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A summary of sodium-cooled fast reactor development

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A B S T R A C T

Much of the basic technology for the Sodium-cooled fast Reactor (SFR) has been established through long term development experience with former fast reactor programs, and is being confirmed by the Phénix end-of-life tests in France, the restart of Monju in Japan, the lifetime extension of BN-600 in Russia, and the startup of the China Experimental Fast Reactor in China. Planned startup in 2014 for new SFRs: BN-800 in Russia and PFBR in India, will further enhance the confirmation of the SFR basic technology. Nowadays, the SFR development has advanced to aiming at establishment of the Generation-IV system which is dedicated to sustainable energy generation and actinide management, and several advanced SFR concepts are under development such as PRISM, JSFR, ASTRID, PGSFR, BN-1200, and CFR-600. Generation-IV International Forum is an international collaboration framework where various R&D activities are progressing on design of system and component, safety and operation, advanced fuel, and actinide cycle for the Generation-IV SFR development, and will play a beneficial role of promoting them thorough providing an opportunity to share the past experience and the latest data of design and R&D among countries developing SFR.

1. Introduction

The Sodium-Cooled Fast Reactor (SFR) system features a fast-spectrum reactor and closed fuel recycle system. The primary mission for the SFR is improved resource utilization, management of high-level wastes and, in particular, management of plutonium and other actinides. With innovations to reduce capital cost, the SFR mission can extend to electricity production.

The SFR uses liquid sodium as the reactor coolant, allowing high power density with low coolant volume fraction. While the oxygen-free environment prevents corrosion, the chemical reactivity of sodium with air and water requires a sealed coolant system.

So far, historical experience of design, construction, test, operation, inspection and repair of past or existing demonstration and/or prototype SFRs such as PFR (UKAEA), Phénix (France), BN-350 (Kazakhstan), Super Phénix (France), BN-600 (Russia), Monju (Japan) has established technology bases of the SFR, though several projects of prototype SFRs development were canceled by government decisions at the times. In BN-350, in addition to electricity generation, heat production for seawater desalination was successfully industrialized. For the basis of such an establishment, pioneering experience was acquired by past experimental SFRs including Fermi (USA), EBR-II (USA), FFTF (USA), DFR (UKAEA), Rapsodie (France), BR-5/10 (Russia), BOR-60 (Russia), Joyo (Japan), FBTR (India).

This knowledge base is an essential asset for all of the countries developing the SFR. A variety of development projects for the Generation-IV SFR have been progressing in several countries under the auspices of Generation IV International Forum (GIF). GIF is expected to play a beneficial role of promoting efficient and effective activities for the Generation-IV SFR development thorough providing an opportunity to share the past experience and the latest data of design and R&D among countries developing SFR.

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2. Historical experience with demonstration and prototype reactors

Historical experience with previously operated and canceled SFR projects is summarized below.

2.1. Previously operated SFRs

2.1.1. PFR (International Atomic Energy Agency, 2006; International Atomic Energy Agency, 2012; Cacuci, 2010)

The Prototype Fast Reactor (PFR) was built and operated at the United Kingdom Atomic Energy Authority's (UKAEA's) site at Dounreay in Scotland to validate and provide operational experience of a large pool-type fast reactor and as a test bed for the fuel, components, materials and instrumentation needed for an eventual commercial-sized station. PFR was designed to produce 250 MWe from 600 MWth core power and its design incorporated lessons learnt from the operation of the former experimental reactor, Dounreay Fast Reactor (DFR) situated at the same site.

