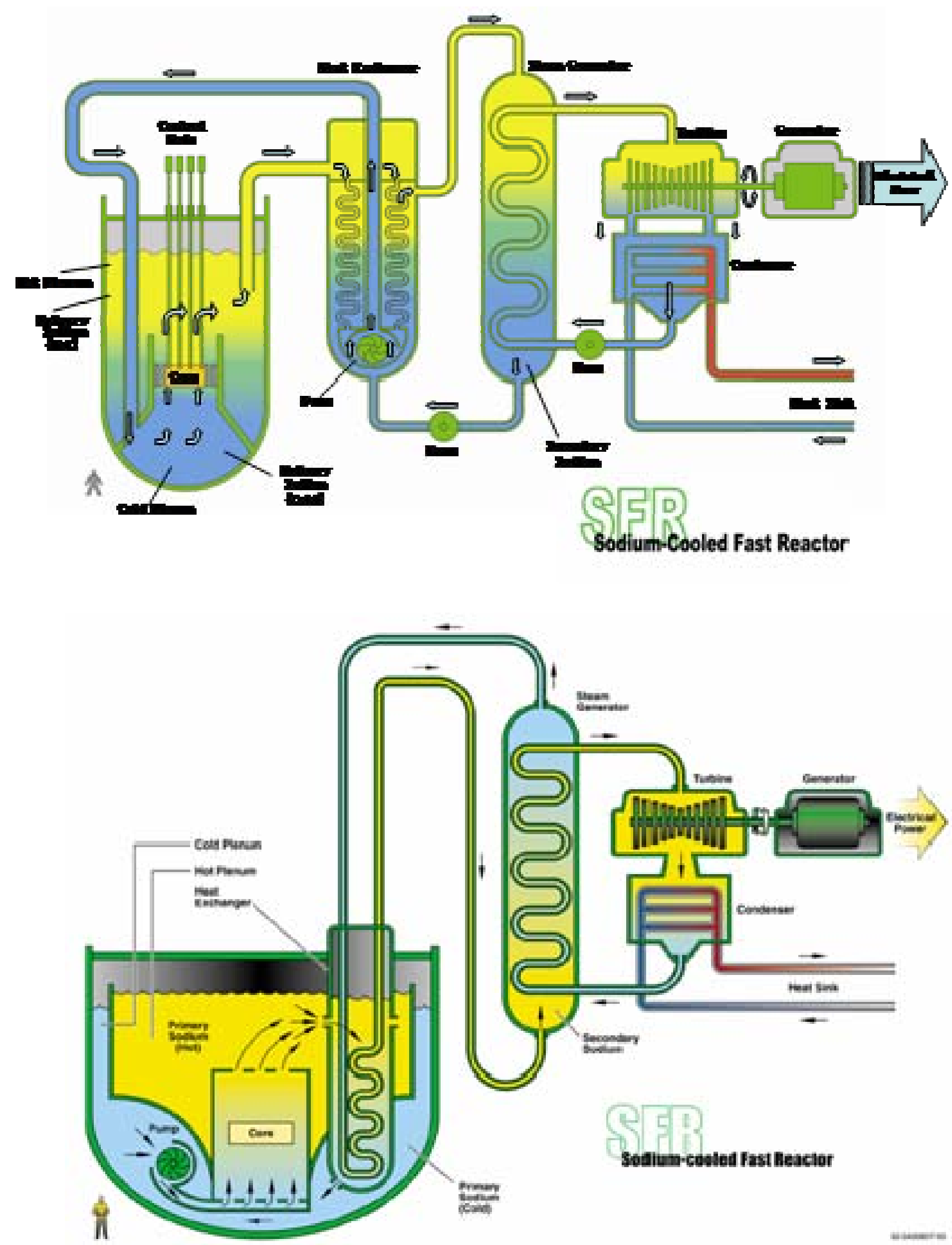


Figure A5.1. Basic SFR power plant system configurations

Two fuel options exist for the SFR: (1) mixed uranium-plutonium oxide (MOX), or (2) mixed uranium-plutonium-zirconium metal alloy (metal). The experience with MOX fuel is considerably more extensive than with metal.

### A5.1.2 Overall System Timeline

The SFR activities will be under the overall leadership of Argonne National Laboratory. The overall development schedule for the SFR, shown in Section 4, is based on the Generation IV performance targets. The performance targets affecting the SFR development, in collaboration with GIF, include completion of the pre-conceptual reference design by 2007 and completion of the initial phase of materials research and reactor design by 2010 in order to select the preferred fast spectrum system by the end of 2010.

## A5.2 RESEARCH AND DEVELOPMENT STRATEGY

Sodium-cooled systems have been significantly developed and may not require as much system design research and development (R&D) as other Generation IV systems. R&D is nevertheless needed for demonstration of the design and safety characteristics, especially with fuels containing minor actinides, and to optimize the design with innovative approaches to meet the objectives of the specific missions of Generation IV, primarily actinide management.

