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Accident tolerant high-pressure helium injection system concept for light water reactors

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HIGHLIGHTS

- Potential helium injection strategy is proposed for LWR accident scenarios.
- Multiple injection sites are proposed for current LWR designs.
- Proof-of-concept experimentation illustrates potential helium injection benefits.
- Computational studies show an increase in pressure vessel blowdown time.
- Current LOCA codes have the capability to include helium for feasibility calculations.

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ABSTRACT

While the design of advanced accident-tolerant fuels and structural materials continues to remain the primary focus of much research and development pertaining to the integrity of nuclear systems, there is a need for a more immediate, simple, and practical improvement in the severe accident response of current emergency core cooling systems. Current blowdown and reflood methodologies under accident conditions still allow peak cladding temperatures to approach design limits and detrimentally affect the integrity of core components. A high-pressure helium injection concept is presented to enhance accident tolerance by increasing operator response time while maintaining lower peak cladding temperatures under design basis and beyond design basis scenarios. Multiple injection sites are proposed that can be adapted to current light water reactor designs to minimize the need for new infrastructure, and concept feasibility has been investigated through a combination of proof-of-concept experimentation and computational modeling. Proof-of-concept experiments show promising cooling potential using a high-pressure helium injection concept, while the developed choked-flow model shows core depressurization changes with added helium injection. Though the high-pressure helium injection concept shows promise, future research into the evaluation of system feasibility and economics are needed.Classification: L. Safety and risk analysis

1. Introduction

In the aftermath of the March 2011 Fukushima events, the current emphasis of reactor designers, regulators, and utilities continues to be focused on the development of advanced fuel and structural materials that can withstand the extreme conditions resulting from design basis accidents (DBA) and beyond design basis accidents (BDBA) without significant impacts to the integrity of reactor components. Future generation reactors using these advanced materials are expected to respond more effectively to events including those beyond DBAs; however, many of these advanced materials are still in their research and development phases, and the application of these materials to reactor concepts may at best be a long-term solution while existing safety concerns still threaten the integrity of current reactor designs (Nuclear Energy Agency, 2009). In the case of an extended severe event such as a large-break loss of coolant accident (LOCA), the immediate dumping of cooling water into the reactor vessel via the emergency core cooling system (ECCS) proves detrimental to the integrity of the cladding due to potential embrittlement and thermal stresses. Furthermore, the existing ECCS components, including the high-head safety injection (HHSI) system, the accumulators, and the low-head safety injection system (LHSI), still allow cladding temperatures to increase to dangerous levels where creep, runaway

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oxidation, and the production of hydrogen are accelerated. One approach to address these issues is the continuing development of advanced cladding materials that are more resistant to accident conditions. Extensive research is being conducted in search of accident tolerant fuels (ATF) that have higher thermal conductivities and that can better contain fission products within the fuel matrix (Zinkle et al., 2014; Terrani et al., 2014). Alternative fuel assembly materials are being investigated as potential replacements to zirconium-based alloys, including iron-based alloys and various materials such as silicon carbide composites (Nuclear Energy Agency, 2009; Yueh and Terrani, 2014). It has been shown that these potential replacements have substantially increased tolerance to accident scenarios and can increase safety margins under design basis and beyond design basis events. Thus, the importance of research in advanced reactor materials should not be understated, but it is important to note that the implementation of advanced materials as a solution to current shortfalls is a longer-term solution and is coupled with subsequent lengthy and potentially expensive licensing review processes.

In lieu of the above approach, a more immediate solution is suggested to enhance LWR accident tolerance keeping in mind practicality, complexity and economics of such design modifications. This proposal is in accordance with the idea that the key to improving the overall 'accident tolerance' is not to build indestructible systems but to increase the response time required for first responders to bring threatened systems under control or find alternative pathways to make the systems safe even in case of beyond design basis events. In shifting from the advanced materials approach to enhanced accident tolerance, the proposed concept explores the thermal hydraulic and power systems enhancements/design modifications that can significantly reduce the severity of post event scenarios. This advanced technology modification concept calls for introducing a high-pressure helium injection (HPHI) system for intermediate core cooling. The proposed research will explore the feasibility and complexity of the stated modifications as supported by experiments, analysis and calculations. This paper provides a description of a HPHI system along with a review of the challenges that must be met and testing that must be completed for its implementation. Current regulatory requirements are discussed along with the current challenges that existing ECCS configurations fail to address such as cladding oxidation and rupture. Finally, the emergency HPHI system concept is proposed to help address these shortfalls.