PFR achieved its criticality in March 1974. The operating history of PFR can be conveniently divided into two phases. For the first ten years (1974–1984), electrical output was limited, mainly because of a series of leaks in the SG units. A leak detected in a superheater in 1974 was found to have occurred in a tube-to-tube plate weld and was the first of 43 similar events; 2 in the superheaters, 1 in a reheater and 41 in the evaporators – which were to have a major influence on operations in the next seven years, with the highest incidents (11 leaks in the evaporators) om 1981. Due to these incidents, the highest load factor was 12% in 1978 when the net electricity generation showed the maximum achievement of 9,678 MWd. After 1984, with the SG weld problems dealt with, plant performance improved and in the final year of operation the load factor was about 57%. In the second decade of operation (1984–1994), there was one major outage. In this period, until 1991, the reactor and primary circuit equipment were responsible for only a very small fraction of unplanned outage time. In mid-1991, a leakage of oil from a bearing of one of the primary pumps into the primary sodium caused suspension of reactor operation for 18 months. Operations then continued, and the total electricity generation from April 1993 to March 1994 achieved 51,546 MWd with a load factor of 56.5%, which corresponded to the best result in any twelve-month period. Then, PFR was shut down in 1994 as the British government withdrew major financial support for nuclear energy development. Until the shutdown, a successful irradiation of approximately 98,000 fuel pins was completed and over 40,000 pins out of them exceeded the original 7.5% target burnup.

The overall survey and the cross-section of the primary circuit of PFR are shown in Fig. 1 and Fig. 2, respectively.

Fig. 1. PFR overall survey.

2.1.2. Phénix (International Atomic Energy Agency, 2012; Cacuci, 2010)

The French prototype fast reactor, Phénix (a pool-type reactor, 250 MWe in electricity) was built to demonstrate the facility's overall capacity of operating over time while meeting expected characteristics. Being a demonstration reactor of what was supposed to become a new reactor technology – the SFR – operation data were to be collected to serve teams working in parallel to the project and the construction of the next-to-come reactor, Superphénix and later the European Fast Reactor (EFR) project.

Phénix went into commercial operation in 1974. From the beginning, the reactor was also used as an irradiation tool: a considerable amount of data was gained on fuel and sub-assembly structural materials, leading to a significant increase of fuel burnup. The closing of the fuel cycle was also achieved for the first time in 1980.

The 35 years of Phénix operations have brought a significant contribution to the development of fast reactors. It has fulfilled its original objective to demonstrate the viability of SFRs and has been throughout its lifetime an outstanding tool for fuel development and for conducting a wide range of irradiation experiments, in particular for minor actinide transmutation. The availability factor above 80%, which was achieved from April 1978 to March 1980 by the continuous operation at full-power without any noteworthy incidents occurring, is also worth describing as a great feature of Phénix. During its 35 years of operation, Phénix encountered several events including sodium leaks (most of the leaks were located on welds of secondary loops and auxiliary circuits, but there were no consequences on the plant safety.), water–sodium reactions on its modular type of SG different from recent integral type (the origins of the incidents were the initial crack due to a thermal fatigue phenomenon or a manufacturing defect that evolved after cleaning of the module, and many improvements and modifications were completed to make the hydrogen detection systems faster and more reliable. Given the progress made vis-à-vis the risk of leakage in the SG and economic considerations, the modular design of SG was abandoned for Super Phénix in favor of high power SGs.), incidents on IHX (sodium leaks from the IHXs took place at the secondary sodium outlet header, and all IHXs were repaired and design modifications were made.). However, these events which were managed without difficulty vis-à-vis the safety of the reactor are rich in terms of feedback for operating this type of reactors.

After 35 years of operation, a campaign of end of life tests was performed at Phénix before the final shutdown. The first test was carried out in May 2008, and most were performed after the end of the last electricity production cycle between May 2009 and January 2010. These tests aim to broaden the experimental base for validating neutronics, thermal-hydraulics and fuel computer codes. Ten different tests of four types (thermal-hydraulics, core physics, fuel, negative reactivity transient investigations) were performed.

By the final shutdown, Phénix run fifty one cycles and produced more than 20 billion kWh.

The overall survey and the plant circuit of Phénix are shown in Fig. 3 and Fig. 4, respectively.

2.1.3. BN-350 (International Atomic Energy Agency, 2006; International Atomic Energy Agency, 2012; Vasilyev et. al, 2013a)

The BN-350 reactor plant, with a loop-type SFR and six primary/secondary loops, is a constituent of Mangyshlak energy integrated