### A5.2.1 Objectives

The objective of the R&D program is to establish the viability of the SFR system and to achieve the overall performance targets discussed under the program schedule to provide sufficient information to support the selection of the preferred fast spectrum system by 2010. The R&D activities are conducted in collaboration with other GIF countries interested in SFR technology. There is a GIF R&D Plan intended to cover the R&D to resolve viability and performance questions to complete the development of the SFR system.

### A5.2.2 Scope

The scope of the current SFR R&D Plan is to maintain the collaboration with GIF countries in the development of the system to meet the overall Program goals of fast spectrum system selection by 2010. The activities included under this R&D Plan are interacting with GIF countries, ensuring that the GIF R&D Plan addresses the needs and goals of the program; maintaining awareness of the R&D progress and accomplishments under the GIF Plan;, and contributing to the GIF SFR R&D with relevant activities being performed under the Advanced Fuel Cycle Initiative (AFCI) and Generation IV Programs in the United States.

### A5.2.3 Viability Issues

Because of extensive previous experience with SFR technologies, few viability questions remain for development of the Generation IV SFR system. Those that remain are, mostly associated with the completion of the fuel cycle and the use of transuranic-bearing fuels. Additional performance R&D is needed for the successful commercialization of the system. The viability and performance R&D elements identified in the GIF SFR R&D Plan can be summarized as follows:

- Advanced fuels and fuel cycles. The completion of the fuel database; the fabrication of ceramic pellets that contain minor actinides and trace amounts of fission products; and the scale-up of the uranium crystallization step and, for the pyroprocess, viability issues include the development and demonstration of engineering-scale recovery of transuranics and the demonstration of large throughput operations.

- Design and safety. The verification of the predictability and the effectiveness of the mechanisms that contribute to an inherently safe response to design basis transients and anticipated transients without scram, and the certainty that bounding events considered in licensing can be sustained without loss of coolability of fuel or loss of containment function.

- Component design and balance of plant. The capital cost reduction to levels competitive with those of other nuclear systems and power sources and the development of advanced in-service inspection and repair (in sodium) technologies.

In order to support the technology selection in FY 2010, the viability R&D must be completed. Outside the fuel development and fuel cycle demonstration elements (assumed to be under the development scope of the AFCI program), viability issues were identified during the Generation IV Technology Roadmap in safety and reactor technology. The viability and performance issues for the reference system (oxide-fueled JSFR, under development in Japan) are being resolved under the GIF SFR R&D Plan, as are those reactor design issues for a metal-fueled system (KALIMER design).

The activities that would be required to complete the viability of the metal-fueled SFR, related primarily with the use of transuranic-bearing fuel, are included in this R&D Plan. The viability safety issues identified in the Roadmap are primarily related to the analysis and modeling of bounding accidents and include:

- Long-term coolability of metal debris after a bounding accident

- In-vessel debris retention for metal fuel

- Experimental evidence that molten metal fuel will drain from the core to prevent recriticality.

### A5.2.4 Research Interfaces

The main interfaces in the SFR R&D Plan are with (1) other elements of the Generation IV program, cross-cutting activities in particular, (2) the AFCI activities that may be relevant to the SFR, and (3) the GIF SFR R&D projects.

Under the AFCI and Generation IV programs, there are activities that can support the SFR system development, primarily in the development of transuranic-bearing metal fuels and nitride fuels (a backup fuel under the GIF SFR R&D Plan). Other cross-cutting activities (advanced energy conversion systems) and activities under the International Nuclear Energy Research Initiative (I-NERI) program (in the area of safety) are also of relevance and are included in the contributions to the GIF R&D Plan.

In interaction with the ACFI program, the preliminary fuel cycle conditions and requirements for an actinide-management SFR should be established. Based on these operating requirements, the remaining development needs for the SFR, with emphasis on safety-related elements, would be identified and documented.

#### A5.2.4.1 Relationship to GIF R&D Projects

The SFR activities in the United States are limited to the interaction with the GIF Steering Committee and with other U.S. programs elements:

- Interface with the Generation IV International Forum, in particular with the GIF countries leading the SFR development effort, has the purpose of optimizing the effectiveness of the GIF R&D plan and maintaining cognizance of progress in SFR development.

- Interface with the AFCI Program on fuel and fuel cycle development activities for their relevance to the SFR.

- Interface with the crosscutting activities for relevance to SFR.

The SFR Plan closely follows the activities of the GIF R&D Projects relevant to the SFR through participation in the GIF SFR Steering Committee and Project Management Boards. The GIF SFR Steering Committee has developed a R&D Plan. The GIF R&D Plan provides (1) a reference concept and an outline of the SFR technical objectives and performance goals, (2) an identification of the technology gaps that exist to achieve and demonstrate those technical objectives and performance goals, and (3) a proposed R&D path to close the technology gaps considered necessary to demonstrate the viability and performance of the reference concept.

