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Revision 0

Eddy Current Inspection, Sodium Bonder, and Wire Wrap Equipment Operational Testing Report

David Pace

July 2017

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CONTENTS

FIGURES

TABLES

Eddy Current Inspection, Sodium Bonder, and Wire Wrap Equipment Operational Testing Report

1. INTRODUCTION

The fuel fabrication process for the TerraPower project includes sodium bonding of fuel pins, eddy current inspection of the sodium bond, and wire wrapping of the pins with a helically wound spacing wire. TerraPower contracted with a third party to fabricate a sodium bonding oven and a combined wire wrap and eddy current inspection machine that were supplied to the INL for project use.

The sodium bonding oven is shown in Figure 1. The oven consists of a vertically oriented commercial clamshell oven. Inside the oven is a fuel pin hanger assembly that is currently configured to hold up to six fuel pins at once.

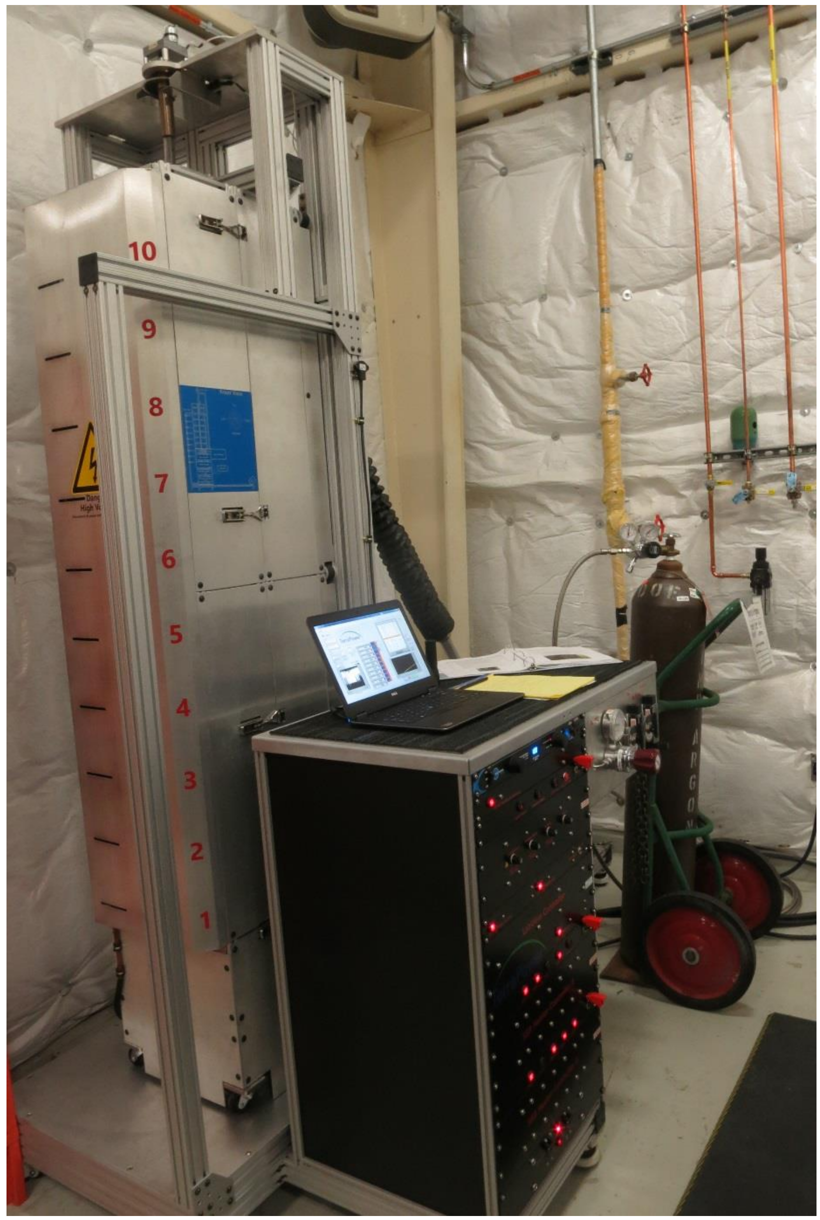


Figure 1. Sodium bonding oven.

The wire wrap and eddy current inspection machine is shown in Figure 2. The machine has an enclosed guarded section that holds the pin vertically and can move a carriage vertically up around the pin and also rotate the pin. For eddy current inspection, the pin is secured, and an eddy current probe surrounding the pin is scanned up the full length of the pin for indication of a solidified bubble (defect) within the sodium bonded area. For wire wrapping, the wire is first attached to one end of the pin on the folding workbench area, then transferred into the enclosed section for wrapping. The machine uses the same vertical scanning axis to move a wire guide up the pin as the pin is rotated, wrapping the wire at a preprogrammed pitch. Once wrapped, the wire is clamped in place and the pin is carefully removed and transferred back to the folding workbench area. Then the wrapped end of the wire is attached to the pin.

Surrogate fuel pins containing unmelted/non-bonded sodium and surrogate fuel slugs were delivered with the equipment for testing. One of these surrogate pins was taken through the full process to verify the full functionality of the equipment. An unbonded surrogate pin was first eddy current inspected in the wire wrap and eddy current inspection machine, along with a calibration standard, to provide an example of unbonded eddy current results. The surrogate pin was then placed in the sodium bonding oven and run through the bonding sequence provided with the equipment. After the oven had cooled, the pin was removed and eddy current inspected again to provide an example of bonded eddy current results. Following successful eddy current verification, a pin was wire wrapped, completing the verification of this phase of the fuel fabrication process.

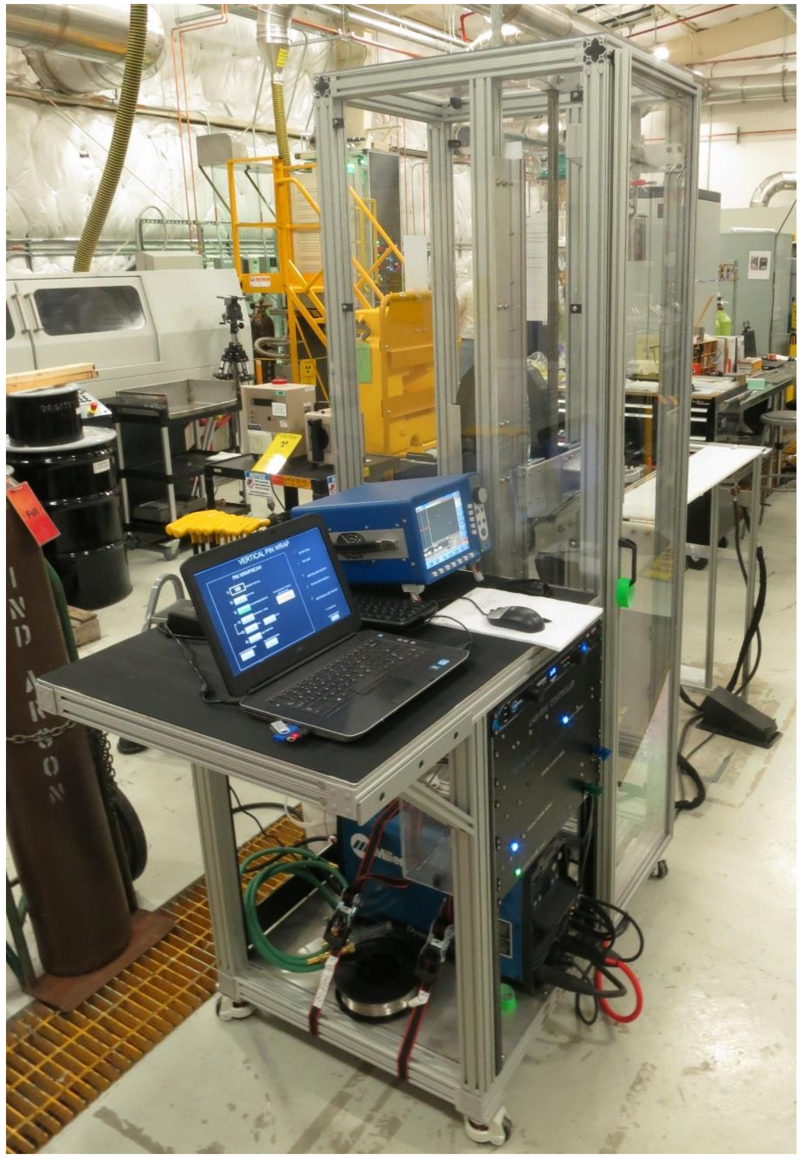


Figure 2. Wire wrap and eddy current inspection machine.

