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Abstract

A study was performed to determine the surface roughness of the corrosion layer on aluminum clad booster fuel plates for the proposed Gas Test Loop system to be incorporated into the Advanced Test Reactor (ATR) at the Idaho National Laboratory. A representative sample coupon autoclaved with the ATR driver fuel to produce a protective aluminum hydroxide coating on the cladding surface was obtained. The coupon was analyzed using optical profilometry to determine the mean surface roughness, a parameter that can have significant impact on the coolant flow past the fuel plates. This information was used to specify the surface finish of flow test plates for a hydraulic flow test model. The purpose of the flow test is to obtain loss coefficients describing the resistance of the coolant flow paths, which are necessary for accurate thermal hydraulic analyses of the water-cooled booster fuel assembly. A sensitivity study was performed to assess the effect of the fuel plate surface roughness on coolant temperature, coolant flow rate, and fuel temperature for the booster fuel assembly in the current Gas Test Loop design.

Introduction

A Gas Test Loop (GTL) is being designed to provide a fast flux irradiation environment in the Advanced Test Reactor (ATR) at Idaho National Laboratory to test fuels and materials for advanced concept nuclear reactors. The design incorporates booster fuel to achieve a fast (energy > 0.1 MeV) neutron flux of at least 10^{15} n/cm^2·s. Within the ATR test lobe, the primary reactor coolant will cool the booster fuel assembly. Twelve 0.1 inch (0.254 cm) thick, 4 foot (1.2192 m) long curved plates are arranged in three concentric rings surrounded by 0.078 inch (0.2 cm) coolant channels (see Figure 1) [1]. A flow test will be performed using a full-scale model of the booster fuel assembly to obtain loss coefficients for the thermal hydraulic analysis. The flow test plates will be fabricated from aluminum tubing that has been machined to the proper thickness and diameter to simulate the nuclear fuel plates. The fuel plates are typically manufactured by rolling. Since surface roughness plays a critical role in the calculation of frictional losses in fluid pipes and channels, it is necessary to specify surface finish for the flow test plates.

When the aluminum cladding on the uranium silicide booster fuel is exposed to water, a corrosion layer forms. It is preferable to pre-treat the fuel plates so that a thin, uniformly dense hydroxide surface is formed on the cladding, rather than allowing the layer to form during reactor operation. A thick buildup of corrosion product on a surface without pretreatment could lead to excessive temperatures in the fuel due to the low thermal conductivity of the boehmite (2.25 W/m·K) and/or spalling of the film [2]. Spalling of a film region would produce a relatively cold spot temporarily, but would subject that area to accelerated corrosion and possible release of fission products. A layer of boehmite (a crystalline, non-porous gamma-alumina hydrate) is typically pre-formed on the surface of the fuel cladding prior to exposure in the reactor to prevent the uncontrolled buildup of corrosion product on the surface. A boehmite layer formed in pre-treatment is more stable and much less likely to spall. A 6061 aluminum coupon (serial number XA-299T), autoclaved with ATR fuel to produce a boehmite film on the cladding surface, was obtained and analyzed. The surface had been coated with boehmite by placing the coupon in a high-temperature autoclave and exposing the hot aluminum to deionized water. The thickness of the coating is specified to range from 60 microinches (1.524 μm) to 300 microinches (7.62 μm) [3]. This coating is expected to be similar to that on the surface of the GTL booster fuel cladding.

Effect of Surface Roughness

As part of this study, results from the RELAP5-3D thermal hydraulic analysis code [4] were compared for five different values of fuel plate surface roughness (Table 1). It is demonstrated that surface roughness can significantly impact the coolant flow past the fuel plates. Frictional losses over the booster fuel assembly account for approximately 82% of the total pressure drop in the coolant loop.

An average boehmite thickness of 2 μm (79 microinches) was used for the RELAP5-3D calculations based upon the data in Ref. 2. As can be seen in Table 1, the order of magnitude of the roughness of the coolant channel surface has a large effect on the coolant flow rate and the corresponding fuel temperatures. Coolant velocity decreases and fuel temperature increases as the surface roughness increases. These calculations should be considered as illustrative only; they do not include the flow reduction effect of the snubber tube that will be present in the actual configuration.

