LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

LIGO-E2500134-v1 *LIGO* May 27, 2025

Report: UF Ring Heater (RH) Reliability Testing at 40m

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0.0 Abstract:

Throughout February and March 2025, in the 40m Clean and Bake Lab in our Vacuum Bake Oven D (VBOD), additional experimentation was conducted on the University of Florida Ring Heater (UF RH) design. The RH is coated in fire-sprayed alumina, which has about ¼ the thermal expansion coefficient of the base material, aluminum. This discrepancy poses the potential for flaking off the alumina material as the RH deforms during thermal load cycles. Vacuum compatibility of the RH was tested through two phases of multiple heat cycle trials: a manual phase (1) and a programmed phase (2). Three trials were conducted in each phase, focusing on results from resistance/temperature data, RGA scans, and physical inspections. Ultimately, after six trials and two physical inspections, no evidence of any particulates was picked up, and no evidence of flaking or damage to the RH surface was observed.

1.0 Introduction:

The ring heater is made up of a two-part inner ring and a six-part outer ring that sandwich a NiCr heater wire. One half of the heater (one inner ring and three outer pieces), installed in a shield, was studied. The bulk material is Aluminum (thermal expansion coefficient=25.2μm/m-°C), and the outer coating is a fire-sprayed Alumina (thermal expansion coefficient=6.4μm/m-°C). The heating conditions this alumina can withstand without flaking off or outgassing material were tested using VBO D in the 40m clean & bake lab.

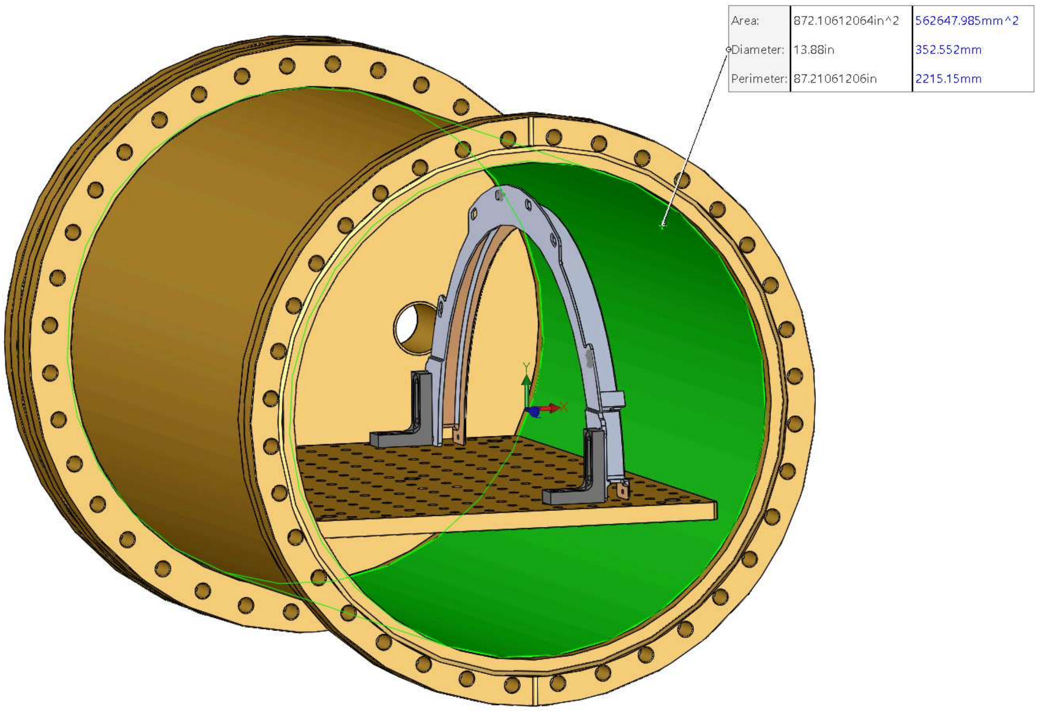

Figure 1.1-1 SolidWorks model of clearance of the RH assembly and breadboard with VBOD's chamber walls

2.0 Assembly and Integration:

2.1 Building the RH

The first thing completed was replacing the old NiCr wire. The new wire was measured (Figure 2.1-1) and crimped in a closed loop through the PEEK endpiece (Figure 2.1-2). The NiCr was threaded through the other endpiece and crimped to a copper conducting wire (Figure 2.1-3), which was installed into selected pins of the feedthrough connector (Figure 2.1-4). Assembly was verified in an open-air room before disassembling the breadboard and RH in preparation for cleaning (Figure 2.1-5).

