Lawrence Livermore
National Laboratory

Incident Analysis (IA)/Root Cause Analysis

Release of Combustion (and Contamination) Products after an Experiment at the Contained Firing Facility (CFF)

or

NA—LSO-LLNL-LLNL-2021-0019

October 21, 2021

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Contents

Identification Information

Title of Event Analyzed:	Release of Combustion Products (and Contamination) after an Experiment at the CFF		
Organization:	WCI/S300 Operations	Report Date:	October 21, 2021
Date of Event	June 10, 2021	eCAR #:	110, 111, 112, 113, 115, 116, 117, 118, 119, 120, 121, 122, 123, 125, 127
WCD #:	See background	Security Inquiry Report #:	N/A
ITS #:	OCCR-51916.01	Occurrence Report #:	LLNL-2021-0019
Location Where Event Occurred:	Building: 801 (CFF)	Room:	Other:

Analyses Teams

IA Team:
Christine Kerr (Lead)–WCI Deputy Assurance Manager/trained HPI practitioner
Eric Bukovsky–Explosive Safety Program Office Lead with a background in chemistry
Stephanie Lopez–O&B Assurance Manager/trained HPI practitioner
Matt Lucas–West Firing Facilities Facility Manager with a background in facility operations
Kevin Merrill–Explosive Safety Expert, Site 300
Matt Virga–Superblock Facility Manager with a background in engineering

Technical Analysis Team:
Jim Hammer (Lead)–Physicist
Libby Glascoe–Chemist
Tom McAbee–Physicist
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Executive Summary

On Thursday June 10, 2021, at 1630 PST, an experiment consisting of three explosive devices was conducted within Lawrence Livermore National Laboratory's (LLNL's) Site 300 Contained Firing Facility (CFF), which houses what is known as the "chamber." Moments after executing the experiment, the devices detonated causing an abnormality resulting in smoke and gases escaping the chamber into occupied areas, triggering carbon monoxide (CO) detectors, automated fire alarm activation, and personnel evacuation of the facility. Thirty-three (33) employees at the CFF safely evacuated to the designated assembly point where personnel potentially exposed to respirable beryllium (Be) and radiological materials were identified while the Alameda County (ALCO) Fire Department (FD) responded. Upon arriving on scene, the responding Fire Chief took control of the scene and assumed responsibility as the Incident Commander (IC). The IC then relocated all personnel to a secondary assembly point farther from the facility and took actions to place the facility into a safe configuration. Concurrently, ES&H personnel initiated employee screening for radiological contamination. Upon ensuring that medical needs were addressed and that the facility was in a safe configuration, including cessation of any release of potentially toxic material, the FD relinquished control of the scene to LLNL personnel and departed Site 300.

On June 21, 2021, a memorandum authorizing the formation of the Incident (Root Cause) Analysis (IA) team was approved by the Weapons and Complex Integration (WCI) Deputy for Operations. The IA team consisted of personnel with backgrounds in chemistry, explosives chemistry, explosives safety, facility operations, engineering, IA/causal analysis, and human performance improvement (HPI) analysis. Immediately following the formation of the IA, the team established control over the scene. The IA team began working hand in hand with programmatic and ES&H personnel to engage in post-event exploratory and information collection activities. Concurrently, the IA team began conducting interviews with personnel involved in, affected by, and/or knowledgeable of the event and its precursor experimental design configuration and collected facility and process specific information to be analyzed.

A Technical Analysis (TA) team was chartered by the WCI Principal Associate Director (PAD) to assist the IA team to provide a more in-depth scientific understanding of interactions that resulted in the abnormal outcome of the event. This team consisted of personnel with backgrounds in physics and chemistry and utilized information collected from interviews, documentation from IA team efforts, acquired data, and detailed experimental information to evaluate the conditions which resulted in over-pressurization of the chamber. From investigative and analytical efforts, the TA team's evaluation determined the over-pressurization resulted from chemical reactions, including combustion, rather than prompt energy release commonly associated with the detonation of high explosives (HE).

