Perceived Low Risk Processes Can Be Important - Lessons to a Regulator Based on a Nuclear Fuel Facility Process Event

Donnie Harrison
U.S. Nuclear Regulatory Commission
Rockville, MD USA
Donnie.Harrison@nrc.gov

Dr. April Smith
U.S. Nuclear Regulatory Commission

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Abstract

On July 14, 2016, a nuclear fuel fabrication facility licensee (i.e., the owner/operator) notified the U.S. Nuclear Regulatory Commission (NRC) that significant amounts of uranium were discovered, potentially exceeding their criticality safety evaluation (CSE) mass limits, during an annual inspection of a scrubber ventilation system. The licensee subsequently confirmed not only significant mass several times higher than the CSE mass limits in the scrubber and associated ventilation ductwork, but also significant concentrations of uranium. As part of the NRC's platform of continuous improvement, a lessons-learned activity was initiated to explore opportunities for improving the NRC's regulatory processes for early identification of facility operational issues and preventing such events in the future. This paper describes the event, some of the licensee's root causes that led to this event, some of the reasons why the NRC did not identify this condition (and similar conditions at this and other facilities) through its regulatory processes prior to the event, and the improvements being considered to enhance these NRC regulatory processes.

Background and Context

Nuclear Fuel Fabrication Facility

Uranium is used as the fuel for the existing commercial nuclear power plants in the United States. To prepare uranium for use, it undergoes the steps of mining and milling, conversion, enrichment, and fuel fabrication. This last step in the process of turning uranium into useable nuclear fuel is performed at a nuclear fuel fabrication facility. Typically such a facility receives uranium in the form of uranium hexafluoride (UF_6) that has been "enriched" so that the amount of the fissile uranium isotope (^{235}U) is increased from its naturally-occurring level of about 0.7 percent to between 3 and 5 percent (referred to as low-enriched uranium).

There are three main stages in the fabrication of the nuclear fuel: 1) chemically converting the incoming UF_6 into uranium dioxide (UO_2) powder, 2) pressing the UO_2 powder into small cylindrical pellets, which are then baked at high temperatures and finished to precise dimensions, producing high-density, accurately shaped ceramic UO_2 pellets, and 3) loading the fuel pellets into fuel rods, whereby they are sealed and assembled into a final fuel assembly structure for shipment to a commercial nuclear power plant.

In this regard a fuel fabrication facility is similar to other facilities that fabricate items from raw materials using chemical manufacturing processes, with the added twist that the material involved is fissionable. That is, at the nuclear level, with the absorption of a neutron the fissionable uranium, especially the fissile uranium isotope ^{235}U, can split and release energy and more neutrons to cause additional fissions in other uranium atoms. Typically, the neutrons must be slowed down (referred to as moderated) for the ^{235}U to be able to capture (absorb) them. This slowing down, or moderation, of the neutrons is achieved by having the neutrons impact light nuclei; the most common being the hydrogen present in water (as such, water is referred to as a moderator). When sufficient fissionable uranium is present in the right geometry and the neutrons are sufficiently slowed down so they can be captured by the uranium, a self-sustained fission chain reaction can occur, which is referred to as achieving criticality. This phenomenon creates a unique and significant hazard to workers in the vicinity of the material, including exposure to potentially lethal amounts of neutron and gamma radiation, which is released during a criticality event.

The regulations for these facilities require the licensee to evaluate the hazards associated with these processes (referred to as an integrated safety analysis (ISA)) and to establish appropriate physical controls and/or management measures to prevent and mitigate these hazards. The regulations also require the licensee to re-evaluate these hazards when process changes and modifications are implemented and to annually submit to the regulator, the U.S. Nuclear Regulatory Commission (NRC), a listing of the changes/modifications to the processes and any revisions to their ISAs. For these types of facilities, controls are established to prevent criticality events from happening. The established controls are typically related to one or more of the aspects mentioned above: limiting the amount of available fissionable material, maintaining a safe geometry or configuration, and/or avoiding the means of moderation.

The Event

What Happened?

