"THE SODIUM-COOLED FAST REACTOR"

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SUMMARY
The Sodium-cooled fast reactor (SFR) features a closed fuel cycle for efficient conversion of fertile uranium and management of minor actinides. A full actinide-recycle fuel cycle is envisioned with two major options: One involves intermediate-sized (150 to 500 MWe) sodium-cooled fast reactors with uranium-plutonium-minor-actinide-zirconium metal alloy fuel, supported by a fuel cycle based on pyrometallurgical processing in co-located facilities. The second involves medium to large (500 to 1500 MWe) sodium-cooled reactors with mixed uranium-plutonium oxide fuel, supported by a fuel cycle based upon advanced aqueous processing at a centralized location serving a number of reactors. Owing to the number of sodium fast reactors built and demonstrated around the world, and thus their technological maturity, the primary focus of the R&D is on the recycle technology and economics of the overall system. On the reactor side, demonstration of passive safety and improvements in inspection and serviceability will be emphasized.

The SFR system is primarily envisioned for missions in actinide management and electricity production. The SFR system is the nearest-term actinide management system of the Generation IV alternatives, with a schedule driven mainly by fuel cycle developments, and estimated to be commercially deployable by about 2020.

I. INTRODUCTION

The primary mission for the SFR is the management of high-level wastes, and in particular, management of plutonium and other actinides. The Generation IV Roadmap Fuel Cycle Crosscut Group (FCCG) found that the limiting factor facing an essential role for nuclear energy with the once-through cycle is the availability of repository space worldwide (Figure 1) [FCCG Report]. This becomes an important issue, requiring new repository development in only a few decades. Systems that employ a fully closed fuel cycle hold the promise to reduce repository space and performance requirements, although their costs must be held to acceptable levels. Closed fuel cycles, working alone or symbiotically with systems using a once-through cycle, permit partitioning the nuclear waste and management of each partitioned fraction. In the longer term, beyond 50 years, or if major new missions requiring nuclear energy production (such as a major growth in the use of hydrogen as an energy carrier) develop, uranium resource availability also becomes a limiting factor (figure 1) unless breakthroughs occur in mining or extraction technologies. Fast spectrum reactors have the ability to utilize almost all of the energy in the natural uranium versus the 1% utilized in thermal spectrum systems.

SFRs are the most technologically developed of the six Generation IV systems. SFRs have been built and operated in France, Japan, Germany, the U.K., Russia or the U.S.S.R., and the U.S. Demonstration plants ranged from 1.1 MWth (at EBR-I in 1951) to 1200 MWe (at SuperPhenix in 1985), and sodium-cooled reactors are operating today in Japan, France, and Russia [Till, Kiryushin, King, still need a PHENIX and MONJU]. The SFR system is the nearest-term actinide management system in the Generation IV portfolio, estimated to be deployable by 2020. With innovations that reduce capital cost, the mission for the SFR can extend to electricity production. Based on the actinide management and electricity production missions, the primary focus of the R&D is on the recycle technology, economics of the overall system, assurance of passive safety, and accommodation of bounding events.

This paper will describe the SFR concept, the known technology gaps, and the necessary R&D to bring the concept to deployment.

II. CONCEPT DESCRIPTION

The primary benefits of the SFR are in sustainability, both actinide management to minimize waste impact and optimal use of fuel resource through recycle. SFRs use a closed fuel cycle to enable their advantageous features. There are two primary fuel cycle technology options for the SFR: (1) an advanced aqueous process, and (2) the *pyroprocess*, which derives from the term, pyrometallurgical process. Both processes have similar objectives: (1) recovery and recycle of 99.9% of the actinides, (2) inherently low decontamination factor of the product, making it highly radioactive, and (3) never separating plutonium at any stage. The scales of commercial oxide and metal facilities are different. An oxide treatment facility would likely be centralized with throughput on the order of about 1000 MTHM per year for LWR fuel, or about 100 MTHM per year for fast reactor fuel. Collocation of the fuel cycle facility and the reactor plant is not excluded however. A metal fuel cycle facility would likely be located with a fast reactor and have a throughput on the order of 5 MTHM per year.