The IA and TA teams reviewed documents, records, processes, and other attributes of operational execution as well as the aforementioned interviews with over 30 personnel. This review identified 15 physical barriers and 11 operational processes warranting further analysis. Of the 15 barriers assessed, three were determined to have failed: (1) staying within the engineering design pressure constraints of the chamber, (2) the overlay seal, and (3) seals around equipment and personnel access doors. Of the 11 operational processes assessed, more than 50 process steps were analyzed resulting in nine apparent causes or differences in process steps. Failed barriers and process differences were then further analyzed to understand and determine root causes, of which five were identified. The IA team developed 28 recommended corrective actions in response to identified causes. Note that 16 observations were identified as issues that were not causes of this event. The IA team developed 36 recommendations to address the observations.

In summary, a collaborative effort between the IA and TA team provided an extensive in-depth review of fielding experiments at the CFF. The overarching direct cause of the loss of containment at the chamber during (b) (7)(F)

(b) (7)(F) and environments experiments, was a combustion-induced, over-pressure event that exceeded the chamber's capabilities to contain pressure effects of experiments. The IA team analyzed physical barriers and related processes and identified root causes that relate to improvements needed in the following areas: processes to analyze, assess, and review experiments and associated analysis in the chamber, including the peer review process; expertise utilized in areas of chemistry and chemical combustion and evaluation of combustible materials and other attributes of chamber protection; communication of chamber pressure boundary and operating limits; and inspection and maintenance of the chamber's physical barriers. As a result of the direct, apparent, and root causes and analysis efforts, the IA team and TA team have developed 64 recommendations encompassing attributes of fielding experiments from the design phase through data collection and chamber maintenance and recovery.

Issue Statement

Release of combustion products and contamination after an experiment at the CFF with personnel present in the affected areas.

Event

On Thursday, June 10, 2021, at approximately 1630 hours, experiments were executed at the B801 CFF. Within moments of execution, a call was received over the radio that a release of combustion products from the firing chamber had occurred–smoke was observed in multiple areas. Two areas had personnel present. Automated alarms in the facility triggered a Lab FD response.

During the shot, 33 personnel were in B801A. Of the 33, 15 personnel were located south of the chamber in the Vault Type Room (VTR), and one person was in the Capacitor Discharge Unit (CDU) west of the chamber. Other personnel were in room 111 (control room) and room 2036. Note that due to COVID controls, all personnel were wearing face coverings.

Workers described what they heard and saw seconds after the initial detonation. These testimonies are described below in no particular order:

- Heard a suction, pressure noise, and then a pop. Thought maybe there was a breach in the wall somewhere through the overlay. The equipment door puffed and stopped, so it appeared that the pressure went somewhere else, maybe towards the VTR.
- Heard a noise like a tea kettle boiling louder and louder. Then heard a pop like a seal broke, and smoke came through the platform.
- Had time to disable lasers but was not able to save the data.
- Shot sequence, a rumble, ceiling flakes. Saw data on scopes, then heard something ramping up, then a pop. Smoke entered the room from where a floor tile used to be.
- There was a pop, and then the VTR filled with smoke. The smoke traveled faster than we did. I was in smoke the entire way out. It smelled like burnt rubber.
- Heard whistling and then a pop. The first sign of smoke came through a floor tile from a hole around the cables. When I saw smoke, I turned around, and the whole room was filled with smoke.
- Heard more of a vacuum suction sound, thought that is not right. Worker said, "I think we need to get out" and then saw greyish-brown smoke coming in from the floor. Could not see to go out the emergency exit so walked across the room to the other exit.

- Heard a soft hissing sound that grew louder.
- Did not see smoke immediately, but eventually brownish-black smoke started leaking into the VTR. One worker saw a co-worker yelling something; however, the hissing sound was so loud that he could not make out what his co-worker was saying but evacuated the facility.
- Workers noted that the hallways and VTR were filling up with smoke.
- There was smoke across the entire VTR. A worker yelled to get out–took a whiff of smoke.
- Was close to the emergency exit, but it soon became hard to see, so the worker rushed to the other door to exit, the door that most workers were exiting. Worker said had he waited a few seconds he would have been blind to see the exits into the room due to how fast the smoke was filling the VTR.
- Heard a boom, diagnostics reported in, everything looked good. Heard whistling at first, but it went away and then heard something like a jet engine spinning up. Continued post-shot tasks when saw smoke coming into the room. Upon evacuation, received a lungful of bad air.