On May 28-29, 2016, a licensee conducted an annual inspection and cleaning of a scrubber ventilation system. This particular scrubber is one of the main air scrubbers for the nuclear fuel conversion process, which as described above is part of the first stage in fabricating fuel. The scrubber is connected to numerous processes within the nuclear fuel conversion area and operates as a cross-flow horizontal wet-packed bed scrubber where a recirculating scrubbing liquid is used to absorb soluble gas molecules and knock down suspended solids, including uranium bearing particles, from the ventilation air stream prior to discharge to the atmosphere. The scrubber system consists of: an inlet transition area from the ventilation ducting, a scrubber vessel that contains specialized packing material to increase the surface area of the scrubber liquid to allow for more absorption of gaseous contaminants, a demister that removes moisture prior to HEPA filters, a duct heater that removes vapor, sump tanks that collect the liquid from the scrubber drain, and bag filters that collect any solids or salts in the liquid. Being a large wet environment, neither geometry nor moderator are relied upon for critically control in the scrubber ventilation system. Rather, controls and measures that limit the accumulation of any significant quantity of uranium are the sole means of criticality control. In addition to some physical features that are credited in the analysis for minimizing material transport to the scrubber ventilation system, such as vacuum breakers, the annual inspection and cleaning is an activity that could be used to periodically confirm the veracity of their ISA for this system.

When the scrubber ventilation system was inspected, a large mass of material was found inside the large attached scrubber inlet transition area and subsequently within the scrubber vessel itself. At the time, the licensee believed that the uranium concentration of the material was low. The licensee sent samples of the material to a lab for analysis of the composition. The licensee received the results of the initial lab analysis on May 30, 2016, which indicated a significant concentration of uranium. The licensee did not consider the results from the lab and restarted operation of the system. Over a month later, on July 13, 2016, the licensee received the results of additional lab analyses that confirmed the earlier results indicating that the concentration of uranium was almost fifty percent (50%) and significantly exceeded the criticality safety evaluation (CSE) mass limit for the process. The licensee reported the event to the NRC on July 14, 2016.

Why is This Event Important?

This event did not result in a criticality. However, because there were no physical controls or measures available to prevent a criticality (i.e., all controls and measures failed to prevent the accumulation of uranium significantly above the CSE mass limit), this event represented a significant safety concern. The subsequent discovery of similar conditions at this and other fuel fabrication facilities has reinforced the need to address the concerns and weaknesses raised by this event in both the licensees' and regulator's processes.

Root Causes for the Event

What Led Up to This Event?

Throughout a period of more than a decade before the event, a combination of process changes, analysis assumptions, and operational approaches created the environment for this uranium accumulation event. As described below, a number of factors led up to the licensee's slow response to the discovery of a large quantity of material within the scrubber ventilation system, poor decision making after the discovery, and delayed reporting.

In 2002 this scrubber replaced another scrubber and over a number of years ventilation discharges from other processes were rerouted to this scrubber. The scrubber was originally designed to scrub acidic off-gas; however, many of the current feed streams contain ammoniated (basic) off-gas. The feed streams all tied together through a network of ventilation ductwork of various diameters to a large diameter section before entering the transition section of this scrubber, reducing the linear velocity of the flow and allowing greater reaction time between the scrubber solution and the incoming feed streams.

In June 2009 the licensee implemented a new safety basis for the scrubber ventilation system that lowered the CSE mass limit by more than a factor of 60 and installed expansion plenums on a vent line, which the licensee assumed would reduce the amount of particulates that would travel to the scrubber. However, the licensee never considered the potential for the uranium to accumulate in a chronic fashion within the scrubber ventilation system. Further, the licensee incorrectly assumed that only minor amounts of uranium powder were expected to accumulate in the scrubber ventilation system. In December 2009 the licensee identified significant accumulation and performed additional modifications to remove an ammonia line. In 2010 the licensee instituted periodic cleaning of various processes. In April 2015 the licensee revised a procedure and included a note that based on "past experience the [percentage of uranium] of the trapped powder is approximately 45-48%."

Material buildup was still periodically observed and in April through May of 2016 large slabs of material would become dislodged during pressure washing and fall into the scrubber ventilation transition section. The operators were directed to continue to pressure wash the material so it would dissolve. Though not the desired result, it was fortuitous that the material did not dissolve, because the insoluble ammonium-uranyl-fluoride mixture prevented the formation of a critical mass configuration.

Why Did the Licensee Choose Not to Report the Event Immediately?

In accordance with the regulations, licensees should report an event to the NRC within one hour in which there are no items relied on for safety (IROFS) available and reliable to perform their function that results in the failure to meet specified regulatory performance criteria. On May 30, 2016, the licensee received the results of a sample taken from the material removed from sections of the scrubber ventilation system that indicated high uranium concentrations. However, on May 31, 2016, the nuclear criticality safety (NCS) engineer, unaware of the sample results and assuming low uranium concentration, declared that the accumulated material did not challenge the CSE mass limit. As a result, the licensee did not immediately perform a detailed evaluation to determine whether the material discovered could have exceeded the safety basis.