2. EQUIPMENT OPERATION

2.1 Unbonded Eddy Current Inspection

To provide the required data for setting flaw threshold levels, a calibration standard was first scanned with the eddy current inspection machine. Figure 3 shows the calibration standard installed in the machine being scanned by the eddy current probe. After the calibration standard scan was complete and the data verified, an unbonded surrogate fuel pin, ID# FAO-1-03, was mounted in the machine. Figure 4 shows a close-up of the pin support at the top of the fuel pin by the nock-shaped upper end cap. Figure 5 shows a close-up of the support at the bottom of the fuel pin, utilizing the pointed lower end cap. During inspection, the vertical axis of the machine simply moves the eddy current probe up the length of the fuel pin as the eddy current data is collected on the Zetec MIZ-28 hardware. Figure 6 shows the surrogate fuel pin inspection in progress. Once the scan was complete, the data was reviewed on the MIZ-28 to ensure quality data was collected, and the data was transferred to a laptop for complete analysis using Zetec's Velocity analysis package.

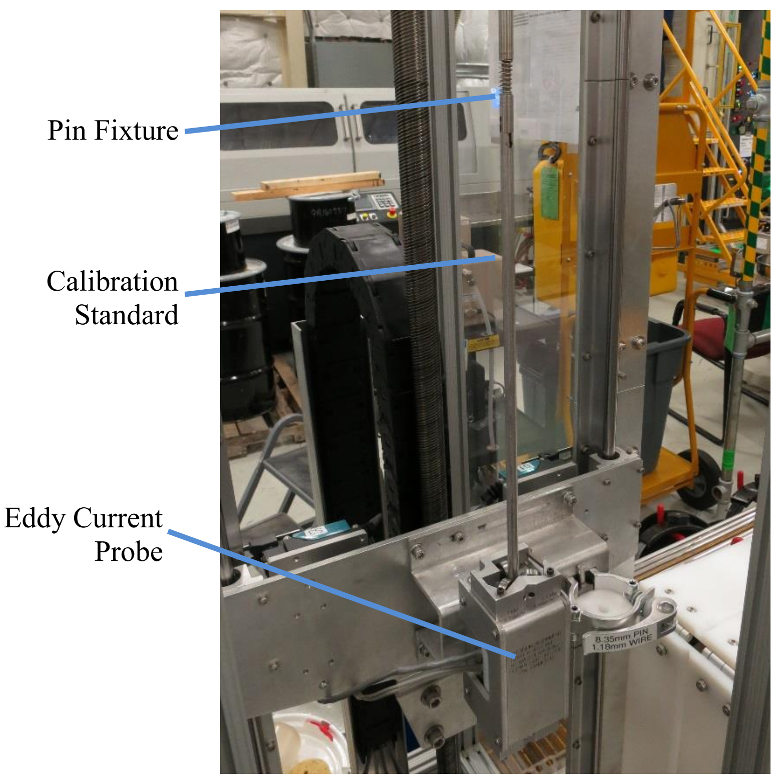


Figure 3. Calibration standard scan.

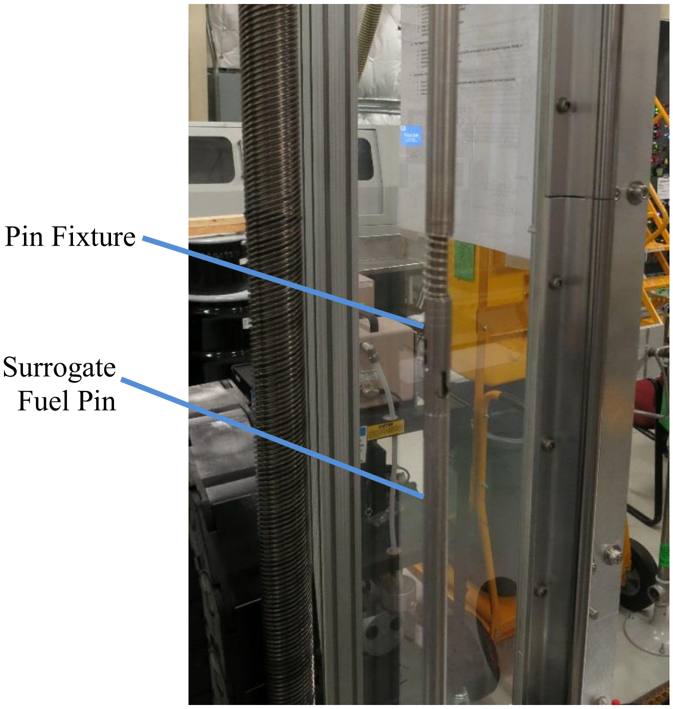


Figure 4. Top support of pin.

Figure 5. Bottom support of pin.

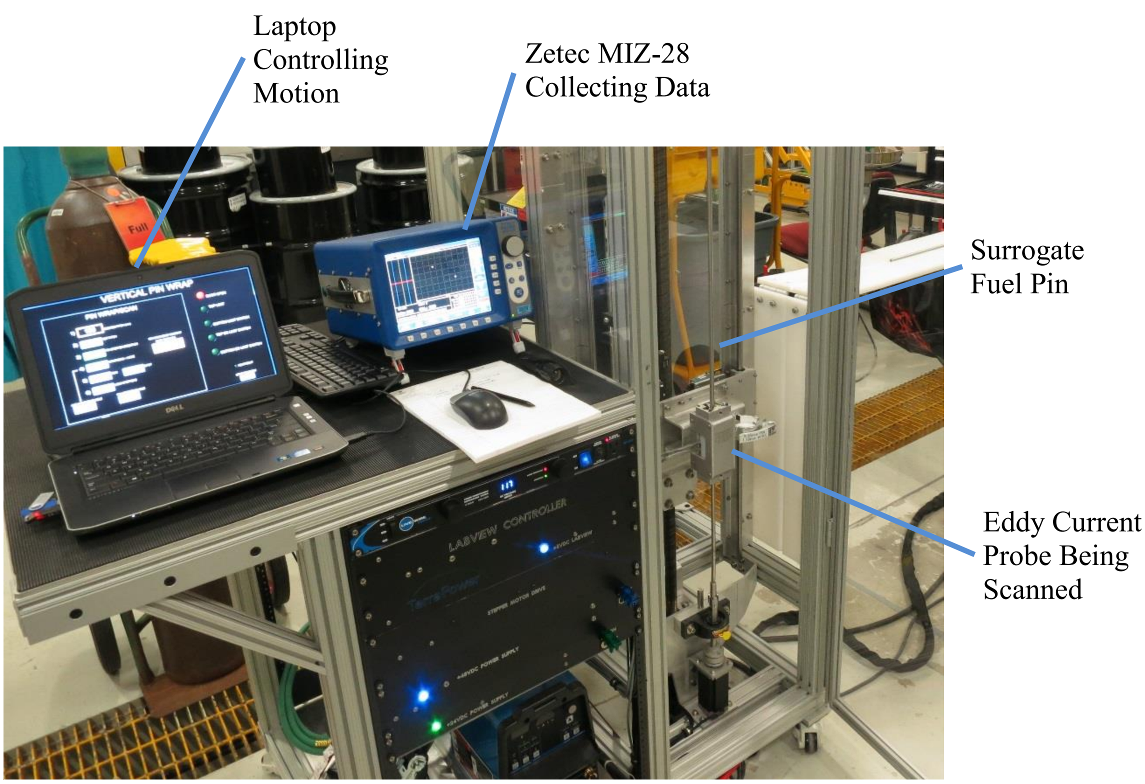


Figure 6. Surrogate pin being inspected.