The technology base for the advanced aqueous process comes from the long and successful experience in several countries with PUREX process technology and oxide fuel. The advanced process proposed by Japan, for example, is simplified relative to PUREX and does not result in highly purified products. The advanced aqueous reprocessing option consists of a simplified PUREX process with the addition of a uranium crystallization step and a minor actinide recovery process (the Japanese version of advanced aqueous can be seen in Figure 2). The purification process of U and Pu in the conventional PUREX is eliminated, and U/Pu is co-extracted with Np with reasonable decontamination factors (DFs) for recycle use. The uranium crystallization removes most of the bulk heavy metal at the head end and eliminates it from downstream processing. The main process stream is salt-free, which reduces the low-level waste. The advanced pelletizing process is simplified by eliminating the powder blending and granulation steps from the conventional MOX pellet process. In the oxide fuel cycle, greater than 99% of U/TRU is expected to be recycled, and the decontamination factor of the reprocessing product is higher than 100. The technology base for fabrication of oxide fuel assemblies is substantial, yet further extension is needed to make the process remotely operable and maintainable. The high-level waste form from advanced aqueous processing is vitrified glass, for which the technology is well established.

The pyroprocess (see Figure 3) has been under development since the inception of the Integral Fast Reactor program in the U.S. in 1984. When the program was cancelled in 1994, pyroprocess development continued by treating EBR-II spent fuel for disposal. In this latter application, plutonium and minor actinides were not recovered, and pyroprocess experience with these materials remains at laboratory scale. Batch size for uranium recovery, however, is at the tens-of-kilogram scale, about that needed for deployment. Remote fabrication of metal fuel was demonstrated in the 1960s. Significant work has gone into repository certification of the two high-level waste forms from the pyroprocess, a glass-bonded mineral (ceramic) and a zirconium-stainless steel alloy. The pyroprocess can recycle metallic fuel from fast reactors, and with appropriate head end steps to reduce actinide oxides to metals, it can process existing LWR fuel to recover transuranics for feed to fast reactors. These two uses have many common characteristics and process steps.

For two reasons, both of these fuel cycle technologies must be adaptable to thermal spectrum fuels in addition to serving the needs of the SFR. First, the startup fuel for the fast reactors must come ultimately from spent thermal reactor fuel. Second, for the waste management advantages of the advanced fuel cycles to be realized (namely, a reduction in the number of future repositories required and a reduction in their technical performance requirements), fuel from thermal spectrum plants will need to be processed with the same recovery factors. Thus, the reactor technology and the fuel cycle technology are strongly linked.

A range of plant size options are available for the SFR, ranging from modular systems of a few hundred MWe to large monolithic reactors of 1500–1700 MWe. Sodium core-outlet temperatures are typically 530-550ºC. A summary of the design parameters for the SFR system is given in Table 1.

The primary coolant system can either be arranged in a pool layout (see Figure 4, 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. 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, pressurized only to the extent needed to move fluid. Sodium reacts chemically with air, and especially with water, which is a safety drawback. To improve safety, a secondary sodium system acts as a buffer between the radioactive sodium in the primary system and the steam or water that is contained in the conventional Rankine-cycle power plant. If a sodium-water reaction occurs, it does not involve a radioactive release.

The fuel options for the SFR are MOX and metal. Both are highly developed as a result of many years of work in several national reactor development programs. Burnups in the range of 150000–200000 MWd/tonne have been experimentally demonstrated for both. Nevertheless, the databases for oxide fuels are considerably more extensive than those for metal fuels.

There is an extensive technology base in nuclear safety that establishes the passive safety characteristics of the SFR and their ability to accommodate all of the classical “anticipated transients without scram” events without fuel damage. Landmark tests of two of these events were done in RAPSODIE (France) in 1983 and in EBR-II (U.S.) in 1986. Still, there is important viability work to be done in safety. A key need is to establish the long-term coolability of oxide or metal fuel debris after a bounding case (i.e. extremely low-probability) accident.

III. TECHNOLOGY GAPS

To bring the SFR to deployment, several fuel cycle and reactor system technology gaps must be closed. With the advanced aqueous fuel cycle, the key viability issue is the minimal experience with production of ceramic pellets (using remotely operated and maintained equipment) that contain minor actinides and trace amounts of fission products. Further, it is important to demonstrate scale-up of the uranium crystallization step. Filling both of these gaps is key to achieving cost goals.

For the pyroprocess, viability issues include lack of experience with larger-scale plutonium and minor actinide recoveries, minimal experience with drawdown equipment for actinide removal from electrorefiner salts before processing, and minimal experience with ion exchange systems for reducing ceramic waste volume.

