Parametric Study of Quenching Behavior of 316L Stainless Steel and ZIRLO Tubes in Simulated LOCA Reflood Conditions

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INTRODUCTION

During a Loss-of-Coolant-Accident (LOCA), the fuel-cladding system can be exposed to very high temperatures, up to 1200 °C, before being quenched by bottom reflooding through activation of the Emergency Core Cooling System (ECCS). At high temperatures, zirconium alloy cladding undergoes rapid oxidation in the steam environment leading to mechanical degradation of the cladding and hydrogen gas production[1]. The severity of this process was highlighted in the Fukushima-Daiichi accident, where hydrogen gas caused an explosion in two of the units. To address the issues posed by conventional Zr-alloy cladding in accident conditions, the U.S. DOE began the Accident Tolerant Fuels (ATF) program to develop fuel-cladding systems that can better tolerate loss of active cooling for a considerably longer time while maintaining or improving fuel performance during normal operation[2]. Thin chromium coatings applied to the surface of Zr-alloy cladding tubes are considered a promising near-term solution due to the oxidation resistance of chromium at high temperatures. Lead test rods (LTA) of Cr-coated Zr-alloy cladding are undergoing full fuel cycle testing at Byron Nuclear Generating Station in Illinois with post-irradiation analysis at several national laboratories. Preliminary analysis has shown significant improvement of oxidation resistance on the Cr-coated cladding tubes and maintenance of fuel performance during normal operation.

Furthermore, ATF development could also provide an avenue for increased economic operation of commercial nuclear power plants by improving fuel reliability with increased discharge burnup[3]. However, increasing burnup limits requires critical research into the phenomena of fuel fragmentation, relocation, and dispersal (FFRD) before licensing. Therefore, it is necessary to understand the performance of ATF during accident conditions in which FFRD potentially poses an issue. Specifically, mechanical properties of the cladding may be degraded due to severe oxidation during LOCA events, leading to higher chances of cladding failure and radioactive material released into the primary system. The ability to cool the cladding quickly by reflooding the core using the ECCS is of utmost importance to prevent degradation of mechanical properties leading to clad failure.

To properly understand quenching phenomena with ATF cladding, it is essential to investigate not only the quenching effect on the cladding (e.g., oxidation), but also the thermal-hydraulic quenching behavior since the quenching parameters (e.g., quench temperature and the quench front velocity) are important for predicting the cladding response under the reflood conditions. In the case of the thermal-hydraulic behavior of quenching phenomena, it is likely to be material independent having more significant impact by other thermal-hydraulic conditions such as the cladding temperature, elevation axially along the cladding, and coolant subcooling.

Thus, this work aims to study the effects of reflood parameters on quenching behavior using stainless steel cladding and Zr-alloy cladding. These comparisons will be beneficial backup data on understanding of quenching behavior of ATF cladding under several different reflood conditions.

METHODS

Procurement of 316L Stainless Steel and ZIRLO® Cladding

The cladding used in this work is 316L stainless steel (SS), and the behavior is being compared to a Zr-alloy **ZIRLO®** provided by Westinghouse Electric Company (WEC). The ZIRLO tubes were manufactured originally with a length of ~3.86 m. Both materials were cut down to 16" samples to fit in the testing apparatus detailed below.

All samples are polished with 600-grit and 800-grit SiC abrasive paper to obtain consistent and well-controlled surface conditions before testing. The cladding is polished by mounting each sample on a lathe, and slowly polishing the surface with SiC abrasive paper, starting with 600-grit and finishing with 800-grit. After a sample has been polished, surface roughness measurements are taken to ensure a standard surface roughness to ensure a smooth surface on every sample to standardize quenching behavior. The surface roughness measurements are obtained using a Zygo 9000 profilometer. Each sample is measured 10 times along the axial length of the sample. The sample is prepared for static contact angle measurement by rinsing with ethanol and DI water then baking in a convection oven for one hour to ensure that the surface is completely dry. The contact angle is measured using a Dataphysics OCA 15 Optical Contact Angle Measuring System. The contact angle is measured on top of the tube with the surface of the cladding orthogonal to the lens. Each sample's contact angle was measured 15 times to minimize measurement uncertainty. Since the ZIRLO and 316L SS both are metal, it is expected that the contact angles before testing should be comparable. Table I gives the average surface arithmetic mean surface roughness and static contact angle with one standard deviation for 316L SS and ZIRLO cladding taken before a reflood test, showing a comparable roughness and contact angle.

