**DEFENSE NUCLEAR FACILITIES
SAFETY BOARD**

Washington, DC 20004-2901

November 18, 2022

The Honorable Jennifer M. Granholm
Secretary of Energy
US Department of Energy
1000 Independence Avenue, SW
Washington, DC 20858-1000

Dear Secretary Granholm:

The Defense Nuclear Facilities Safety Board (Board) conducted a safety review of reactive material hazards at the Y-12 National Security Complex (Y-12). The safety review evaluated the reactivity hazards associated with enriched uranium purification and recovery processes.

The Board believes that Y-12 can improve the site's safety posture by ensuring that uranium pyrophoric and chemical reactivity hazards are adequately addressed consistent with Department of Energy guidance. Additionally, Y-12 should consider revisiting its control strategies for new process technologies, including those to be installed in the Uranium Processing Facility, to ensure that facility worker hazards related to uranium pyrophoricity are addressed. The enclosed report provides additional details from the Board's review.

Pursuant to 42 United States Code § 2286b(d), the Board requests that the National Nuclear Security Administration provide the Board with a written report and briefing—within 120 days of receipt of this letter—on actions taken to analyze hazards and implement control strategies for potential uranium pyrophoric events with a sudden energy release.

Sincerely,

Joyce L. Connery
Chair

Enclosure

c: Mr. Joe Olencz

DEFENSE NUCLEAR FACILITIES SAFETY BOARD

Staff Report

September 1, 2022

Reactive Materials Hazard Review at the Y-12 National Security Complex

Summary. The Defense Nuclear Facilities Safety Board (Board) reviewed enriched uranium purification and recovery processes at the Y-12 National Security Complex (Y-12) to assess reactivity hazards associated with uranium material forms (e.g., chips, briquettes, and buttons). The review included comparison of chemical reactivity and pyrophoric hazards across different Y-12 production facilities' safety analysis reports (SARs) and evaluation of the control strategies for uranium reactions in air to mitigate a thermal runaway reaction with sudden energy release. The review also evaluated events and actions related to unexpected uranium accumulations that occurred in process equipment at Y-12.

Y-12 has experienced 15 pyrophoric events between 2016 and 2021 involving thermal runaway reactions of uranium chips, briquettes, and buttons during storage, handling, and transfer operations. Y-12 personnel identified actions to improve enriched uranium recovery and purification processes and operations. The improvements focused on training, configuration management, statistical analysis, and process reviews.

The Board's review identified that additional Y-12 actions are needed to implement safety controls that address facility worker hazards related to uranium pyrophoric events and other aspects of uranium chemical reactivity consistent with DOE guidance.

- Y-12 should improve controls to prevent and mitigate facility worker impacts from a uranium pyrophoric fire with a sudden energy release.

- Y-12's evaluation of process changes does not adequately identify uranium chemical reactivity hazards.

Background. Since 2016, briquettes and chips of uranium experienced thermal runaway reactions in storage and in recovery process operations at Y-12. During this timeframe, Y-12 also experienced several unexpected accumulations of uranium in process equipment. In response to these events, Y-12 personnel instituted several process changes to improve recovery of enriched uranium materials and prevent unanticipated events.

Y-12 personnel perform enriched uranium purification and recovery processes at various production facilities as detailed below:

Chip Production, Cleaning, Drying, and Briquetting—Enriched uranium chips generated from machining operations are processed to form briquettes for interim storage. These chips are first rinsed with water to remove machine coolant (e.g., propylene glycol) and then placed in cylinder dollies, submerged in Vertrel™, an organic solvent, for transport to another production facility. There, the chips are removed from the dollies and further cleaned by four sequential ultrasonic baths, alternating between water and Vertrel™ in a process known as ultrasonic chip cleaning (USC) [1]. Once cleaned, the chips are stored in Vertrel™ pending briquetting. At briquette operations, the solvent is removed from the chips via vacuum and the chips are then dried in ovens that have been purged and backfilled with argon [2]. The dried chips are compressed into cylindrical pucks, or "briquettes," using a press. The briquettes are then weighed and packaged under argon in slip lid hospital cans sealed with tape for storage. Each can is placed in an individual storage lockbox pending additional processing operations.