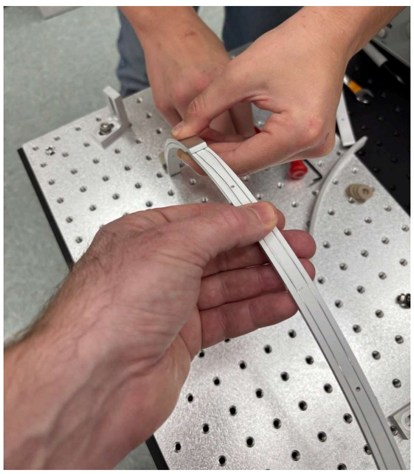

Figure 2.1-1 NiCr length measurement

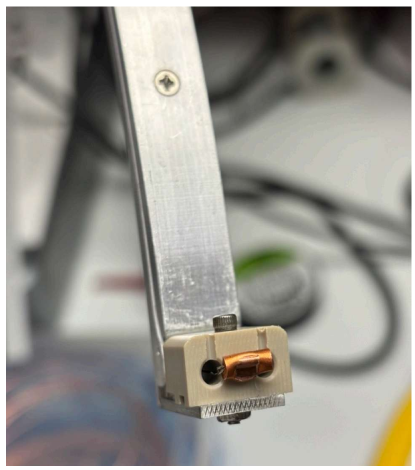

Figure 2.1-2 Crimping of NiCr outside the PEEK endpiece to close the current loop

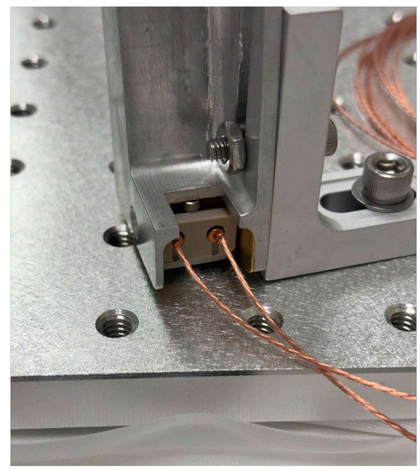

Figure 2.1-3 Crimping of NiCr to Copper wire through the PEEK endpiece

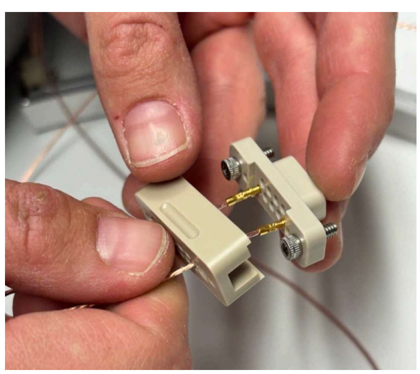

Figure 2.1-4 Feedthrough connector wiring

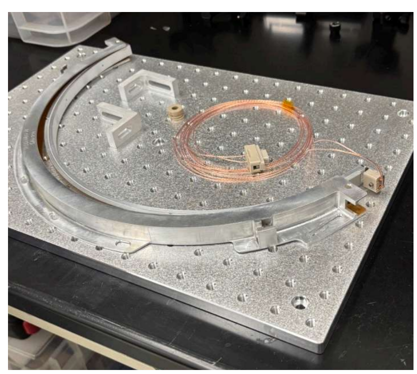

Figure 2.1-5 Dissassembled RH and breadboard/mounts

2.2 Precision Cleaning

The NiCr wire, copper wire, and PEEK connectors were solvent cleaned, sonicated for 10 minutes in methanol, and air dried as per section 13.28 of LIGO-E960022-v26 C&B Procedure. The aluminum ring structure and shield were cleaned with solvent, acid, and detergent as per Table 3 of the same procedure. Once qualified, the RH assembly was put together and mounted onto the breadboard with L brackets in the clean room to be installed in the vacuum chamber (Figure 2.2-1).