Figure 7 shows the configuration screen from the MIZ-28, which drives the probes and collects the data. This configuration was used for all the scans. The machine was set up for multiplexed operation with a digital gain of two. The data was sampled at 400 samples per second. Frequencies of 100, 75, 50, and 35 kHz were used, all with a drive voltage of 20.0 volts. The channels were analyzed both differentially and absolutely.

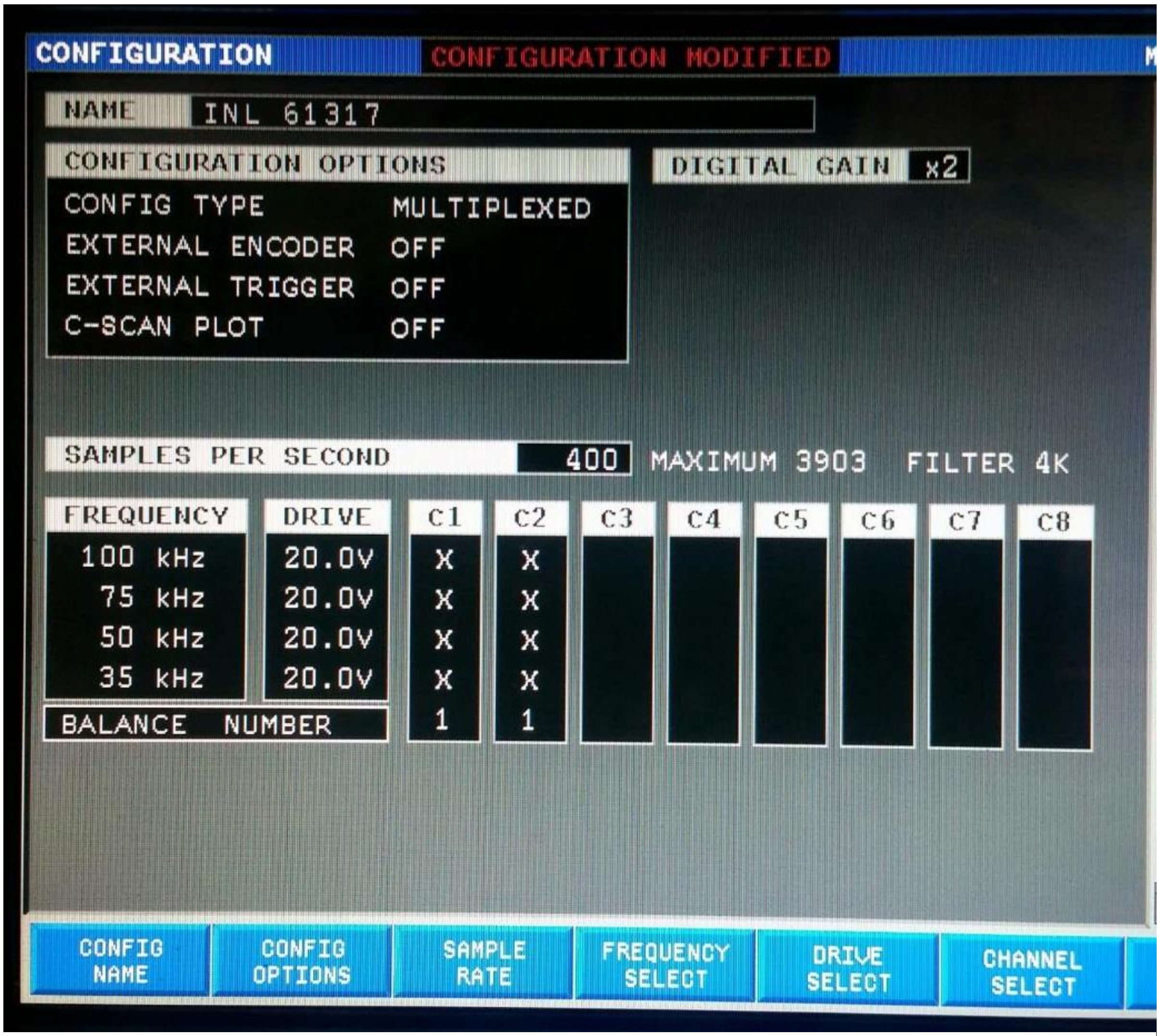


Figure 7. MIZ-28 configuration screen.

The standard consists of an inner core, machined with various features to replicate bonding voids. The core is then press fit into a cladding tube. Calibration standards are used to scale the eddy current signal so a signal voltage can be related to a flaw size. A calibration curve was created utilizing the smallest four circular features in the standard, having diameters of 0.031, 0.063, 0.094, and 0.125 inches. The following table shows the data for the four flaws utilized. Figure 8 shows the analysis results for the calibration standard scan. The far left window shows the signal generated from the scan. Each S-shaped feature is one of the flaws within the standard. The horizontal red cursor in the graph is centered on the second S-shaped feature, which is the second flaw in the standard, with a size of 0.063 inches. This flaw size was set as the rejection threshold so any flaws

0.063 or larger would be rejected as too large. The signal voltage for the 100 kHz and 50 kHz signals are shown in the upper half of the four quadrant graphs in Figure 8. The 9.00 Vpp and 48% utilized for the curve are from the top left 100 kHz window. Utilizing this calibration curve, any scan signal greater than 9.00 Vpp would be considered a rejectable flaw greater than 0.063 inches in size.

Flaw Size [in]	Signal [Volts peak to peak]	Percentage of scale [%]
0.031	1.64	26%
0.063	9.00	48%
0.094	23.30	76%
0.125	46.60	100%

Table 1. MIZ-28 configuration data.

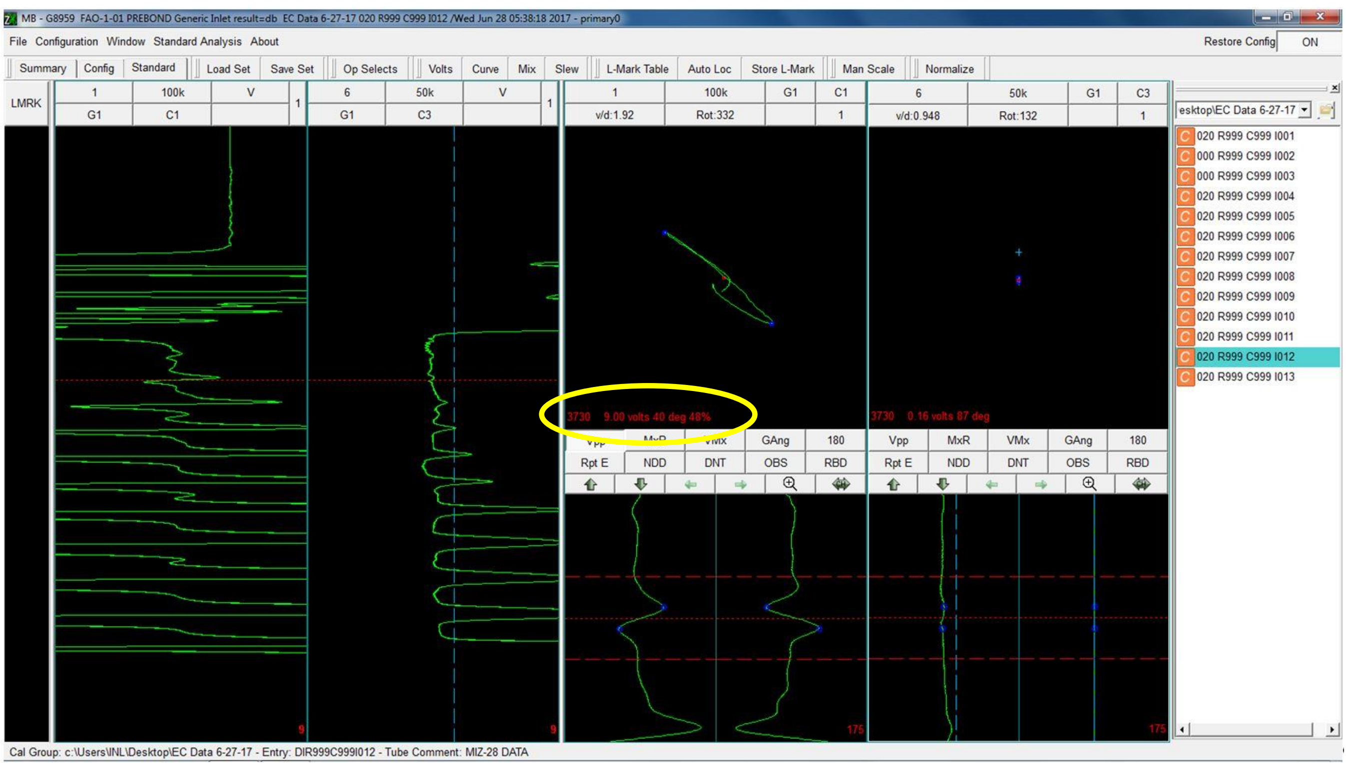


Figure 8. Calibration standard, 0.063 flaw data.

