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The primary reactor coolant system concept of the integral, inherently-safe light water reactor

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ABSTRACT

Nuclear power has enormous potential to provide clean, affordable baseload electricity worldwide. The events at Fukushima demonstrated, however, that nuclear safety must be enhanced in order to fully realize the latent potential of nuclear electricity. Small modular reactors, in particular, create significant safety benefits by eliminating large bore piping and the potential for a large-break loss of cooling accident (LOCA). The I^2S-LWR is a large-scale power plant concept designed to incorporate the integral reactor benefits previously exclusive to small modular reactors into large reactor systems. This paper presents and discusses the base design of the integral, inherently safe light water reactor (I^2S-LWR) primary coolant system, highlighting the impact of five major design constraints and their impact on the design development. Key deviances from the primary coolant system for both current LWRs and SMRs are indicated where appropriate, and key component design drawings of the I^2S-LWR integral reactor pressure vessel (RPV) and supporting systems are provided. These include the reactor pressure vessel, reactor coolant pumps, the pressurizer, the microchannel heat exchangers, the decay heat removal exchangers, and the reactor vessel internals. The final integrated design of the primary coolant system described in this paper serves as the base design configuration for the I^2S-LWR, while component performance and analyses are described in companion papers in this issue.

1. Introduction

Nuclear power has enormous potential to provide clean, affordable baseload electricity worldwide. The events at Fukushima demonstrated, however, that nuclear safety must be enhanced in order to fully realize the potential of nuclear electricity (Kramer, 2013). Recent developments in nuclear technology have resulted in "passive" safety systems capable of removing decay heat from a nuclear reactor without outside electricity or operator action for up to 3.5 days for large reactors (ML113560390, 2011; Ye et al., 2013) and up to 7 days for small modular reactors (SMR) Smith and Wright, 2012. Small modular reactors, in particular, create significant safety benefits by eliminating large bore piping and the potential for a large-break loss of cooling accident (LOCA). They also include a compact containment which facilitates an elevated containment pressure during design-basis transients. This elevated pressure increases the liquid fraction of the equilibrium system, increasing the heat transfer through the containment wall, and increases the liquid level in the reactor vessel (The Economics of Nuclear Power, 2016). In essence this reduces the potential for core uncovery during events which actuate the automatic depressurization system (ADS). These SMRs, however, are limited to electricity production of under 300 MW. Therefore, it is of great interest to translate the enhanced safety of the SMRs to a larger sized reactor. The integral, inherently safe light water reactor (I^2S-LWR) has been developed to satisfy this interest.

The integral, inherently safe light water reactor (I^2S-LWR) is a large-scale power plant concept designed to incorporate the integral reactor benefits previously exclusive to small modular reactors into large reactor systems. The primary difference between prior integral reactor concepts (the SMRs) and the I^2S-LWR is that the I^2S-LWR design allows for the scale-up of electricity production capabilities to 1000 MWe while utilizing the integral design, thus

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benefiting from both economies of scale and integral reactor pressure vessel (RPV) enhancements. Additionally, the passive safety features of the I^{2}S-LWR were designed to facilitate indefinite cooling, rather than the current 7 day limitation of the SMRs. In developing the I^{2}S-LWR, however, there are three primary challenges associated with scaling that need to be addressed.

First, local economic competiveness has become a significant concern for certain light water reactors in the US (The Economics of Nuclear Power, 2016). With several closures on the horizon for operating nuclear plants, a primary concern of reactor operators is that plants maintain economically competitive prices. Thus, in order to be considered as a viable reactor concept, the I^{2}S-LWR must remain cost competitive with, or more ideally, be significantly cheaper than current Gen III+ reactor systems (Rothwell, 2006). A brief investigation into the economics of small modular reactors reveals that there are several factors affecting their capacity to compete economically with larger reactors, including the economies of scale (Carelli et al., 2007). However, it is proposed that economic challenges associated with decreasing reactor size can be offset through 2 factors: integral system design and modularity in design (Carelli et al., 2010). Although integral system design can be attempted by reactor design of any size, factory fabrication can be accomplished only by small to medium reactor concepts due to factory fabrication constraints.

