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ABSTRACT

The neutron Radiography Reactor (NRAD) is a training, research, and isotope (TRIGA) reactor located at the INL. The reactor is normally shut down by the insertion of three control rods that drop into the core when power is removed from electromagnets. During a routine shutdown, indicator lights on the console showed that one of the control rods was not inserted. It was initially thought that the indicator lights were in error because of a limit switch that was out of adjustment. Through further testing, it was determined that the control rod did not drop when the scram switch was initially pressed.

The control rod anomaly led to a six month shutdown of the reactor and an in depth investigation of the reactor protective system. The investigation looked into: scram switch operation, console modifications, and control rod drive mechanisms. A number of latent issues were discovered and corrected during the investigation. The cause of the control rod malfunction was found to be a buildup of corrosion in the control rod drive mechanism. The investigation resulted in modifications to equipment, changes to both operation and maintenance procedures, and additional training. No reoccurrences of the problem have been observed since corrective actions were implemented.

Key Words: NRAD Control Rod

1. INTRODUCTION

The NRAD reactor is a 250 kW reactor located at the Materials Fuels Complex (MFC) at the INL. The reactor is a TRIGA conversion reactor brought from the Puerto Rico Nuclear Center in 1976. NRAD first went critical in 1977 using General Atomics (GA) 80/20 fuel. The reactor is currently being converted to low-enriched uranium (LEU) fuel. The conversion should be complete in March 2010.

The NRAD core is made of 60 fuel elements in an 8 x 8 square array. There is one water hole and three control rods in the core. NRAD uses two shim rods that are fully withdrawn during normal operations and a regulating rod that is used to control power. Each of the NRAD control rods has sufficient reactivity to shut down the reactor by itself. As is typical of TRIGA reactors, the control rods have a connecting rod that extends up above the surface of the reactor pool. An armature, which is lifted by an electromagnet, is attached to the top of the connecting rods. The electromagnet is moved up and down by a control rod drive mechanism. When the reactor is scrammed, power is removed from the electromagnets and the control rods drop under the force of gravity into the core. Scramming the reactor is the normal method of shutdown for the NRAD reactor as opposed to lowering the control rods using the control rod drive mechanism.

The NRAD reactor is located beneath the Hot Fuel Examination Facility (HFEF) main cell, which is a hot cell with an inert gas atmosphere. The NRAD facility was an add-on to HFEF. Difficulties during the construction of the NRAD reactor room resulted in NRAD having a tank depth of only 11 feet 6 inches. Because of the unusually shallow reactor tank, radiation fields get as high as 3 R/hr in the reactor room during operations.

The primary function of the NRAD reactor is to perform Neutron Radiography on activated targets such as spent nuclear fuel and control rods. NRAD's location beneath the hot cell makes it well suited for this purpose. Targets can be placed in the path of one of the NRAD beams by being lowered into a pit inside the HFEF main cell that intersects the beam. This arrangement allows radiography to be performed without removing targets from the hot cell environment.

2. Anomaly During Shutdown

On 30 September 2008, the NRAD reactor was performing a routine run at 250 kW when an anomaly occurred during shutdown. To terminate the run, the reactor operator pressed the Manual Scram switch. The Regulating Rod and the Shim Rod No. 1 indicator lights showed that the connecting rods had dropped, and the corresponding rod drive position indicators began to count down. None of these typical indicators of proper rod function occurred for Shim Rod No. 2. The indicator lights did not show the rod was down, and the rod drive position indicator did not count down. The reactor operator pushed the Manual Scram switch two more times, but the indications did not change. After some discussion with the reactor supervisor, the reactor operator pushed the Manual Scram switch and held it in. A moment later, the appropriate indications for Shim Rod No. 2 were observed. The indicator lights showed that the rod was down, and the rod drive position indicator began to count down.