2.2 Sodium Bonding

After the baseline eddy current inspection of the surrogate pin was complete, it was transferred to the sodium bonding oven to undergo the bonding sequence. Figure 9 shows the surrogate test pin installed in the sodium bonder. Figures 10 and 11 show close-up views of how the pin is secured in the fuel pin hanger. Note that only one pin was installed for this test, although the machine has the capacity to do six pins at one time. The pins are suspended from the cross-hole in the nock-shaped end cap. The pin is secured by the rotating clamps at all four levels. The clamps are secured by wrapping wire thorough securing holes, which keeps the two halves of the clamps from rotating and opening. The securing wire wraps can be seen in the close-up figures showing the top and bottom. Also visible in the figures are the control thermocouples protruding through the insulation. There are two thermocouples, one in the fixed back and one in the door, for each of the 10 heating levels.

Figure 9. Surrogate pin loaded in sodium bonding oven.

Figure 10. Top support of surrogate pin.

Figure 11. Bottom support of surrogate pin.

Figure 12. Sodium bonder in operation.

Figure 12 shows the sodium bonder in the tilted position during the bonding operation. The sequence of the bonding operation is controlled by a laptop computer that controls the 10 temperature zones, oven tilt, pin hanger rotation, and impact. A sequence was developed by TerraPower during the development of the equipment and proven to successfully bond the pins without solidification voids. The delivered sequence was used to bond the surrogate test pin. A summary of the sequence is provided below, and a complete listing of the sequence is provided in Appendix A.

During the bonding process, the pin is secured by the upper end cap. In this position, the sodium slug with in the pin is on the bottom, followed by four copper tungsten slugs to simulate the fuel slugs. On top of that is a longer stainless steel slug to simulate the axial blanket in the fuel design. The cladding and end caps on the surrogate rods used in this operational testing are 304SS. During the bonding process, the sodium is melted to its liquid form and the copper tungsten slugs and the stainless axial blanket sink down into the liquid sodium, which forces it to flow up, around, and over the entire slug stack-up. The process cools the pin from the bottom up, allowing solidification to move vertically up and keeping any solidification voids from forming.

Sodium Bonding Sequence Used for This Operational Testing:

- Initiate oven warm-up—Simultaneously ramp temperature zones 1–10 from ambient to 550°C over 15 minutes
- Begin rotation
- Tilt furnace to 30 degrees
- Soak at temperature for 10 minutes
- Repeat impact sequence 90 times (5 seconds impact, 15 seconds soak)
- Return furnace to vertical
- Stop rotation

- Begin initial cool-down to 150°C, just above solidification temperature for sodium
  - Simultaneously ramp temperature zones 10–2 from 550°C to 150°C over 6 minutes
  - Ramp temperature zone 1 (bottom) from 550°C to 150°C over 2 hours
- Begin final cool-down to ambient cooling from the bottom up to eliminate solidification voids caused by liquid trapped between solidified material
  - Sequentially ramp temperature zone 1, bottom, to zone 10, top, from 150°C to 0°C over 40 minutes for each zone.

Total run time 9.7 hr

Figure 13 shows the temperature profiles recorded during the bonding sequence run. While the total run time was 9.7 hr, it does take an additional 7 hr to cool down to ambient after the last zone is given its final cooldown command. One of the critical parts of the sequence is the final cooling through the solidification temperature from the bottom of the oven to the top. Each lower zone must solidify before the zone above it to ensure no liquid pockets are captured between solidified areas. The sequential cooling used maintains approximately a 30°C difference between adjacent zones. As a lower zone crosses the solidification temperature, the zone above it is still 30°C above the solidification temperature, still safely liquid.

Figure 14 shows the first 10 impact cycles. While executing the sequence, the rotation motor was observed to slow down between impact cycles. When the next impact cycle started, the rotation freed back up and the speed increased. After the impact cycle, it began to slow down again until the next cycle. The assumption is that the rotation axis is binding to some degree between impact cycles and that the binding is broken free by the impact. In some cases the speed drops by a factor of three. This may or may not have an effect on the bonding success. If the binding gets worse over time, it may indeed affect the success of the bonding cycle. This issue should be further investigated and tracked in the future.

After experiencing the very long run time for the sequence discussions were held with TerraPower and the third party to see how optimized the process was. They shared issues identified with early solidification near the clamping rings during quick cooling. The clamping rings provide greater thermal mass and cool slower, slowing pockets of liquid sodium to be trapped and creating solidification voids when they finally did solidify and shrink. To solve the issues, they created the current sequence with the conservatively long cooling times. To increase productivity, the initial cool-down time to 150°C could be shortened, cooling as fast as the oven is capable. The 40-minute ramp time for each zone during the sequential cooling might also be shortened some.