Table 1: Chronology of actions/conditions leading to and during the event

WHEN	WHAT
7/6/2017	(b) (7)(F) [redacted] hysics preliminary design review (PDR)
7/28/2017	[redacted] equirements review
8/28/2017	[redacted] ngineering PDR
4/21/2020	[redacted] final design review (FDR)
8/13/2020	[redacted] FDR
Nov/Dec 2020	[redacted] ngineering FDR. This FDR included the environmental addon assessments.
9 months prior	Finalized physics objectives for the experiment.
March 2021	Bunker scheduling request packet submitted.
April 2021	Chamber protection review completed and experiment activity report (EAR) presented and formally reviewed.
Late April 2021	Work package was approved; this includes the bunker scheduling request and the S300 Shot Materials Database input.
Early May 2021	The EAR was signed, and release was provided to begin setup of the experiment.
6/7/2021 a.m.	Prepared for the integrated dry run of the entire system.
6/7/2021, 45 minutes after lunch	Integrated dry run of the entire system performed. No issues were identified.
6/7/2021 ~2:00 p.m.	Cooling of the experiment started after successful dry run.
6/7/2021 p.m., - 6/9/2021 a.m.	Performed radiography using portable M9a of the device as it cools.
6/8/2021	Dry run performed.
6/9/2021	The chamber configuration was converted from that needed for inspection to that needed for experiment execution. Equipment was removed from the chamber following approval that the device configuration met physics requirements. This includes the removal of the M9a Linatron and associated cabling. Objects moved to field the M9a diagnostics were placed into the final desired experimental location. Shielding was placed in the chamber, water stacks were placed around the device and in the corner for standard Be dust suppression, and fragment protection was placed arounds the ports. The mirrors were adjusted for final object views and triggers on lights adjusted for proper illumination timing. One set of lamps did not trigger as expected, and testing was continued the following day.
SHOT DAY–6/10/2021	
10:30 a.m.	Final dry run performed with all systems triggering nominally.

WHEN	WHAT
SHOT DAY–6/10/2021 (Cont.)	
~11:00 a.m.	Results of the dry run were checked on all systems. One change was identified–lamps were triggering too late–so the timing was moved and tested with subsystem testing. Signals were checked and radiography plates reviewed, no interference from image plate seams were identified.
~1:30/1:45 p.m.	Static pre-shot image plate scanning completed.
~2:00/2:30 p.m.	Received approval to proceed into final setup operations.
~2:30/3:30 p.m.	Physically assembled the cassette and placed it in the chamber. The dynamic cassette was placed by use of a forklift and the final northeast fragment catcher was moved by use of a pallet jack into place after the forklift path was no longer needed.
	The fragment catcher and shield for primary chamber protection was put in place. Devices were connected to the fire sets, and th(b) (7)(F) vas sealed.
~3:45 p.m.	The thermal control unit (TCU) was disconnected and removed, along with its ducting and cabling, and holes in the box were sealed. The associated port in the chamber wall where the M9a and TCU cabling come through was also sealed. Final pictures were taken as part of the final chamber sweep.
	The chamber was closed and sealed, and control keys were handed out to control energy in the chamber. Power supplies and lasers were powered up for optical diagnostics. Power supplies and initiation leads were connected from the CDU room and placed on sources and fire sets. The timing system and camera speeds were verified, and optical diagnostic final checks completed.
~4:33 p.m.	Permission to proceed was provided by different groups including the Ramrod and bunker supervisor.
~4:38 p.m.	The shot was fired. Initial chamber pressure readings for the shot were within the normal range at 4 psi according to the pressure gauge (PIT-205).
10 to 30 seconds following the shot	Workers heard a loud hissing, suction sound, and a pop. The sound quickly grew louder. Workers did not immediately see smoke, but eventually smoke started to fill the CDU and VTR.
	From the control room, high pressure readings were observed from the chamber's pressure gauge (PIT-205)–20, 40, and then 50 psi (the max pressure on the gauge). The pressure reading stayed at 50 for some time. All 17 CO monitors, both primary and secondary, triggered showing readings outside of the normal range. Note that there are CO monitors on all three levels of B801A, five on the first floor, 11 on the second floor, and one on the third floor. The automatic facility announcement of fire and FD response was triggered.

