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Progress in reliability of fast reactor operation and new trends to increased inherent safety

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HIGHLIGHTS

- SFRs have shown a remarkable operational performance in the last 10 years.
- Real reliability of BN-600 is comparable to German LWRs.
- Inherent safety of well-balanced SFRs has been demonstrated.
- Distributed moderator opens the possibility to improve inherent safety.

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ABSTRACT

The reasons for the renewed interest in fast reactors and an overview of the progress in sodium cooled fast reactor operation in the last ten years are given. The excellent operational performance of sodium cooled fast reactors in this period is highlighted as a sound basis for the development of new fast reactors. The operational performance of the BN-600 is compared and evaluated against the performance of German light water reactors to assess the reliability. The relevance of feedback effects for safe reactor design is described, and a new method for the enhancement of feedback effects in fast reactors is proposed. Experimental reactors demonstrating the inherent safety of advanced sodium cooled fast reactor designs are described and the potential safety improvements resulting from the use of fine distributed moderating material are discussed.

One sentence summary: Operating fast reactors have shown excellent in-service behavior within the last 10 years, new designs and methods are available to significantly improve safety.

1. Introduction

One major focus in the nuclear future are fast reactors (FRs), especially sodium cooled fast reactors (SFRs), which have been investigated and operated since the 1970s [1]. The introduction of the technology has been a complicated, expensive and controversial story. As a legacy of these times, many preconceptions still exist, namely, that fast breeder reactor operation is a high risk and that it is impossible to deal with, and control safely, the required sodium technology [2]. In contrast to this public perception, which is still influenced by these preconceptions from 'old times', the SFR has found a completely new focus in nuclear science and technology [3]. SFR technology can now draw on a long period of operational experience and the last years of SFR operation have demonstrated that the sodium technology has overcome its growing pains [4].

Major milestones for the future development of a challenging technology like SFRs are: demonstrated operational reliability on the one hand and advanced design features including new scientific progress on the other hand. The reliability of operating reactors has important impact due to several drawbacks. First of all, reliable operation is to be seen under "minimizing deviations from normal operating conditions", the request in Level 1: 'Prevention of abnormal operation and failures' in the Defence-in-depth concept of the International Nuclear Safety Advisory Group of the IAEA [5,6]. This has to be achieved by 'conservative design and high quality in construction and operation'. Additionally, reliable operation is to be seen as a clear sign for readiness and maturity of a technology for the further application, since it is the basis for safe

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operation, see the statement above, and it is a cornerstone for economic operation of a future facility. Advanced designs are a clear sign for the requested scientific progress. Ideally, the progress should be achieved on different levels of maturity. Older progress should already be proven by experiments under real conditions, while new progress and ideas should be available for the next steps of development. Form technological point of view, FRs are the future of nuclear reactor technology, since this kind of reactor is the backbone of future sustainable reactor development, as defined in the Generation IV International Forum [3]. This Forum is a collaborative international endeavour established to coordinate and to carry out the R&D needed to ascertain the feasibility and performance capabilities of the next generation of nuclear energy systems. This process is supported by IAEA, reflected by the organization of a series of conferences [7,8] related to Fast Reactors and Related Fuel Cycles. One new FR is already operating [9] and two ones are under construction and close to commissioning [10,11]. In Europe, two substantial projects on FR technology are running with a commissioning target of 2020–2025 (ASTRID [12] and MYRRHA [13]). It does not help to 'turn a blind eye' to this technology, as it represents an important option for future global energy production.

This article discusses SFR technology and focuses on operational lessons learned, reflected in the operational performance in the last decade, and the new trends for improved operational and inherent safety performance. The operating experience of the past provides important input to the design process and has the potential to improve the maturity level. The longer the operating experience, the greater the opportunity to modify the design based on lessons learned during operation. The experience gained gives confidence in the performance of fuel assemblies and sodium components and in the overall operational safety of the plant. However, not only the successful operation, but also the various operational problems and incidents experienced are major contributors to the 'learning curve'.