For the reactor system, technology gaps exist in assurance or verification of passive safety, completion of the fuels database including establishing irradiation performance data for fuels fabricated with the new fuel cycle technologies, and developing in-service inspection and repair (in sodium) technologies.

A key issue for the SFR is cost reduction to competitive levels. None of the SFRs constructed to date have been economical to build or operate. However, design studies have been done, some of them very extensive, in which proponents conclude that both overnight cost and busbar cost can be comparable to or lower than those of the advanced LWRs. In the General Electric S-PRISM design, the key proposed cost reduction feature is its modular construction. In Japanese design studies at the Japan Nuclear Fuel Cycle Development Corporation, innovations such as (1) a reduced number of primary loops, (2) an integral pump and intermediate heat exchanger, and (3) the use of improved materials of construction are the basis for cost reductions.

III. R&D NEEDS

Research on both the fuel cycle and the reactor system is necessary to bring the SFR to deployment. The highlights of the critical research are described in this section.

A. Fuel Cycle Technology R&D

The ultimate objective of the SFR fuel cycle R&D is to complete the process development required to initiate the design of commercial fuel cycle facilities for both oxide and metal fuels of the SFR.

Few viability R&D activities are needed for advanced aqueous reprocessing because the main process technology builds heavily on prior light water and fast reactor fuel cycle technology. Therefore, this fuel cycle can be rapidly advanced to the demonstration stage. To achieve economic competitiveness and reduced environmental impact, the following R&D is needed:

- Determine the crystallization performance of actinides, the crystallization performance of uranium, and the separation efficiency of solids at engineering scale

- Develop the salt-free minor actinide recovery process with high extraction capability for Am and Cm, and separation from lanthanides
- Develop compact centrifugal-type contactors to enable a reduction of the facility size
- Establish the fabricability of low-decontamination factor minor actinide-bearing pellet fuel (with an emphasis on sinterability), and develop the apparatus for remote system operability and maintainability in a hot cell facility
- Extend current studies of the proliferation resistance of this technology.

For the pyroprocess, two process steps and high-level waste volume reduction options have not been pursued beyond laboratory-scale testing. The first needed process step is the reduction of actinide oxides in LWR fuel to metal. Laboratory-scale tests have been performed to demonstrate process chemistry, but additional work is needed to progress to the engineering scale. The second needed step is to develop recovery processes for transuranics, including plutonium. With regard to volume reduction, additional process R&D could potentially increase fission product loading in the high-level waste and reduce total waste volumes. With regard to achieving the high recovery of transuranics, pyroprocessing has been developed to an engineering scale only for the recovery of uranium. Recovery of all transuranics including neptunium, americium, and curium has so far been demonstrated only at laboratory scale. Viability phase R&D is recommended to verify that all actinides can be recycled with low losses.

Both the advanced aqueous process and the pyroprocess will be evaluated and adapted for application to other closed cycle Generation IV systems such as the Gas Fast Reactor (GFR), Lead-cooled Fast Reactor (LFR), and Supercritical Water Reactor (SCWR). This is primarily an issue at the head end of the process (where e.g., fuels from the GFR or LFR systems would be converted to oxide or metal and introduced into the processes described above), and at the tail end (where they would be reconverted to fuel feedstock). Feasibility evaluations and bench-scale testing would enable comparisons to be made between the advanced aqueous and pyroprocess options.

The principal aim of the uranium crystallization process step in advanced aqueous reprocessing is the inexpensive separation of bulk quantities of low-enriched uranium from spent fuel from LWRs. The motivation for this approach is clear: separating the bulk uranium yields an LWR spent fuel process stream that is reduced in heavy metal content by two orders of magnitude, which offers significant potential for volume and cost reduction. The uranium crystallization technique is the favored technology in Japan, and it shows considerable promise. Other means of removing the uranium component of spent LWR fuel are being explored internationally. Principal among these is the uranium extraction (UREX) process, which is under development in the U.S. In UREX, uranium is extracted in a first step of advanced aqueous processing technology, and the plutonium, minor actinides and nonvolatile fission products are sent to the next process step. The relative advantages and disadvantages of uranium crystallization and UREX need to be established through international comparison and development.

Alternative nonaqueous, i.e., *dry* fuel cycle processes, have been investigated in Russia and more recently in Japan. These processes generally aim at pyroprocess methods for oxide fuels. Perhaps more importantly, these activities also aim to establish remote fuel refabrication methods that eliminate the need for remotely operable and maintainable ceramic pellet fabrication production lines, through vibratory compaction or vibropac. Research in these areas may eventually benefit the SFR.

