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Invited Article

SAFETY ASPECTS OF INTERMEDIATE HEAT TRANSPORT AND DECAY HEAT REMOVAL SYSTEMS OF SODIUM-COOLED FAST REACTORS

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ABSTRACT

Twenty sodium-cooled fast reactors (SFRs) have provided valuable experience in design, licensing, and operation. This paper summarizes the important safety criteria and safety guidelines of intermediate sodium systems, steam generators, decay heat removal systems and associated construction materials and in-service inspection. The safety criteria and guidelines provide a sufficient framework for design and licensing, in particular by new entrants in SFRs.

1. Introduction

Twenty sodium-cooled fast reactors (SFRs) were in operation between 1951 and 2014 in nine different countries, with a total combined operation time of over 420 years. Presently, SFRs are in operation in China, India, and Russia. SFRs are now also in different stages of design and development in China, France, India, Russia, and South Korea. Valuable operating experience has been accumulated and this feedback is being utilized in designing a new reactor [1,2]. SFRs are favored choices for sustainability of nuclear energy and high level waste management through incineration of minor actinides and long-lived fission products. SFRs are one of the strongest options for Gen IV reactors. To start with, when the

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program to design a country's first SFR is initiated, for example by South Korea, it is necessary to prepare a safety criteria document incorporating the basic safety objectives of nuclear power plants, feedback from meetings on specific topics of the International/Technical Working Group on Fast Reactors, lessons learnt from other types of reactors, in particular the Fukushima accident, related aspects from the safety criteria of SFRs of other countries and safety design criteria for Gen IV sodium-cooled fast reactor systems [3,4]. The safety criteria of SFRs take inspiration from the safety criteria of thermal reactors (as applicable). However, one also faces the issues of relevance to thermal reactors during technical discussions with regard to licensing of SFRs, as a large number of experts have a background in thermal reactors.

This paper attempts to define safety criteria and safety guidelines of intermediate heat transport systems, steam generation systems, decay heat removal systems, associated construction materials, and in-service inspection aspects of SFRs. Safety criteria concerning general requirements in evolving a safe design are bullet marked in the text. Safety guidelines, design recommendations, and suggestions to meet safety criteria are also examined.

2. Physical and chemical properties of sodium and impact on design

The physical and chemical properties of sodium have a strong influence on the safety design aspects of SFRs. The high boiling point of 883°C, high thermal conductivity, and low viscosity are conducive to nuclear decay heat removal by natural convection. The freezing temperature of sodium (98°C) imposes preheating requirements on sodium systems, along with measures to prevent freezing during various reactor operation modes and in particular during decay heat removal. It also allows ease of leak tightness requirements towards the exterior for sodium frozen seal valves and ease in maintenance and repairs.

The most important concern arising from sodium as a coolant is its high chemical reactivity. It burns in air leading to fire, and reacts violently with water. Thus the safety aspects of dealing with sodium leaks and sodium-heated steam generators are among the most challenging aspects of designing SFRs. The strong interaction of sodium with water and air calls for incorporation of an intermediate sodium circuit from the safety aspects of the reactor core, and double wall piping with the interspace inerted in the primary sodium piping of a loop type primary circuit configuration. In some reactor designs, the double wall arrangement is also extended to the intermediate system to avoid risks associated with sodium fires.

The high operating temperatures of SFRs in comparison with light water reactors (LWRs), the excellent thermal conductivity of sodium, coupled with high temperature differences across the reactor core and heat exchangers have a strong bearing on the mechanical design aspects of creep due to high temperature usage, thermal fatigue, thermal striping, and stratification under different modes of reactor operation. The low pressure in the sodium systems, sodium leak detection provisions, and usage of ductile materials allow adoption of the leak before break concept.

3. Safety criteria and safety guidelines

3.1. *Intermediate heat transport system (IHTS)*

Important system related safety criteria along with associated guidelines that are relevant to intermediate heat transport systems (IHTSs) are discussed below.

Safety criteria

- An intermediate heat transport circuit shall be interposed between the primary sodium circuit and the steam-water circuit.

Safety guidelines

The need for an intermediate circuit is to avoid sodium water reaction products from entering the core thereby risking reactivity perturbations and plugging of the narrow passages in the core cooling path.

- The pressure in the intermediate sodium circuit (IHTS) at the intermediate heat exchanger shall be higher than the primary sodium so that any tube leak results in flow of secondary sodium to radioactive primary sodium.
- Sodium systems shall be designed with reliability to prevent sodium leaks, in particular, large leaks.

Safety guidelines

The design of sodium components and piping should be designed for safe shutdown earthquake (and operating basis earthquake) irrespective of safety classification to avoid large sodium fires.

- The design of sodium systems should identify potential locations of thermal striping and be designed accordingly.
- An all-welded construction should be used. Socket welds in piping should not be used.
- Unless proven by equivalent life cycle tests, the use of bellows for piping flexibility should be avoided.

Safety criteria

- Sodium leakages and fires shall be detected and located with adequate reliability and provisions shall be made to minimize the amount of sodium leaking and the risk of resulting fires.
- The heat transport items important to safety shall be independent, redundant and physically separate from each other to prevent common cause and cross-linked failures.
- The IHTS and its components shall be designed to withstand the maximum credible transient pressure associated with various design basis events (e.g., sodium water reaction).