From a scientific point of view, the world is entering a new phase of SFR development. In the 1970s, the main focus was the possibility of breeding new nuclear fuel. "To conserve the abundant energy resources, the utilization of uranium, plutonium and thorium fuels in a breeder economy is necessary" [14]. The driving force for SFR development was the oil crisis and the expectation of a rapid growth in nuclear energy production causing a shortage in uranium resources. At that time, the fast breeder reactor was reported to provide nearly unlimited fuel resources and thus to satisfy future global energy demand (compare [15,16]). Today, the focus of FR development has changed significantly. Massive breeding of nuclear material is no longer a priority. The major task is the closing of the nuclear fuel cycle by incineration of plutonium and minor actinides to reduce the long term toxicity of the nuclear waste [17,4] in combination with the possibility of achieving high uranium utilization. The design objectives are given by the Generation IV International Forum, "Generation IV nuclear energy systems will provide sustainable energy generation that meets clean air objectives and provides long-term availability of systems and effective fuel utilisation for worldwide energy production. Generation IV nuclear energy systems will minimise and manage their nuclear waste and notably reduce the long-term stewardship burden, thereby improving protection for the public health and the environment" [3]. With the significant mitigation of the long term nuclear waste problem suggested by partitioning and transmutation (P&T) [18], nuclear energy could provide an excellent carbon dioxide free energy source for sustainable development. Thus, FRs with closed fuel cycles have the potential to enhance significantly the sustainability indices of energy production.

Unfortunately, there is still the preconception, sometimes discussed even in the scientific columns of widely recognized and renowned newspapers: breeder reactors are always inefficient, unreliable, and dangerous [19]. To disprove this perceptions and in contrast to prove the maturity and technological readiness of the technology and thus to fulfil the requests determined by the Generation IV International Forum, convincing answers to two major questions, have to be given to ensure acceptance and hence the success of fast reactors in the future.

The first question addresses the reliability issue which is an important part of maturity and technological readiness: has it been possible to operate an industrial SFR with real availability comparable to LWRs? This would be a clear indicator for stable and reliable operation of fast reactors demonstrating the maturity of SFR technology, especially if an availability of more than 90% of the scheduled operation time can be demonstrated.

The second question addresses the new scientific progress. Does the new design feature using fine distributed moderating material offer an improvement in the safety related Doppler effect by more than 20–30% with sufficient thermal stability up to more than 1000 °C and without compromising the fuel assembly design? This would offer a completely new degree of freedom for the design of well balanced and inherently safe fast reactor cores.

The first question will be tackled with an investigation of the available experience in fast reactor operation. Here, the major focus will be on the operational results achieved in the last ten years. The second question will be answered by providing an insight into the development already demonstrated in the experiments at the experimental breeder reactor EBR-II in the 1980s. The trend to achieve improved safety by designing a well-balanced reactor is complemented by a new desire to enhance the inherent feedback effects in liquid metal cooled reactors. The importance of this topic has been discussed and demonstrated in two special IAEA meetings [20,21].

2. Methods, code and reference configuration

In the first part the reliability of fast reactor operation is evaluated on the basis of a new approach, viz. using real operational feedback data. The data will be compared for different kinds of availabilities and different reactor types. The investigation is based on the analysis of the operational performance, based on newest operational data and experience gained in operating fast reactors. The results are used for a comparison with newest operational data of industrial standard reactors (LWR). The main focus on reliability will be given to the operation of the industrial fast reactor. Its reliability is analyzed by comparison to German standard LWRs based on the real availability, which is a figure of merit for the robustness of the full power operation of the reactors. The real availability is calculated by weighting the availability of the plant given in the operational charts by the scheduled availability, i.e. the foreseen operational time without planned outages.

The investigation is complemented by an evaluation of the operational performance of key components in an experimental fast reactor. Special attention is given here to performance of critical components, the steam generators and the sodium pumps. The values are compared to data for a thermal reactor nuclear power plant provided by a German plant operator.

The second part of the study investigating new developments regarding inherent safety is based on computer simulations. The requested reference case for comparison is derived from data for the European Fast Reactor design (EFR) developed in the 1990s. The data is mostly given in the IAEA Fast Reactor Database – 2006 Update [1]. Additional data is taken from Waltar, Reynolds: Fast Breeder Reactors [22] and from European fast reactor (EFR) fuel assembly design [23]. The major parameters used for the reference calculation are given in Tables 1 and 2.