Accident Tolerant High-Pressure Helium Injection System Concept for Light Water Reactors

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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.

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 [1]. 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 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 [2, 3]. 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 [1, 4]. 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 seconds, 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 [5-6].

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 [7]. 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.

Figure 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 [8], 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 Figure 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 $34.1 \text{ m}^3/\text{hr}$ (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 gallons) and 3.4 m^3 (900 gallons) 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 has been depressurized through the large break, the core pressure is in equilibrium with the outer containment pressure and no driving differential pressure exists to expel the superheated steam from the core. This lack of RCS cooling, coupled with the stagnant steam within the core leads to a rapid increase of cladding temperature. The three accumulators (one for each cold leg) are held at a pressure between 4.13 MPa (599 psig) and 4.60 MPa (667 psig). Once the RCS pressure drops below the design pressure of the accumulators, the differential pressure induces flow from the accumulators to the cold legs of the two intact lines to the lower core plenum. This accumulator flow begins the re-flood phase of the LOCA condition. The accumulators are designed to hold 28.7 m^3 (7580 gallons) of borated water and rapidly empty to supply water to the lower core plenum [8]. However, by the time the accumulators begin to re-

flood the core, cladding temperatures have already increased to their threshold temperatures. Since the LHSI system doesn't begin to deliver cooling water until the pressure drops below 1.2 MPa (175 psig), this system has no effect on supplemental cladding cooling during the preliminary LOCA transient and is therefore omitted in the present conceptual discussion. Therefore, since the HHSI cooling capabilities are minimal and neither the accumulators nor the LHSI systems activate until well after cladding burst and oxidation thresholds, an intermediate system is needed to supplement cooling after core uncovering.

3. Zirconium-Alloy Cladding Shortcomings

It is well known that zirconium interacts with water at higher temperatures to form zirconia and hydrogen gas. This oxidation reaction is specifically important because of its impact during the high-temperature conditions of a design basis LOCA. Oxidation decreases the load-bearing capacity of the cladding; furthermore, it produces hydrogen gas that can either pose an explosion risk or absorb into the zircaloy matrix and cause embrittlement [1, 9]. The increase in temperature during a LOCA gives rise to higher oxidation rates, which then leads to more heat generation from the exothermic oxidation reaction between the high temperature cladding and steam. At higher temperatures, it has been found that this release of exothermic energy is significant in comparison with the decay heat being released from the fuel. Though the cladding temperature has been found to positively correlate with oxidation reactions, the temperature and pressure of the reacting steam are not significant in the reaction rate [1, 10]. Another study found no significant difference in oxidation rates for irradiated versus non-irradiated samples [11]. This means that accelerated oxidation can be minimized if the cladding temperature is kept as low as possible, regardless of the volatile state of the surrounding environment. Multiple experiments have been conducted to study isothermal oxidation of zirconium-alloy cladding. Since oxidation is a function of oxygen diffusion to the zirconium surface through the oxide, most isothermal oxidation conditions follow diffusion laws and the Arrhenius equation. The Baker-Just [10] correlation is the most widely used correlation for the calculation of zirconium oxidation, but other experiments have shown that this is an overly conservative correlation [1, 12-14]. For experiments estimating the oxidation levels required for the breakaway condition, most zirconium alloys have breakaway times greater than 50 minutes. Because fuel rods undergo uniform corrosion during normal operation, the actual safety factor with respect to rod burnup for accident oxidation conditions is much lower since some pre-existing oxidation already exists under steady state operation [15, 16]. This is especially the case when fuel cladding has been either scratched or ruptured, since experiments have shown that the time for breakaway oxidation is severely lowered in these instances [17].

Zirlo cladding is the popular replacement for the Zircaloy-4 cladding. Developed by Westinghouse, this cladding material's success is attributed to its higher burnup potential and its increased corrosion resistance. Zirlo has been proven superior to Zircaloy-4 cladding with respect to high-temperature steam oxidation in the temperature range of 700-1200°C [18]. Zirlo has also been found to transition in oxide phase from monoclinic to tetragonal at higher temperatures in comparison to other competitors [19]. Even with its improved properties in comparison with Zircaloy-4 cladding, Zirlo still experiences many of the same oxidation and temperature concerns that would be encountered in a LOCA. Thus, after decades of optimization of zirconium-based alloys it is doubtful that substantial increases in accident safety margins are

to be expected. Because of these shortfalls in both emergency systems and current cladding materials, a new method of lowering the cladding temperature in the event of a pressurized water reactor LOCA is described in this paper.