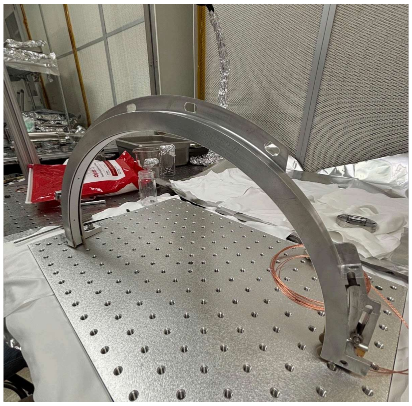

Figure 2.2-1 Assembled and mounted RH on the C&B clean room flow bench

2.3 Integration into Vacuum Chamber (VBOD)

The size and layout of the RH and breadboard were modelled in SolidWorks to ensure that the RH does not contact the chamber walls (Figure 1.1-1). Once the breadboard with the RH assembly was put into VBOD (Figure 2.3-1), the feedthrough connector was fed through the back of the chamber through a reducing Tee. Plenty length of copper wire was added for margin, and the unused wire was coiled and clamped to the breadboard with foil and screws.

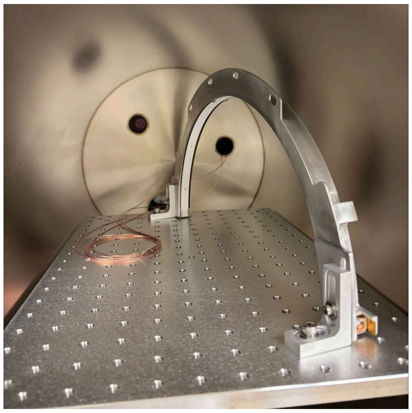

Figure 2.3-1 RH in VBOD

The heater needed a current run-through while under vacuum, so a feedthrough port was installed on the Tee with a pressure gauge on the rear chamber door (Figures 2.3-2 through 2.3-4).

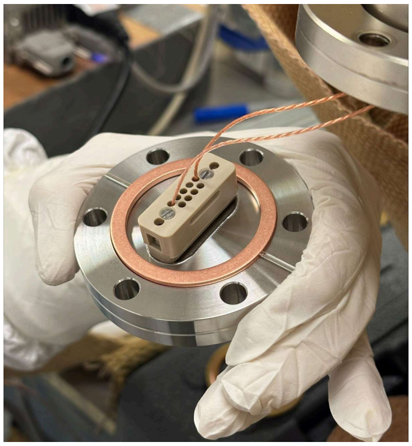

Figure 2.3-2 In-vac feedthrough port

Figure 2.3-3 Underside view of feedthrough exposed to room air

Figure 2.3-5 Tee-assembly of feedthrough and pressure gauge

To verify the functionality of the feedthrough and connector, a multimeter was connected to pins 1 and 5, and the resistance was measured to be 16.3Ω (Figure 2.3-6)

