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Design and development of innovative passive valves for Nuclear Power Plant applications

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HIGHLIGHTS

- Passive valves are self-acting valves requiring no external energy to function.
- These valves have been developed for Advanced Heavy Water Reactor (AHWR) of India.
- Passive valves are core components of passive safety systems of the reactor.
- Accumulator Isolation Passive Valve (AIPV) has been developed and tested for ECSS.
- AIPV provided passive isolation and flow regulation in ECCS of Integral Test Loop.

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ABSTRACT

The recent Fukushima accident has resulted in an increased need for passive safety systems in upcoming advanced reactors. In order to enhance the global contribution and acceptability of nuclear energy, proven evidence is required to show that it is not only green but also safe, in case of extreme natural events. To achieve and establish this fact, we need to design, demonstrate and incorporate reliable 'passive safety systems' in our advanced reactor designs.

In Nuclear Power Plants (NPPs), the use of passive safety systems such as accumulators, condensing and evaporative heat exchangers and gravity driven cooling systems provide enhanced safety and reliability. In addition, they eliminate the huge costs associated with the installation, maintenance and operation of active safety systems that require multiple pumps with independent and redundant electric power supplies. As a result, passive safety systems are preferred for numerous advanced reactor concepts. In current NPPs, passive safety systems which are not participating in day to day operation, are kept isolated, and require a signal and external energy source to open the valve. It is proposed to replace these valves by passive components and devices such as self-acting valves, rupture disks, etc.

Some of these innovative passive valves, which do not require external power, have been recently designed, developed and tested at rated conditions. These valves are proposed to be used for various passive safety systems of an upcoming Nuclear Power Plant being designed by India. For example, the Hot Shutdown Passive Valves (HSPV), developed for the decay heat removal system keep the main heat transport system under hot conditions by passively sensing and controlling the system pressure. Another crucial and important valve which has been successfully developed is the Poison Injection Passive Valve (PIPV) for the Passive Poison Injection System. It not only provides higher reliability, but also ensures safe shutdown of the reactor in case of insider threats or malevolent acts in disabling active shutdown system of the reactor.

Recently, an innovative valve called the Accumulator Isolation Passive Valve (AIPV) has been developed for the Emergency Core Cooling System (ECCS), which is engineered to mitigate the consequences of Loss of Coolant Accident (LOCA). During normal operation of the reactor, the pressurized accumulators (55 bar) are kept isolated from the reactor core (70 bar) by means of AIPVs. In case of a LOCA, these passive valves open when the main heat transport system pressure falls to a desired value. For prolonged cooling of the core, these passive valves regulate the discharge in a desired manner. These are non-standard, high pressure and high temperature valves, which are unavailable commercially and hence have to be indigenously designed and developed.

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This paper primarily deals with the design, development and testing of Accumulator Isolation Passive Valves (AIPV) proposed to be used in the ECCS. A 25 NB size AIPV has been designed and successfully tested at Integral Test Loop (ITL) under simulated reactor conditions. It is a self-acting, ANSI 600 rating valve, which requires no external energy (i.e., neither air nor electrical power). It not only provides passive isolation but also passively controls high pressure liquid discharge through it. The design concept of the valve, functional performance, in situ valve testing methodology and the test results at simulated conditions are discussed.

1. Introduction

Following the Fukushima accident, which occurred on Friday, March 11, 2011, in the Fukushima Daiichi Nuclear Power Plant on the east coast of northern Japan, the safety features of Nuclear Power Plants (NPPs) are being re-examined to demonstrate their capabilities to cope with severe accidents. An increasing need is being recognized to provide systems with passive or intrinsic characteristics which would ensure the continued cooling of fuel and its containment systems (Vijayan et al., 2013a). The use of passive safety systems such as accumulators, condensation and evaporative heat exchangers, and gravity driven safety injection systems eliminate the costs associated with the installation, maintenance and operation of active safety systems that require multiple pumps with independent and redundant electric power supplies. As a result, passive safety systems are being considered for numerous reactor concepts (including in Generation III and III+ concepts) and are expected to find applications in the Generation-IV reactor concepts, as identified by the Generation IV International Forum (GIF). Another motivation for the use of passive safety systems is the potential for enhanced safety through increased safety system reliability (IAEA, 2009).