Chip and Briquette Casting—Chips and/or briquettes previously served as feedstock material for casting operations. When used in casting operations, the briquettes were transferred from hospital cans to casting crucibles in preparation for casting. The casting process was done in a vacuum induction melt process. The products from casting were consolidated into logs to provide a more stable form for storage [3]. A high throughput of processing briquettes in the casting furnaces contributed to an increase in uranium accumulation within the casting line. Following the uranium accumulation issues in the casting line in 2018, Y-12 ceased using briquettes as a feedstock in the casting process. Instead, it burns the briquettes to convert them to oxide.

Metal Purification by Electrorefining—The electrorefining process is a new technology for Y-12 enriched uranium operations that will be located in Building 9215 and will help transition enriched uranium production operations out of Building 9212. This process uses a salt bath cell to remove uranium from impure uranium metal items and deposit pure uranium dendrites on the cell's cathode. The uranium dendrites are removed from the electrorefining cell and processed in the salt vaporization furnace to remove the adhered salts, resulting in pure uranium crystals. The uranium crystals are consolidated in a furnace to form a metal button. The salt vaporization furnace uranium product can be pyrophoric before it is consolidated into a button [4-5]. Y-12 is completing installation of the electrorefining equipment in Building 9215 and anticipates beginning the associated readiness activities in fiscal year 2023.

Metal Processing by Direct Chip Melt—The direct chip melt process provides the capability to create uranium metal buttons by consolidating enriched uranium chips from machining operations. This capability will be in Building 9215 and is planned to eliminate the briquette pressing operation as well as subsequent storage and processing of briquettes. Ultimately, the direct chip melt process will consist of bottom loading furnaces with integrated inert glovebox systems and chip compaction capabilities to directly process chips from machining operations by melting the compacted chips to create a button [6]. The bottom loading furnace and glovebox system is expected to start operations in 2026. Y-12 is also pursuing an earlier, front loading furnace design that does not have an integrated glovebox. The front-loading furnace is expected to start operations in 2024.

Staff Team Review. The staff team evaluated the operations and safety controls at Y-12 to understand conditions that contributed to hazardous events. The objectives of the review were to (1) evaluate reactive hazards associated with enriched uranium storage and process operations, including process changes and process drift; (2) assess Y-12's response to thermal runaway events involving uranium reactions; and (3) evaluate the control strategy for hazards associated with sudden uranium pyrophoric events. The review included Y-12's response to past pyrophoric events as related to handling, transporting, and storage of uranium forms.

Enriched Uranium Thermal Runaway Reaction Hazards—In general, uranium is very reactive in air, particularly moist air. Enriched uranium process operations generate various uranium products that are very reactive. Figure 1 shows examples of uranium forms generated at Y-12.