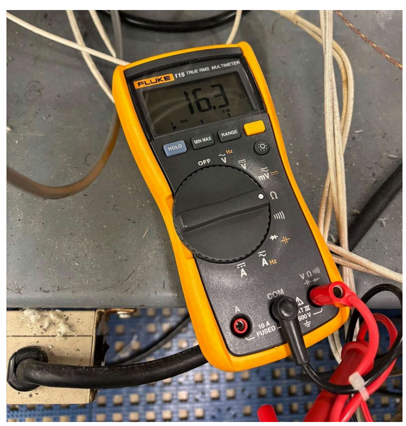

Figure 2.3-6 RH resistance level

3.0 Testing Procedure

Fluctuating current, and thus temperature, ON and OFF allowed for rapid deformation of the aluminum part and its outer alumina coating. Due to the expansion difference with aluminum, alumina flaking was expected to occur here. The current driver (Agilent E3644A DC power supply) was connected to the feedthrough port and set to a maximum power of around 10W. As shown in Figure 3.0-1, the current driver was set to 13V, and the resulting current is displayed. From the equation R=V/I, resistance can be determined as the current fluctuates at the set voltage. Initial conditions were analyzed to find the resistance at room temperature (R_o) and the temperature coefficient of the NiCr (dR/dT). Next, to understand the temperature increase of the RH, the equation $R=R_0(1+dR/dT*\Delta T)$ can be rearranged to $\Delta T=(R/R_0-1)/(dR/dT)$. Using this power control and equations, two phases of testing trials were conducted: a manual phase and a programmed phase.

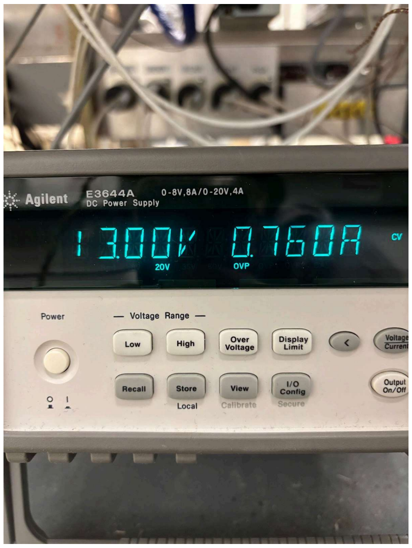

Figure 3.0-1 Agilent E3644A DC power supply at a set Voltage and resulting Current

3.1 Phase 1: Manual Cycling

For the first phase of trials, manual control involved turning the power ON and OFF through the driver's front interface. Applied voltage and current were then recorded at regular time intervals.

- Trial 1.1 ran with 13V for 3½ hours straight before being turned OFF. This was to understand the current, thus resistance, and therefore temperature, change over time with the heater element ON constantly.
- Trial 1.2 ran at 13V for approx. 5 hours with the driver getting turned ON and OFF in 30-minute increments. This was done to create rapid deformation of the aluminum/alumina against each other under heating and ‘cooling’ conditions.

- Trial 1.3 ran under the same conditions as 1.2, but for half of the total length of time. This allowed for confirmation of patterns with 30-minute cycling periods before moving away from manual cycling

To conclude phase 1, VBOD was vented, and the ring heater was visually inspected for any changes. The breadboard surface was also inspected and wiped with an IPA wipe to pick up any particulate that had fallen off the RH.

3.2 Phase 2: Computer Control

For the second phase of trials, a Python program was written by Aidan Brooks to interface with the driver. This allowed the setup of automatic cycling for two weeks. Current and voltage data were recorded every minute, and approximately 120 cycles were achieved over the period. Note: the “OFF” state of these trials is technically powered at 1V to keep an active current reading with low enough power input such that the RH is close to an OFF state.

- Trial 2.1 ran for one week at 13V with 1-hour increments between ON and OFF states to simulate long-term rapid temperature deformation
- Trial 2.2 also ran for a week at 13V, but with 2-hour increments between ON and OFF states to allow for more sustained temperature states over long-term use
- Trial 2.3 was a final two cycles with 4-hour increments between ON and OFF states for a final intensive heating and cooling period for the RH

To conclude phase 2, VBOD was vented, and the ring heater was visually inspected for any changes. The breadboard surface was also inspected and wiped with an IPA wipe to pick up any particulate that had fallen off the RH.

4.0 Results

4.1 Phase 1

The most notable occurrence in phase 1 trials was the initial jump in resistance. This occurred in the first heating trial (Figure 4.1-1), where the resistance initially started at 16.332 Ω and then rose logarithmically to an eventual 17.356 Ω. For the remainder of the trials (Figures 4.1-2 and 4.1-3), the resistance never dropped below 17.083 Ω when in the OFF state. It also didn’t increase past 17.356Ω at any point for the remainder of phase 1.