Considering these points, the I^{2}S-LWR is an attempt to capitalize on two strong economic benefits: first, the integral design of an SMR, which is an economic benefit to the concept (Carelli et al., 2010), is maintained as a basis for the light water reactor design. However, the power rating of the concept is increased in order to benefit from the economies of scale. Thus, by incorporating the strongest benefit of economies of scale in addition to the benefit of simplicity and integration in design, it is anticipated that the I^{2}S-LWR can ultimately be cost competitive, despite being a novel concept that must undergo licensing efforts. This paper recognizes the need to maintain economic competition through the design process and some brief comments on costs relating to the scaleup of an integral LWR are included. Note that in addition to production and operation costs, licensing costs for any new reactor are significant, but as all new LWR concepts require this step, no significant comparison is made regarding these licensing costs.

An obvious impact of a power scale-up of a small integral reactor is that the reactor will have larger components and systems to accommodate the larger thermal power rating. This means that forgings sizes and concrete pour volumes will be increased. Ideally, a scaled-up design should attempt to minimize the raw materials used in order to minimize material costs. Unfortunately, although economy of scale will provide some benefit for the I^{2}S-LWR, there is the potential for these cost benefits to be offset due to even larger cost increases of key components where the cost scaleup is nonlinear. In addition material and forging cost challenges in scale-up, a larger reactor means larger and often more complex components. Thus, wherever possible, equipment requirements should be minimized to reduce capital costs of the I^{2}S-LWR. Thus, in order to maintain cost competitive designs in a scaled-up reactor, system simplicity and component/material minimization approaches must be adopted. As a result the I^{2}S-LWR design focuses on compact, combined, and simplified systems in order to minimize vessel and system volumes. Additionally, any vessels and components included in the design must be fabricated using current technologies.

Secondly, integral reactor concepts in the design phase can potentially struggle to prevent difficult maintenance in the design concept due to the minimal free volume and awkward arrangement of equipment within both the containment and the RPV, effectively preventing licensing of the concept. This potential challenge arises because significant innovation must contribute to maintaining a factory fabricable size while still including the systems and components required to meet licensing requirements (Cronje et al., 2012). In order to facilitate licensing efforts, as well as to build utility company confidence in the mechanical design of the containment and RPV of the I^{2}S-LWR (as well as other integral concepts), systems and components must be designed and incorporated in ways that minimize maintenance frequency and difficulty. Further, in the I^{2}S-LWR, components were designed so that maintenance requirements did not include additional specialized tools or systems relative to current light water reactors (LWRs), with the goal of having maintenance cycles that can be completed within a 17 day refueling outage.

Third, increasing the output of an integral reactor to 1000 MWe increases the volumetric heat output of the reactor vessel, thus making safe operation during certain transients more difficult. This is primarily due to larger amounts of heat that must be removed per volume of coolant, taxing currently devised integral reactor passive safety system operations which rely primarily on boiling water (Reyes, 2012; Halfinger and Haggerty, 2012). This increase in volumetric heat generation is a result of limitations on RPV size due to fabrication constraints, as explained in Section 3. As a result, the heat generation increases more than the RPV volume, which increases the volumetric heat generation of the primary system. This in turn challenges the capacity of the reactor to transfer heat from the core to the secondary system or external environment during normal and off-normal operation, respectively. Although compact heat exchangers solve this challenge during normal operation, accident performance can be negatively impacted due to potential vapor locking and crud deposition in the millimeter channels of the heat exchangers. An additional primary focus of the I^{2}S-LWR design based on the higher volumetric heat output is to facilitate enhanced passive safety through the design of the systems, structures, and components. The I^{2}S-LWR design team has developed several innovative technologies which were integrated into the RPV design to realize this goal without drastically altering the LWR licensing and commercialization pathways.

This paper presents and discusses the base design of the I^{2}S-LWR primary coolant system, highlighting the impact of five major design constraints and their impact on the design development. Key deviances from the primary coolant system for both current LWRs and SMRs are indicated where appropriate, and key component design drawings of the I^{2}S-LWR integral RPV are provided.

2. Primary coolant system design criteria

The development of the primary reactor coolant system is based upon several design criteria. Although these criteria are common to current light water reactors, their impact on the design can be quite different for integral reactors, primarily due to the compact RPV and containment sizes. The application of these design constraints directly impact the component development for the primary coolant system design, and thus these design criteria are referenced when component and system selections are made. The design criteria selected to guide the design of the integral reactor pressure vessel of the I^{2}S-LWR are:

1. All components must fit within the reactor pressure vessel with sufficient peripheral spacing to perform maintenance work.
2. All components common to primary coolant systems of LWRs should be included unless specifically precluded by innovative technology applications.
3. Capital costs should be minimized through the use of known and proven technologies and materials.