Figure 1. *Uranium Material Forms at Y-12.*

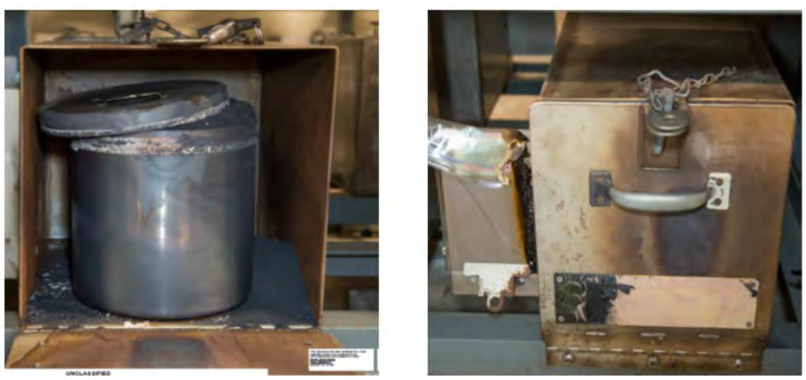
These forms include chips, briquettes, metal buttons, and uranium oxide powder, whose reactivity is dependent on parameters such as: specific surface area; morphology; and oxidation kinetics. The DOE-HDBK-1081-2014, *Primer on Spontaneous Heating and Pyrophoricity*, defines a pyrophoric material as one that "even in small quantities and without an external ignition source can ignite at or below 130°F in contact with air" [7]. The handbook further states that uranium in a finely divided form (e.g., chips and powders) is pyrophoric in air. Y-12 has experienced 15 pyrophoric events in production and development facilities between 2016 and 2021 [8 – 18] due to the physical forms of uranium (Figure 1) generated during processing. Seven of those events are described in Table 1. The full list of all 15 events is provided in Appendix A.

The seven events in Table 1 demonstrates that different uranium physical forms (chips, briquettes, or buttons) generated at Y-12 can undergo a thermal runaway reaction. The event in the DNFSB resident inspector activity report for the week ending on June 30, 2017 [16], shown in Figure 2 is an example of a severe thermal runaway reaction that could have caused significant injury to a facility worker if one had been present.

Table 1. *Representative Uranium Exothermic Events at Y-12*

Resident Inspector Report Date	Event Description	Y-12 Immediate Response

October 1, 2021	Chip fire in disposition operations. (Note similar event occurred on March 15, 2007)	Operator poured Vertrel™ on chips to extinguish fire. This was not a step per operating procedure.
August 7, 2020	Pieces of enriched uranium buttons started to glow red after shearing by operators.	Firefighter used coke (i.e., charcoal particles) to extinguish fire.
August 7, 2020	Sparking of depleted uranium metal cut by saw in development facility.	Technician sprayed fines with coolant water then covered with coke.
July 3, 2020	Chip fire during unloading in direct chip melt prototype furnace.	Operators placed coke on chips and closed hood sash.
December 7, 2018	Briquette fire when removed from inert glovebox.	Operators placed sparking briquette into argon-filled box and moved away.
February 23, 2018	Briquette fire initiated when operator used screwdriver to remove briquette stuck in hospital can.	Operators allowed briquettes to burn to extinction because they could not respond to the event using the abnormal event procedure.
June 30, 2017	Exothermic reactions of multiple cans containing briquettes.	Fire department used thermal imaging to verify storage box was at ambient temperature before opening. Operators opened storage box and observed containers were burned and the tape seal melted.



Inner container with briquette   Outer lock box

Figure 2. *Briquette Thermal Runaway Reaction Event in Storage at Y-12*

Extinguishing Uranium Pyrophoric Fires—The significant fire potential of pyrophoric materials requires careful consideration of several factors to ensure safe handling and storage. These factors include extinguishing methods and presence of accelerants (such as hydrides). The DOE-HDBK-1081-2014 provides guidance on how to extinguish uranium fires properly, including improper actions to avoid. For example, the following actions should not be taken to fight a uranium fire:

- The use of flammable (organic) liquids to extinguish hot or burning metals may react violently upon contact and decompose to hazardous organic products.
- Water should never be applied to burning metals since it can cause violent reaction due to hydrogen generation.

- The use of dry chemical agents are not effective extinguishing agents.

In contrast, the handbook provides strategies to fight a uranium fire as noted below:

- An effective agent for extinguishing uranium fires has been found to be magnesium oxide (MgO) sand. Gloveboxes containing pyrophoric forms of uranium should also contain a supply of MgO sand. And studies have shown that covering uranium with 1-2 inches of MgO sand has been effective at extinguishing a uranium fire.
- Argon is a very effective extinguishing agent, if the oxygen content in the atmosphere is maintained at less than 4%.

