Root Cause Investigation of February 2021 Fuel Failure

NCNR Technical Working Group

Revision 2

September 13, 2021

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Abbreviations and Definitions Used

AR: Administrative Rule

CHP: Chief of Health Physics, NCNR

CRE: Chief of Reactor Engineering, NCNR

CRO: Chief of Reactor Operations, NCNR

CROE: Chief of Reactor Operations and Engineering, NCNR

EI: Emergency Instruction

NBSR: National Bureau of Standards Reactor

NCNR: NIST Center for Neutron Research

NI: Nuclear Instrument (neutron detectors used as an indication of relative reactor power)

NOUE: Notification of Unusual Event (lowest level of emergency declaration)

NRC: U.S. Nuclear Regulatory Commission

OI: Operator Instruction

OMARR: Operations and Maintenance Assessment of Research Reactors (IAEA report)

ROE: Reactor Operations and Engineering group at NCNR

RFO: Research Facility Operations group at NCNR

RS: Reactor Supervisor

SAC: Safety Assessment Committee (NCNR external committee)

SEC: Safety Evaluation Committee (NCNR internal committee)

SRO: (licensed) Senior Reactor Operator

T: Trainee (person in training for a reactor operator or senior reactor operator’s license)

Executive Summary

On February 3, 2021, the NBSR reactor was conducting a normal start up one month after the refueling on January 4, 2021. Upon approaching full power, a release of fission products occurred, indicating a fuel failure. A post-incident in-core video inspection revealed that one fuel element had lifted out of its secured position in the lower core grid plate and was skewed in an apparent unlatched condition.* This resulted in a lack of cooling to the element and eventual fuel failure. A root cause analysis was performed to identify the reason the fuel failed.

This analysis identified the following five (5) root causes:

1. **The training and qualification program for operators was not on par with programmatic needs.**
2. **Procedures as written do not capture necessary steps in assuring elements are latched.**
3. **Procedural compliance was not enforced.**
4. **Inadequacies existed in the fidelity of latch determination equipment and tools**
5. **There was inadequate management oversight of refueling staffing.**

Existence of all of these causes was necessary for the February 3 incident to occur.

Additionally, the root cause analysis identified the following contributing factors:

1. A loss of experienced operators over the past few years resulted in significantly fewer personnel with experience in refueling and latching.
2. The crew performing latch checks had limited experience in performing the check.
3. A large influx of trainees and NCNR closure in 2020 due to COVID-19 concerns resulted in a lack of opportunity for training on refueling.
4. The importance of latch checks was not appreciated by the staff, resulting in some complacency.
5. Facility procedures did not capture sufficient institutional knowledge and requirements.
6. Culture in ROE was that of relying on training and experience rather than procedure.
7. There was no engineering analysis of the effect of new pickup tools on the height gauge test.
8. There is no mark on the index plate for proper orientation of rotation latch check as stated in written procedures.
9. There was a false sense of security in the fidelity of height gauge tools and in redundant checks.
10. There was no sign-off or review of refueling sheets by the supervisor.

* It is surmised that this fuel element was unlatched prior to reactor startup on February 3.

The following corrective actions are recommended to prevent recurrence of this type of incident. Institution of each of these will prevent occurrence of the circumstances that could lead to a repeat of the incident:

1. Require proficiency training for personnel prior to all refuelings, emphasizing the importance of latching and procedural compliance.
2. Develop a program for robust qualification of operators and candidates in moving fuel.
3. Develop a system for knowledge and skills management in the presence of personnel attrition.
4. Rewrite fueling procedures to capture aspects of movements to align with training.
5. Reinstitute the requirement for latch checks prior to final pump restart.
6. Institute a redundant rotation latch check, performed by a second individual.
7. Update procedures to require training for all personnel on procedure use, placekeeping, and adherence.
8. Revise procedures to be consistent with INPO 11-003.
9. Modify the index plate so that it is consistently positioned in the same place and rotational fiduciary marks are clear.
10. Institute a requirement and develop equipment for performing latch checks visually.
11. Document that improved latching and latch check processes provide adequate defense against unlatching.
12. Assess the suitability for all tools used in the refueling process and implement changes as necessary to assure adequacy in latching and latch checks.
13. Develop a program for robust qualification of supervisors overseeing refueling operations.
14. Require training for supervisors on oversight.
15. Prioritize and elevate the Aging Reactor Management program emphasizing oversight of communications between groups.

Group Charge

This root cause technical working group was an internal NCNR team (primarily consisting of ROE personnel), commissioned by NCNR Director Rob Dimeo, to gather relevant facts and determine the root cause and contributing factors leading to the event on February 3, 2021. The group consisted of: Tom Newton (Chair), Paul Brand, Randy Strader, Paul Bobik, Justin Hudson, Dan Flynn, David Griffin, Chris Berg, Scott Slaughter, Jeff Burmeister, Sam Colvard, Paul Liposky, Dagistan Sahin, Sam MacDavid, Bryan Eyers, Steven Dewey, Daniel Mattes, Bob Williams, George Baltic, Mike Rowe, David Hix, and Don Pierce.

Methods

Investigation Process

The investigation was performed by conducting interviews, reviewing video surveillance, and reviewing procedures, reports, data, historical records, and emails.

The interviews were held with seventeen individuals over the course of about eight weeks. Key operations personnel were interviewed by the CRO and reactor operations training coordinator.

In addition to the references listed, the following records were referenced in creation of this report:

SAC reports 2011-2020
OMARR reports 2012, 2013, and 2018 review
NBSR Safety Analysis Report
NBSR Technical Specifications
NBSR Operations and Shift Supervisor logs
NBSR refueling sheets
NBSR Operations Schedule
NBSR Operating Instructions

SEC reports

Analysis Method for Causal Factor and Root Cause Analysis

Narrative (section 1) and Timeline (section 2). The information from logs, data, interviews, and records was used to create a timeline of events and associated conditions.

Causal Factor Analysis. The timeline was also used to highlight events and associated conditions for the causal factor analysis. The team evaluated each of these to determine which were direct factors, which were contributing factors, and which events or conditions were not relevant. Participating members received formal root cause analysis training, such as that provided by NIST's Office of Safety, Health, and Environment (OSHE). The root causes are fundamental or systemic causes that permitted the development of the direct and contributing causal factors.

Development of Proposed Corrective Actions

The team reviewed each type of causal factor and developed a list of proposed corrective actions that would help prevent reoccurrence.

Results of the Incident Investigation

Narrative Summary

1.1 Introduction

The neutron source for the NCNR is a 20 MW reactor, the NBSR. The NBSR is moderated and cooled by heavy water (D_2O). The core of the NBSR consists of 30 plate-type U_3O_8 fuel elements, with upper and lower fuel sections 33 cm in length, with a 17.8 cm gap in between (see Figures 1 and 2). The NBSR operates on a 38-day fuel cycle followed by a 12-day maintenance and refueling period. Thus, refueling is done about every 50 days.