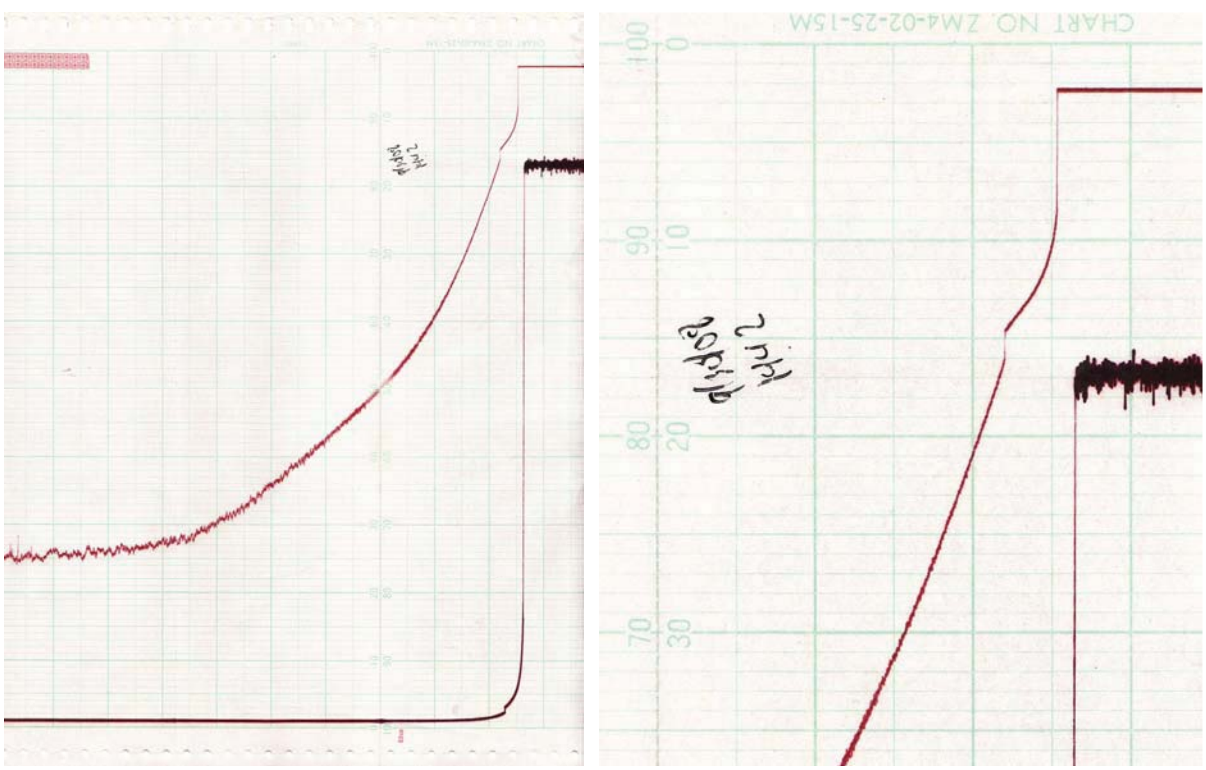

Figure 1. 9-30-08 Power Trace.

In addition to the indications described above, the log and linear channel power traces for the shutdown have a sharp drop or step that coincides with the timing of the final push of the Manual Scram switch. The step appears at the same time in both channels, but is easier to identify on the log trace. The power traces also show that the reactor was safely shutdown and the traces appeared to have the same negative 80-second period that is typically observed at shutdown. At no time was there any concern about the safety of the shutdown. While the reactor tank water was still warm, and with the reactor shutdown Shim Rod No. 2 was raised and scrammed several times in an effort to repeat the problem. The rod functioned normally during all of the tests.

3. Initial Inspections

The first question that needed to be answered was whether the control rod actually dropped when the scram button was initially pressed. It was postulated that the indicator lights on the console could have indicated improperly because of limit switches on the control rod drive mechanism being out of adjustment. The step or drop in the power trace could have come from electrical noise from facility equipment interfering with the nuclear instruments.

To answer the question of whether the control rod dropped, a test was proposed. This test would simulate a control rod getting stuck and dropping into the core late. The test would work by operating the reactor at full power and pressing the individual scram buttons for Shim Rod No. 1 and the Regulating Rod. Approximately 40 seconds later the individual scram switch for Shim Rod No. 2 would be pressed. If the power trace for this shutdown had a step similar to the power trace from the day of the anomaly, then it would be likely that Shim Rod No. 2 did not drop during the anomaly when the Manual SCRAM button was initially pressed. If the traces appear to be different, the console indications and the drop in the power traces were probably caused by something else. Because of concerns that Shim Rod No. 2 was not working properly, every effort was made to troubleshoot the problem without operating the reactor. It was agreed that this test would be performed after other troubleshooting activities were completed.

Lights on the console indicated that Shim Rod No. 2 was in the full up position after the Manual SCRAM button was pressed during the anomaly. The indicator lights are controlled by limit switches that require precise adjustments to function properly and occasionally need to be readjusted. An inspection of Shim Rod No. 2 found the limit switches to be slightly out of adjustment. The lock nut on the rod that actuates one of the switches was loose, so the settings could change, perhaps explaining why the problem was not repeatable.

Next, an examination of the nuclear instruments was made. NRAD has four nuclear channels. Safety channel 1 and 2 provide over power protection by scramming the reactor if a set point is reached. Both channels receive signals from uncompensated ion chambers that are on opposite sides of the core. The console meters show the safety 1 and 2 power levels as a percent of 300 kW. Because the safety channels are not connected to a chart recorder, no data is available on the anomalous shutdown from these channels.

The linear channel receives its signal from a compensated ion chamber that is located at the tank wall approximately level with the core. This channel uses a picoammeter located in the console and displays power as a percent of the selected range. The range selector switch has two outputs per decade. When the reactor is shutdown from full power, the selector switch is in the 300 kW range. The lower of the two traces shown in Figure 1 is the linear power channel trace from the anomalous shutdown. The small drop in power can be seen in the linear power trace although it is not as pronounced as in the log power trace.

The wide-range or log-power channel uses a fission chamber detector located at the tank wall near the other detectors. This channel has 10 decades of output that allow it to monitor the core from shutdown to full power. In 1972 when the NRAD console first went online, the ability to monitor 10 decades of neutron flux from a single channel accurately was a significant improvement. The wide-range channel accomplished this by using a campbelling circuit for the upper 4 decades and a pulse-log count rate for the lower 6 decades. The pulse-log count rate utilizes a discriminator circuit to remove the alpha and gamma noise from the output signal. This portion of the wide-range channel has a linear output voltage from approximately .3 to 30000 counts per second.