On June 1, 2016, after completion of the cleaning activities, the NCS engineer communicated to the process engineer that there were no issues from the NCS group with restarting the scrubber ventilation system. Even though the process engineer was aware of the sample result that clearly indicated the CSE mass limit had been exceeded and a detailed evaluation of the credited controls (i.e., IROFS) was needed (because it had failed to prevent the accumulation), the licensee restarted the system. Only after receiving additional lab results confirming the high uranium concentration did the licensee stop the process and report the event to the NRC on July 14, 2016.

What Were Some of the Root Causes for the Event?

Fundamentally, the licensee's configuration management program did not ensure that process operational and physical changes were properly designed, implemented, and analyzed (including inadequate consideration in the affected ISAs) to prevent adverse impacts to the scrubber ventilation system safety basis. The larger than assumed carryover of uranium to the system and the complex chemical interactions that occurred due to the various input streams created ammonium uranyl fluoride, which is mostly insoluble in water, plated out on the scrubber ventilation surfaces and within the scrubber vessel. Over time, as the process and operations were changed, the licensee's assumptions regarding uranium accumulation, chemical interactions, and process controls, upon which the licensee's safety basis was established, became invalid. Thus, the licensee's safety basis was invalid, resulting in essentially no effective controls for avoiding the potential for a criticality within the scrubber ventilation system.

Furthermore, although the licensee conducted periodic inspections of the ventilation ductwork and was detecting material accumulation, they did not effectively use procedures to weigh and sample the uranium concentration in the material collected, undermining their ability to properly evaluate scrubber performance. Since scrubber ventilation system visual inspections did not effectively detect and remove significantly concentrated uranium from the system, eventually the established CSE mass limit was exceeded.

The licensee completed its own root cause evaluation in October 2016 and identified two root causes and two contributing causes for the event.

Root Cause 1: Programmatic controls for configuration management did not have the rigor to mitigate increased uranium accumulation in the scrubber ventilation system when design changes were made to the system and when operational requirements for the scrubber spray system were changed in the procedure.

Root Cause 2: Management did not scrutinize the content of the CSE and as-found conditions in the scrubber ventilation system with the questioning attitude and conservative bias required for a healthy nuclear safety culture. Further, management did not ensure the organization had sufficient procedures and training to recognize and respond to deviations from the safety basis described in the CSE.

Contributing Cause 1: Operating experience and the corrective action processes were not effectively used to pursue the actions needed to detect, estimate, and mitigate deposited uranium in the scrubber ventilation system.

Contributing Cause 2: The scope of licensee audits and assessments did not provide a comprehensive review of the nuclear criticality safety program with an appropriate level of intrusiveness as is applied to higher risk activities.

The licensee's root cause analysis team also concluded that the event occurred due to long-standing weaknesses in the safety culture at the facility. The organization did not exhibit the behaviors expected to recognize that nuclear work is unique and that complex technologies can fail in unpredictable ways, resulting in adverse latent conditions not being recognized. Weaknesses in this pattern of thinking contributed to invalid assumptions and non-conservative decisions not being challenged. As a result, CSE mass limits were not well communicated and instructions for verifying the effectiveness of criticality controls were not well established. The licensee's root cause analysis team also identified a number of corrective actions to prevent either recurrence or significant consequences.

The Potential for this Event Was Not Flagged by the Regulatory Processes

While the facility conditions and the licensee's initial responses to the conditions indicate a breakdown in their processes and programs, the NRC's overall response to the event was appropriate and as to be expected. An augmented inspection team (AIT) was chartered on July 28, 2016, to: 1) review the facts surrounding the failure to maintain the CSE mass limits and controls in the scrubber ventilation system and the potential for similar failures in other production areas using the same control protocols, 2) assess the licensee's response to the failures, and 3) evaluate the licensee's immediate and planned long-term corrective actions to prevent recurrence. Performance issues identified by the AIT were submitted for additional NRC inspection follow-up and further review and enforcement activities followed normal regulatory processes.

In addition, as part of the NRC's overall platform of continuous improvement, NRC management initiated a lessons-learned activity to explore opportunities for improving NRC regulatory processes in identifying facility operational issues and preventing such events in the future. The team was chartered on October 28, 2016, to evaluate five areas: the licensing process, the inspection program, the operating experience program, roles and responsibilities, and knowledge management. The first two areas (licensing and inspection) are specific programmatic areas that periodically interface with the licensee and their analyses and programs. The other three areas (operating experience, roles and responsibilities, and knowledge management) support improving the capability, efficiency, and effectiveness of the regulatory staff in performing their responsibilities in the first two areas.