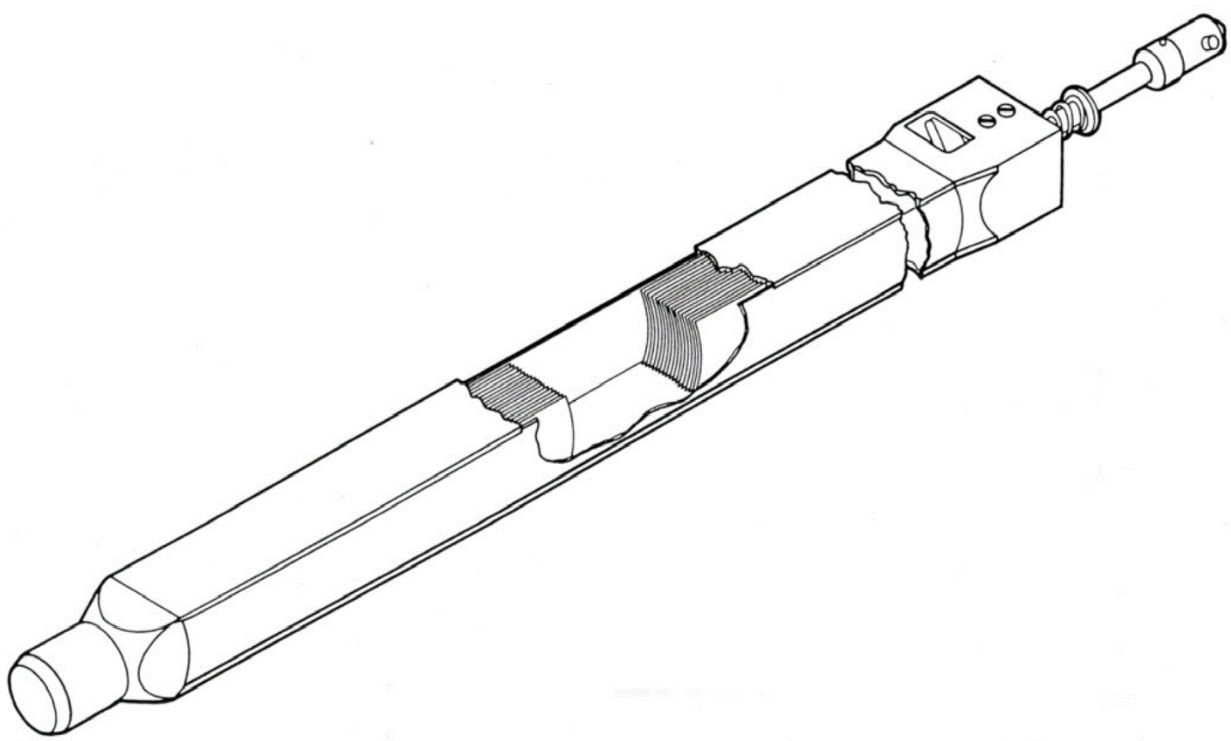


Figure 1. NBSR fuel element

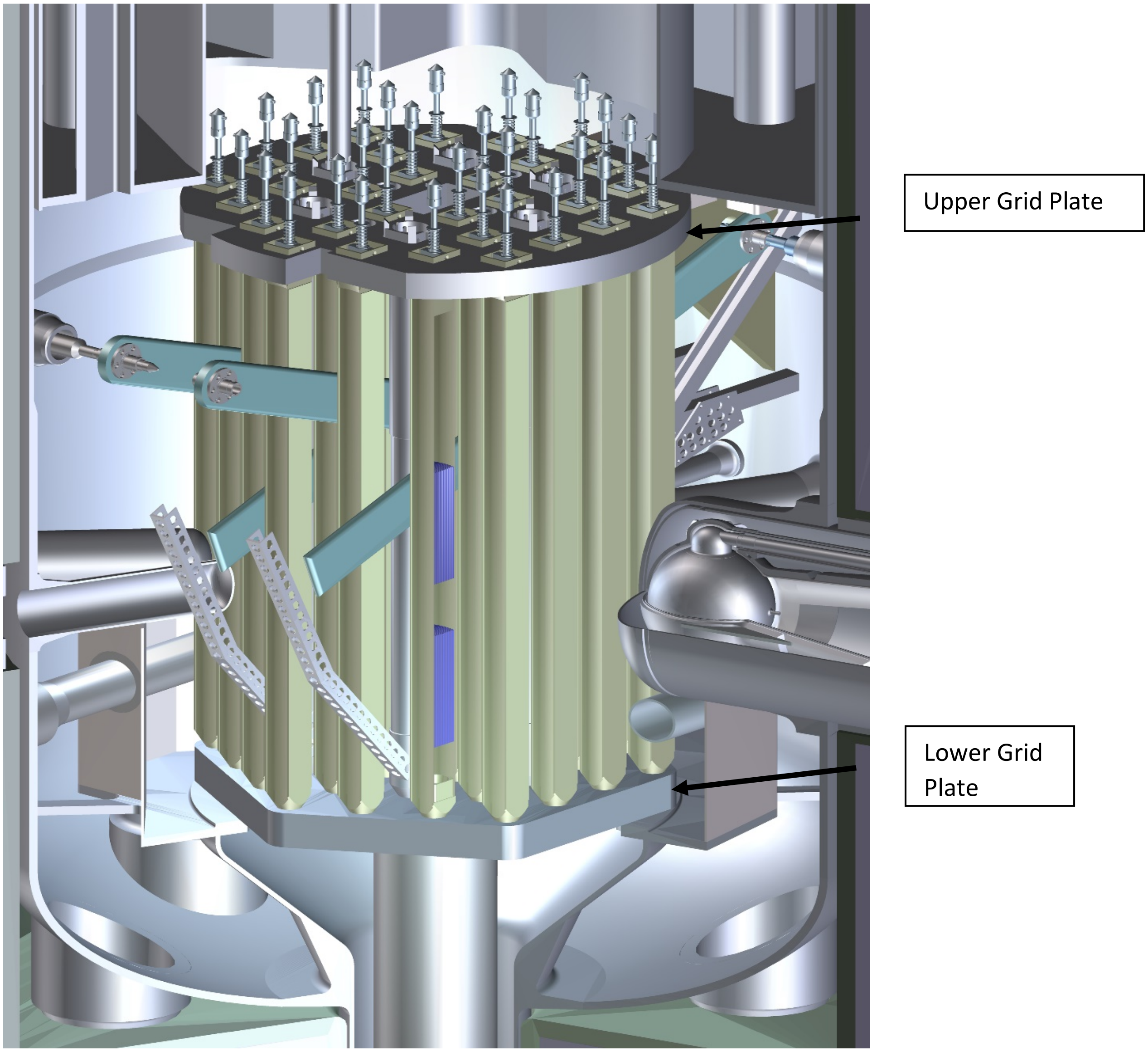


Figure 2. The NBSR core.

On February 3, 2021, following a refueling the previous month, the reactor was conducting normal startup operations. Upon approaching 20 MW, a sudden power decrease was observed, followed about a minute later by increases in radiation levels on radiation and effluent monitors, including the helium sweep fission product monitor, RM 3-2 and stack monitor, RM 4-1, which automatically initiated a major scram. Recognizing the probable presence of fission products and that the stack monitor had exceeded its setpoint for major scram at 50 kcpm, the operator declared an Alert in accordance with EI 0.3,"Emergency Classification and Criteria". The presence of fission products in the ventilation and primary system were confirmed, indicating a fuel element failure. A detailed timeline of events is given in Section 2.

A post-incident in-core video camera investigation revealed that element 1175, a second cycle element in core position J-7, was skewed out of its seat with the nozzle resting on the lower grid plate in an apparent unlatched configuration. The contributing and root causes for this condition are the subject of this report. **Although there is no direct evidence that the fuel element was unlatched prior to reactor startup on February 3, we are assuming that it was unlatched prior to startup.**

1.2 Description of Fuel Latching Process

Refueling at the NBSR is done manually with tools positioned above each core fuel position. Operators are unable to visually observe actual fuel movements and must rely on procedure and feel to position each element. Fuel movements are done remotely with tools ("pickup tools") inserted into the core, as the closed heavy water (D_2O) system must be kept separate from air to reduce tritium exposures to personnel and possible degradation of the D_2O. A positioning plate, the "index plate," is placed above the reactor to guide refueling and positioning of transfer arms (used to move fuel from position to position). Once the element is seated in the lower grid plate, a latch spring mechanism on the fuel element head, shown in Figure 3, must be rotated to secure the element in a notch under the upper core grid plate (Figure 4) so that the element does not move when primary coolant flow is started.