With the proposed helium injection system, the cladding temperature can be lowered, which will then lower the rate of cladding oxidation. This is important because studies on tube rupture for high burnup cladding has shown brittle fracture of fuel rods due to irradiation-induced embrittlement combined with thermal expansion [20,21]. With this proposed helium-injection concept, not only can the peak cladding temperature be lowered during a LOCA transient, but the rate of temperature rise can also be lowered due to the added convective cooling, thus lowering thermal expansion and the buildup of thermal stresses in the cladding. Previous studies have investigated the effect of varying the argon concentration in a steam-argon mixture and found that oxidation rates remained relatively constant for Zircaloy-4 even at high argon concentrations [10, 22, 23]. Even at argon volume percentages as high as 90 percent the oxidation rate remained the same due to a readily abundant supply of oxygen molecules in the mixture. Though these studies indicate that high concentrations of noble gases do not decrease the surface oxidation of zirconium-based alloys in a steam environment, all of these experiments used a well-mixed combination of steam and argon and were conducted in isothermal conditions. No studies have investigated the prospects of using a noble gas to supplement convective cooling by steam in a LOCA condition.

4. Concept Visualization

Current safety injection systems are great at providing the negative reactivity and re-flooding capabilities needed to handle large-break design basis accidents (DBAs), but they are also inefficient when it comes to providing sufficient cladding cooling during a large-break LOCA or BDBA conditions. To help alleviate the thermal stresses and cladding oxidation problems associated with these accident conditions, a proposed high-pressure helium injection (HPHI) system is hereby presented.

During the blowdown phase of a LOCA, most of the coolant is vaporized and is expelled from the core due to the differential pressure between the core and containment. A high-pressure helium tank (HPHT) held above the operating pressure of the system (2250 psig) is coupled to either the HHSI or accumulator lines that are connected to the cold legs of the ECCS. When a large-break LOCA occurs causing the rapid depressurization of the core, high-pressure helium is injected into the cold legs and helps pad the upper plenum of the core while the HHSI and accumulators supply cooling to the lower core plenum. The existence of helium, with its excellent thermal conductivity and heat transfer characteristics, will supplement superheated vapor and help cool the cladding during temperature transients. Helium will bubble through the coolant in the downcomer and will travel up through the fuel assemblies. Though the helium will eventually exit through the break with the superheated water, this will ultimately help heat transfer since the helium will not stay stagnant within the vessel and can be constantly replaced by new helium through the cold legs of the RCCS. Since helium is an inert gas with no detrimental health effects, the presence of helium within containment will not pose a health threat.

Figure 2: Proposed flow paths for helium injection

Figure 2 shows a schematic of the ECCS with the proposed flow path of helium into the cold legs. Since the accumulators do not begin injection until the RCS pressure falls below 600 psig, the initial flow path of helium can be injected through the accumulator lines into the reactor core until the RCS pressure falls below 600 psig. At this point, an active shut off valve can be closed and the helium can be redirected into the HHSI lines to supplement the low-flow cooling in the HHSI system while the accumulators supply coolant flow into the lower plenum of the core. The high-pressure helium tank (HPHT) can be either an underground reservoir/sump or can take the form of a hermetically sealed steel-lined concrete tank stored above ground on site. Because the system only involves the transport of an inert gas, flexible tubing can be used as opposed to rigid piping that is more susceptible to damage in the event of an earthquake or other natural disaster. This provides the added advantage of accommodating current piping configurations since the flexible tubing can be more easily maneuvered to connect to existing systems with only a few added connections and valves. An illustration of RCS injection sites for the proposed concept are provided in Figure 3.

Figure 3: Proposed injection sites for helium injection

Manngard et al. have developed a simplified LOCA burst model for zircaloy cladding in a steam environment that compares well to REBEKA program experimental data [6]. This code takes

into consideration the interrelationships between creep deformation, phase transformation, and oxidation kinetics for zirconium alloys and compares developed hoop stress values with an oxidation and temperature dependent burst criterion developed elsewhere [24]. Though assumptions such as specified initial oxygen content, differential cladding pressure, and isotropic expansion limit its applicability in certain scenarios, it provides an excellent framework for modeling reactor fuel cladding burst properties in conditions having a constant pressure and heating rate. Results indicate an inversely related dependence on heating rate and cladding overpressure on zirconium alloy cladding burst times.