Active safety systems have the advantages of easily allowing a power increase and using proven technologies, on the other hand, while passive safety systems are operated by means of natural phenomena such as gravity, natural circulation and pressure differences. Passive safety systems have the advantages of high reliability, minimal human errors, simplification and easy modularization. Based on advantages and disadvantages of active and passive safety systems, both active and passive safety systems must be installed in Nuclear Power Plants for enhanced safety (Chang et al., 2013). A large scale simplified pressurized water reactor as a candidate for the Japanese Next Generation Pressurized Water Reactor (PWR) has innovative features such as hybrid safety systems (an optimum combination of active and passive safety system) and horizontal steam generators. Here passive safety systems act as backups to prevent core damage if the active safety systems do not operate correctly due to operational or other errors (Yonezo Tujikura et al., 2000).

The Advanced Heavy Water Reactor (AHWR) being designed in India incorporates several passive safety systems which will enable the plant to survive potential severe accidents without fuel damage and require no human intervention (Nayak and Sinha, 2007). This paper describes some of the important passive safety systems adopted in the AHWR design. These passive systems use innovative passive valves which are custom designed to suit process requirements and have been developed in-house. The development and testing of passive valves and experimental demonstrations of passive safety systems of the AHWR under simulated process conditions are included in this paper. The development and testing of one of the innovative passive valves called the Accumulator Isolation Passive Valve (AIPV) is discussed in detail.

2. Advanced Heavy Water Reactor (AHWR)

Advanced Heavy Water Reactor (AHWR) shown schematically in Fig. 1 is a 300 MWe, vertical, pressure tube type, heavy water-moderated, boiling light-water-cooled reactor fueled by dual mixed oxide (MOX) consisting of $(PUTh)O_2$ and $(^{233}U\text{-}Th)O_2$ with a 100 year lifetime. The fuel cluster is designed to generate maximum energy from thorium, to maintain self-sufficiency in ^{233}U and to achieve a slightly negative void coefficient of reactivity. Natural circulation mode of coolant circulation is adopted during normal operation, transient and accident conditions, which eliminates all accident scenarios resulting from pump failure in addition to reducing capital and operating costs (Sinha and Kakodkar, 2006).

3. Passive safety systems

The AHWR incorporates passive systems for core heat removal during normal operation, shutdown conditions and postulated accident conditions such as a Loss of Coolant Accident (LOCA). During normal operation, the core heat is removed by the natural circulation of coolant through hot fuel channels. In Station Black Out (SBO) conditions, the decay heat is removed in a passive mode by Isolation Condensers (ICs) immersed in a large pool of water in a Gravity Driven Water Pool (GDWP), located near the top of the reactor building. During a postulated accident such as a LOCA, high-pressure coolant is directly injected into fuel clusters in a passive mode initially from accumulators and later from GDWP for removal of decay heat. Passive containment cooling and isolation, core submergence, passive poison injection in the moderator by usage of system steam pressure during high pressure transients, and passive cooling of concrete structure in high temperature zones are the additional passive features of AHWR.

As per IAEA-TECDOC – 626, the passive safety systems are defined as “Either a system which is composed entirely of passive components and structures or a system which uses active components in a very limited way to initiate subsequent passive operation” (IAEA, 1991). There are four categories to distinguish the different degrees of passivity, namely: Category A, B, C and D as described below;

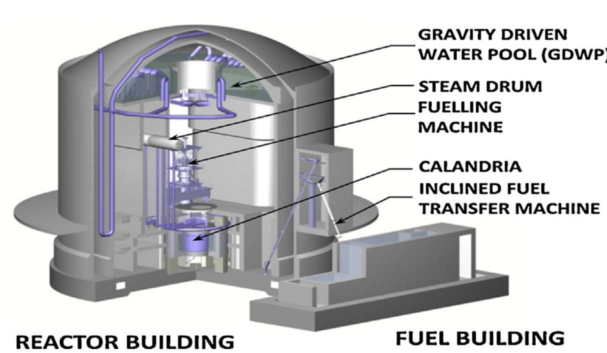

Fig. 1. Schematic of AHWR.