In each case, when a thermal runaway reaction occurred due to uranium pyrophoric behavior, the immediate actions by operators and sometimes firefighters in response were inconsistent. These inconsistent actions all differed from what is recommended in the DOE-HDBK-1081-2014 [7] and indicate a lack of adequate knowledge by personnel on extinguishing uranium fires. Y-12 should ensure personnel processing uranium have adequate knowledge of DOE-HDBK-1081-2014 and how to extinguish uranium fires.

Discussion. Y-12 actions are needed to implement safety controls that address facility worker hazards related to uranium pyrophoric events and other uranium chemical reactions.

- Y-12 should improve **controls to prevent and mitigate facility worker impacts** from a uranium pyrophoric fire with a sudden energy release.

- Y-12's **evaluation of process changes** does not adequately identify uranium chemical reactivity hazards.

Controls to Prevent and Mitigate Facility Worker Impacts—Y-12 has not performed an adequate unmitigated analysis and identification of controls for uranium thermal runaway reactions. Such a reaction can occur during handling and storage operations when uranium reacts with air to reach its ignition temperature. These reactions can cause serious injury to the facility worker.

The current Y-12 control strategy to mitigate fire events relies on safety significant fire suppression systems and a specific administrative control to limit the amount of unattended transient combustibles in areas of Building 9212 without sprinkler coverage. These controls help prevent a small fire from becoming a large fire but do not protect the facility worker from a uranium thermal runaway reaction with a sudden energy release since the facility worker injury could occur prior to the fire suppression system being activated. The potential for facility worker impacts is exacerbated by the different operator responses to the pyrophoric events as detailed in Table 1 and Appendix A. For example, the use of the organic solvent Vertrel™ to extinguish the chip fire event (Table 1, activity report for the week ending October 1, 2021) and the spray of water on the sparking depleted uranium (Table 1, Oak Ridge activity report for the week ending August 7, 2020) were inappropriate actions for fighting a uranium fire as highlighted by DOE-HDBK-1081-2014 [7].

Y-12 should improve its control strategies to prevent and mitigate uranium pyrophoric hazards and identify thermal runaway uranium reactions with sudden energy release as an initiating event for fire in its safety bases. An improved hazard analysis and control strategy could be used to reduce the likelihood of (i.e., prevent) and ensure appropriate response to (i.e., mitigate) pyrophoric events. This should include improved procedures and training to ensure responses to pyrophoric events are consistent with the guidance in DOE-HDBK-1081-2014 [7] throughout the enriched uranium processes.

In addition to current operations, this issue applies to new process technologies Y-12 is pursuing including electrorefining and direct chip melt. These technologies will create and purify uranium metal in an efficient way that will eliminate existing wet chemistry processes currently performed for enriched uranium recovery and purification. However, the design strategies and hazard analyses for electrorefining and direct chip melt do not analyze for a sudden energetic pyrophoric event involving uranium. Additionally, the safety bases do not analyze uranium as a pyrophoric material. In particular, the crystal intermediate product for the electrorefining process can be pyrophoric, but this hazard is not analyzed. Moreover, a thermal runaway event occurred in the prototype direct chip melt furnace in 2020, as noted in Appendix A [11]. For these new technologies, Y-12 has not incorporated lessons learned from the events identified in Table 1 and Appendix A in evaluating hazards and developing control strategies.

Evaluation of Process Changes—Y-12 has not adequately evaluated process changes that could affect facility worker safety due to chemical reactions of various forms of uranium. Y-12 should strengthen its evaluation of process changes that could affect chemical reactivity of uranium, including unintended consequences for downstream processes. The examples below show process changes that Y-12 instituted that created additional safety risks:

- ***Change in Process Solvent***—Y-12 in 2007 instituted a process change to use an environmentally friendly solvent, Vertrel™, to wash and clean enriched uranium chips. Prior to this change, Y-12 used Freon-113. Though Y-12 made the process solvent change, the Y-12 production facilities' SARs only analyze for chemical incompatibility between Freon-113 and uranium, but not Vertrel™. Since the change, Y-12 project personnel observed the following process impacts:

    - Notable changes in chip appearance in chip cleaning and poor metal yield in casting operations [19],

    - Residual powder-like material in empty chip dollies discovered in 2021 [20], and

    - Significant solvent leakage and evaporation in chip dollies [21-25].