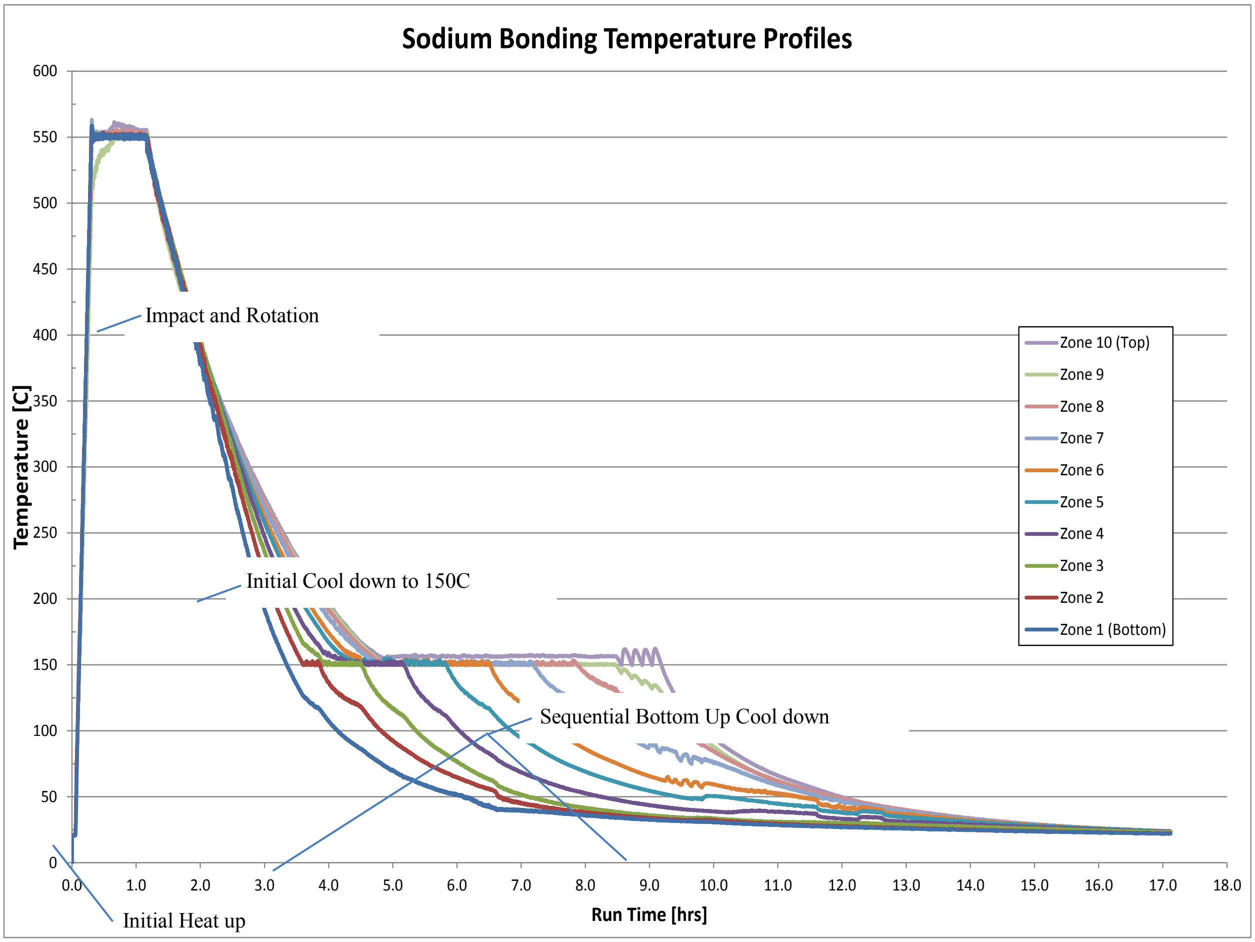


Figure 13. Sodium bonder run temperature profiles.

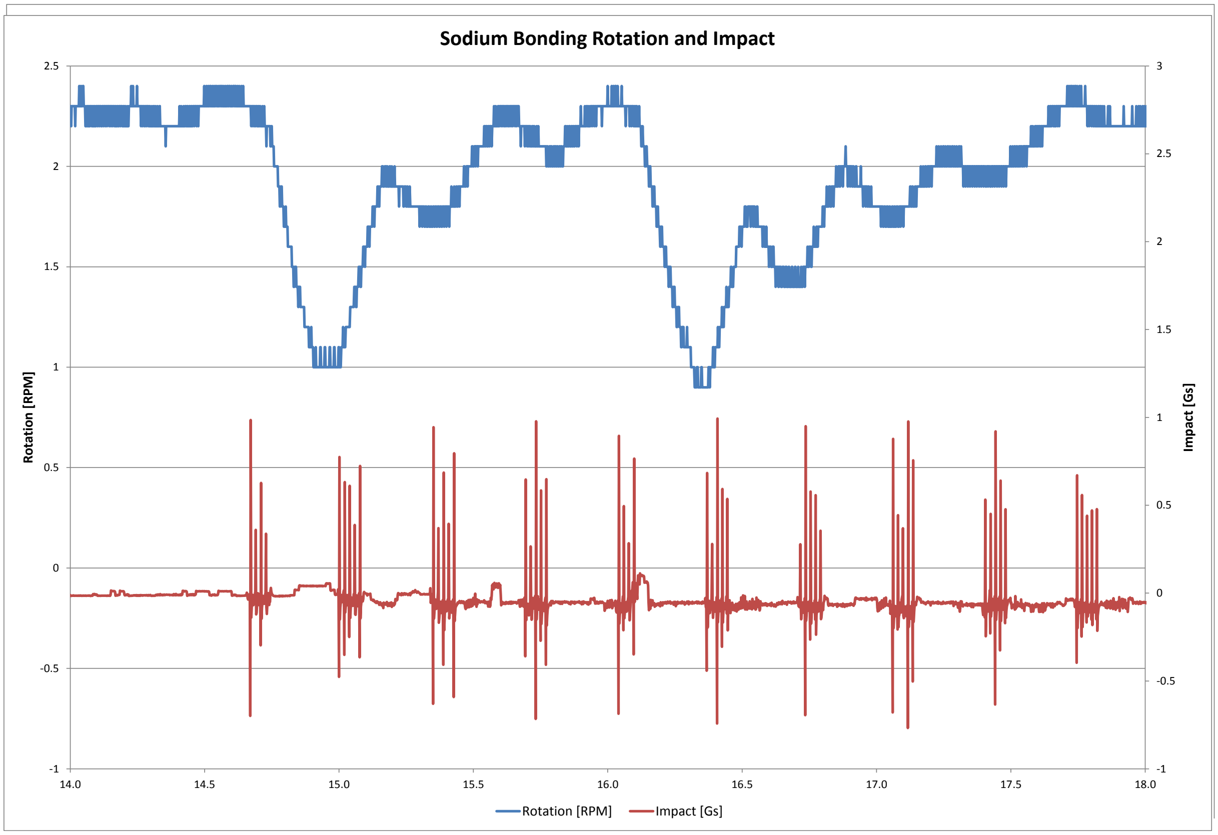
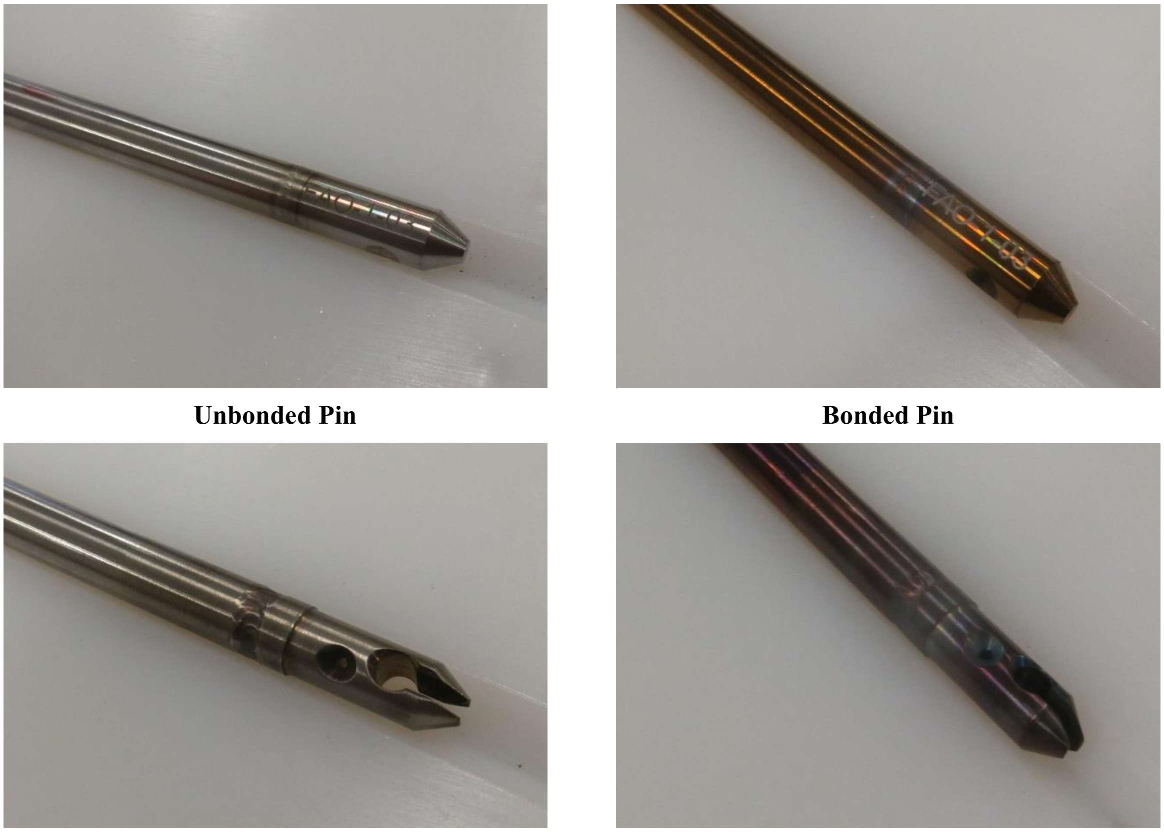


Figure 14. Sodium bonder run rotation and impact profiles—zoomed.