Sodium-cooled fast reactors require a closed fuel cycle to take advantage of their actinide management and fuel utilization features, such as transuranic burning and tranusuranic recycle, for sustainability considerations. Therefore, completing and demonstrating the development of the fuel cycle is as important as completing the development of the reactor design. The GIF R&D Plan provides for coordination with the GIF Fuel Cycle Management Board.

#### A5.2.4.2 University Collaborations

University collaborations of relevance to the SFR are not established directly, but they may exist for other elements of the Generation IV program (e.g., supercritical $CO_2$ energy conversion systems) and in the AFCI program (e.g., development of transmutation fuels).

#### A5.2.4.3 Industry Interactions

No direct industry interactions are carried out under the SFR program. Relevant interactions with industry may be concluded by international partners under the GIF R&D Plan.

#### A5.2.4.4 I-NERI

An I-NERI collaboration with the Republic of Korea is currently under way in the area of SFR safety modeling and analysis. The current project is due to conclude in FY 2005.

## A5.3 HIGHLIGHTS OF R&D

### A5.3.1 System Design and Evaluation Methodology

Overall R&D activities in this area are conducted under the GIF SFR R&D Plan.

Innovations for the SFR systems include means to reduce capital cost. Both economy of scale and economy of modular factory fabrication and just-in-time capacity additions are proposed. For monolithic, loop-type reactor designs, innovations include simplification based on reducing the number of loops and simplifying and increasing the size of components. Here the availability of qualified advanced materials (for example 12Cr-1Mo) is considered a technology gap requiring viability R&D.

Additional R&D needs have been identified for basic nuclear data enhancements for certain minor actinides, since they are recycled in the SFR. The basis for the actinide management strategy needs to be well established. Studies in the fuel cycle options for actinide management are programmatically under the ACFI program.

Recommended R&D also includes operations and maintenance items, such as the development of under-sodium viewing and/or ultrasonic testing in sodium, development of high-reliability steam generators, and development or selection of materials for components and structures.

In reactor safety, the technology gaps center around three general areas: basic properties; assurance of passive safety response, including the modeling and validation of the models through experimentation; and the technology for evaluation of bounding events. Basic property needs include data on fuel performance for SFR fuels that contain minor actinides (see Section A5.3.2, Fuel and Fuel Cycle). For modeling and validation of passive safety, it will be necessary to verify the reactivity feedback mechanisms of the MA-bearing fuels and to establish their transient fuel behavior prior to failure. These safety R&D needs related to basic properties and passive safety confirmation have also been determined to relate to performance R&D. Viability R&D focuses on the technology for evaluating bounding accidents.

## A5.3.2 Fuel and Fuel Cycle

SFR fuels will contain a relatively small fraction of minor actinides and a small amount of fission products. The systems based on MOX fuel are primarily under development in Japan, and their preferred recycle option is an advanced aqueous process. Metal-fueled reactor systems under development in the United States use a pyroprocessing recycle process as the preferred fuel cycle option.

The GIF countries leading the development of the SFR will develop the draft strategy for proliferation resistance and physical protection. Studies undertaken under the ACFI program related specifically to pyroprocessing of metal fuels can complement the draft strategy.

### A5.3.2.1 Advanced Aqueous Process

Viability R&D work remains to demonstrate the high actinide recoveries (99.9%) and the proliferation resistance features of the process.

Demonstration of remote fabrication processes for ceramic fuels, whether the process is simplified pellet fabrication or one of the particle compaction approaches, is also needed.

### A5.3.2.2 Pyroprocess

It will be essential to conduct plutonium and minor actinide extraction experiments from electrorefiners at a much larger scale than have been done until now (~50 g plutonium). Significant work on electrorefiner salt cleanup and high-level waste form production needs to be done in order to achieve the very high actinide recoveries (~99.9%) that are the objective of the process. It is important to develop any secondary waste stream treatment that may become necessary to achieve this recovery goal. In

addition, it is necessary to complete certification of the two high-level waste forms (metal and ceramic) for repository disposal.

The viability issues can be summarized as follows:

1. Scale process from laboratory to engineering scale
2. Demonstration of recovery process for transuranics
3. Development of salt cleanup to extract actinides for waste processing
4. Development of ion exchange systems for ceramic waste volume reduction

Viability items for pyroprocess are functionally part of the ACFI program and are not included in the SFR development plan under Generation IV.

#### A5.3.2.3 Fuels

A significant technology gap for fast reactor systems using recycled fuel is a need for performance data and transient safety testing of fuel that has been recycled using prototypic processes.