Rotation of the latch is accomplished via a pickup tool that has a slot machined into it to allow removal of the tool in only one azimuthal position (see Figure 5). The upper part of the tool also has a pin positioned so that once the tool is pushed (lowered) against the spring on the fuel element head and rotated, the pin is captured underneath the index plate and not allowed to be brought back up until full rotation is attained, indicating a "fully latched" element. This is designed to prevent "partial" latching where the latch is not fully seated in the notch in the upper grid plate (See Figure 6). In this situation the fuel element is retained in the grid plate, but there is a possibility of the latch key still rotating to a fully unlatched state.

A study of dimensional tolerances [1] was undertaken as a result of this incident. This study showed that, if dimensional tolerances were at or near their specified limits in the correct direction, it would be possible to remove the tool with the element in a "partially" latched position. In addition, post-incident testing has demonstrated this possibility.

After the element is moved and latched into position, two latch checks take place to verify that the latch key is in the latch slot in the upper grid plate. The first is a height check of the tool to judge whether the head of the element height corresponds to that of an element whose latch is in the slot in the upper grid plate. As part of this root cause analysis the fidelity of this height check was examined. It was determined that the dimensional tolerances of this check (about +/- 1/16") were not adequate to verify if an element was partially latched or fully latched. The second check is a rotational check whereby the tool is lowered onto the ears of the element head, then rotated counterclockwise only to verify that the latch is fully rotated into its slot. As stated in the existing refueling procedure, the angle of the fuel element head was to be verified by comparing marks fiduciary on the tool to fiduciary marks on the index plate. However, rotational marks were never put on the index plate, so most operators used their own methods of checking this, usually checking the facing of the tool as compared with the north wall of C200. As a final check, the height of the tool collar is confirmed to be flush with the index plate. It is noted that this check should fail on a fully unlatched element.

1.3 Evolution of Fuel Latch Checks

Upon commissioning in 1967, the original latch check required by the facility license was a height check with flow. A tool was lowered to 12" above the expected top of each fuel element while coolant pumps were running to check if an element was not secured in place. A visual inspection was also allowed by the license, but to prevent coolant contamination, it was not used during a typical refueling.

Over the years, there have been several instances of elements found unlatched after installation but before reactor startup.[2] In addition, there were also two previous occurrences where an unlatched element was discovered during the startup process. On October 14, 1981, an element in core position I-6 was determined to be unlatched after power oscillations were seen at 10 MW. As a corrective action, the latch check procedure was modified to lower the tool to touch the element head.[3] And on September 10, 1993, there was another instance of an element in position J-7 being found unlatched after reactor startup, again by observing power oscillations at 10 MW. The corrective action for this instance was a second redundant check after cycling the pumps off and on.[4]

In 2009, the technical specifications were modified to add the option of a rotational latch check, which has since become the default latching check as described above. The reason for the change was a concern that the on-contact height check might cause an element to become unlatched during the check. The new rotational check is considered to be a more robust method, and the elevation check with flow remains in the technical specifications but is no longer used in facility procedures. The frequency of elements found unlatched or "partially" latched (and subsequently latched) was reduced after 2009 but was not completely eliminated.

Height checks without coolant flow are also performed to meet the intent of the 1993 corrective action for redundant verification, though only the initial rotational check is required by the technical specification. After several years of study, a "go/no-go" gauge was built to more easily verify that the height of the tool (attached to the element) was at the appropriate position.

There is also a check to see if the pickup tool collar is flush with the index plate as a second height check. This was seen as a redundant check but has the same fundamental issues with the height check using the go/no-go gauge and thus may have led to a false sense of security.

1.4 Current Limitations of the Latch Checks

There is currently a requirement in OI 6.1 "Fueling and Defueling Procedures", section 4.3.1, that rotation checks are to be performed after starting the primary pumps for the last time before reactor startup. However, this requirement is neither captured in training, nor referred to in the procedure for starting primary pumps (OI 2.1), so operators are prone to miss this requirement, particularly in an unusual situation where primary pumps are started and stopped multiple times prior to reactor startup.

It should also be noted that the notch in the upper grid plate is 3/16" deep, thus, the height difference between a fully latched element and "partially latched" (i.e. under the grid plate, but not in the notch) is -3/16". If the latch is in the fuel element window, but not under the grid, the height difference is +1/8". Thus, any height measurement must have a resolution (i.e. fidelity) of less than 1/8" to be reliable.

1.5 Tools

Because of wear, the refueling pickup tools above each element position had become more difficult to move over time. These tools were systematically replaced, one-by-one, beginning in 2017 and completing in 2019, except for four positions in the small transfer arms (fabrication of these had been initiated, but is currently on hold). Use of these new tools proceeded uneventfully, but some operators noted a slight difference in using the go/no go gauge during latch height checks. This was not generally communicated to the engineering staff. After the February 3, 2021 event, measurements were made on the tools and it was found that the new tools were, on average, 1/16” longer than the previous tools. A 1/16” change compounds any uncertainties already noted and led to the operators having less confidence in the use of the go/no go gauge for height checks.

Figure 3. Dummy fuel element with latch in latched position

Figure 4. Fuel element head latched into a mockup of the upper grid plate

Figure 5. "J" tool used for element moves, latch rotation and rotation checks.	Figure 6. Mock fuel element head in a "partially latched" position

1.6 Refueling training

Operator candidates are initially trained on the use of refueling tools by use of a fuel test stand in C200. Once the reactor supervisor feels that the candidate is proficient, the candidate is then allowed to participate in fuel handling under supervision, including latching and latch checks. Note: OI 6.2 "Operation of the Fuel Transfer System" was modified in 2018 to include the following requirement: "Non-licensed operators shall not handle fueling tools or manipulate any components on the reactor top during refueling unless competence is demonstrated on the refueling test stand and documented by their Crew Chief in their SRO Qualification Standard." However, this was not implemented in the SRO or shift supervisor qualification documentation, and thus there existed no real qualification of fuel handling or fuel handling oversight. It should be noted that refueling training is primarily focused on the movement of fuel, as it is somewhat complex and there have been occurrences of fuel elements being dropped during movements. The latch check processes, and the importance of the latch checks was not stressed during training. Latching and latch checks are not able to be simulated on the test stand and are only taught during actual refueling.

1.7 Staffing

Since 2015, a total of fifteen licensed operators have either retired or left the organization. Almost every year, several new operator candidates have been hired as replacements. A graph of number of operators in experience categories over the past twelve years is shown in Figure 7.   The decline in experienced operators over the years, as well as the relative youth of the current staff, can be clearly seen. Figure 8 shows a similar decline in the average experience of the SROs and qualified Reactor Supervisors for the past twelve years. The 1/4/21 point shows the experience of the crew performing latch checks after the January 4, 2021 refueling (discussed below).