RELAP5-3D calculates single-phase wall friction using the Darcy-Weisbach friction factor. For turbulent flow, the code

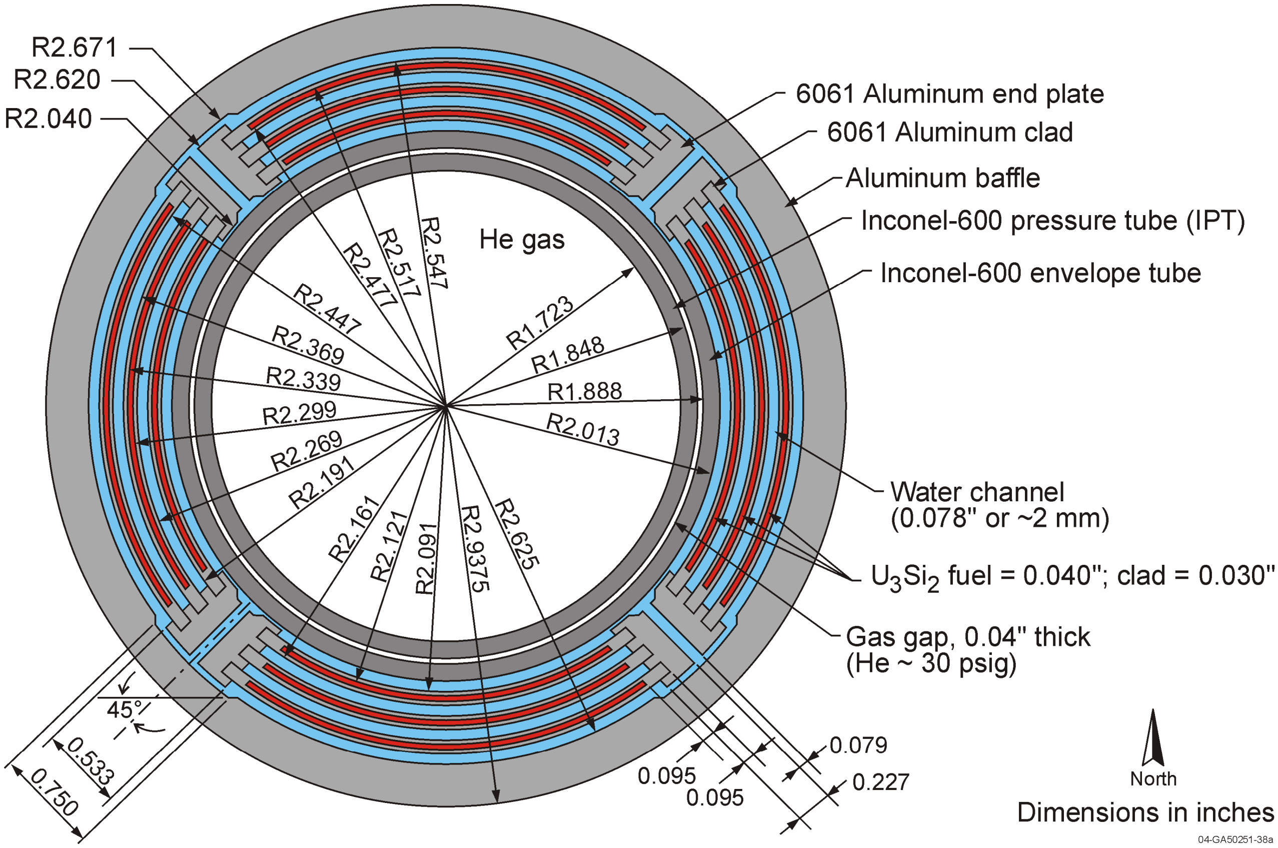

Fig. 1. Cross section of GTL booster fuel assembly (dimensions in inches).