There are many important implications from [6] that are worth noting with respect to an added helium injection system. First, the heating rate increases during the blowdown phase of a LOCA because of the poor heat transfer characteristics of the stagnant steam within the core. Helium injection through the unused accumulator lines at the start of blowdown will slow the heating rate through both forced convection and through the expulsion of stagnant steam from the core. It is imperative to note that the presence of helium in a steam environment alone will not prohibit detrimental oxidation; however, oxidation rates will decrease with decreasing cladding temperature. This means that the helium will slow oxidation rates by decreasing temperature and thus the rate of oxygen diffusion through the oxide layer. An argument can be made that the injection of helium into the core during blowdown may slow depressurization and increase the time until accumulators are able to begin refilling the lower plenum. If the helium is sufficiently lowering the rate of cladding temperature increase, then the relatively slower rate of depressurization will only decrease the thermal shock to the system. Furthermore, in the instance of a large break LOCA, the helium will also be exiting the same large-breaks with the steam, allowing a constant flow of helium and steam to provide a continuous transfer of heat during the slower depressurization of the core. To balance heat transfer and depressurization characteristics, future parameteric evaluations of blowdown phenomena must be undertaken, as discussed in the following sections. In the event of a small break, however, this pressurization is an added advantage since the injection of helium through the accumulator injection lines can also be used to maintain core pressure while the reactor shuts down. Thus, a possible delay in accumulator activation must be balanced with the potential heat-transfer benefits of utilizing emergency helium-injection for current generation reactor designs.

The most significant benefit for the HPHI system is that it is a completely passive safety system that is pressure driven like the accumulators in current safety systems. In a DBA like a large-break LOCA, a passive check valve can be used like the ones only allowing accumulators to inject once the pressure falls below a given threshold. In this case, the HPHI designers have great flexibility in determining the optimum threshold pressure for this high-pressure injection. This system is also of benefit in BDBA scenarios where there is a loss in on-site power. In this case, both the HPHI system and the accumulators will both be able to remove both decay heat and excess reactivity since the density of helium is low and because accumulator injection uses highly borated water.

5. Experimental Methods

To test this helium injection concept, both experimental and computational studies have been developed to study heat transfer and depressurization characteristics. At the Virginia

Commonwealth University High Temperature Materials Laboratory (HTML), a helium-steam injection apparatus was developed using a high-amperage joule heating methodology. As shown in Figure 4, the setup consisted of a resistance heated tungsten rod within a 304SS tube (1.27 cm OD, 0.21 cm thickness). UHP Argon Gas (99.999% Ar) continually flowed at a generating pressure of 34.47 kPa (5 psi) between the tungsten heating element and the heated tube. 304SS is used as a preliminary cladding test material due to its former use as a reactor cladding material and its wide availability as a commercial alloy. After the simulated cladding exceeded 1100 C, steam was injected at a constant rate with a generating pressure of 68.95 kPa (10 psi). Helium gas was injected at various generating pressures to study its ability to decrease cladding temperatures with various mixtures of helium/steam within the apparatus. A helium-only injection experiment was also conducted without the prior steam injection to compare the heat transfer capabilities for both helium and helium-steam injection conditions.

Figure 4: Heated 304SS rod within the operating apparatus (right) and the experimental setup design (left)

To investigate the dependency of reactor vessel pressure with added helium injection, a simplified computational study was implemented using a subsonic flow assumption for helium and the choked-flow condition for steam under a large-break LOCA analysis. This approach utilized two control volumes: one with a pressurized helium tank and one with pressurized saturated steam. For the present analysis, it was assumed that the limiting factor in depressurization is not the vaporization rate of water to steam, but was instead limited by the rate of steam expulsion from the pressure vessel under choked-flow conditions. Thus, a complex analysis of the two-phase water/steam dynamic was not implemented in the current proof-of-concept computational study. Furthermore, internal heat generation was not studied in the current analysis and only the depressurization phenomenon was investigated in this simplified model using coupled differential equations.