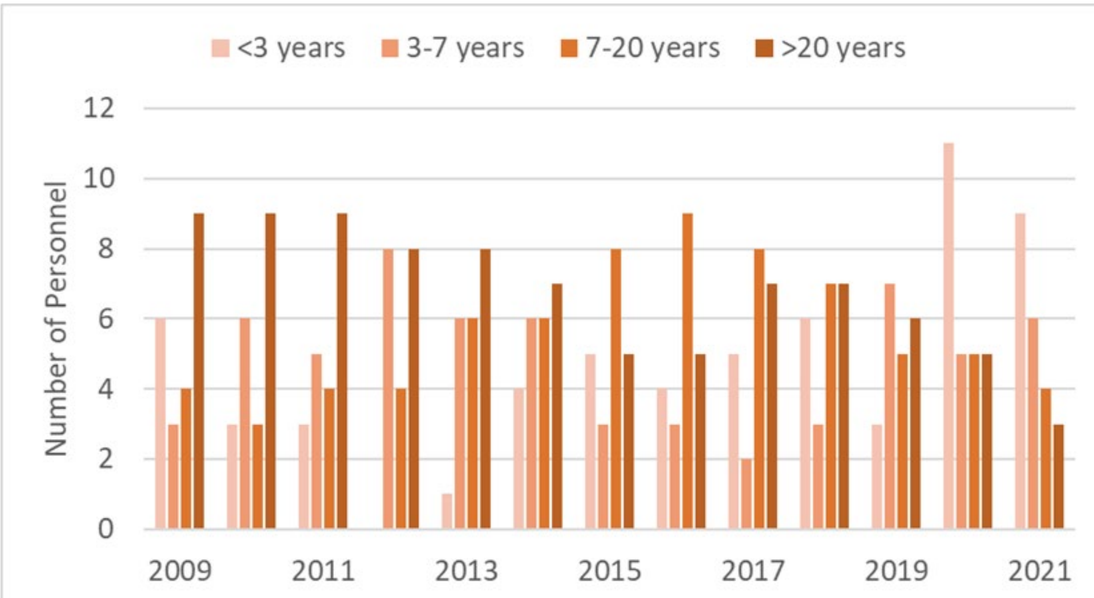


Figure 7. Experience of Reactor Operators

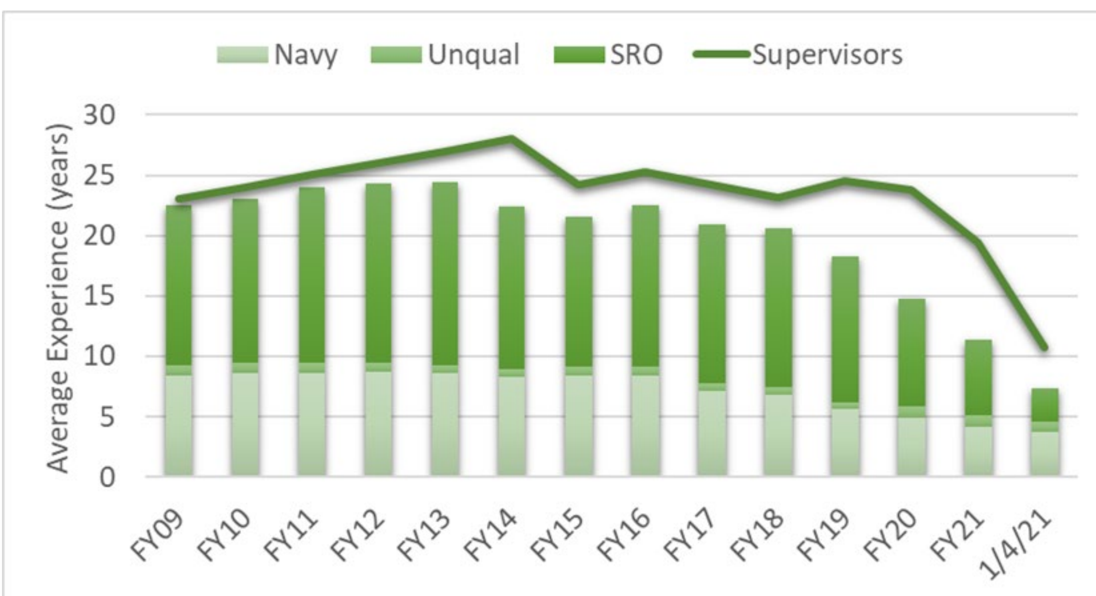


Figure 8. Average experience of SROs and Reactor Supervisors

In the past, operator experience was relied upon to perform many tasks, including refueling. Because of the loss of experience, the NCNR started a transition from knowledge-based performance to a greater reliance on written procedures.   A new CRO was hired in 2019 in part to spearhead this transition and to address complacency issues.   This CRO left in 2020 to pursue other career opportunities. For the remainder of 2020, there were two interim CROs, followed by the current acting CRO who assumed the role in December of 2020. This was noted in the 2020 SAC report:

> "*The Chief of Reactor Operations position has experienced two turnovers in the past year. Additionally, the Deputy Chief of Reactor Operations is expected to retire within the next few months. Volatility in these critical positions and the general loss of facility experience and expertise introduces risk in the proper conduct and oversight of the Reactor Operations Group.*"

Because of the reactor operating cycle and operator shift rotation schedule, the rotating and fixed crews were generally fixed to be in the same cycle where the same limited group individuals were involved in refueling.   Discussions were had for several years about changing shift rotation and possibly adding a fifth training shift. A shift in rotations was periodically made, including in October 2019. As licensed staffing levels decreased, a decision on major changing of shifts was deferred until licensed operator staffing levels could reach more normal levels.

New operator candidates were added to each shift so that in late 2020 and early 2021, a shift typically contained two licensed SROs and two trainees. The COVID shutdown from March to July of 2020 had a fairly substantial impact on training in that candidates did not have the opportunity to participate in refuelings, among other reactor operations duties. There was an operator licensing exam given in late June of 2020 by the NRC. This exam had been postponed twice at NRC request and due to COVID, it was uncertain when another exam would be able to be scheduled. Fuel handling qualification of some candidates (including SRO#1) were made by discussion and observation on the practice stand by the shift supervisor. As a result, there were four individuals that received an operating license without ever having performed actual fuel movements on the reactor top.

1.8 Chain of Events

1.8.1 January 4 refueling

A routine refueling was scheduled on January 4, 2021. The day shift crew consisting of two experienced SROs (RS#2) and two trainees (switching positions, T#1 and T#2) performed the refueling and latching of the elements. Review of video footage could identify no improper movements, including that of the installation and latching of the J-7 element, although the difficulty in moving the tool can be seen. However, this footage is not conclusive of the final status of the J-7 latch. The following are excerpts from notes from an interview with the day shift crew:

> *"The licensed operators stated that there was a trainee on the reactor top learning how to move fuel. Both indicated the trainee had to realign the element for insertion through the upper grid plate. They also indicated that there was difficulty moving the collar through the index plate (rubbing) when performing the height verification. They presumed that this caused the height check to fail. A licensed operator resumed control and was able to "wiggle" the tool into proper position. The height check passed after moving the tool into position. Both operators stated they believe the element was latched or at least partially latched upon*

> *completion of the procedure. One operator stated that it is difficult to verify the steps of the procedure without the "feel" while visually watching. One operator stated that J-7 was the last element moved in vessel. One operator stated that there were many issues with the index plate alignment where the tool would rub during the process."*

During shift turnover, the outgoing day shift supervisor asked the incoming (swing shift) crew if they were comfortable with performing their assigned tasks, which was to perform the latch checks. The crew stated that they were. The oncoming crew consisted of two trainees (T#3 and T#4) and one newly licensed SRO (SRO#1) for which all of them was their first refueling as reactor top crew members. The reactor supervisor overseeing this crew on the reactor top (RS #1) had only recently been promoted to supervisor and had performed latch checks four times previously. The first element checked was in position J-7.