The following is a description of the Campbelling circuit from H.A. Thomas and A.C. McBride:

> "A linear neutron level Campbell channel is obtained by eliminating the d.c. component of the ion chamber signal (e.g., by capacitor coupling) and squaring the instantaneous value of the remaining a.c. component of the signal which is then passed through an average indicating device like a meter. Because α, γ and fission produced ion pulses are present, each with its own average rate of occurrence, r, the output reading for a fission chamber will be proportional to $(r_\alpha + q_\alpha^2 + r_\gamma q_\gamma + r_f q_f^2)$. Since q_f^2, the mean square charge transfer per pulse from fission fragment ionization, is so much larger than that for γ induced pulses or the α background pulses, the output signal can be considered proportional to the average fission pulse rate r_f for rates well below the level where good overlap with pulse counting techniques is achieved."

The output from the pulse-log circuits and campbelling circuit are both displayed on a single meter. The ability to adjust the cutoff points and the slope of the campbelling circuit output provides a smooth transition as the meter moves from one output to the other.

The sharp vertical drop that appears in the log power trace occurs about 40 seconds into the shutdown. If Shim Rod No. 2 dropped when it was supposed to, another explanation was needed for the vertical drop on the power trace. It was thought that the drop might be caused by an alignment issue with the pulse-log counting and campbelling circuits. A Realignment was performed according the General Atomics instructions for this nuclear instrument. Without operating the reactor, the results of the realignment were not immediately obvious, but the alignment did not require significant adjustment. Additionally the drop in the curve occurred between the 8th and 9th decade. The crossover region is between the 5th and 6th decade making it unlikely that the drop was the result of an alignment problem. A small drop in reactor power can also be seen at the same time on the linear power trace. An issue with log channel alignment would not explain why the linear channel showed a similar drop in power.

The drop in power observed in the shutdown traces prompted an investigation into what a normal shutdown trace looks like. All of the NRAD chart recordings for the last several years were examined. An odd bump or discontinuity was found in almost all of the shutdown traces in approximately the same location as the drop that that occurred on the 30 September power trace. The discontinuity is more severe in some traces than others. Figure 2 and Figure 3 show two of the extremes, although it is hard to compare them because a different chart speed was used for Figure 3.

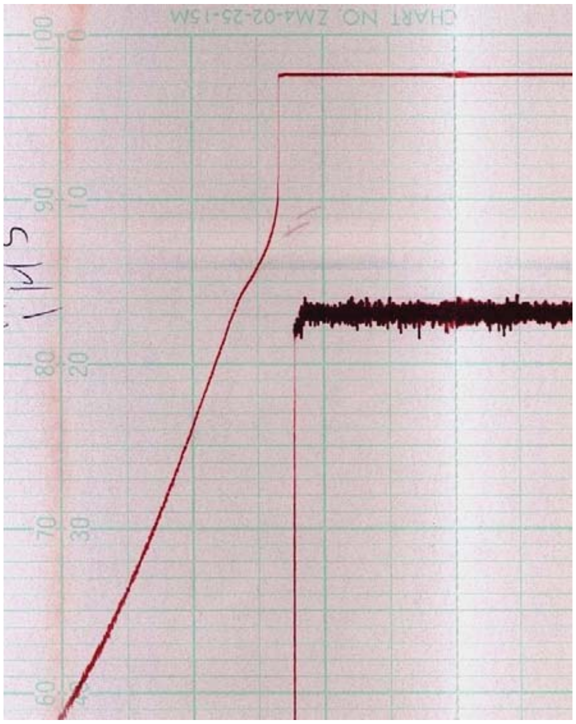

Figure 2. 9-10-08 Power Trace.

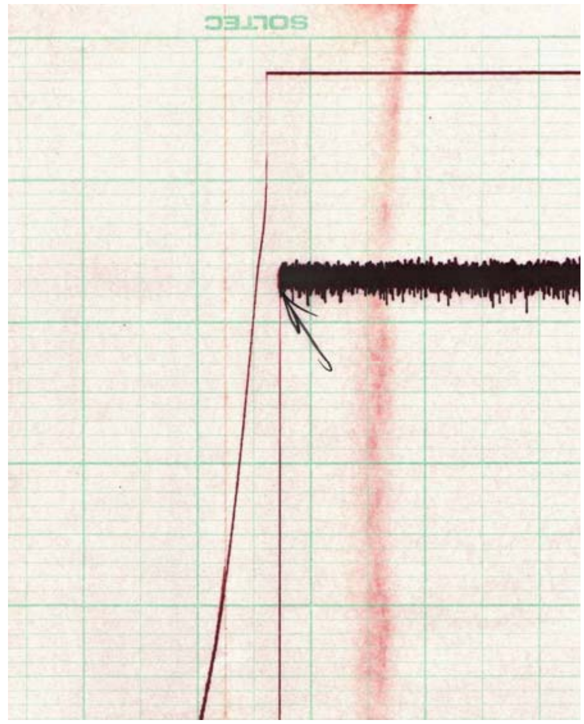

Figure 3. 8-26-08 Power Trace.