The flow model for the computation is illustrated below. The subscript h was used to denote the properties of helium within the first control volume (helium tank) and the subscript s was used to denote the steam properties within the pressure vessel control volume. Due to the low intermolecular forces between helium atoms, this noble gas was modeled in this study as an ideal

gas without an expectation of significant errors from ideal gas law deviations. To model the choked-flow condition for steam, a correction factor C_R was used from published data in literature to account for the deviation of steam from the ideal gas law [25]. Thus at each point in time, the properties for helium and steam were calculated. The choked flow condition will be applicable at during the majority of the LOCA sequence, but will eventually break down when both the helium tank and pressure vessel reach the containment pressure, which is assumed constant for this proof of concept calculation. Containment safety analyses will need to be further investigated to ensure that containment pressures to not exceed regulatory limits with added helium injection.

Figure 5: Flow path for computational model

For control volume 1 (He tank), the time dependent properties were modeled using subsonic isentropic flow conditions for helium alone:

$$\dot{\rho}_h = \frac{-A_h}{V_{HPHT}} \frac{P_h}{\sqrt{RT_h}} \sqrt{\frac{2\gamma}{\gamma-1} \left(\frac{P_s}{P_h}\right)^{\frac{2}{\gamma}} \left[1 - \left(\frac{P_s}{P_h}\right)^{\frac{\gamma-1}{\gamma}}\right]} \dots\dots\dots (1)$$

where γ is the specific heat ratio for helium, assumed constant in the current model, $\dot{\rho}_1$ [kg/s] is the mass flow rate of helium in terms of density exiting the HPHT and entering the core, and P_h [Pa] and ρ_h [kg/m³] are the pressure and density of helium, respectively. A_h [m²] is the cross sectional area of helium injection and V_{HPHT} [m³] is the constant volume of the high pressure helium tank. C_{v_h} [J/mol/K] is the isochoric heat capacity of helium, which is assumed constant over the temperature range for this simplified model.

Using conservation of energy and the state equations for the assumed ideal gas, the temperature change can be modeled as:

$$\rho_h C_{v_h} \dot{T}_h = \dot{\rho}_h R_h T_h \dots\dots\dots (2)$$

For control volume 2 (pressure vessel), conservation equations must take into account helium injection and the steam/helium expulsion through the break. For this simplified model, it is assumed that the steam/helium mixture is dominated by the steam properties as the mixture exits the large break; thus, per this assumption a detailed investigation of choked-flow variations due to the partial pressure of He in the mixture is not investigated. Instead, steam expulsion through the large break is dominated by the pressure, density, and temperature of the steam within the pressure vessel. The exiting media is assumed to be in the choked condition and a correction

factor C_R is utilized to provide a corrected steam mass flow rate through the orifice. From the conservation of mass and energy balances for the pressure vessel with injected He and exiting steam, the following equations were derived:

$$\dot{\rho}_s = -\dot{\rho}_h - \frac{A_s}{V_{PV}} \sqrt{P_s \rho_s} C_R \dots\dots\dots (5)$$

$$\rho_s C_{v_s} \dot{T}_s = -\frac{V_{HPHT}}{V_{PV}} \dot{\rho}_h R_h T_h - \frac{A_s}{V_{PV}} C_R P_s \sqrt{R_s T_s} \dots\dots\dots (6)$$

where P_s [Pa] is the steam saturation pressure, ρ_s [kg/m³] is the density of the steam within the pressure vessel, C_R is the choked flow correction factor for saturated steam, A_s [m²] is the LOCA break area, V_{PV} [m³] is the constant pressure vessel volume, and $R_{s,h}$ is the specific gas constant for steam or helium, respectively.

6. Results and Discussion

For the experimental setup heated to 1100 C under steam, Figure 6 shows the temperature profile for the heated 304 SS rod for both helium-steam and helium injection. From this graph, it can be seen that a small increase in helium generating pressure, and thus flow rate, achieves a substantial decrease in rod temperature under a steam environment. With just an increase in 103.42 kPa (15 psi) helium generating pressure, the measured temperature of the metallic rod dropped by over 300 C, which in turn implies that helium injection can substantially decrease oxidation rates in the event of a DBA or BDBA. This shows that an on-site HPHI system may not require extremely high pressures to achieve a substantial increase in safety margins with respect to peak cladding temperatures in the event of a DBA or BDBA. In comparison with the no steam injection condition, it can be seen at higher flow rates, the heat transfer for the system is dominated by helium-injection and not by steam, since the equilibrium temperature after injection for both cases are the same at the higher helium injection generating pressure. This relatively simple proof-of-concept experiment thus provides valuable insights into what heat transfer mechanisms will dominate under accident conditions when this proposed helium injection system is implemented.