Video surveillance of this and all other checks shows that the latch checks were performed <u>improperly:</u> (1) the tool was rotated in the wrong direction, and (2) the rotation orientation check used an improper reference. In addition, the subsequent check of height of J-7 (a check to see if the tool collar was flush with the index plate) was found to be slightly high. This was attributed to the longer new tools. The effect of this improper check is uncertain but could possibly have worsened the condition of a partially latched element, rotating it towards a more fully unlatched position. The following are excerpts from notes from an interview with the swing shift crew:

> *"The shift supervisor stated that they were not referencing the procedure and not performing the procedure as written. One of the reactor top operators [RS #1] stated that the rotational check tool did not go down correctly. They stated that he did rotate the bottom part of the clutch to get the tool over the ears. To them it seemed the collar notch referenced in [OI 6.1] 4.3.6 was in the proper alignment. This operator noted that the procedure was out but was not being referenced. They stated that this was the first time both trainees performed the latch verifications. The operator stated that he usually has performed setup for fuel movement and has not performed the latch verifications often. He also stated that the go/no go gauge used to be used to ensure the collar of the tool was flush with the index plate. Since the new tools were installed collar is no longer flush.*
>
> *The second reactor top operator [SRO #1] stated it was their first time performing rotational latch verifications. They stated they were watching one of the trainees go through the maze down to element 1175. The operator stated they did rotate the tool in the clockwise direction and that they were not referencing the procedure during the check. They also stated that they did not know that an unlatched element may result in a failure of the cladding and a fission product release. The trainee using the tool does not remember turning the tool in the counterclockwise direction. They did feel that their questions were answered as they arose. The second trainee was operating the crane. They stated there was a pre-job brief. They were observing and listening as the checks were being performed."*

Because of concerns of COVID exposure to NCNR personnel, the reactor startup was postponed to February 3. In order to maintain primary and secondary temperatures at appropriate levels, the primary pumps were started and stopped at least daily in accordance with standard practice. The pumps were started and stopped a total of 44 times prior to reactor startup on February 3 after the refueling operation on January 4. Although there is no way to fully confirm this, it is believed that during this time, the unlatched element in position J-7 moved out of its seat in the lower grid and skewed toward the element in position H-7, preventing any forced primary flow from reaching the fuel. As mentioned above, the rotation check was not repeated prior to reactor startup, as is specified in OI 6.1.

1.8.2 The February 3 Event

Preparations for reactor startup on February 3 proceeded without incident. Startup of the reactor began at 0800 and reactor power was taken to 10 MW (half power) at 0900, as is routinely done during a startup (see Nuclear Instrument Response section below). In accordance with OI 1.1 step 5.14, the operator (RS #2) paused to look for potential power oscillations. No oscillations were observed. Startup then proceeded. The following excerpt is from the initial report to NRC, dated February 16, 2021:

> *"At 0906, the operator began raising power to go to full power. At 0907, when the reactor power had just reached 15 MW, there was a sudden drop in power, down to about 7 MW, followed less than a minute later by sudden increases on several radiation monitors, including the stack radiation monitor, RM 4-1. At 0909, the stack monitor reached its setpoint of 50kcpm, tripping a major scram, which scrams the reactor and seals the confinement building, preventing the possibility of any further release. Based on the fact that the fission product monitor in the helium sweep gas system indicated well above the 50 kcpm criteria for an alert, the reactor shift supervisor recognized the potential for a fuel cladding failure and declared an Alert at 0916, in accordance with NBSR Emergency Instruction 0.3 2.2.2."*

Although there are several lessons learned and proposed corrective actions about the event response, these are not considered germane to this root cause investigation and are not covered here.

1.8.3 Nuclear Instrument Response

As noted above, it is standard procedure that the reactor power be leveled off at 10 MW to check for any power oscillations. Oscillations of 5-7% power on nuclear instrument (NI) channels had been previously seen with unlatched elements in the 1981 and 1993 events and had been attributed to reactivity changes of an unlatched element moving in the core due to flow pressures. On February 3, no oscillations of significance were observed by the operator. Subsequent analysis shows that there were small, statistically significant (1-2% power) oscillations on the NIs at 10 MW, but they did not exceed the anticipated threshold of 5%. It was determined that these small power oscillations were likely not visibly significant to the operator with the currently installed displays.

The NIs were replaced in 2003 (from intermediate range to full range), but were installed in the same locations and had the same or better responsiveness as the former system, so any oscillations similar to the 1993 event should have been seen. It is speculated that the small amplitude of the oscillations on Feb 3 may have been due to the element becoming stuck in a skewed position during the multiple pump starts and stops over the previous month as shown in Figure 9. Nuclear analyses of the event show that minor power oscillations are predominantly caused by partial coolant voiding due to departure from nucleate boiling in the fuel element; but any rattling movements of the element itself in the core could also have an impact.

During the approach to 20 MW, a large, sudden drop in power was observed on the NIs. The negative reactivity insertion required to cause this drop has been estimated between 25-35 cents. Simulations of the event show this was most likely due to an onset of significant voiding, which causes a complete voiding of coolant inside the element that reduces neutron moderation. The fission product monitor response occurred approximately one minute later, as seen in Figure 10.

All NIs recorded a typical shutdown decay pattern following the scram.

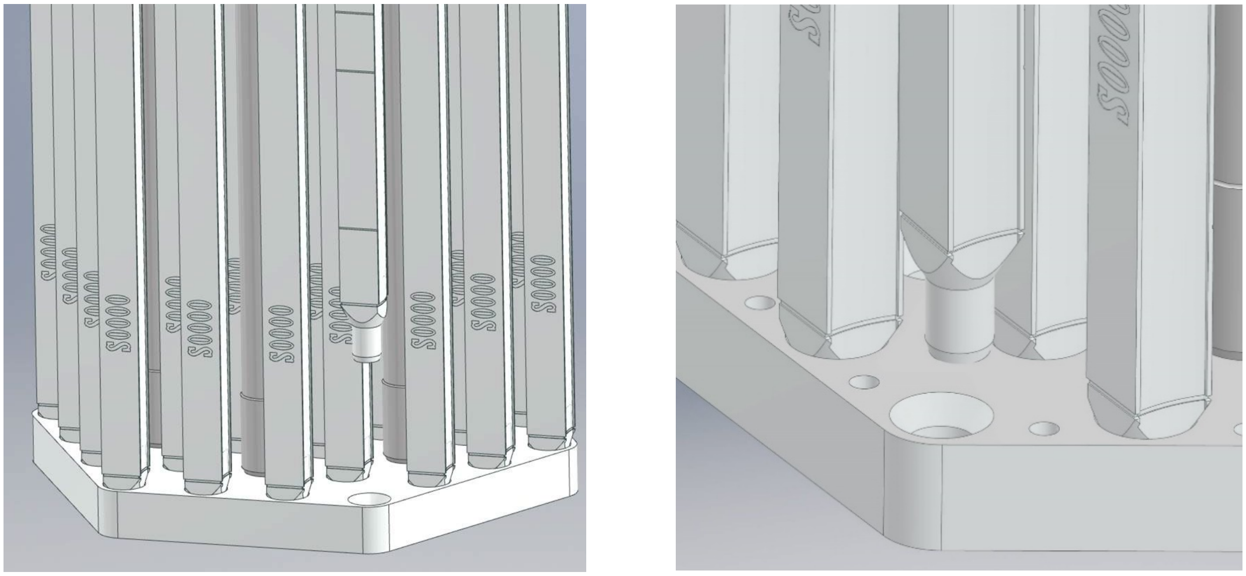


Figure 9 (left) An unlatched element floats on a jet of primary coolant emitted by the lower grid plate. (right) An unlatched element skews out of its conical seat due to multiple pump starts. It is speculated that “floating” elements were seen in 1981 and 1993, while a “skewed” element condition was discovered in 2021 (after securing flow) using an in-core camera.

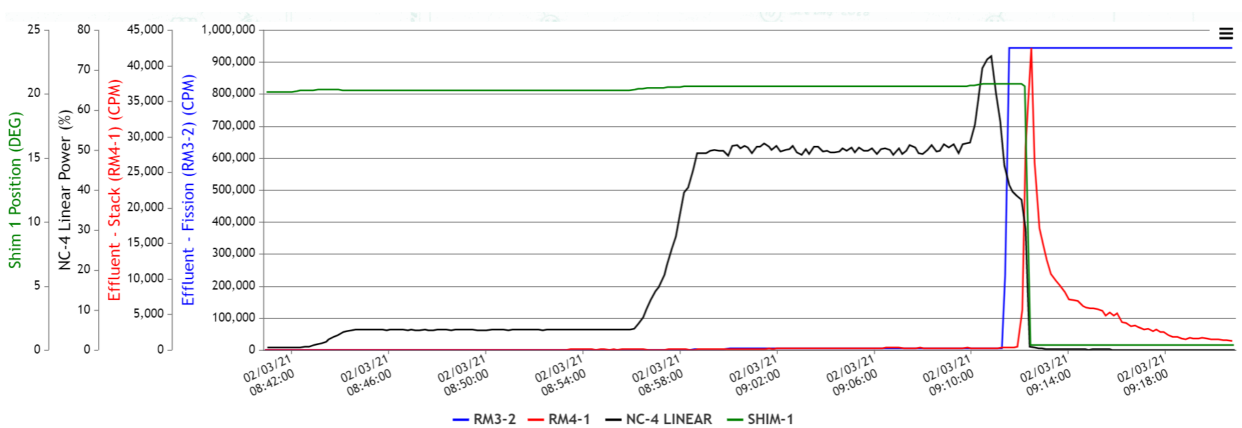


Figure 10. NI-4 record of rise to power (black) on Feb 3 with stops at 1 MW and 10 MW. Although this scale was not seen on the control room chart recorder by the reactor operator, the noise due to departure from nucleate boiling at 10 MW is readily apparent. The rise in fission product monitor (blue) and stack monitor (red) can be seen shortly after power ascension.