TABLE I. Pre-test arithmetic mean surface roughness and static contact angle

	316L SS	ZIRLO
Roughness [μm]	0.10 ± 0.02	0.21 ± 0.02
Contact angle [°]	81 ± 3	83 ± 4

Experimental Procedure

Full details on the experimental facility design can be found in the authors' previous work[4,5], and in Figure 1 below.

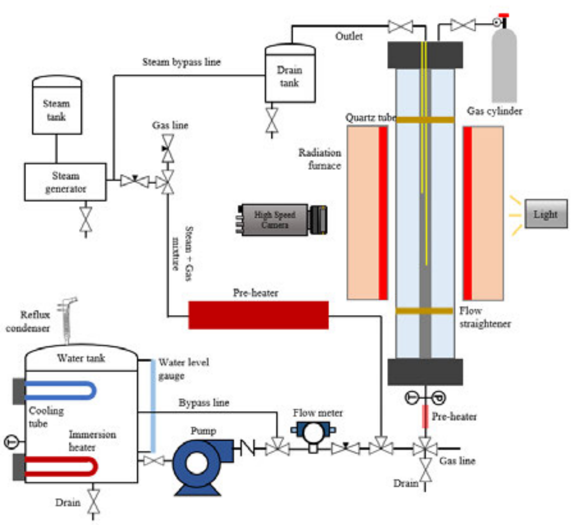

Fig. 1. Schematic design of single rod reflood facility

Each cladding sample is prepared by loading surrogate metallic pellets containing thermocouples inside the cladding tube and securing it to the facility using Swagelok compression fittings. Reverse osmosis (RO) water at <20 ppm dissolved solids is degassed for no less than one hour before being brought to desired subcooling using a cooling coil within the water tank. For each of the tests using ZIRLO cladding, tests are performed using a target subcooling of 20 K. For the purposes of this work on 316L SS cladding, the subcooling will be variable. Meanwhile, the furnace is ramped up to the target temperature at a ramping rate of 10 C/min. During the furnace heat-up, argon gas is flowed through the system to minimize high-temperature oxidation of the cladding sample. Once all components in the system have reached the target temperature, the main waterline is heated by flowing water from the tank into a drain for 10 minutes. To initiate the test, the furnace is turned off and the drain valve at the bottom of the test section is closed to allow water from the tank to reflood the hot cladding tube. For each of the tests, the target reflooding velocity is 5 cm/s. Inlet water temperature, water flow rate, and pellet periphery temperature are measured with a frequency of 50 Hz. The test is completed once quenching is exhibited along the cladding tube and active boiling has ceased along the sample.

Following the experiment, the sample is carefully removed from the facility and allowed to dry completely in the convection oven. Subsequently, surface roughness and contact angle measurements are taken in the middle 150 mm section of the sample corresponding to the uniform temperature zone of the furnace[5]. The temperature data is analyzed using inverse heat conduction analysis[6] to calculate clad surface temperature and heat flux from thermocouple data located within the cladding.

RESULTS

Initial Clad Temperature Effect on Quench Temperature

The thermal history of hot tubes during reflood is described by the quenching curve, shown in Fig. 2 using one of the thermocouples inside the cladding with three distinct regions. The first region shows the steady-state temperature of the sample before the test has initiated, followed by a period of linear temperature decrease through cooling by dispersed flow film boiling, and finally a large temperature drop, signifying collapse of the vapor film and quenching of the sample. Figure 2 shows the measured thermocouple data at the pellet periphery and the calculated cladding surface temperature history of the test using a 316L SS sample, reflood velocity of 5 cm/s, inlet subcooling of 20K, and furnace temperature of 800 °C with the transitions marked as vertical solid lines. The specific quench temperature is defined as the point at which curvature of the time derivative of surface heat flux is maximized. This agrees with methods in literature which define the quench temperature as the point where the time derivative of temperature is minimized[7]. Additionally, this method can handle data in which there is no local minimum realized before significant temperature change.