After the bonding sequence was complete, the surrogate test rod was removed from the bonding oven. Figure 15 compares both ends of the surrogate rod before and after the bonding process. Note the gold color produced by the heating cycle in the argon atmosphere. Figure 16 shows the full length of the rod after the bonding process.



Unbonded Pin **Bonded Pin**

Figure 15. Before and after comparison of the surrogate test pin.

Figure 16. Bonded surrogate test pin.

2.3 Bonded Eddy Current Inspection

After being processed through the sodium bonding oven the surrogate pin was scanned again with the wire wrap and eddy current inspection machine. The calibration standard was scanned again first for setting the flaw thresholds. After the calibration data was verified, the surrogate fuel pin was mounted in the machine and scanned. The post bond scan in Figure 17 provides an example of eddy current data for a bonded pin.

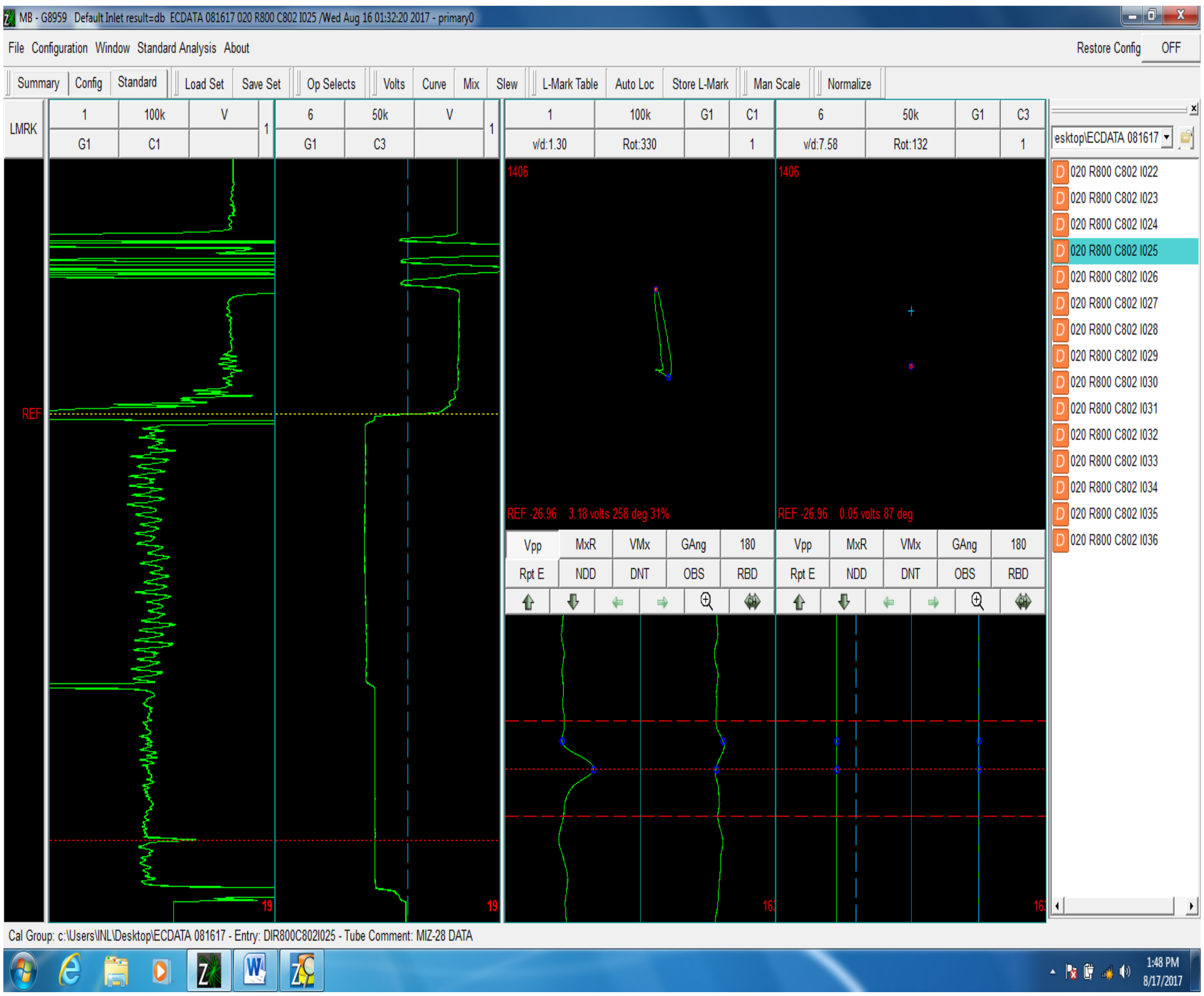


Figure 17. Bonded pin eddy current scan results.

Figure 18 shows the scan of the unbonded pin. The signal from the scan shows large signals levels from these unbonded area.

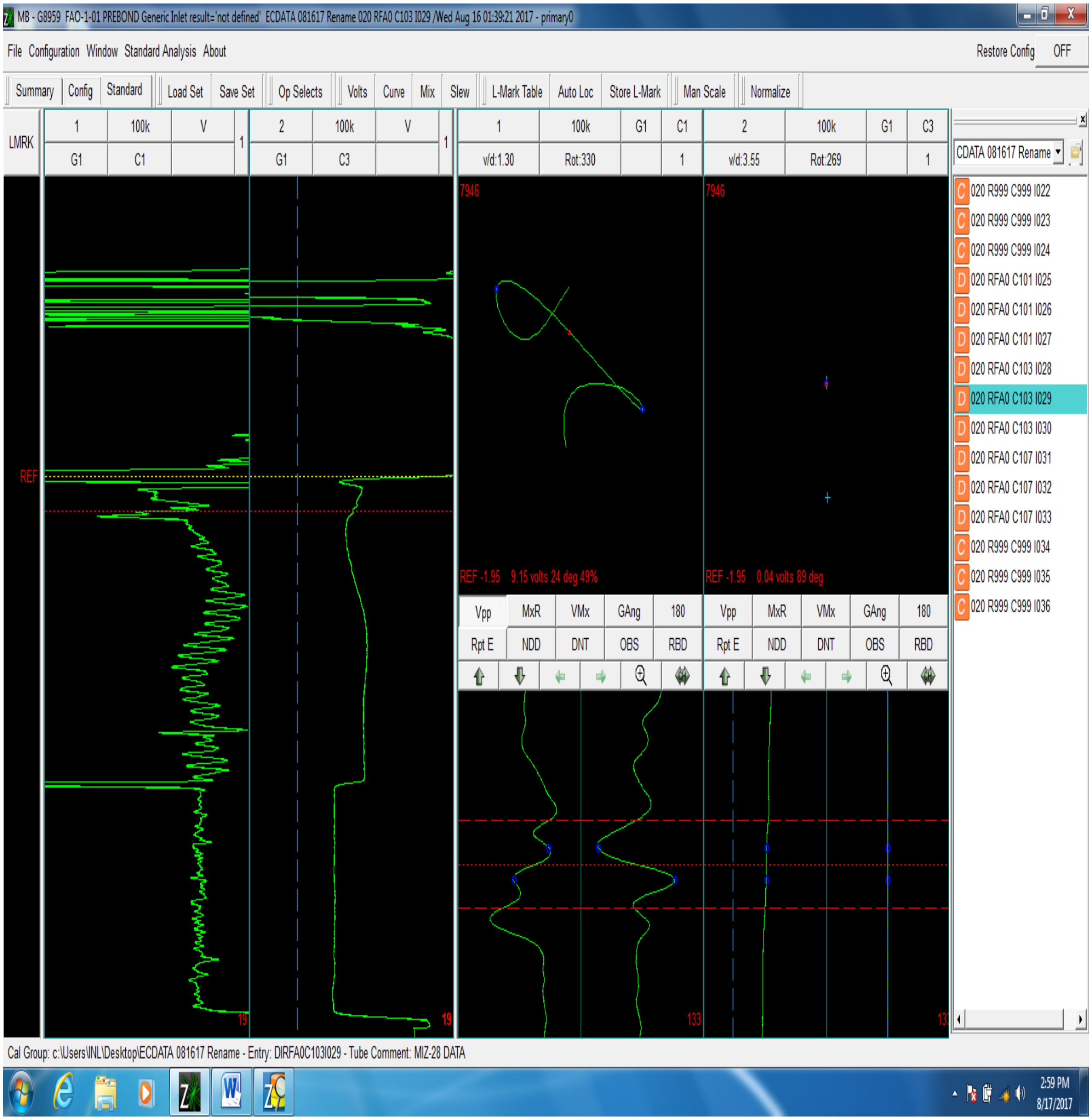


Figure 18. Bonded pin eddy current with non-bonded indication scan results.