1.9 Conclusion / Fuel Failure

The fuel failure was a direct result of element 1175 being unlatched when the reactor was started. When primary coolant flow was started it displaced the element. As a result of the displacement, the fuel in the element received significantly reduced cooling. Simulations demonstrate that above approximately 8 MW of power fuel elements could begin to blister in a reduced cooling state. As power was increased in the reactor above 10 MW, the temperature of the fuel in the displaced element rose dramatically resulting in failure of the fuel cladding (aluminum) and release of fission products from the fuel. This group determined that element 1175 was unlatched as a result of inadequate training of reactor operators, inadequate refueling procedures, a lack of procedural adherence and enforcement, and inadequate methods for verifying elements were latched.

1.10 References

1. Hix, David, "Tolerance Stackup for Fuel Element Locking Mechanism", Powerpoint presentation to root cause group, 3/31/21.
2. Memo from Tom Myers, 10/30/06
3. NBSR Hazards Evaluation Committee minutes, meeting 237, October 15, 1981
4. NCNR Safety Evaluation Committee minutes, meeting 319, September 13, 1993
5. December 22, 2020 NCNR Report to NRC, "NRC Event Report 55034"
6. OI 6.1
7. OI 6.2
8. NBSR Technical Specifications

1. Timeline

Date	Time	Event	Notes
2/9/17		Begin systematic replacement of refueling pickup tools	All but four tools had been replaced by 7/10/19. J-7 tool was replaced on 3/6/19.
5/13/19		New CRO starts at NCNR	
3/2/20		Trainee T #1 starts at NCNR	Conducted refueling operation on January 4th, 2021, day shift.
3/16/20		Trainee T #2 starts at NCNR	Conducted refueling operation on January 4th, 2021, day shift.
3/17/20 – 7/6/20		NCNR closed due to COVID pandemic	Shut down with 25 days left in cycle 651.
3/30/20		Trainee T #3 starts at NCNR	Conducted latch checks on January 4th, 2021, swing shift.
4/27/20		Trainee T #4 starts at NCNR	Conducted latch checks on January 4th, 2021, swing shift.
6/26/20 – 7/2/20		NRC licensing exam for SRO#1, another operations candidate and four engineers.	Exam had been postponed twice at NRC request due to NRC staffing issues.
7/6/20		Reactor restart for the remainder of cycle 651	
8/14/20		CRO resigns; interim CRO #1 starts	
9/2/20		Reactor startup for cycle 652	
9/28/20		Supervisor qualification board for RS #1	RS #1 passed and was certified to be a reactor supervisor. Exam focused on management and emergency response, not refueling.
10/7/20		Element 1175 received at NCNR	There were no anomalies noted.
10/23/20		Element 1175 inserted into core position J-1 for its first cycle (653).	
11/8/20		Interim CRO #1 leaves; Interim CRO #2 starts	
11/10/20		Reactor startup for cycle 653	
12/8/20		Interim CRO #2 retires; Interim CRO #3 starts	
12/19/20		End of cycle 653	
1/4/21	0800	Day shift (RS #2, SRO #2, T #1 and T #2) perform refueling to prepare for cycle 654. During the shift turnover, the day shift supervisor asked the oncoming (swing shift) supervisor if they were comfortable with their assigned tasks of latch checking.	Routine refueling. T #1 and T #2 switched off training duties. Difficulties noted moving through index plate. Height check fail attributed to these difficulties.
1/4/21	1500	Swing shift (RS #1, SRO #1, and T#3 and T#4) performs latch checks.	Element 1175 in position J-7 was the first one to be checked. These checks were done incorrectly and may have resulted in a causing or worsening of an element 1175 unlatched condition.

1/4/21		Decision made to postpone startup until 2/3 due to concerns of COVID spread among the staff.	
1/4/21-1/31/21		Primary pumps were started and stopped a total of 44 times.	This follows normal shutdown practice of periodically circulating the primary and secondary systems to remove decay heat and keep the secondary system warm in the winter. There is potential that element 1175 was skewed out of position during these pump operations.
1/31/21	2100	OI 1.1 "Reactor Startup" completed	There was no final latch check performed. Although this requirement is noted in OI 6.1 "Fueling and Defueling", it is not listed in OI 1.1 or OI 2.1 "Startup, Operation, and Shutdown of Primary Coolant System".
1/31-2/2/21		Eight training startups completed.	All startups were to 100 kW or below. No abnormal conditions noted.
2/3/21	0816	Reactor startup begins	
2/3/21	0831	Reactor power leveled at 100 kW	All indications normal.
2/3/21	0846	Reactor power leveled at 1 MW	All indications normal.
2/3/21	0900	Reactor power leveled at 10 MW	Operator (RS #2) looked for but did not observe any significant oscillations on neutron instruments.
2/3/21	0906	Ascension to full power began.	
2/3/21	0907	Sudden drop in power	It is believed that this was caused by the onset of significant voiding in element 1175.
2/3/21	0908	Increases of radiation seen on area and effluent monitors	Beginning of failure of element 1175.
2/3/21	0909	Automatic reactor major scram on high stack radiation levels	Confinement building sealed.
2/3/21	0916	Alert declared	

2. Causal Factors and Recommended Corrective Actions

Root Cause Analysis			
Causal Factor:	***Description:***	***Root Cause:***	***Proposed Corrective Actions****
1. A loss of experienced operators over the past few years resulted in fewer personnel having experience in refueling and latching. 2. Training and proficiency in the process of latching and latch checking was inadequate 3. The crew performing latch checks had limited experience in performing the check. On 1/4/21, except for the supervisor, the crew performing the latch checks had never performed a latch check. 4. A large influx of trainees and NCNR closure in 2020 due to COVID concerns resulted in a lack of opportunity for training on refueling. 5. The importance of latch checks was not appreciated by the staff, resulting in some complacency.	During the 1/4/21 refueling, the element was not properly latched. Personnel performed the latch checks incorrectly.	**Root #1: The training and qualification program for operators was not on par with programmatic needs.** a. Lack of robust qualification and specification for personnel performing fuel movements and latching. b. Lack of opportunity for operators to be adequately trained in latching. c. Lack of fully understanding the consequences of inadequate latch checks.	1. Require proficiency training for personnel prior to all refuelings, emphasizing the importance of latching and procedural compliance. 2. Develop program for robust qualification of operators and candidates in moving fuel. 3. Develop system for knowledge and skills management in the presence of personnel attrition.
1. OI 6.1 was not adequately written to capture all aspects of latching and latch checks. 2. OI 2.1 did not capture the requirement to perform a latch check prior to final pump restart. 3. Overall procedures did not capture sufficient institutional knowledge. 4. There was a false sense of security in having redundancy in checks.	Procedure inadequacy.	**Root #2: Procedures as written do not capture necessary steps in assuring elements are latched.**	1. Rewrite OI 6.1 and OI 6.2 to capture aspects of movements to align with training. 2. Reinstitute requirement for latch checks prior to final pump restart and modify OI 2.1. 3. Institute method of visual checks.