  These observations suggest uranium in contact with organic solvent such as Vertrel™ for prolonged periods of time may react to generate unstable organic and/or uranium-reaction products that are susceptible to potential pyrophoric behavior by changing the chemical and metallic properties of the uranium metal surface (e.g., hydride inclusion).

- ***Change in Chip Cleaning Operations***—The shutdown of the USC system due to unanalyzed uranium accumulations and restrictions imposed for chip cleaning operations led to longer than usual storage of chips in chip dollies. Y-12 instituted a "triple-rinse" method with water to clean chips in lieu of USC cleaning operations. This change may have caused increased reactivity of the chips due to residual water and unremoved machining oil and may have contributed to one of the briquette fire events in 2018 listed in Table 1 (activity report for week ending on December 7, 2018) [12].

Y-12 Improvements—In 2021, Y-12 personnel presented improvements to the enriched uranium recovery and purification process to the staff team. The presentation focused on improvements in training, configuration management, and process reviews. The improvement activities being instituted include employing field training specialists to deliver formal on-the-job training to operators that will impart and validate in-depth process knowledge in fundamental subject areas. However, the improvements actions presented did not include how operators should respond to effectively fight uranium fire using the guidance provided in the DOE-HDBK-1081-2014.

Conclusion. Y-12 should improve controls to prevent and mitigate facility worker hazards for a uranium pyrophoric fire with a sudden energy release. This hazard poses risk to the facility worker during handling and packaging of enriched uranium chips and briquettes. Y-12 has not identified and incorporated the lessons learned to mitigate uranium pyrophoric events into its safety control strategy for the electrorefining and direct chip melt technologies.

As construction progresses for the Uranium Processing Facility (UPF) and the National Nuclear Security Administration prepares to commence operations, Y-12 should revisit its control strategies for new process technologies to ensure that facility worker hazards related to uranium pyrophoric behaviors are adequate. Y-12 may need to incorporate uranium thermal runaway reactions with sudden energy release as an initiating fire event in the UPF safety basis analysis to establish controls that protect the facility worker.

Y-12 has instituted a strategy to improve enriched uranium recovery processes such as workforce training, configuration management improvements, and process reviews. However, the strategy should also evaluate process changes that include all potential uranium chemical reactivity hazards that may occur throughout the enriched uranium recovery process, including uranium pyrophoric behavior. Y-12 should identify and implement safety controls to include training on how operators should effectively respond to uranium pyrophoric fires using the guidance in the DOE-HDBK-1081-2014.

Appendix A: Pyrophoric Events at Y-12

Pyrophoric Events at Y-12 Production and Development Facilities from 2016 to 2021. Y-12 experienced 15 pyrophoric events between 2016 and 2021 involving different forms of enriched uranium material during processing, handling, and storage at production and development facilities. The table below provides a complete synopsis of the events that occurred at Y-12. The table includes potential initiating events identified by the staff team. These conditions are not analyzed in the Y-12 production facilities' safety analysis reports.