Figure 6: Temperature profile for cooled rod under helium and helium-steam injection

The highly non-linear set of ordinary differential equations (1) through (4) were solved using MATLAB[®] software by utilizing the ODE45 function with a timestep of 0.05 seconds. XSteam [26] was used to calculate saturated steam properties at each time step for the pressure vessel steam. For this model, the volumes of both the helium tank and pressure vessel were specified as 400 m³. Two cases were run for the model. First, the initial pressure and temperature of the helium were 20 MPa and 300 K, while the steam was assumed saturated at 15 MPa. The second case only used a helium pressure of 1 MPa, which was used to simulate a case where helium was essentially non-existent and only a slight pressurization occurred due to a standard high pressure steam injection system. For both cases, a break area of 1 m² was assumed to correspond with a break in a RCS cold leg in a LWR, while the helium injection area was 0.25 m².

As shown in Figure 7, the helium injection slows the depressurization rate of the pressure vessel substantially. As compared to Figure 8, where the time to accumulator injection is 24 seconds, the 20 MPa injection case increases this onset time to 250 seconds. This is a substantial increase in the onset time to the reflood of the lower core plenum, which gives more time for the cladding to heat up and potentially fail. However, it is important to note that forced helium convection is occurring over the entirety of this added time. From the proof-of-concept experimentation, it can be seen that the thermal conductivity benefits of helium in a helium-steam mixture can sufficiently cool the cladding with only marginal differences in generating pressure. Furthermore, as the helium gas performs work to depressurize the HPHI tank, the temperature of the helium gas within the HPHI tank decreases over the course of depressurization, increasing the differential temperature between the helium and cladding and thus increasing heat transfer. With helium injection through the throttling of high pressure gas, injection temperature concerns must be addressed and the tank should be designed such that the injected helium must not cause localized freezing or thermal shock to the inlet tubes due to the Joule-Thomson effect. However, because the differential pressure between the HPHI tank and the core is highest at the initial blowdown phase and because the temperature of the system will only increase with time, designers can design the HPHI tank so that only the inlet temperature at the time of initial injection is within safety margins. With the current configuration of 20 MPa for the HPHI and 15 MPa for the core, the initial He inlet temperature is ~270K, slightly below freezing. Since the ambient temperature within the nuclear plant will likely be higher than 300K, injected He gas at

this pressure will not serve as a cause for localized freezing; furthermore, as the LOCA sequence progresses, the backflow of high temperature lower-plenum water will cause the inlet to be of even higher temperature, negating the need for heating the inlet location after the accident scenario has initiated. If safety designers are concerned about the inlet temperature of helium, localized heaters like the ones used to keep the BIT above solubility limits for boric acid can also be used to increase the helium tank temperature and pressure during normal operation.

This proof-of concept work must be further modeled to incorporate the two-phase flow within the core as well as to incorporate internal decay heat generation so that a better understanding of the potential detriments and benefits of this system can be investigated. This computational modeling can be performed using codes such as RELAP5 or RETRAN-3D, which already have the capability to model complex multiphase flow systems. Parametric studies can focus on the combined effects of helium tank generating pressure, volume, and orifice size, as smaller sizes will limit the mass flow rate and affect depressurization time.

Figure 7: Simulated depressurization with 20 MPa initial helium tank pressure

Figure 8: Simulated depressurization with 1 MPa initial helium tank pressure

To this point, much of the discussion has been limited to DBA incidents, but this system can also be incorporated to help alleviate BDBAs as well. Briefly, the large helium tank can be either held at a higher pressure or increased in volume to provide high-pressure helium flow for longer durations in the event of a loss of power. The helium tank can be connected to the existing systems using an active valve that can disengage when power is lost, allowing helium to continually flow into the pressure vessel to provide cooling and pressurization. In this case, the added convection and pressurization is advantageous because the depressurization rate will decrease and there will be continuous cooling on a larger time scale by both the HPHI system and eventually the accumulators. Further computation will also be needed for these BDB scenarios.