The team reviewed numerous documents related to each of the evaluated areas, including licensing review staff guidance, inspection procedures, and management directives, and also reviewed documents directly associated with the event, including the AIT report, an information notice, and a confirmatory action letter. The team also conducted individual and group interviews of nearly all project managers, technical reviewers, inspectors, and managers within the NRC's fuel fabrication arena, including the highest level of management within the region responsible for inspection of these facilities.

Through this effort, the team made a number of specific observations and recommendations associated with each evaluation area. The team issued its report on January 31, 2017, and many of the observations are summarized in the following subsections.

The First Opportunity Comes During Facility Licensing

These facilities are typically large process facilities with numerous individual processes and associated analyses. There is significant review effort expended during licensing and license renewal. Much of this effort ties to fully understanding the facility and its processes and the review of the licensee's identification and control of the multitude of hazards associated with these processes. A significant focus of the review is on the potential for criticality events, but detailed reviews are not performed for all areas. Instead, consistent with the licensing review staff guidance, reviewers primarily review the overarching facility safety program (a "horizontal review") and sample specific areas for more detailed ("vertical slice") review. This prioritization of the scope, focus, and detail of review is based on many aspects, including operating experience and reviewer experience, but also relies heavily on the perceived risk associated with the process as conveyed by the licensee's ISA. In fact, the current licensing review staff guidance specifically states that the reviewers should more closely review processes and systems with a relatively high unmitigated risk than processes and systems with low risk. In the context of this event, the scrubber ventilation system was considered low risk by the licensee based on the assumptions: 1) that only minor amounts of uranium powder were expected to accumulate in the scrubber ventilation system, 2) low uranium concentration would be present within the scrubber ventilation system, 3) minimal amounts of small uranium particles were entrained within the intake ventilation ductwork, and 4) the scrubber constantly diluted the uranium concentration with the addition of makeup water during normal operation and anticipated upsets. These assumptions by the licensee are reflected in their ISA and established controls (i.e., IROFS).

The NRC licensing review staff guidance does not establish the level of review for processes and systems determined by the licensee to be low risk. Further, there is no specific guidance for reviewing processes and systems determined to be low risk that rely heavily on licensee assumptions. This lack of guidance resulted in the reviewers not reviewing this system in any depth during the prior facility license renewal. As a result, during the prior license renewal and amendment reviews, the reviewers did not challenge the overall performance of the system and related controls, including the assumption of low accumulation.

The Inspection Program Complements Licensing

One of the main purposes of the inspection program is to confirm continued compliance with the regulations and conformance with the approved license. Similar to the license review process, it is not practical to perform entire facility inspections, but rather, inspectors use a sampling approach. This approach is particularly relevant for facilities that do not have resident inspectors, which is the case for the subject facility (i.e., NRC inspectors are not located at the facility on a daily basis). For these types of facilities, over the year, inspectors visit the facility periodically to inspect specific programmatic aspects of the license, such as plant modifications, fire protection, operational safety, etc.

Similar to the license review process, the current inspection focus is on perceived high risk areas of the facility, which is based on the licensee's ISA. Because the licensee considered the scrubber ventilation system to be low risk, as stated above, the NRC did not consider this system for detailed inspection. Several inspectors noted that had the system been part of a detailed inspection, the licensee's deficiencies in the CSE and implementation of associated management measures and controls would likely have been identified.

Various inspection procedures appear to recognize that inspectors should examine presumably low risk processes and systems, but again, very limited guidance is provided on how to select samples from such processes and systems or the focus of such inspections.

Operating Experience Could Have Provided Insight and Focus on This System

Operating experience can be a valuable tool to help provide additional input to determining the appropriate focus and scope of facility areas to review and inspect. However, most license reviewers and facility inspectors did not rely upon the fuel fabrication facility operating experience program, which had previously been identified as needing to be improved. In fact, most inspectors and many reviewers were not aware of the fuel fabrication facility operating experience database or did not know how to access it. For those that were aware of the database, they observed that the database contained only relatively recent, publically available, US data and were unsure if it could trend events to support use in inspection planning. Furthermore, while a criticality inspection procedure had recently been revised to include the consideration of operating experience in inspection planning, other inspection procedures did not give any formal, structured guidance on considering operating experience. All of these conditions were considered to limit the usefulness of the operating experience database to the license reviewers and facility inspectors.

Understanding Roles and Responsibilities

Understanding individual and organizational roles and responsibilities is key to efficient and effective regulatory reviews and inspections. At the NRC, the licensing reviews are performed within one organization located near Washington, DC, while the inspections are performed within another organization located in Atlanta, Georgia. Communication and collaboration is essential in ensuring full understanding of licensing reviews and their implications for the inspection regime, especially when the organizations are physically separated by such a great distance.