The viability issues identified with SFR fuels are summarized as follows:

Oxide Fuels

- Fabricability, as included under fuel cycle.

Metal Fuels

- Confirmation of properties of minor-actinide bearing fuels
- Confirmation of fuel-cladding constituent interdiffusion behavior for minor actinide-bearing fuels
- Modeling of fuel-cladding interdiffusion and fuel constituent migration

The viability items for SFR fuel development are also programmatically under the ACFI program and are not included in the SFR development plan here.

### A5.3.3 Energy Conversion

The basic R&D in energy conversion for SFR systems is (1) to establish the technical basis for coupling supercritical carbon dioxide Brayton cycles to sodium-cooled fast reactors and (2) to develop revolutionary steam generator technologies to minimize plant cost. The first activity, coupling to a supercritical carbon dioxide cycle, is expected to take place as part of an effort on Crosscutting Energy Products R&D.

Brayton cycle development for application to the SFR is addressed in the GIF R&D Plan. SFR systems will also benefit from innovative balance of plant simplifications pursued under crosscutting activities in the U.S. Generation IV program, as discussed under the Energy Conversion section of the program plan.

### A5.3.4 Materials

Materials-related issues are covered under different subsections of this R&D Plan. These issues include (1) fuel-cladding constituent interdiffusion behavior for MA-bearing fuels, (2) development of high-strength steels for use in structures and piping to improve economics, and (3) improved materials for recycle systems.

## A5.4 10-YR PROJECT COST AND SCHEDULE

### A5.4.1 10-yr Project Budget

The budget projection for the 10-yr period starting in FY 2005 is shown in Table A5.3. The major project milestones covered in this budget projection are described below. The current plan does not address the resolution of the remaining viability issues under System Design and Safety. Only the GIF interaction is currently funded under this 10-yr program plan.

Table A5.3. Ten-year budget profile for SFR activities ($K).

| Task | FY-05 | FY-06 | FY-07 | FY-08 | FY-09 | FY-10 | FY-11 | FY-12 | FY-13 | FY-14* | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Interaction with GIF | 40 | | | | | | | | | | |
| **TOTAL** | **40** | | | | | | | | | | |

* Amounts and scope for System Design and Safety will need to be determined after system selection in FY 2010, if applicable.

Note, if the SFR technology were selected in FY 2010, a design activity would be started in preparation for the construction phase. This is not included in the current plan.

### A5.4.2 10-yr Project Schedule

Under the current scope, the only activity is the GIF interaction and no detailed schedule is needed.

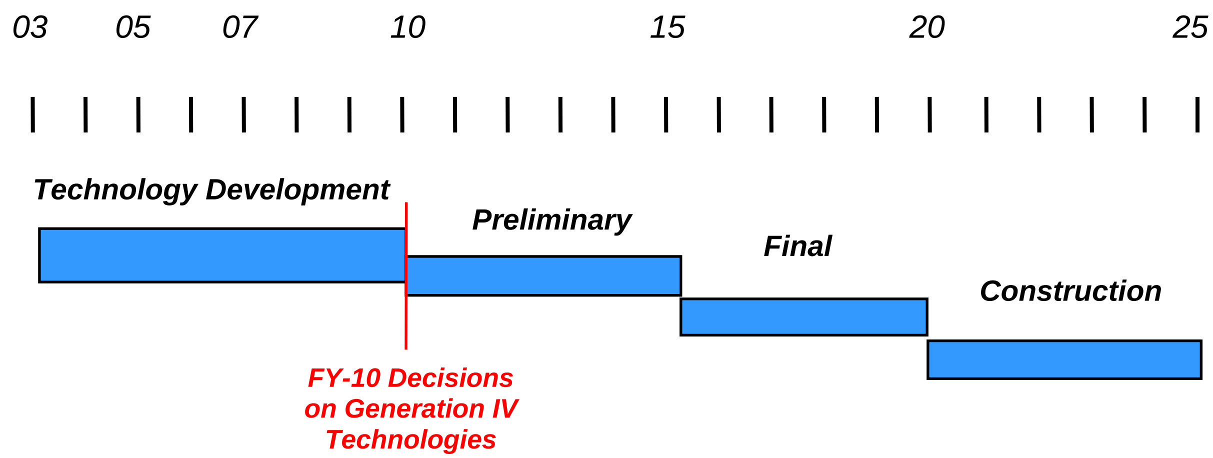


Figure A5.2. SFR Development timeline

### A5.4.3 10-yr Project Milestones

Project milestones and deliverables for GIF Interaction during the period will be:

- Annually: Collect information on SFR-related R&D in Generation IV International Forum countries to support the future development of the SFR R&D plan for Generation IV and update Program Plan as needed.

- Deliverables: Periodic reporting on GIF SFR Steering Committee activities.

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