It was thought that the discontinuities in the shutdown traces might be caused by some type of systematic noise. Because the nuclear instruments rely on extremely small signals, a small induced current from a nearby motor or electromagnet might produce the observed discontinuities and might be the source of the step in the 30 September shutdown trace. All of the shielding for signal wires was checked for proper grounding. The signal wiring was also confirmed to be in the proper conduits, which are separate from the power wiring conduits. The drawers containing the nuclear instruments in the console were removed and a thorough examination was done on all four channels. A number of minor problems were found and corrected in the nuclear instrument drawers. One card had a failed relay, and another card had a failed opamp. Some of the connections were dirty so each card was removed and the contacts were cleaned. Repairs made to the console did stabilize the log channel at low power, but it was still unknown how the corrections would affect the shutdown traces.

4. Delayed Rod Drop Test

After all of the troubleshooting and repairs were complete, the proposed test to delay the insertion of Shim Rod No. 2 intentionally during a shutdown was performed. The reactor was operated at 250 kW. The Regulating Rod and Shim Rod No. 1 were both scrammed. After 40 seconds, Shim Rod No. 2 was then scrammed. The power trace from this test can be seen in Figure 4. The obvious similarity between this power trace and the one from the anomalous shutdown on 30 September 2009 indicated that Shim Rod No. 2 did not drop immediately during the 30 September shutdown. It was now clear that the problem was actually a stuck control rod, not a limit switch or nuclear instrument problem.

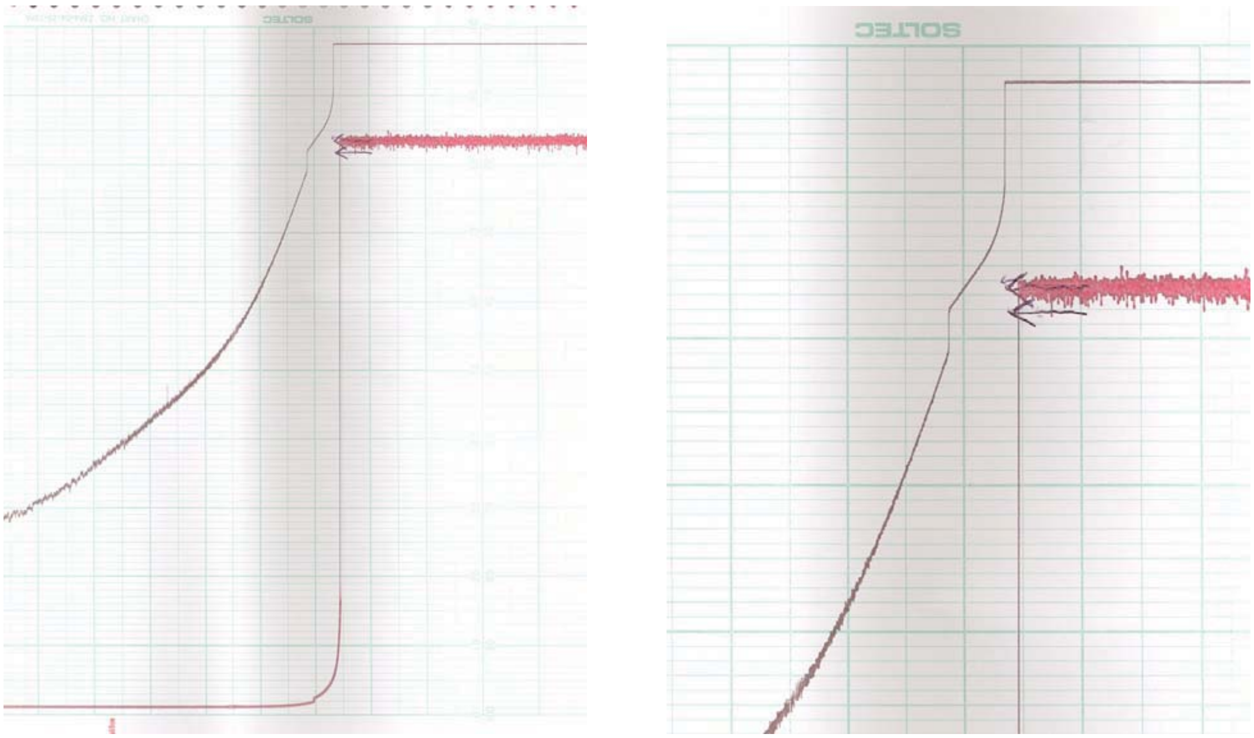

Figure 4. Delayed Rod Insertion Test 2-5-09

5. Electrical Inspections

The new troubleshooting plan that was developed focused on electrical systems. The Manual Scram switch in the NRAD console that scrams all three control rods is a momentary or spring return switch. When the Manual Scram switch is pressed, power to the electromagnets that hold up the control rods is interrupted. When the switch is released, the power is returned. Any mechanism that could maintain power to one of the electromagnets for a short period could prevent a control rod from dropping. When the switch is released, power would return and the rod would stay up indefinitely or at least until power was successfully removed. Because the control rod finally dropped when the Manual Scram switch was pressed and held for an extended time, it was thought that this might have provided the time needed for power to the electromagnet to fully decay. Another possibility was that the electromagnet after years of use might be retaining some residual magnetism, which prevented or delayed the control rod from dropping long enough for it to be recaptured when the Manual Scram switch was released. Each of these possibilities was thoroughly investigated by the troubleshooting activities that followed.