The licensed facilities are required to provide annual summaries that describe the prior year's facility and process modifications and separately updates to their ISAs. These summaries can be, and are expected to be, used to inform inspection planning for the subsequent year. In the past, the NRC licensing organization primarily performed the review of these summaries and provided its input to the NRC inspection organization, but in 2016 the NRC changed the lead role for the ISA summary reviews to the inspection organization to avoid overlapping efforts. However, the expectation of obtaining insights from the facility licensing review project manager and technical staff in these annual submittal reviews was not clearly established. Likewise, it was recognized through the lessons learned effort that the licensing review staff guidance did not clearly establish an expectation for obtaining insights from the inspection organization. In both cases, the potential for missing valuable insights was identified since the regulatory guidance did not establish a formal expectation for the various regulatory staff to collaborate in these areas.

Knowledge Management

It is recognized that knowledge management is inextricably linked to all the other areas evaluated by the lessons learned team. It is an element critical to performing technical evaluations of licensee submittals, selecting relevant inspection samples, administering a successful operating experience program, clearly understanding respective roles and responsibilities, assessing the significance of an event, etc. Most of the lessons learned team recommendations involve some aspect of knowledge management. However, the lessons learned team did identify some fundamental knowledge management issues.

The current licensing and inspection qualification programs rely heavily on documentation reviews supported with some coursework and site visits. Certain skills that are important to regulatory staff success, however, are mostly left for the staff to pursue outside the qualification program, such as critical thinking, effective communication, and conflict resolution. All of these aspects require continuous practice and reinforcement and are invaluable when performing license reviews, conducting inspections, and interacting at all levels of the organization.

In addition, ensuring all regulatory staff are kept informed of current (and periodically reminded of past) licensing, inspection, operational, and technical issues improves the understanding and ultimately, performance of the regulatory staff and organization as a whole. While the inspection organization held periodic knowledge management seminars of selected topics, such a program was not being fully implemented within the licensing organization. As a result, lessons learned by some regulatory staff were not being effectively shared among all the other regulatory staff.

Recommended Improvements to the Regulatory Processes

The lessons learn team recommended improvements in all five regulatory areas. Most recommended improvements are associated with the verification of the technical bases and assumptions in the licensee's ISA and improving the knowledge bases and resources used by the reviewers and inspectors.

For the license review process, the lessons learned team identified for further evaluation the need to clarify the licensing review staff guidance to include guidance on the examination of the technical justification for processes and systems designated as low risk, especially those justifications related to key analysis assumptions.

For the inspection program, the team identified for further evaluation the need to modify the scope and focus of inspections so that all facility processes and systems with the potential for intermediate and high consequences are inspected within some periodicity, regardless of perceived risk significance. The team also suggested the development of additional guidance associated with reviewing and using the summaries of facility modifications and licensee ISA updates in support of inspection planning. Such additional guidance could also focus specific inspections on these analyses, with the intent of verifying the continuing validity of the technical bases and assumptions of the analyses.

For the operating experience program, the team identified for further evaluation the need to improve the framework and guidance for the flow of information from this program to the licensing and inspection programs. Related to the fuel fabrication facility operating experience database, the team suggested enhancing access to the database so that the information is more readily available to the licensing review staff and inspectors and to include legacy and international operating experience so that the database is more complete.

For the area of roles and responsibilities, the team suggested for further evaluation improving the guidance related to using the licensee's annual submittal of summary descriptions of facility modifications and ISA update summaries in inspection planning, setting the expectation to gain inspector facility knowledge and experiences within the licensing process, and providing rotational opportunities between the licensing review staff and inspectors to foster a better understanding of the diverse roles and responsibilities.

Finally, the need for improving knowledge management within these regulatory organizations is pertinent to all the above aspects. The team specifically identified for further evaluation the need to improve the qualification programs for the licensing review staff and inspectors, to implement continuous knowledge management activities, such as regularly scheduled seminars and debriefings on topics of interest, and to periodically perform systematic reviews of the licensing and inspection programs to identify gaps and support continuous improvement.

Concluding Comments

The NRC created an action plan to guide and track the evaluations of the recommended improvements identified by the lessons learned team and their subsequent implementation, as appropriate. Some activities, such as the operating experience database, had previously been identified as needing to be improved and were already in the early implementation stages. Other activities involve additional considerations (e.g., priority, schedule, budget, and potential benefit) and are being evaluated and implemented, as appropriate. Through these efforts, the regulatory programs should improve, be more effective and efficient, and enhance the assurance of safety of the facilities.