In any of these cases, helium should be the primary choice for the pressurized gas when designing a high-pressure injection system for LWR designs. Though helium is more expensive, using more economical choices such as nitrogen gas or carbon dioxide will cause their own oxidation reactions that not only generate exothermic energy but also produce detrimental byproducts. Helium is also an obvious choice in context of its very high specific heat and thermal conductivities. Multiple experiments have been conducted on both air and nitrogen oxidation of popular cladding types, such as Zirlo, Zircaloy-4, and M5. These experiments show severe degradation of these cladding types due to the growth and re-oxidation of nitride particles within the pre-existing oxide; furthermore, this re-oxidation reaction can result in large amounts of heat being generated from the exothermic reaction between the produced nitrides and the pre-existing steam within the pressure vessel [27-29]. Carbon Dioxide has also been shown to cause detrimental oxidation in existing cladding types with the added detriment of producing carbon monoxide as a product of the reaction [30-31]. Thus, for any of the discussed DBA or BDBA conditions, the use of inert helium with its excellent thermal properties is recommended for future investigations. In addition the presence of helium gas in the reactor is also expected to act as a retardant when present in a combustible mixture of hydrogen and oxygen which is the primary source of concern in nuclear reactors during a severe accident. The retardation capability has been shown to arise from the high thermal diffusion coefficient of helium relative to oxygen [32].

With helium being the obvious choice for this injection concept, the question of handling a non-condensable gas in a reactor arises. It is generally accepted that the presence of non-condensable gases in a mixture (of steam) reduce the overall heat transfer coefficient. Although not much experimental data is currently available, some investigations have been conducted to study the changes in the total heat transfer coefficient with the addition of helium to steam. One study in particular found an enhancement in the overall heat transfer coefficient if concentration of helium in the mixture was limited $< 30\%$ [33] but a decrease in the overall heat transfer coefficient with increasing helium content. Although it is expected that the presence of such non-condensable gases may be detrimental during normal operation and small break LOCA events, their role during intermediate and large break LOCA events which potentially could lead to core uncovering is not well understood. To further confirm this, separate experiments will be required in the future. If the phenomenon mentioned above is confirmed, then further investigations of controlling the mass flow of helium to achieve the required concentrations in the mixtures during small break LOCA will be necessary. It is noted that at present, the concept being proposed is intended to largely address the large break LOCA events in general. In any event, the non-condensable helium is expected to vent out of the reactor pressure vessel either into the

containment or any other intended route (such as the suppression pool) along with the steam. Nevertheless in case of an event where the zircaloy cladding is completely dry due to uncovering, and the helium gas is injected to reduce the cladding temperature below 800°C, the blanketing effect of the gas which could potentially interfere with active cooling during quenching may arise. Here again detailed studies will have to be conducted on the of core re-flooding parameters (example: coolant injection flow rates) to effectively disrupt the blanket following the helium injection step.

7. Conclusions

The proposed high-pressure helium injection (HPHI) system has the potential to reduce peak cladding temperatures and substantially increase safety margins in the event of design basis accidents and beyond design bases accidents. Existing ECCS systems rely solely on rapid re-flood to prevent cladding temperatures from reaching regulatory limits while the proposed system provides a way to ensure cooling during both blowdown and re-flood phases. Even lowering cladding temperature by a few degrees can decrease oxidation rates and cladding failure probabilities substantially and this system provides these safety margins with only minor changes to existing ECCS configurations.

Proof of concept experiments at the Virginia Commonwealth University HTML show promising heat transfer characteristics of He-steam mixtures, while the simplified choked-flow model presented identifies key parameters that still need to be better understood for the application of this concept. Multiple injection sites for current ECCS configurations are identified that can be incorporated into existing LWR systems with minimal effort. Feasibility experiments for pressurized mixtures should be coupled with computational modeling to provide a better estimate of cladding temperature and oxidation changes with decreasing core and helium tank pressure, while economic models should be developed to analyze the added cost-benefits with the added HPHI system. *Although the concept looks promising with limited demonstrations, there are several important aspects such as the effect of helium blanketing during quenching and effect of helium on the overall heat transfer coefficient in context of steam-helium mixtures in addition to studies on the helium pressures necessary to attain required temperature drops will need to be investigated to determine whether a such a HPHI system can be designed and incorporated into existing LWR systems.*

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9. References

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