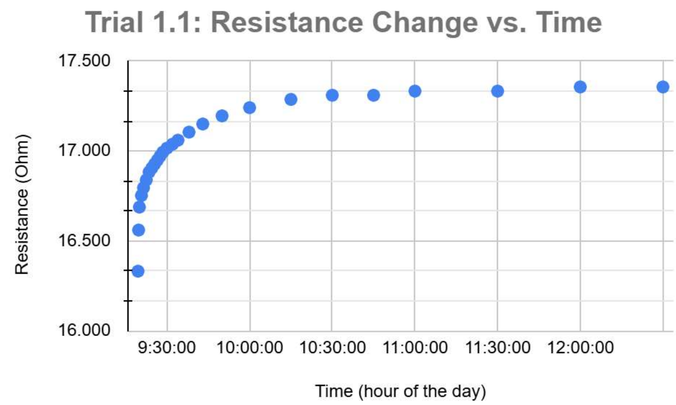

Figure 4.1-1 Trial 1.1: Resistance change over 3½ hours of constant 13V

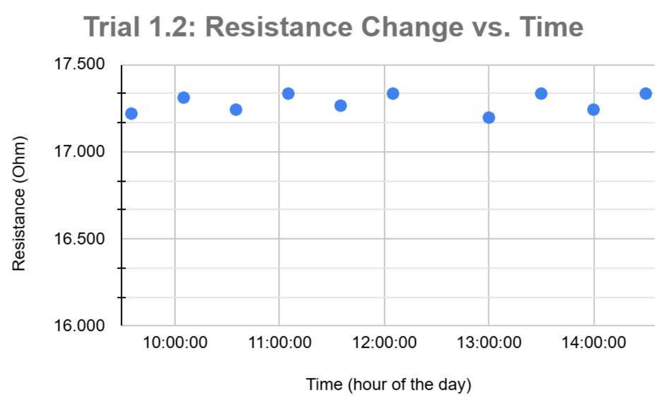

Figure 4.1-2 Trial 1.2: Resistance change over 5 hours of fluctuating 13V ON/OFF states (30 min increments)

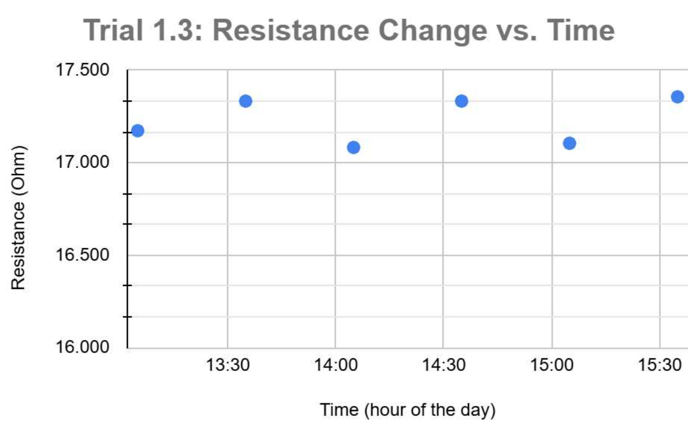

Figure 4.1-3 Trial 1.3: Resistance change 2½ hours of fluctuating 13V ON/OFF states (30 min increments)

RGAs taken during trial 1.2 show an increase in outgassing in the ON state. As seen in Figure 4.1-4, the water peak was about 4.5×10^{-12} before jumping to 2.25×10^{-11} after the first round of ON (Figure 4.1-5). When returned to the OFF state, Figure 4.1-6 shows the peak dropping back into the 10^{-12} range, and lastly, Figure 4.1-7 shows the end of the final ON state for the day with water peaking at 2.08×10^{-11}.