2. Description of LOCA transient

The main factors influencing the degradation of PWR cladding include oxidation, hydride formation, and radiation damage. In the event of a large-break LOCA, the cladding temperature rises due to the loss of convective cooling and the redistribution of temperature from the fuel pellet to the cladding. Within the first 30 s, the rapid depressurization of the core leads to detrimental heat transfer coefficients resulting from a transition from nucleate boiling to film boiling within the core, preventing the cladding from expelling heat properly. Plastic deformation and thinning causes ballooning and ultimately cladding burst by the end of the blowdown phase, permitting fission products to escape into containment. Though anisotropic expansion and ballooning make simulating accident conditions difficult, relatively accurate models have been created to simulate cladding conditions during a design basis LOCA (Lee and Woo, 2012; Manngard and Massih, 2011).

Safety criteria specifying maximum allowable cladding temperatures and oxidation levels are established to protect against excessive cladding embrittlement and overheating. In Title 10, Part 50.46 of the Code of Federal Regulations, the allowable peak cladding temperature is limited to 1204 °C. Furthermore, the maximum cladding oxidation thickness is limited to 0.17 times the pre-oxidation cladding thickness. Limits on hydrogen generation as well as conditions associated with a long-term coolable geometry are mandated to ensure safe removal of decay heat after shutdown. These criteria are based on the properties of unirradiated zirconium cladding, which makes it more difficult to extrapolate these criteria to alternative cladding types (Billone et al., 2008). Even though current reactor systems can provide a somewhat coolable geometry and long-term cooling in the event of a large-break LOCA, the peak cladding temperature rises to 1000–1200 °C in a matter of seconds. Though these temperatures are technically still below the peak cladding temperature requirements, oxidation and hydrogen production is exponentially accelerated at these temperatures due to zirconium-alloy cladding's phase transformation and oxidation properties.

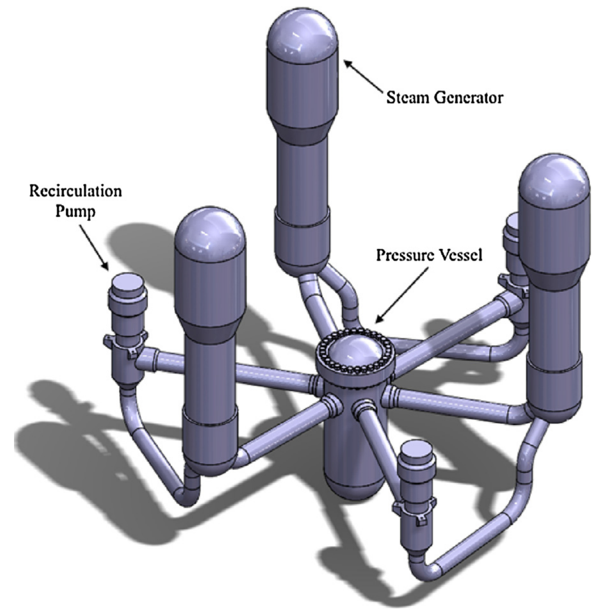

Fig. 1. Visualization of a three-loop PWR configuration.

To better describe the changes to existing safety injection systems proposed in this work, it is first important to understand the purpose and operation of current systems. Based on the specifications of a standard three-loop pressurized water reactor (PWR) design (North Anna Power Station UFSAR, 2007), the ECCS is comprised of three integral systems: The high-head safety injection system (HHSI), the accumulators, and the low-head safety injection system (LHSI). For the present analysis, a visualization of the corresponding reactor design is shown in Fig. 1, which shows only the pressure vessel, recirculation pumps, and steam generators. During a large-break LOCA for a representative PWR, the initial blow down phase is characterized by the rapid depressurization of the reactor coolant system (RCS). During blow down, a transition occurs from fully developed nucleate boiling to bulk boiling after the pressure drops to the RCS saturation pressure. During this time, each HHSI pump delivers approximately 34.1 m^3/h (150 gpm) of borated water to each of the two remaining cold legs, primarily to remove excess reactivity since the flow rate is too low to provide ample core cooling. Both the refueling water storage tank (RWST) and the boron injection tank (BIT) that have maximum capacities of 1843.5 m^3 (487,000 gal) and 3.4 m^3 (900 gal) respectively supply this high-pressure flow. However, due to the low flow rate of the HHSI pumps and the rapid increase in temperature within the system, all of the flow is saturated or superheated by the time it enters the core at the end of the blow down phase. After the core