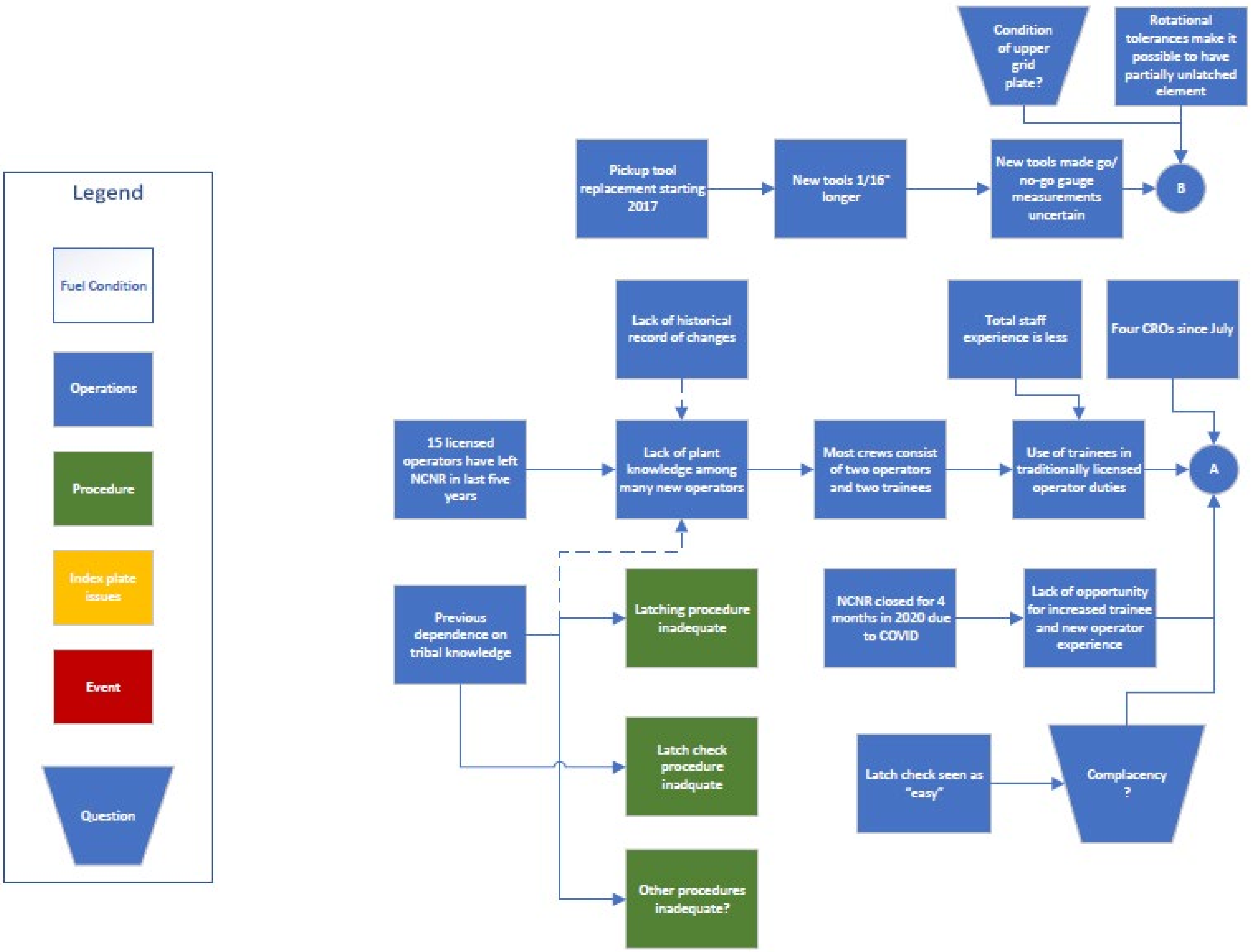
			4. Institute a redundant rotation latch check, performed by a second individual.
1. Culture in ROE was that of relying on training rather than procedure. 2. AR 1.0, "Conduct of Operations" was not fully adhered to.	OI 6.1 was not followed during latch checks on 1/4/21.	**Root #3: Procedural compliance was not enforced.** a. Latch check procedures were not followed.	1. Update procedures to require training for all personnel on procedure adherence. 2. Revise procedures to be consistent with INPO 11-003.
1. Partly because of new pickup tools being used, the lack of adequate height fidelity caused confusion. 2. There was a false sense of security in the fidelity of height gauges. 3. There was no engineering analysis of the effect of new pickup tools impact on height gauge. 4. There is no mark on the index plate for proper orientation of rotation latch check.	Latch determination issues were not addressed.	**Root #4: Inadequacies existed in the fidelity of latch determination equipment and tools** a. Lack of adequate rotation fiduciary marks.	1. Modify index plate so that it is consistently positioned in the same place and rotational fiduciary marks are clear. 2. Institute method of visual checks. 3. Document that improved latching and latch check processes provide adequate defense against unlatching. 4. Assess efficacy of all tools used and determine necessary improvements.

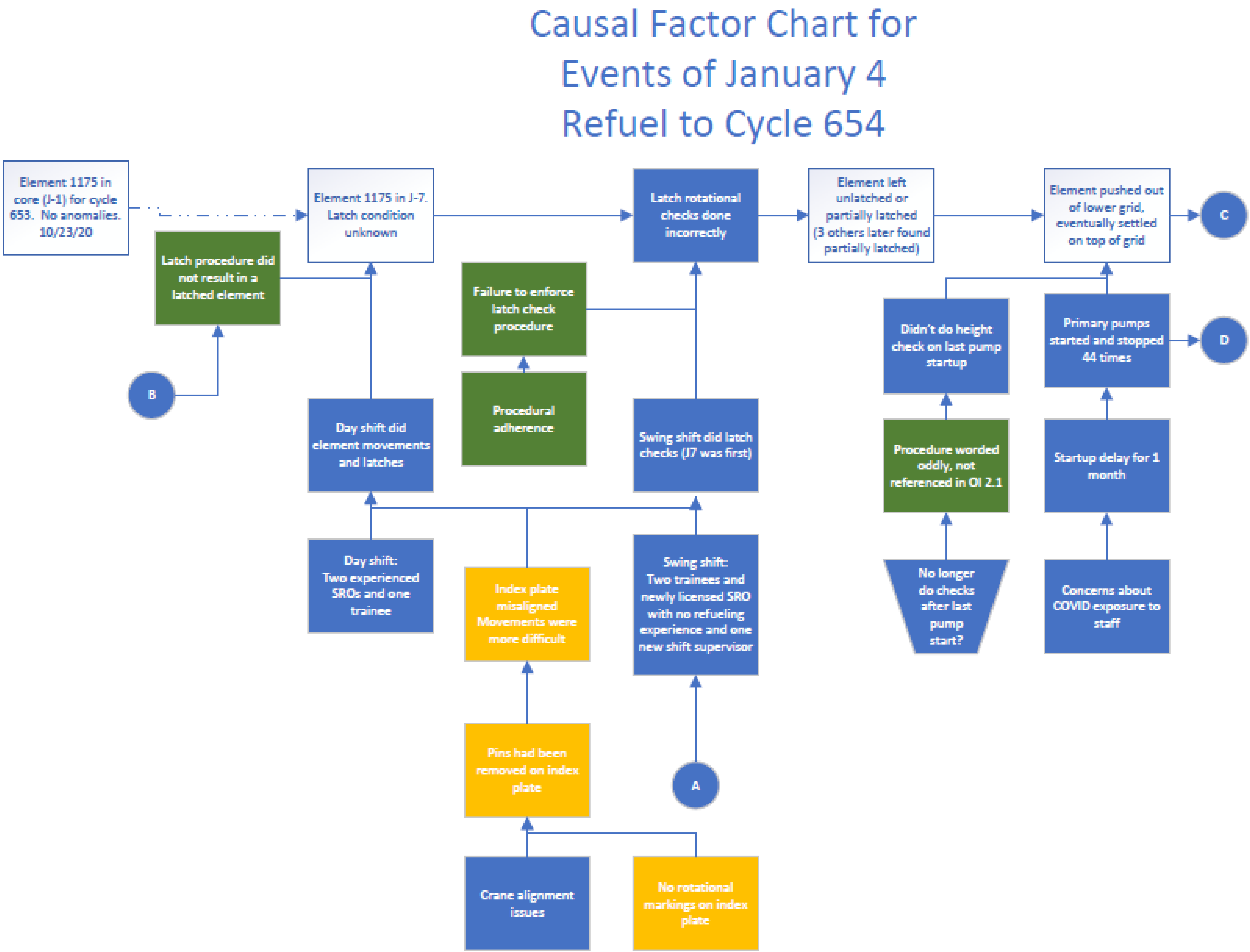
1. No sign off/review of refueling sheets by supervisor.		**Root #5: There was inadequate management oversight of refueling staffing.** a. Lack of training for oversight of refueling operations. b. There was inadequate oversight in following procedures as written. c. Lack of communication and addressing of fidelity issues.	1. Develop program for robust qualification of supervisors overseeing refueling operations. 2. Require training for supervisors on oversight. 3. Prioritize and elevate the Aging Reactor Management program emphasizing oversight of communications between groups and ensuring that maintenance and other issues identified are resolved.