Board Resident Inspector Report Date	Event Description	Potential Initiating Event (Staff Evaluation)	Y-12 Immediate Response
October 1, 2021	Chip fire during transfer from hospital can to chip dolly in assembly/ disassembly operations.	Exposure of uranium metal to air resulted in exothermic reaction.	• Operator poured Vertrel™ on chip to extinguish fire. • Not a step per operator procedure.
August 13, 2021	Sparking of oiled uranium cast part in storage device in enriched uranium process operations.	Exposure of uranium cast in air headspace of storage device resulted in exothermic reaction.	• Operators re-cast part after it stopped sparking per subject matter expert guidance.
August 7, 2020	Sheared enriched uranium buttons glowing red in enriched uranium process operation glovebox.	Exposure of cut uranium buttons to glovebox atmosphere resulted in exothermic reaction.	• Firefighter used coke to extinguish fire. • Operators transferred pieces to a can and noticed a piece still glowing; additional coke was added per nuclear criticality safety direction.
August 7, 2020	Sparking of depleted uranium metal cut by saw in development facility.	Exposure of uranium fines to air resulted in exothermic reaction.	• Technician sprayed fines with coolant and water. • Another technician covered fines with coke.

Board Resident Inspector Report Date	Event Description	Potential Initiating Event (Staff Evaluation)	Y-12 Immediate Response
July 3, 2020	Sparking of depleted uranium chips during unloading operations in prototype direct chip furnace at development facility.	Exposure of uranium chips to air once removed from process equipment resulted in exothermic reaction.	• Operators put coke on chips, closed hood sash, and moved away from hood.
December 7, 2018	Sparking of newly generated briquette removed from inert removal box in enriched uranium process operation	Exposure of uranium briquette to air once removed from inert process equipment resulted in exothermic reaction.	• Operators placed sparking briquette back into argon filled box and moved away.
February 23, 2018	Sparking of briquettes in cans prior to start of enriched uranium casting operations.	Potential expansion of uranium briquette in can changed its material and pyrophoric properties resulted in exothermic reaction.	• Operators could not respond to event per abnormal operating procedure because briquette stuck in can. • Operators allowed briquettes to react and cool in crucible loading hood.
September 29, 2017	Exothermic reaction of briquettes stored in inert container.	Possible in-leakage of air in inert container exposed uranium briquette resulted in exothermic reaction.	• Consolidated Nuclear Security, LLC (CNS) issued letter to National Nuclear Security Administration Production Office for "briquette blitz" campaign.
September 8, 2017	Exothermic reaction of briquettes stored in non-inert container.	Exposure of uranium briquette to air in container headspace resulted in exothermic reaction.	• Update job hazards analysis to include leather gloves for handling.

Board Resident Inspector Report Date	Event Description	Potential Initiating Event (Staff Evaluation)	Y-12 Immediate Response
			• Special training to handle abnormal reactions during transfer.
August 18, 2017	Exothermic reaction of two briquettes stored in non-inert containers.	Exposure of uranium briquette to air in container headspace resulted in exothermic reaction.	• Re-institute inert containers. • Pause briquette and casting operations.
August 18, 2017	Exothermic reaction of briquette loaded in crucible prior to enriched uranium casting operations.	Mechanical friction resulted in exothermic reaction.	• See actions above.
June 30, 2017	Exothermic reaction of three briquettes stored in non-inert containers.	Exposure of uranium briquette to air in container headspace to result in exothermic reaction.	• Fire department used thermal imaging to verify storage box was at ambient temperature before opening. Operators opened storage box and saw lids of inner containers were off and tape melted. CNS action to evaluate process changes to prevent recurrence, including inerting newly containerized briquettes.
January 6, 2017	Exothermic reaction of enriched uranium fuel plates during re-containerization process.	Exposure of uranium fuel plates to air resulted in exothermic reaction.	• Institute process change, instead of re-containerizing plates, directly transfer from shipping container to casting crucible.

Board Resident Inspector Report Date	Event Description	Potential Initiating Event (Staff Evaluation)	Y-12 Immediate Response
December 16, 2016	Exothermic reaction of loaded briquette casting assembly during transfer to casting glovebox line.	Mechanical friction resulted in exothermic reaction.	• Operators left assembly in enclosure and paused work.
December 6, 2016	Exothermic reaction of loaded briquette crucible prior to casting operations.	Mechanical friction between briquettes resulted in exothermic reaction.	• Operators moved crucible further into enclosure.

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