B. Reactor Technology R&D

The fuel options for the SFR are MOX and metal alloy. Either will contain a relatively small fraction of minor actinides and, with the low-decontamination fuel cycle processes contemplated, also a small amount of fission products. The presence of the minor actinides and fission products dictates that fuel fabrication be performed remotely. This creates the need to verify that this remotely fabricated fuel will perform adequately in the reactor. These minor actinide-bearing fuels also require further property assessment work for both MOX and metal fuels, but more importantly for metal fuels. Also for metal fuels, it is important to confirm fuel/cladding compatibility behavior when minor actinides and additional rare earth elements are present in the fuel.

The SFR reactor system technology R&D is aimed at enhancing the economic competitiveness and plant availability. For example, development and/or selection of higher strength-to-weight structural materials for components and piping is important to development of an economically competitive plant. 12Cr ferritic steels, instead of austenitic steels, are viewed as promising structural materials for future plant components because of their superior elevated temperature strength and thermal properties, including high thermal conductivity and low thermal expansion coefficient.

A focused program of safety R&D is necessary to support the SFR. Worldwide experience with design and operation of such systems has shown that they can be operated reliably and safely. The safety R&D challenges for these systems in the Generation IV context are (1) to verify the predictability and effectiveness of the mechanisms that contribute to passively safe response to design basis transients and anticipated transients without scram, and (2) to provide assurance that bounding events considered in licensing can be sustained without loss of coolability of fuel or loss of containment function.

Since many of the mechanisms that are relied upon for passively safe response can be predicted on a first-principles basis (for example, thermal expansion of the fuel and core grid plate structure), enough is now known to perform a conceptual design of a prototype reactor. R&D is recommended to evaluate physical phenomena and design features that can be important contributors to passive safety, and to establish coolability of fuel assemblies if damage should occur. This R&D would involve in-pile experiments, primarily on metal fuels, using a transient test facility.

The second challenge requires analytical and experimental investigations of mechanisms that will assure passively safe response to bounding events that lead to fuel damage. The principal needs are to show that debris resulting from fuel failures is coolable within the reactor vessel, and to show that passive mechanisms exist to preclude recriticality in a damaged reactor. A program of out-of-pile experiments involving reactor materials is recommended for metal fuels, while in-pile investigations of design features for use with oxide fuel are now underway.

Improvement of in-service inspection and repair technologies is important to confirm the integrity of safety-related structures and boundaries that are submerged in sodium, and to repair them in place. Motivated by the need to address sodium-water reactions, it is also important to enhance the reliability of early detection systems for water leaks. New early detection systems, especially those that protect against small leaks, would be adopted to prevent the propagation of tube ruptures and to allow a rapid return to plant operation.

While there are design studies in progress in Japan on SFRs, there is little design work in the U.S., even at the pre-conceptual level. Design work is an important performance issue, and it should accelerate given the importance of economics for the SFR. Additionally, fuel cycle development needs to be done in the context of design development. R&D activity is needed with a focus on the base technology for component development. Noting the temperatures at which the SFRs operate, there may be interest in investigating the use of a supercritical CO_2 Brayton cycle.

IV. CONCLUSIONS

The primary mission for the SFR is the management of high-level wastes, and in particular, management of plutonium and other actinides. The SFR is the nearest term Generation IV concept and offers the shortest path forward to implementing an effective actinide management strategy. With successful R&D, the SFR is also expected to become economically competitive as an electricity producer. Development of the SFR involves research for both the fuel cycle and the reactor.   The fuel cycle R&D supports (1) recovery and recycle of 99.9% of the actinides, (2) inherently low decontamination factor of the product, making it highly radioactive, and (3) never separating plutonium at any stage. The reactor R&D supports assurance or verification of passive safety, completion of the fuels database including establishing irradiation performance data for fuels fabricated with the new fuel cycle technologies, and developing in-service inspection and repair (in sodium) technologies. As is the case for all Generation IV concepts, for both the reactor and the fuel cycle, technology development to achieve cost competitiveness is necessary.