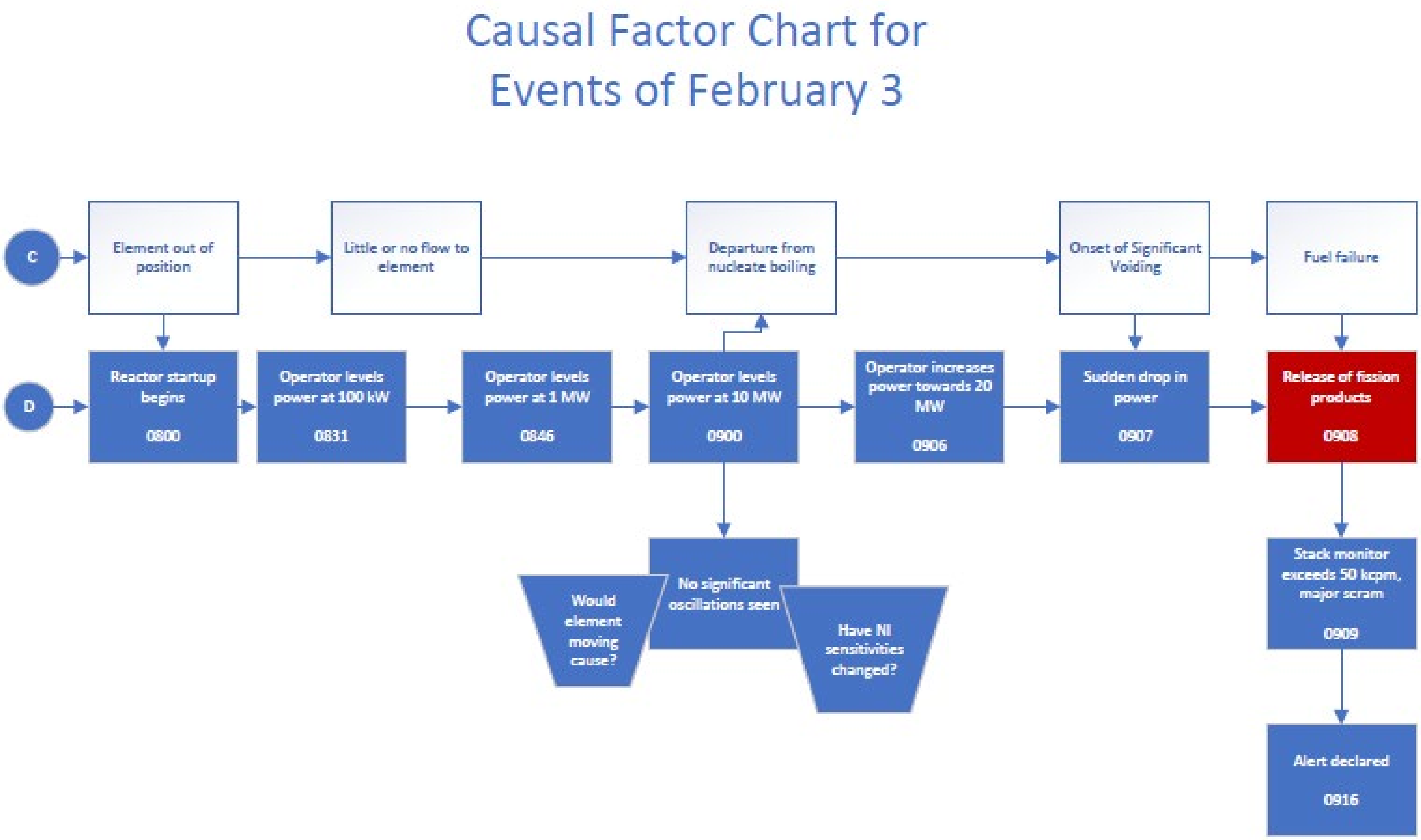
***For details see Corrective Action List, updated periodically**

Appendix A

Causal Factor Chart


Legend
Fuel Condition
Operations
Procedure
Index plate issues
Event
Question
Condition of upper grid plate?
Rotational tolerances make it possible to have partially unlatched element
Pickup tool replacement starting 2017
New tools 1/16" longer
New tools made go/ no-go gauge measurements uncertain
B
Lack of historical record of changes
Total staff experience is less
Four CROs since July
15 licensed operators have left NCNR in last five years
Lack of plant knowledge among many new operators
Most crews consist of two operators and two trainees
Use of trainees in traditionally licensed operator duties
A
Previous dependence on tribal knowledge
Latching procedure inadequate
NCNR closed for 4 months in 2020 due to COVID
Lack of opportunity for increased trainee and new operator experience
Latch check procedure inadquate
Latch check seen as "easy"
Complacency ?
Other procedures inadequate?


Causal Factor Chart for
Events of January 4
Refuel to Cycle 654
Element 1175 in core (J-1) for cycle 653. No anomalies. 10/23/20
Element 1175 in J-7. Latch condition unknown
Latch rotational checks done incorrectly
Element left unlatched or partially latched (3 others later found partially latched)
Element pushed out of lower grid, eventually settled on top of grid
C
Latch procedure did not result in a latched element
Failure to enforce latch check procedure
Didn't do height check on last pump startup
Primary pumps started and stopped 44 times
D
B
Procedural adherence
Day shift did element movements and latches
Swing shift did latch checks (J7 was first)
Procedure worded oddly, not referenced in OI 2.1
Startup delay for 1 month
Day shift: Two experienced SROs and one trainee
Index plate misaligned Movements were more difficult
Swing shift: Two trainees and newly licensed SRO with no refueling experience and one new shift supervisor
No longer do checks after last pump start?
Concerns about COVID exposure to staff
Pins had been removed on index plate
A
Crane alignment issues
No rotational markings on index plate


Causal Factor Chart for
Events of February 3
C
Element out of position
Little or no flow to element
Departure from nucleate boiling
Onset of Significant Voiding
Fuel failure
D
Reactor startup begins 0800
Operator levels power at 100 kW 0831
Operator levels power at 1 MW 0846
Operator levels power at 10 MW 0900
Operator increases power towards 20 MW 0906
Sudden drop in power 0907
Release of fission products 0908
No significant oscillations seen
Would element moving cause?
Have NI sensitivities changed?
Stack monitor exceeds 50 kcpm, major scram 0909
Alert declared 0916