A piece of steel shim stock was placed on the Shim Rod No.2 magnet and armature to feel for residual magnetism. This test was performed with the magnet deenergized. No Residual magnetism was felt. For comparison purposes, this test was also performed on Shim Rod No. 1. Again, no residual magnetism was felt. Residual magnetism could decay off after the magnets are deenergized for some time. After leaving the electromagnets energized for 2 hours, the test for residual magnetism was repeated, and again no residual magnetism was felt on Shim No. 1 or Shim No. 2.

In parallel with the electromagnet coil, is a diode that helps limit voltage spikes that can occur when the field in the coil collapses. If the diode had failed, it could take longer for the magnetic field to collapse that might delay the drop of the control rod. One leg of the diode was unsoldered from the Shim No. 2

circuit board to isolate it from the circuit. The voltage drop across the diode was measured. The diode was then heated with a heat gun to approximately 50 C and the voltage drop was measured again. A thermal imaging camera was used to confirm the diode temperature during the test. For comparison, the same test was performed on the Shim Rod No. 1 diode. The diodes on both drives were found to be working properly at ambient and 50 C. No significant difference between the diodes was observed in the voltage drop off times.

An oscilloscope was connected directly to the Shim Rod No. 2 magnet coil. A series of rod drops was then performed. The traces from the scope showed that the voltage in the coil dropped off in approximately 20 msec. The oscilloscope was connected to Shim Rod No. 1 and the test was repeated. The voltage in the Shim Rod No. 1 coil also dropped off in approximately 20 msec. These tests were repeated with the diodes heated to approximately 50 C and no significant differences were observed.

While the oscilloscope was connected to the electromagnet coil, the length of time the operator held down the scram switch could also be observed. What the operator described as a typical press and release of the switch was approximately 150 msec. The operator was asked to press and release the switch as quickly as possible. The shortest observed press and release was 80 msec. Even with the relatively short 80 msec. depressed time, Shim Rod No. 2 responded properly. This test ruled out the unlikely possibility that the operator had pressed the switch so quickly that the control rod was recaptured by the electromagnet turning back on.

An oscilloscope was installed in the console to monitor the magnet coil voltage of Shim No. 1 and Shim No. 2. A camera was also placed in the reactor room so Shim No. 2 and Shim No. 1 could be observed from the NRAD console. Multiple rod drops were performed and the traces on the oscilloscope were found to be typical of the shape and length that was observed with the oscilloscope in the reactor room. Shim Rod No. 1 and No. 2 were fully raised and held in this position for 2 hours. The regulating rod was fully inserted, so this test was not performed with the reactor at power. The rods were dropped by pressing the Manual SCRAM switch. The voltage of both coils was observed with the oscilloscope. Both drives responded properly, and the voltage drop at the coils appeared normal.

After performing all of the planned troubleshooting activities with the tank cold, the reactor was operated at 250 kW and held at that power for 4 hours. The tank temperature stabilized at 37 C. The reactor was shut down by pressing and holding the Manual Scram switch and all three control rods responded properly. The voltage drop at the coils was typical of what was observed earlier. While the reactor tank was still at operating temperature, the primary and demineralizer pumps were secured to maintain the tank temperature. Individual rod drop time tests were then performed on each of the shim rods. This was done to see if performing the tests at operating temperatures would change the rod drop times. The hot drop times were consistent with typical cold rod drop times.

While the troubleshooting activities were being performed, new control rod drive mechanisms were found in storage at MFC. It was determined that the drives had not been used. General Atomics, the manufacturer of the control rod drive mechanisms, informed us that the drives had a newer electromagnet with a slightly recessed magnet face. The magnet potting was also intentionally left rough instead of being polished smooth as on older drives. General Atomics stated these changes were to prevent a buildup of film or moisture on the magnet that could prevent the release of the armature when the magnet is deenergized. General Atomics also mentioned that a buildup of film or moisture has not been a problem for facilities where the typical shutdown method is to scram the reactor verses driving the rods in. One of the new style control rod drive mechanisms and electromagnets was installed in the Shim No. 2 position. Pictures of the two magnet faces are shown in Figure 5.