2.3.1 Wire Wrap Operation

After successful verification of the sodium bond with the eddy current inspection, the final step in the process is to wrap the pin with a spacing wire. To accomplish this, the wire wrap and eddy current inspection machine was utilized again. For this demonstration a different solid 304L stainless surrogate pin was used to allow the bare bonded rod to be re-bonded and inspected again for future testing. The spacer wire used was 308L MIG filler wire in a 0.045-in diameter. A section of wire was cut and a 90 degree bend was formed near the end, which was inserted through the cross-hole in the nock-shaped end cap. Figure 19 shows the wire in this condition ready for welding, held in place with a customized vise grip clamp. The wire was melted with a standard TIG torch, forming a ball that rests in a chamfer in the cross-drilled hole in the end cap. Figure 20 shows the wire secured by the formed ball after welding. The wire is not actually welded to the pin (i.e., there is no fusion between the wire and end cap) but the ball formed mechanically secures the wire by being too large to be pulled back through the cross-hole.

After this first end of the wire had been secured, the wire and surrogate pin were loaded into the machine with the nock-shaped end cap down. The pin is secured at the bottom with a spring-loaded bottom collar that holds the pin by the nock feature in the end cap. Figure 21 shows the surrogate rod secured in the machine. The clamping ring with the white center just above the spring-loaded collar clamps around the pin and has a slot in the back through which the wire passes. During the wrapping process, the collar is moved vertically up the pin, with the wire being guided by this slot as the pin is rotated, wrapping the wire around the pin.

Figure 19. Spacing wire ready for welding.

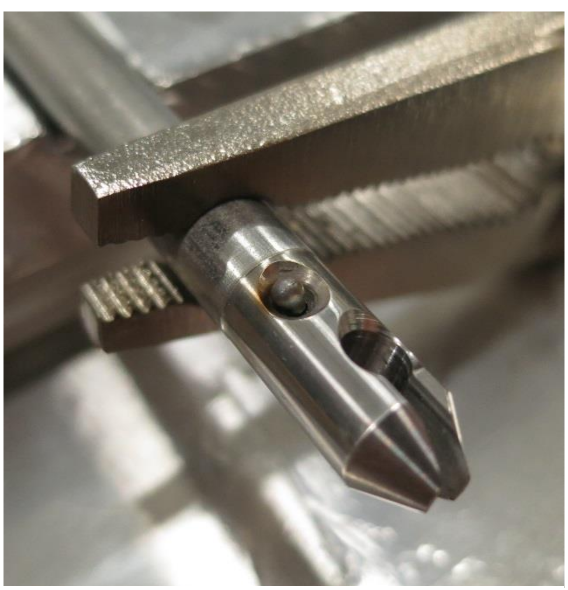


Figure 20. Formed wire ball.

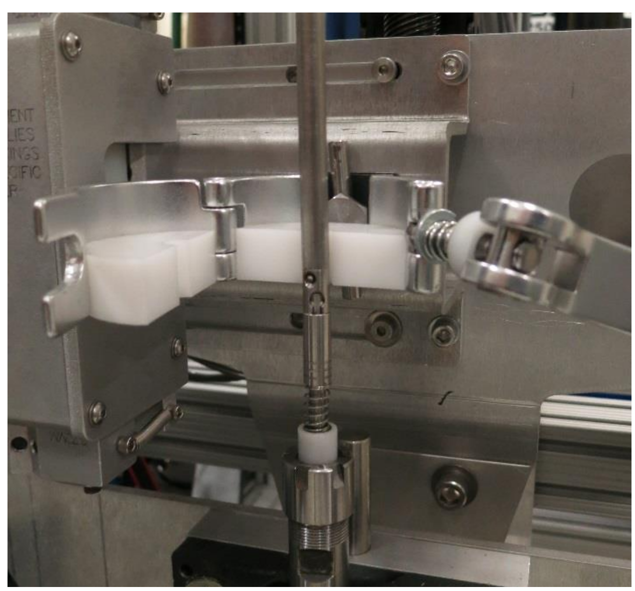


Figure 21. Pin secured for wrapping.

The loose end of the wire was taken up to the top of the pin and secured to a swivel, which is attached to counterweight as shown in Figure 22. The counterweight provides the proper tension on the wire during wrapping, keeping the wire tight to the pin. The top of the pin is held in place by a sliding guide, also shown in Figure 22. The guide holds the top of the pin in place as the carriage is moved up the pin. At the top of the carriage stroke, the carriage lifts the guide up, clearing the end of the rod and allowing the wire to be wrapped to the very end of the rod. Figure 23 shows the pin after the carriage has traversed to the top and the wire has been fully wrapped. A clamping collar was attached to the pin near the top to temporarily secure the wire, the wire was cut, and the assembly was transferred back to the folding workbench area. On the workbench, the end of the wire was carefully threaded through the cross-hole in the end cap, taking care not to kink the wire. Once through the hole, a rivet gun was used to pull all slack out of the wire, forming a tight bend in the wire into the cross-hole as shown in Figure 24. Once the wire was tight, the vise grip clamping pliers were used again to secure the wire, it was trimmed to length and ready for welding as shown in Figure 25. Figure 26 shows the completed wire-wrapped surrogate pin.

Figure 22. Top of pin ready for wrapping.

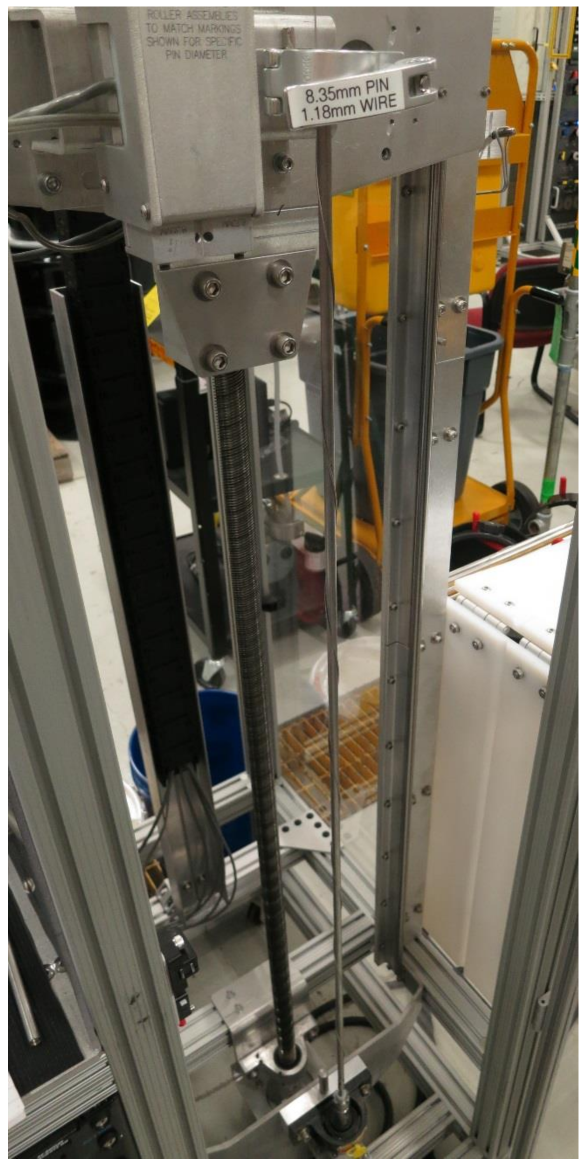


Figure 23. Wrapped pin.