Table 1. Results of sensitivity study.

	quasi-smooth [5]	ATR fuel [6]	drawn tubing [7]	commercial steel [7]	galvanized iron [7]
roughness	3.96×10^{-12} m (1.56×10^{-10} in)	1.31×10^{-6} m (52 microinch)	1.52×10^{-6} m (60 microinch)	4.57×10^{-5} m (1800 microinch)	1.50×10^{-4} m (6000 microinch)
max. coolant temp.	385 K (233 °F)	388 K (239 °F)	389 K (240 °F)	417 K (291 °F)	439 K (330 °F)
max. fuel centerline temp.	520 K (476 °F)	522 K (480 °F)	523 K (481 °F)	555 K (540 °F)	580 K (585 °F)
max. fuel surface temp.	424 K (304 °F)	427 K (310 °F)	428 K (311 °F)	462 K (373 °F)	488 K (419 °F)
avg. coolant velocity	14.2 m/s (46.6 ft/s)	13.4 m/s (44.0 ft/s)	13.3 m/s (43.6 ft/s)	9.3 m/s (30.5 ft/s)	7.3 m/s (24.0 ft/s)
avg. coolant flow rate	37.2 (l/s) 589 gpm	35.1 (l/s) 557 gpm	34.9 (l/s) 553 gpm	24.4 (l/s) 386 gpm	19.1 (l/s) 303 gpm

uses the Zigrang-Sylvester (1985) [8] approximation to the Colebrook-White (1939) [9] correlation to compute the friction factor [10]. The Zigrang-Sylvester approximation is accurate to within 0.5% of the Colebrook-White correlation [8]. However, to apply an appropriate friction factor for the thermal hydraulic calculations, a representative value for the roughness of the booster fuel surface is needed.

Experimental Method

Surface roughness measurements were made using a Wyko NT1100 Optical Profiler (Fig. 2) operating in vertical scanning interferometry (VSI) mode. The size of the sample coupon is approximately 7 cm × 8 cm. Measurements were taken over areas measuring 1.9 mm × 2.4 mm. The parameter used to characterize the roughness average, R_a, is the arithmetic mean of the absolute values of the surface departures from the mean plane per ANSI standard B46.1 [11]. The digital approximation for R_a is [12]

$$R_a = \frac{1}{MN}\sum_{j=1}^{M}\sum_{i=1}^{N}\left|Z_{ij}\right| .$$

Fig. 2. Wyko Model NT1100 Optical Profiler used to obtain surface roughness measurements.

Results and Discussion

Table 2 lists the results of the surface roughness measurements for 8 different areas on the front side of the coated coupon. Figure 3 illustrates the surface topography and provides roughness data for measurement area Top #1. The peaks and valleys are distributed randomly over the sample surface. The mean surface roughness, $\overline{R}_a$, of the boehmite layer on the front side of the coupon is 532.03 nm or 0.53 µm (21 microinches). Table 3 lists the results of surface measurements of the back side of the aluminum coupon taken at four different locations. The mean surface roughness, $\overline{R}_a$, of the back side of the coupon is 454.11 nm or 0.45 µm. For comparison, as-rolled aluminum sheet has a typical surface roughness (R_a) of 0.25 to 0.75 µm (10 to 30 microinches) [13].

Table 2. Summary of surface roughness measurements for the front side of coated coupon.

Sample	R_a (nm)
Top #1	541.1
Top #2	574.03
Top #3	509.56
Top #4	509.98
Top #5	537.49
Top #6	514.03
Top #7	529.05
Top #8	540.96
Mean	532.03

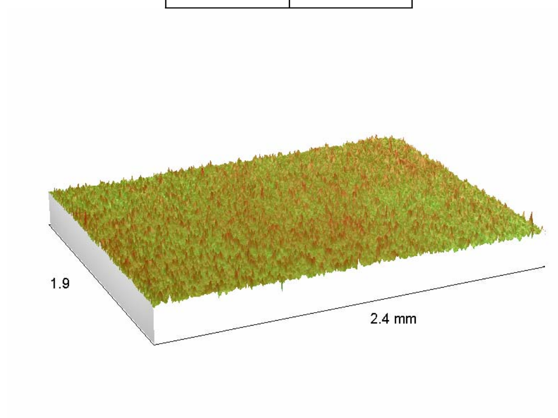

Fig. 3. Measured topography for Top #1 sample surface.

Table 3. Summary of surface roughness measurements for the back side of coated coupon.