V. ACKNOWLEDGMENTS

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4. FCCG Report

Table 1. Design Parameters for the SFR

Reactor Parameters	**Reference Value**
Outlet Temperature (^oC)	530-550
Pressure (Atmospheres)	~1
Rating (MWth)	1000-5000
Fuel	Oxide or metal alloy
Cladding	Ferritic or ODS ferritic
Average Burnup (MWd/kgHM)	~150-200
Conversion Ratio	0.5-1.30
Average Power Density	350 MWth/m^3

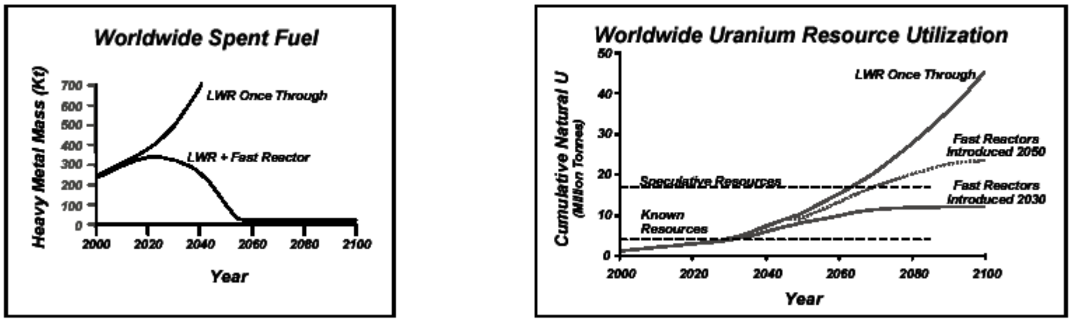

Figure 1. The effect of closed fuel cycles on waste burden and resource utilization