Figure 24. Wire tensioning.

Figure 25. Wire ready for second ball forming weld.

Figure 26. Completed wire wrapped surrogate pin.

2.4 Conclusions

Overall, the sodium bonding oven and combined wire wrap and eddy current inspection machine performed well. A surrogate test pin was successfully taken through the full process. The pin was eddy current scanned prior to bonding to collect an unbonded pin example for future comparison. The pin was then successfully bonded with the bonding sequence delivered with the oven. The pin was then eddy current scanned again to provide an example of a bonded pin for future comparison. The scan verified the bond had been successfully preformed. Finally, a pin was wire wrapped, successfully providing a tightly wound spacing wire at the desired pitch adequately secured at both ends.

The only issue identified during the test was a slowing of the rotation motor on the sodium bonding oven during the heated run. The rotation would slow down between impact cycles but be freed back up to the original speed after each impact cycle. The cause and possible results of this will need to be further investigated prior to actual fuel bonding.

Another topic identified during testing prior to this run was the likelihood of actually bonding the spacing wire to the pin when forming the ball on the wire. In several initial training welds, the ball was actually fused to the pin. In some cases, the fusion was not visible but only found when the wire was being removed for subsequent tests with the same pin. The consequences of having the wire fused to the end cap should be investigated. If no negative issues are identified, the fuel fabrication specification should be written to allow some fusion of the ball. With additional practice, the fusion could likely be avoided; however, if no driver is identified for avoiding fusion, the specification should allow for it to minimize unnecessary rework in the future.

Appendix A

Sodium Bonding Sequence Used for Operational Testing

1	Temperature	ID10	550	0.25	Immediate
2	Temperature	ID9	550	0.25	Immediate
3	Temperature	ID8	550	0.25	Immediate
4	Temperature	ID7	550	0.25	Immediate
5	Temperature	ID6	550	0.25	Immediate
6	Temperature	ID5	550	0.25	Immediate
7	Temperature	ID4	550	0.25	Immediate
8	Temperature	ID3	550	0.25	Immediate
9	Temperature	ID2	550	0.25	Immediate
10	Temperature	ID1	550	0.25	Gate
11	Rotation	TRUE			
12	Angle	USER DEFINED			30
13	Soak 600	Seconds		Gate	
14	Impact	TRUE			
15	Soak 5	Seconds			
16	Impact	FALSE			
17	Soak 15	Seconds			
18	Impact	TRUE			
19	Soak 5	Seconds			
20	Impact	FALSE			
21	Soak 15	Seconds			
22	Impact	TRUE			
23	Soak 5	Seconds			
24	Impact	FALSE			
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234	Impact	TRUE
235	Soak 5	Seconds
236	Impact	FALSE
237	Soak 15	Seconds
238	Impact	TRUE
239	Soak 5	Seconds
240	Impact	FALSE
241	Soak 15	Seconds
242	Impact	TRUE
243	Soak 5	Seconds
244	Impact	FALSE
245	Soak 15	Seconds
246	Impact	TRUE
247	Soak 5	Seconds
248	Impact	FALSE
249	Soak 15	Seconds
250	Impact	TRUE
251	Soak 5	Seconds
252	Impact	FALSE
253	Soak 15	Seconds
254	Impact	TRUE
255	Soak 5	Seconds
256	Impact	FALSE
257	Soak 15	Seconds
258	Impact	TRUE
259	Soak 5	Seconds
260	Impact	FALSE

261	Soak 15	Seconds
262	Impact	TRUE
263	Soak 5	Seconds
264	Impact	FALSE
265	Soak 15	Seconds
266	Impact	TRUE
267	Soak 5	Seconds
268	Impact	FALSE
269	Soak 15	Seconds
270	Impact	TRUE
271	Soak 5	Seconds
272	Impact	FALSE
273	Soak 15	Seconds
274	Impact	TRUE
275	Soak 5	Seconds
276	Impact	FALSE
277	Soak 15	Seconds
278	Impact	TRUE
279	Soak 5	Seconds
280	Impact	FALSE
281	Soak 15	Seconds
282	Impact	TRUE
283	Soak 5	Seconds
284	Impact	FALSE
285	Soak 15	Seconds
286	Impact	TRUE
287	Soak 5	Seconds
288	Impact	FALSE
289	Soak 15	Seconds
290	Impact	TRUE
291	Soak 5	Seconds
292	Impact	FALSE
293	Soak 15	Seconds
294	Impact	TRUE
295	Soak 5	Seconds
296	Impact	FALSE
297	Soak 15	Seconds
298	Impact	TRUE
299	Soak 5	Seconds
300	Impact	FALSE
301	Soak 15	Seconds
302	Impact	TRUE
303	Soak 5	Seconds
304	Impact	FALSE
305	Soak 15	Seconds
306	Impact	TRUE
307	Soak 5	Seconds
308	Impact	FALSE
309	Soak 15	Seconds
310	Impact	TRUE
311	Soak 5	Seconds
312	Impact	FALSE
313	Soak 15	Seconds
314	Impact	TRUE
315	Soak 5	Seconds
316	Impact	FALSE
317	Soak 15	Seconds
318	Impact	TRUE
319	Soak 5	Seconds
320	Impact	FALSE
321	Soak 15	Seconds
322	Impact	TRUE
323	Soak 5	Seconds
324	Impact	FALSE
325	Soak 15	Seconds
326	Impact	TRUE
327	Soak 5	Seconds
328	Impact	FALSE

329	Soak 15	Seconds			
330	Impact	TRUE			
331	Soak 5	Seconds			
332	Impact	FALSE			
333	Soak 15	Seconds			
334	Impact	TRUE			
335	Soak 5	Seconds			
336	Impact	FALSE			
337	Soak 15	Seconds			
338	Impact	TRUE			
339	Soak 5	Seconds			
340	Impact	FALSE			
341	Soak 15	Seconds			
342	Impact	TRUE			
343	Soak 5	Seconds			
344	Impact	FALSE			
345	Soak 15	Seconds			
346	Impact	TRUE			
347	Soak 5	Seconds			
348	Impact	FALSE			
349	Soak 15	Seconds			
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351	Soak 5	Seconds			
352	Impact	FALSE			
353	Soak 15	Seconds			
354	Impact	TRUE			
355	Soak 5	Seconds			
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357	Soak 15	Seconds			
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359	Soak 5	Seconds			
360	Impact	FALSE			
361	Soak 15	Seconds			
362	Impact	TRUE			
363	Soak 5	Seconds			
364	Impact	FALSE			
365	Soak 15	Seconds			
366	Impact	TRUE			
367	Soak 5	Seconds			
368	Impact	FALSE			
369	Soak 15	Seconds			
370	Impact	TRUE			
371	Soak 5	Seconds			
372	Impact	FALSE			
373	Soak 15	Seconds			
374	Soak 600	Seconds			
375	Angle	HOME			
376	Rotation	FALSE			
377	Temperature	ID10	150	0.1	Immediate
378	Temperature	ID9	150	0.1	Immediate
379	Temperature	ID8	150	0.1	Immediate
380	Temperature	ID7	150	0.1	Immediate
381	Temperature	ID6	150	0.1	Immediate
382	Temperature	ID5	150	0.1	Immediate
383	Temperature	ID4	150	0.1	Immediate
384	Temperature	ID3	150	0.1	Immediate
385	Temperature	ID2	150	0.1	Immediate
386	Temperature	ID1	150	2	Gate
387	Temperature	ID1	0	0.66	Gate
388	Temperature	ID2	0	0.66	Gate
389	Temperature	ID3	0	0.66	Gate
390	Temperature	ID4	0	0.66	Gate
391	Temperature	ID5	0	0.66	Gate
392	Temperature	ID6	0	0.66	Gate
393	Temperature	ID7	0	0.66	Gate
394	Temperature	ID8	0	0.66	Gate
395	Temperature	ID9	0	0.66	Gate
396	Temperature	ID10	0	0.66	Gate