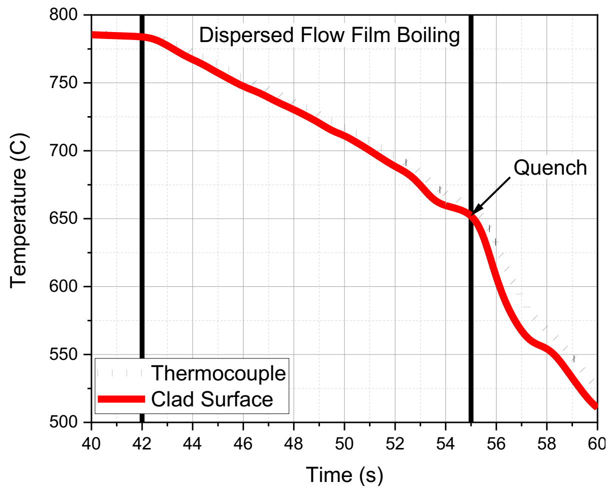

Fig. 2. Measured and calculated clad surface temperature during reflood of 316L SS cladding at 800 °C.

The quench temperatures for 316L SS and ZIRLO as a function of initial furnace temperature are plotted in Fig. 3, which were tested at 20 K water subcooling and 5 cm/s of reflood velocity.

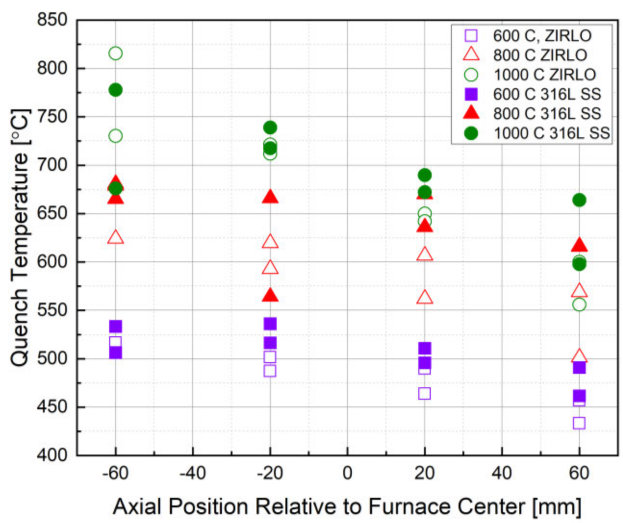

Fig. 3. Quench temperature vs axial position for 600, 800, and 1000 °C tests using 316L SS and ZIRLO.

Figure 3 shows quench temperatures for both materials increasing with the increase of initial cladding temperature, which has been reported in previous work on quenching of tube geometries[8]. The decreasing linear trend was observed in both clad materials at all initial cladding temperatures along different axial positions. Given that two different materials show comparable quench temperatures with the same quench temperature trend with the initial temperature change and the axial position change, we assume the primary factors affecting quench temperature behavior are material independent for metals and will use 316L SS to further investigate the effect of thermal-hydraulic parameters on reflood quenching.

Subcooling Effect on Quench Temperature

316L SS was used to determine behavioral trends when changing inlet subcooling before performing similar experiments using ZIRLO cladding. Figure 4 describes the effects of variable subcooling on quench temperatures obtained with an initial cladding temperature of 800 °C.

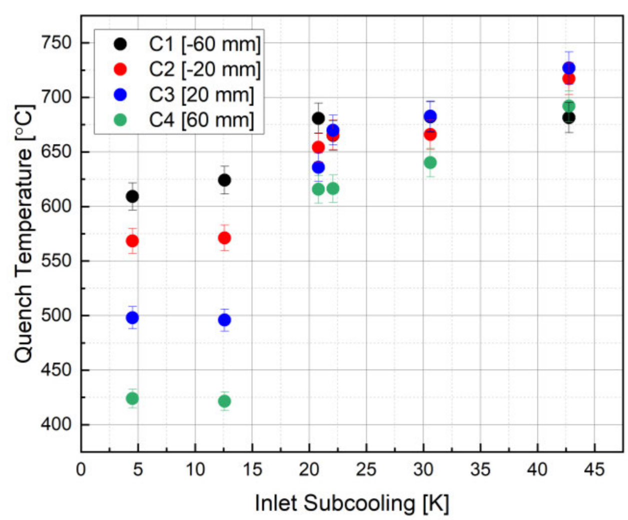

Fig. 4. Quench temperatures at various inlet subcooling for reflood tests with 800 °C initial temperature.