Sample	R_a (nm)
Bottom #1	496.33
Bottom #2	434.55
Bottom #3	424.80
Bottom #4	460.77
Mean	454.11

The measured mean roughness of the front and back sides of the coated coupon are within 15%. It is possible that the back side of the coupon did not experience the identical environment as the front side or that the underlying roughness of the substrate was different as a result of the metal forming process, causing the coating roughness to be lower. To be conservative, the larger of the two mean roughness values should be used. Using a mean surface roughness of 0.53 µm for the plates, the conditions listed in Table 4 are obtained.

and adherent, and thus not likely to be considerably altered during reactor operation [2].

Table 4. RELAP5-3D calculations for $\overline{R}_a$ = 0.53 µm.

Max. coolant temp.	386 K (236 ˚F)
Max. fuel centerline temp.	520 K (476 ˚F)
Max. fuel surface temp.	425 K (305 ˚F)
Avg. coolant velocity	13.6 m/s (42.7 ft/s)
Avg. coolant flow rate	36.2 l/s (574 gpm)

Thermal hydraulic effects resulting from a ±15% deviation from a roughness value of 0.53 µm were estimated. Using $\overline{R}_a$ values of 0.61 µm (24 microinches) and 0.45 µm (18 microinches), RELAP5-3D calculations at any given location show a maximum difference in fuel centerline temperatures of 1 K and flow velocities of less than 1% from the case with a wall roughness of 0.53 µm. The booster fuel region is modeled using 4 axial segments and four radial quadrants to account for an asymmetric heat load, which causes the coolant flow velocity to be slightly different in each region. As a point of comparison, calculated coolant velocities (using a wall roughness of 0.53 µm) show a maximum difference of 5.3% between the four coolant channels.

Figure 4 shows the effect of fuel plate roughness on maximum fuel centerline temperature, maximum coolant temperature, and coolant flow rate. The curves are fairly flat in the range of roughness expected for the GTL booster fuel plates. This indicates that as long as the surface finish of the flow test plates is in the 0.5 to 1.5 µm (20 to 59 microinch) range, achieving an exact value of the surface finish is not necessary. However, the curves in Figure 4 show that if the surface roughness is increased beyond that of drawn tubing, the fuel centerline and coolant temperatures increase and the coolant flow rate decreases sharply.

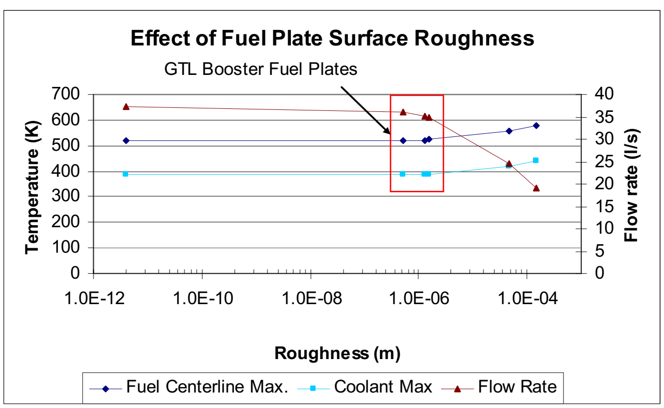

Fig. 4. RELAP5-3D results showing the effect of fuel plate surface roughness.

The surface roughness measurements were made on a coupon with a coated surface that had not been exposed to irradiation heat flux or long-term water flow. After reactor operation, the roughness of the boehmite surface may be different than it was initially. However, the corrosion data indicate that a crystalline boehmite layer formed using the recommended application process prior to reactor operation is very stable and adherent, and thus not likely to be considerably altered during reactor operation [2].

Conclusions and Recommendations

Surface profilometry analysis was performed to determine the surface roughness of a boehmite coating representative of that on ATR fuel cladding. It is recommended that the surface roughness of the boehmite layer on the fuel cladding be replicated for the GTL flow testing. Since the fabrication process for the flow test plates is different than that of the actual fuel plates (i.e., machining vs. rolling), the surface finish must be specified on the fabrication drawings for the flow test plates. While it is very important to know the order of magnitude of the surface roughness, the value does not need to be matched exactly. The RELAP5-3D results indicate that ±15% deviation from a surface finish of 0.53 µm would have a minimal effect on coolant temperature, coolant flow rate, and fuel temperature. Maintaining a reasonable dimensional tolerance for the surface finish on both sides of the 12 flow test plates would ensure relative uniformity in the flow among the four coolant channels.

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