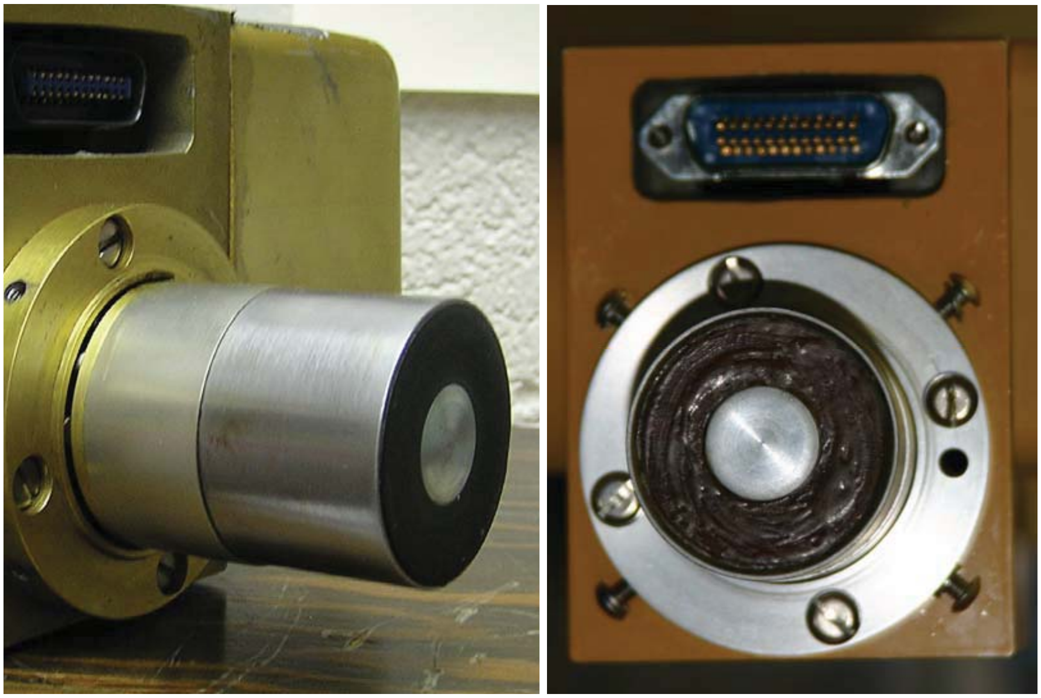

Figure 5. Old Electromagnet (left) New Electromagnet (right)

6. Return to Routine Operations

After replacing the control rod drive mechanism, the NRAD reactor returned to routine operations with several caveats. Full rod drops were to be performed before each reactor run to demonstrate operability. The camera that was placed in the reactor room was left installed to monitor both shim rods. The oscilloscope was also left in place and used to monitor the electromagnet coil voltage during each shutdown. The reactor operated intermittently for three weeks until Shim Rod No. 2 failed to drop again. It was estimated that approximately 40 routine scrams had taken place during the 3 weeks of operation. There were several notable differences between this failure and the one that occurred on 30 September 2009. This failure occurred during the daily operability check before the reactor had been operated. The reactor tank was cold, approximately 25°C. None of the coolant pumps were running, so there was no flow in the tank. The electromagnet was only energized for about 1 minute before the failure verses several hours. These conditions ruled out cross flow, thermal expansion, and heating of electrical components as possible causes. Another troubleshooting plan was developed, this time focusing primarily on mechanical issues.

7. Troubleshooting of Mechanical Systems

To prevent disturbing any evidence, troubleshooting of the mechanical systems began with underwater video inspections. Shim Rod No. 2 was observed by camera while it was moved through its full range of motion. Care was taken to look for places that some type of binding might occur. A small amount of misalignment was observed, but nothing was quantified at the time. Corrosion was found on several fasteners at the bottom of the barrel assembly.

The upper portion of the connecting rod has a piston assembly that travels inside of a barrel. The piston was only visible through small holes in the barrel. To inspect the piston and barrel thoroughly, a complete disassembly was necessary. The barrel and control rod were lifted from the reactor tank. The radiation levels were low enough to permit moving everything to an inspection lab. The control rod was dimensionally inspected and found to be within tolerance. Light rub marks were observed at the upper and lower end of the control rod, see Figure 6. The marks were evenly distributed around the circumference, indicating the rod was not sticking or binding at a certain location. The upper and lower weld beads were uniform and smooth with no protrusion that might catch in the holes of the guide tube. No excessive wear, burrs, corrosion, foreign material, or algae were observed on the control rod.

Figure 6. Shim Rod #2 Bottom End

During disassembly, the buoyant weight of the connecting rod and control rod assembly was measured. The combined weight in water was 3.5 pounds. Because the NRAD tank is only 11 feet deep, the connecting rods are shorter than other TRIGA facilities. General Atomics informed us that the typical weight of a control rod assembly is about 10 pounds and that the electromagnets are designed to lift up to 40 pounds.

The barrel and connecting rod assembly were removed from the guide tube in the inspection lab. The corroded fasteners at the bottom of the barrel are shown in Figure 7. One of the fasteners and three of the washers were found to be carbon steel instead of stainless steel. Discoloration from the corroded fasteners was also found on the piston area of the connecting rod (see Figure 8). The connecting rod had small gritty particles on it along with grease or oil residue. The connecting rod was removed from the barrel and checked for straightness. The total indicated runout of the rod was 0.15 in. The piston to barrel wall clearance varied from 0.003 in. to 0.043 in. Figure 9 shows the side of the piston with the smallest clearance to the barrel ID. The piston connection used two fasteners that go through holes in the piston assembly. The piston/connecting rod assembly was moved back and forth in the barrel by hand, to feel for friction, sticking, or binding. The piston did not catch on any edges, but there was a noticeable amount of resistance. For comparison, the resistance was also checked in a new barrel. The new barrel required less force to move the piston and had a smoother feel. With the connecting rod removed, a ring of grease was observed in the barrel where the armature normally stops in the down position (see Figure 10). The grease likely came from the lubrication of the control rod drive mechanism. The grease had run down to the armature and barrel where it collected over many years of service.