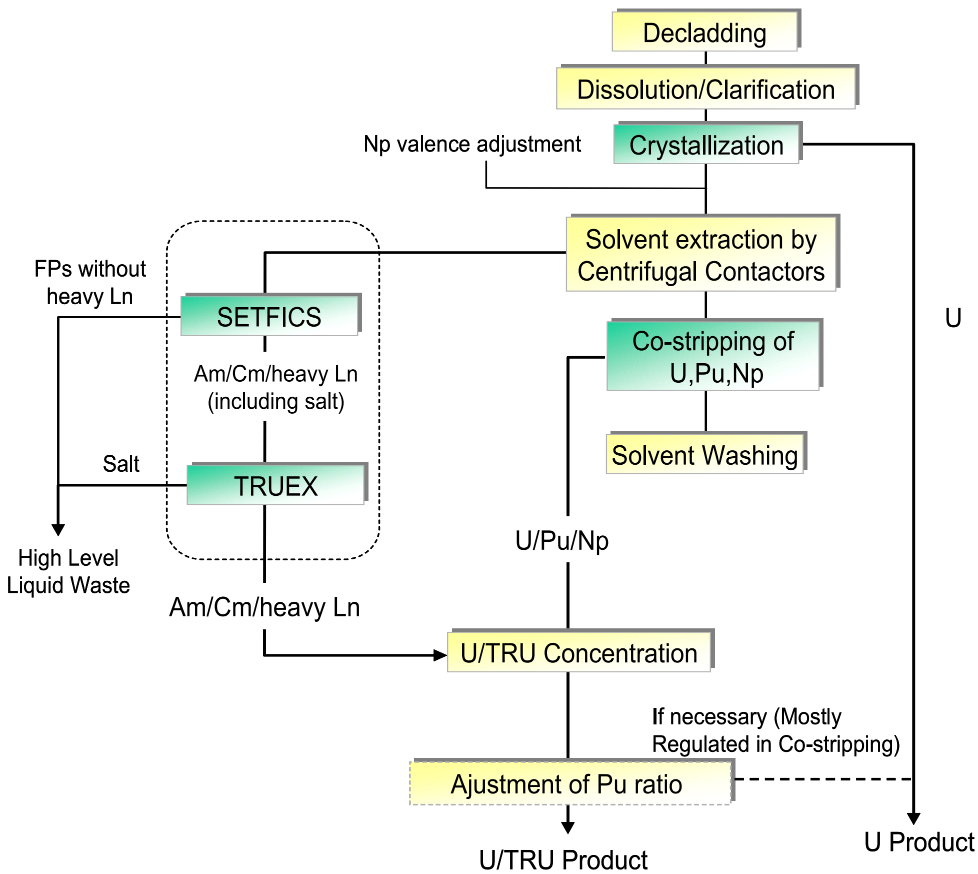

Figure 2. Schematic flow diagram of Advanced Aqueous Reprocessing

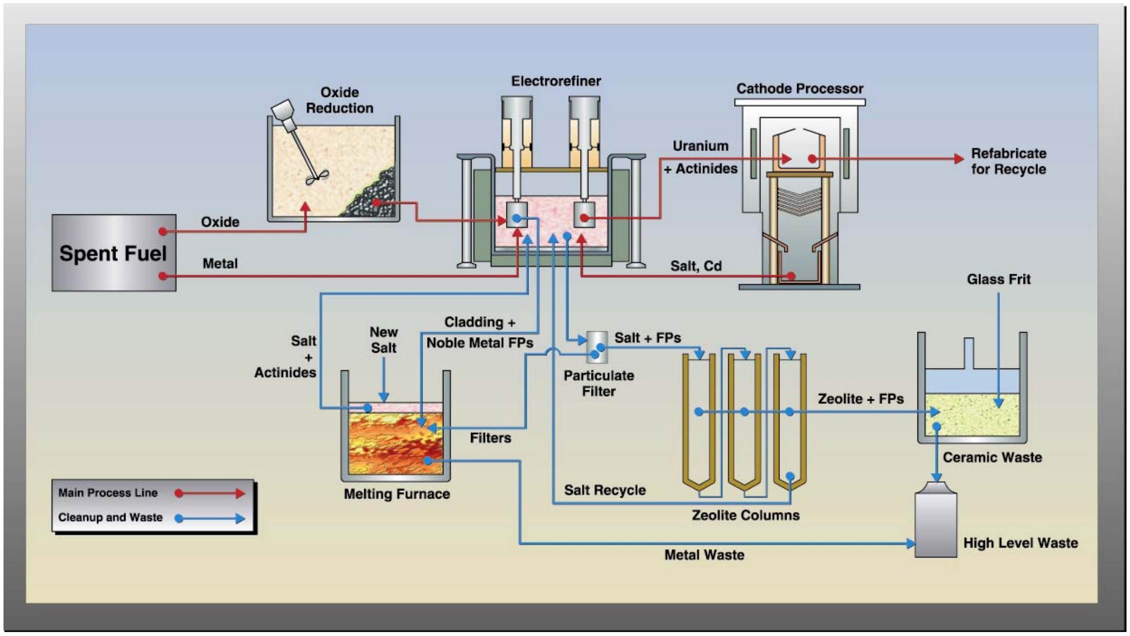

Figure 3. Schematic flow diagram of Pyroprocess

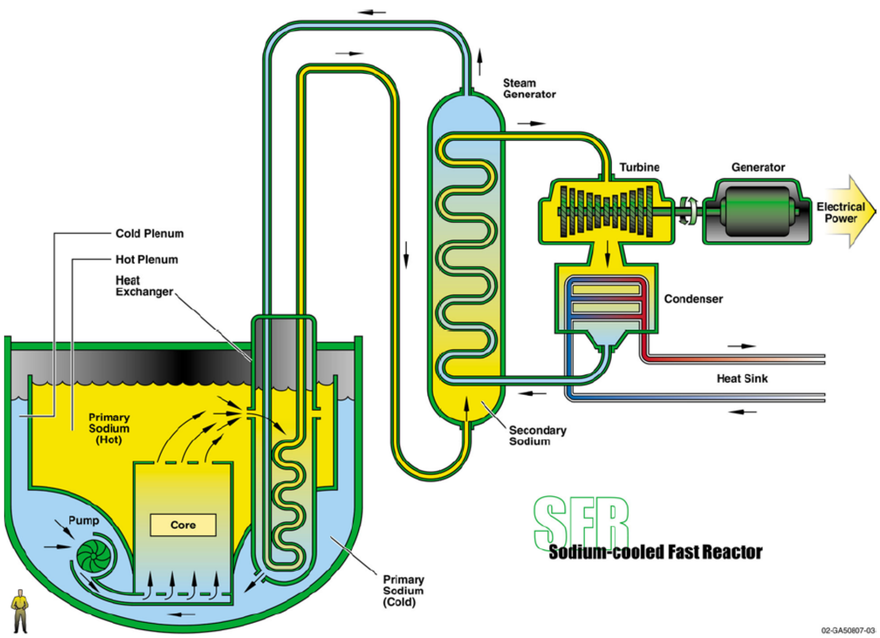

Figure 4. Pool layout option for the SFR