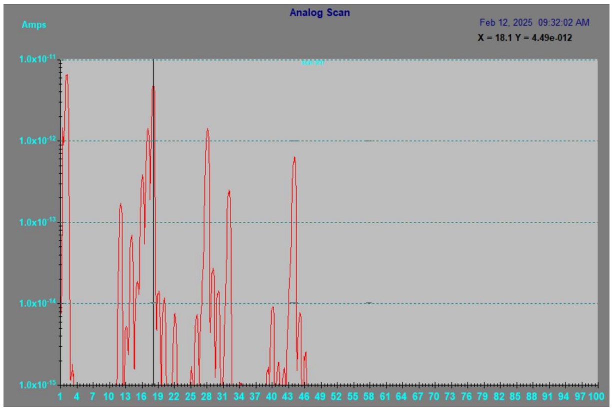

Figure 4.1-4 RGA scan in trial 1.2 Initial OFF state

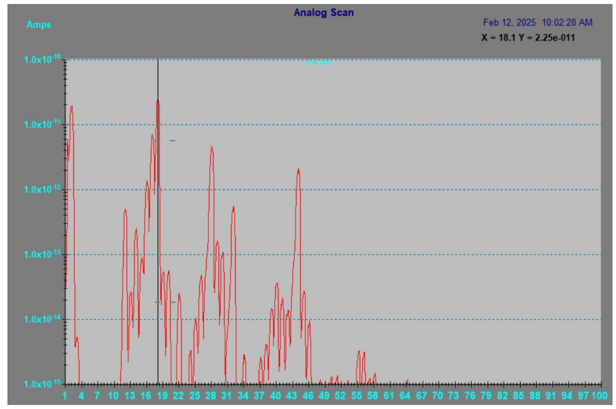

Figure 4.1-5 RGA scan in trial 1.2 First ON state

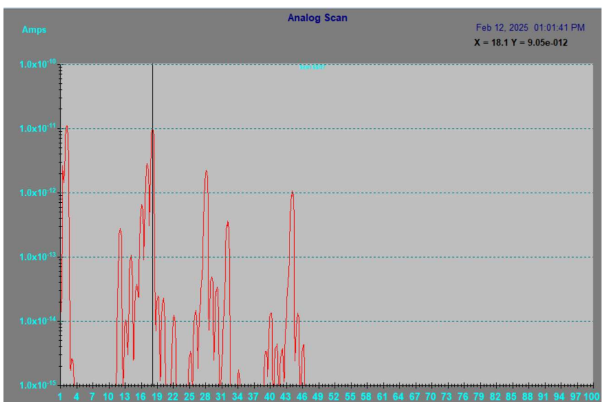

Figure 4.1-6 RGA scan in trial 1.2 Third OFF state

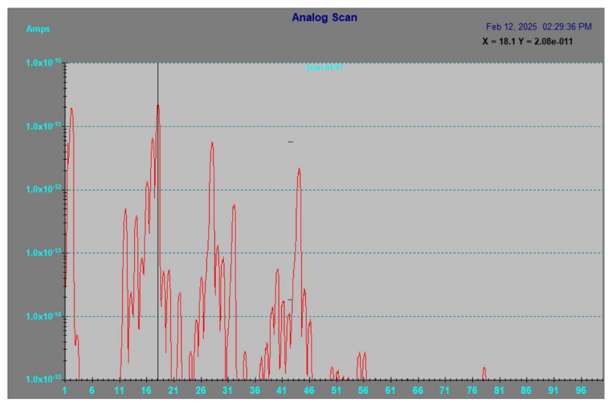

Figure 4.1-7 RGA scan in trial 1.2 Last ON state

4.2 Phase 2

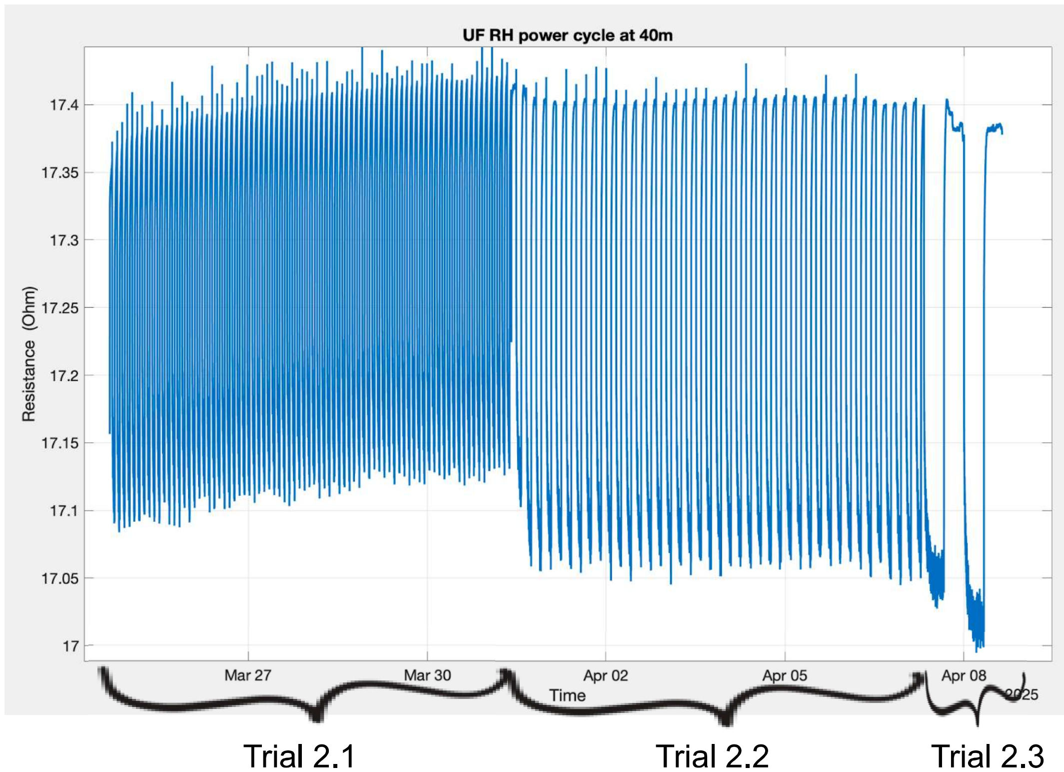

Figure 4.2-1 Trials 2.1-2.3: Resistance change over 2 weeks of fluctuating 13V ON/OFF states (1 hr, 2 hr, and 4 hr increments)

5.0 Conclusion

After three manual trials and three programmed trials, as well as two physical inspections, no evidence of alumina flaking was detected. There was, however, a notable change in the NiCr wire properties, as seen in the change of resistance. Initial measurements found a 16.3 Ω resistance level, but after the first round of heating, it was permanently altered. Phase 1 trials found a maximum resistance of 17.356 Ω, which was the highest witnessed in manual trials, and regardless of power input, it never dropped below 17.083 Ω, certainly not back to its original state. This permanent alteration in the properties of NiCr wire suggests an inelastic change in the crystalline structure of NiCr due to prolonged temperatures. As for the resistance witnessed in manual trials, it had a sustained rise for the first week before plateauing during the more rapid heating in the second week. It appears that the maximum resistance of NiCr can be altered to a certain point before material properties and temperature coefficients reach equilibrium. As for manual phase RGA scans, each ON state brought the water peak into the 2.0-2.5 $x10^{-11}$ range of values. It would fall back down in the OFF state, into the $9x10^{-12}$-$1x10^{-11}$ ranges, but not back to the long-term cold state of $4.5x10^{-12}$. The surface properties and enclosed spaces of the RH assembly are complex and textured, thus capable of holding onto a lot of water. The RH assembly was not vacuum-baked and qualified before the experiment, and it is believed that a lot of the outgassing would occur during such a bakeout, but unacceptable outgassing does not appear to be coming from the alumina coating specifically.

In conclusion, the fire-sprayed alumina coating is a suitable material for a ring heater application under vacuum. To further confirm these results, additional testing is needed with a known witness sample added to the assembly breadboard. This would provide data unattainable by the human eye and more specific than RGA results.