Figure 7. Corroded Fasteners on Shim Rod #2 Barrel

Figure 8. Corrosion on Shim Rod #2 Piston

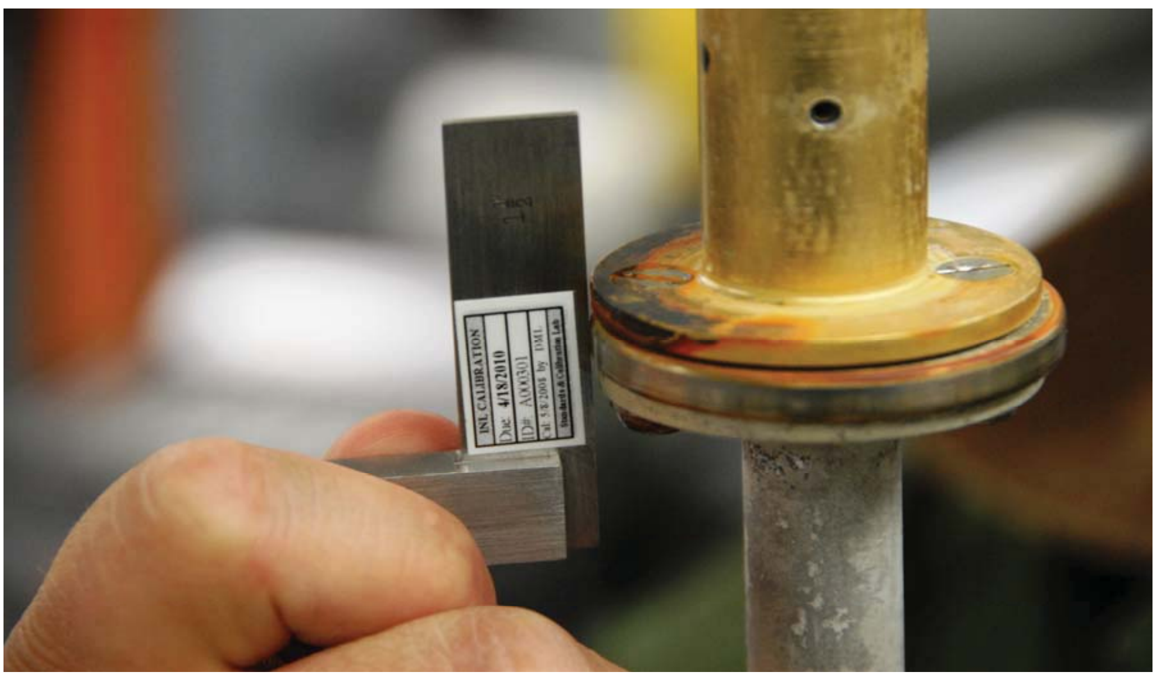

Figure 9. Shim Rod #2 Piston Clearance

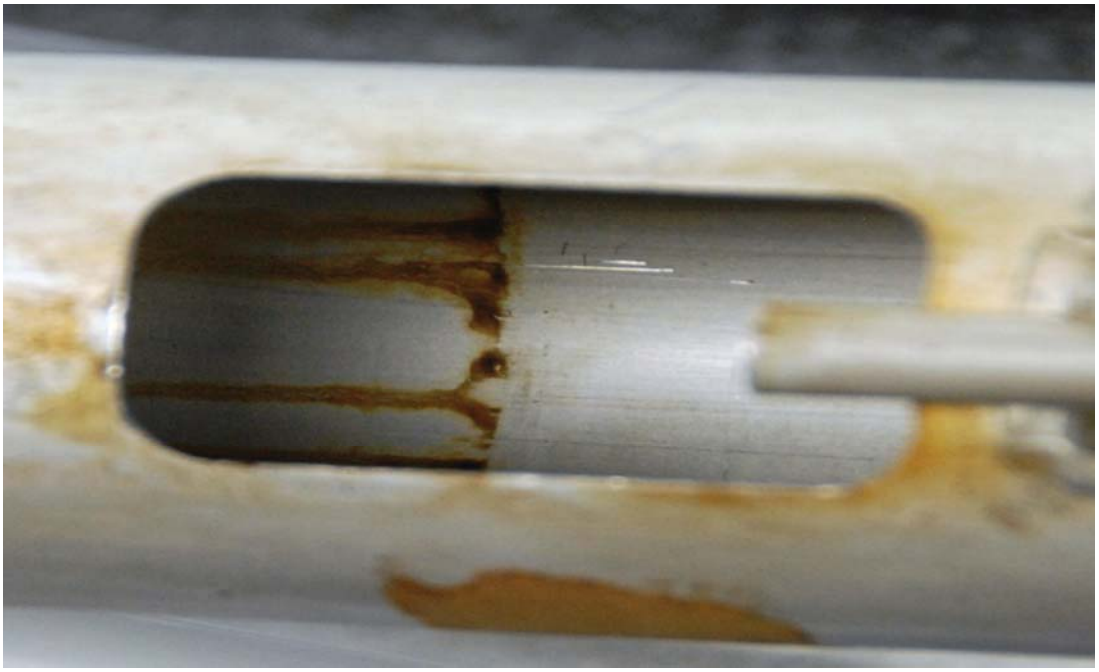

Figure 6. Grease in Shim #2 Barrel

8. Conclusion

The failing of Shim Rod No. 2 to drop during a scram was ultimately attributed to a combination of factors. The buildup of grease and corrosion products in the barrel combined with the unusually light weight of the controls rod assembly caused the control to stick in the barrel. Because a momentary switch was used to scram the reactor, power to the electromagnets was restored when the switch was released. A delay in the movement of the control rod during a scram resulted in the control rod being recaptured. The possibility of a control rod being recaptured was eventually confirmed when an operator was able to intentionally press the scram switch fast enough to demonstrate a recapture. An evaluation of rod recapture that was part of an internal INL report is included in appendix A.