Based on the current data in Fig. 4, the quench temperature has two regions with different trends along the inlet subcooling. Below some threshold of subcooling for these initial conditions between 12.6K and 20K inlet subcooling, the magnitude of subcooling has negligible effect on quench temperatures, and the effect of axial position becomes more pronounced. In contrast, above that threshold, the quench temperatures increase linearly with inlet subcooling showing a reduced effect of axial position. This qualitative trend in inlet subcooling will be validated with additional reflood tests at different initial temperatures.

CONCLUSIONS

Quenching behavior during reflood was tested using 316L stainless steel tubes and ZIRLO cladding tubes. Preliminary data suggests that trends of quench temperature are similar between the two materials. Both materials also show similar behavior of decreasing quench temperature as a function of axial position. This was proven when studying quench temperature as a function of initial cladding temperature, demonstrated in Fig. 2. The parametric study on the qualitative trends in quenching behavior in 316L SS allows us to move onto studying and testing other thermal-hydraulic parameters in 316L SS with confidence that similar trends on the hydraulic parameters will be obtained when testing ZIRLO cladding.

When holding the initial cladding temperature constant, we studied quenching behavior in 316L SS cladding tubes as a function of inlet subcooling. Preliminary data shows a separation into two regions of quenching behavior. One region below a threshold inlet subcooling that shows minimized quench temperature change and larger axial position effect, while the other region shows minimized axial position effect and a linear increase of quench temperature with subcooling increase. It is assumed these two regions would appear again at varied initial cladding conditions, with the threshold temperature changing based on the initial conditions. Further, it is assumed that ZIRLO cladding tubes would exhibit similar behavior as seen in the testing of 316L SS cladding.

Future testing will include reproducibility tests to reduce uncertainty in calculated quench temperatures as a function of inlet subcooling in 316L SS, as well as tests of varied subcooling at 600 °C and 1000 °C to further solidify the qualitative trends found at 800 °C initial cladding temperature described in Figure 4. Tests to study qualitative trends in quenching behavior when varying reflood velocity will also be done to further investigate a wider set of thermal-hydraulic parameters. Lastly, if the tests prove to be successful on the 316L SS cladding, further testing can be done on ZIRLO cladding tubes with narrower parameter ranges.

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ZIRLO cladding samples were provided by Westinghouse Electric Company. ZIRLO® is a registered trademark of Westinghouse Electric Company LLC, its affiliates and/or subsidiaries in the United States of America and may be registered in other countries throughout the world. All rights reserved. Unauthorized use is strictly prohibited. Other names may be trademarks of their respective owners.
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REFERENCES

1. J. V. CATHCART et al., "Zirconium metal-water oxidation kinetics IV Reaction rate studies," NRC, ORNL/NUREG-17, p. 204 (1977).
2. J. CARMACK et al., "Overview of the U.S. DOE Accident Tolerant Fuel Development Program," INL/CON-13-29288, Idaho National Laboratory (INL) (2013).
3. K. SHIRVAN, "Implications of accident tolerant fuels on thermal-hydraulic research," Nuclear Engineering and Design **358**, 110432 (2020).
4. W. JUNG et al., "Project Overview of Thermal-Hydraulic and Mechanical Behavior of Near-Term ATF Design in Reflood Conditions," in Transactions of the American Nuclear Society, Phoenix, AZ (2022).
5. C. DUNBAR et al., "Investigation of Cladding Thermal Behavior Under Simulated Reflood Conditions," in Proceedings of the 20th International Topical Meeting on Nuclear Reactor Thermal-Hydraulics (NURETH-20), Washington, D.C. (2023).
6. "INTEMP Inverse Heat Transfer Analysis User's Manual," TRUCOMP, 1986 (2003).
7. K. JUN-YOUNG et al., "Control of minimum film-boiling quench temperature of small spheres with micro-structured surface," International Journal of Multiphase Flow **103**, 30 (2018).
8. J. STEPANEK, V. BLAHA, and V. DOSTAL, "QUENCH FRONT PROPAGATION IN THE ANNULAR CHANNEL," in Acta Polytechnica CTU Proceedings **4**, pp. 97–101 (2016).