Besides a thorough cleaning of all of the components a number of modifications were made to prevent future failures of the scram system. First, the design of the upper connecting rod was changed to increase the weight. The total buoyant weight of the new control rod and connecting rod assembly was approximately 9 pounds. Second, the design of the piston flange was changed to use four bolts that more securely maintained the proper geometry. Third, maintenance procedures for the control rod drive mechanism were changed to stop unnecessary lubrication. Fourth, the Manual Scram switch was changed to a latching or push-pull type switch to prevent the electromagnets from being reenergized when the switch is released. After making the changes, 100 consecutive rod drops of Shim Rod No. 2 were performed. The average rod drop time decreased approximately 0.15 seconds. The NRAD reactor operated successfully for a 2-month period before being shutdown to undergo a conversion from highly enriched uranium (HEU) to LEU fuel. At the time of writing, this conversion is still underway.

After making repairs to the console the bump observed in many of the shutdown traces is still present. The cause of the bump has not yet been determined.

ACKNOWLEDGMENTS

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APPENDIX A

Rod Recapture Evaluation

ORIGINAL ROD CONFIGURATION

The original rod configuration for shim rod No. 2 has experienced several spurious instances where the rod has failed to drop. The rod is released by deenergizing a magnet via a pushbutton switch. When the button is released, the power is restored to the magnet. The following discussion evaluates the possibility of recapturing the rod prior to the rod falling a sufficient distance before the magnetic field is reenergized.

During periodic rod drop testing the rod drop time (t_{drop}) and the corresponding rod drop distance (s_{drop}) are:

$t_{drop} := 0.66s$ $\qquad\qquad$ $s_{drop} := 15\,in$

Assuming the rod undergoes uniform acceleration, the following equation of motion can be used to determine the uniform or average acceleration (^{a}drop) during the drop. The initial velocity (vo) is 0.

$$s_{drop} = V_o\ t_{drop} + \frac{1}{2} a_{drop} \left(t_{drop}\right)^2$$

$$a_{drop} := \frac{2\ s_{drop}}{\left(t_{drop}\right)^2} = 68.871 \frac{in}{s^2} \qquad \text{or} \qquad a_{drop} = 5.7 \frac{ft}{s^2}$$

The above assumption is conservative since, the buoyant weight of the rod decreases as the rod drops resulting in less force to overcome drag through the water and the dashpot effect. Both of these effects slow the acceleration. The maximum acceleration occurs when the rod is dropped from full height but the calculated acceleration averages the accelerations resulting in a lower value than the actual condition.

Based on testing performed and documented in TEV-455, "Troubleshooting and Replacement of NRAD Shim Rod #2 Drive," the average time of de-energization observed during scram switch operation is:

$$t_{ave} := 0.150\ \mathrm{s}$$

During this timeframe the rod drops

$$s_{ave} := \frac{1}{2}\, a_{drop} \left(t_{ave}\right)^2 = 0.775\ \mathrm{in.}$$

The observed distance the rod captures a static rod is approximately 0.25 in. Therefore, re-capture of the rod after the magnet is re-energized is not likely under this scenario.

During retesting of the rod drive, operators purposely attempted to operate the switch as fast as possible. On 05 May 2009, the operators operated the switch with a de-energization time of 0.070 seconds. It should be noted that this is much faster than the switch is actuated during normal operations.

$$t_{min} := 0.070\ \mathrm{s}$$

During this timeframe the rod drops

$$s_{min} := \frac{1}{2}\, a_{drop} \left(t_{min}\right)^2 = 0.169\ \mathrm{in.}$$

The observed distance the rod captures a static rod is approximately 0.25 in. Therefore, re-capture of the rod after the magnet is re-energized is possible under this scenario. The time for the field to collapse and release the rod has not been quantified and may even shorten the effective time the rod has to drop before re-energizing the field.

New Rod Configuration

The upper-rod was replaced with a heavier rod to provide additional reliability. This rod was tested 100 times satisfactorily. While attempting to operate the switch rapidly the operators were successful in preventing the rod from dropping when the de-energization time was 0.070 seconds as previously mentioned.

During rod drop testing the time to drop the heavier rod was

$$t_{dropnew} := 0.51\ \mathrm{s}$$

The average acceleration for this rod drop time is

$$a_{dropnew} := \frac{2\,s_{drop}}{\left(t_{dropnew}\right)^2} = 115.34\,\frac{in}{s^2}$$

For the minimum drop time observed

$$t_{min} = 0.070\ s$$

During this timeframe the rod drops

$$s_{new} := \frac{1}{2}\,a_{dropnew}\left(t_{min}\right)^2 = 0.283\text{ in.}$$

This distance is close to the observed distance the rod captures a static rod of approximately 0.25 in. especially considering the readability of the oscilloscope used to measure the de-energization time. Therefore, re-capture of the rod after the magnet is re-energized is also possible under this scenario.