WHEN	WHAT
SHOT DAY–6/10/2021 (Cont.)	
30 seconds to minutes after the shot	The bunker supervisor called for an evacuation of the facility (facility residents were most likely already evacuating) and called 911 as evacuating. Some also heard the facility announcement regarding fire alarms. One of the operators saw the pressure from the chamber start to decrease to 40, and another worker recalls the pressure reading in the mid-20s upon evacuation. No temperature reading was observed.
30 seconds to minutes after the shot	As evacuating, the bunker supervisor noticed the closed-circuit television view of the area immediately outside of the chamber's large equipment door and saw that smoke was leaking through the door. One of the operators also saw steam (a white cloud) leaking through the equipment door. However, the puff through the equipment door appeared to stop (possibly indicating that the pressure in the chamber went in another direction). Evacuees also saw smoke coming out the stack upon exiting the facility.
Minutes after the shot	All personnel in the B801 complex evacuated to the assembly point located west of the B801 facilities near the cooling tower (upwind). All personnel were accounted for by way of a head count.
	The FD arrived at the B801 complex, along with the Facility Manager (FM), Integrated Safety Team Lead for S300, and a Protective Force Officer.
	The FD directed personnel to move to a secondary assembly point located at the entrance gate to the B801 complex (further west of the facility).
	ES&H representatives performed Alpha Meter scans of the 16 personnel who were in the VTR and CDU room at the time of the shot. They used the FD meters since facility meters were inaccessible. The scans detected no contamination.
	There was considerable coordination and discussions with the FD about potential hazards and the layout of the facility. For example, the bunker supervisor communicated that the methane bottles for the experiment were still on, even though the system does have an automatic shut-off feature. The bunker supervisor also communicated that the VTR was in an unsecured state with classified data inside, and there was helium and nitrogen still supplying equipment in the camera room.
	The FD waited for HAZMAT units to arrive on the scene. They also wanted the fire alarm data from the multiplexed alarm reporting (MXL) panel; they called an alarms technician to try to reset the fire alarms remotely, but they would not reset. A technician from S200 was asked to come to S300 to help reset the alarms.
	The FD coordinated a plan for re-entry with ES&H and reviewed the run card data.
	Some employees who had their personal belongings in their possession were identified and released to leave the area.

WHEN	WHAT
SHOT DAY–6/10/2021 (Cont.)	
~7:00 p.m.	The FD entered the rattlesnake room of B801D and viewed the video feed for visual indications of concerns. They also viewed the alarms and located the methane bottles outside of B801D and shut them off.
	The health physicist (HP) and industrial hygienist (IH) made the determination that B801D was not considered contaminated due to the physical separation of the ventilation and buildings.
~8:45 p.m.	B801D and its surrounding area was determined by the FD and ES&H to be safe to approach and enter.
	The FM walked with the alarms technician to the MXL panel that is at the entrance and outside of B801A and reset all alarms except for the one in the camera room, which would not reset. The camera room is a small area, and it is assumed that the sensor was overwhelmed since there is less ventilation in that area.
~9:30 p.m.	Remaining personnel were brought into the Rattlesnake Room of B801D to re-group and determine the path forward. Concurrently, workers tried to remote login to the camera data from the Rattlesnake Room to recover shot data but were unsuccessful. Workers went to B851 to remote login and were able to save and review camera data. The camera data review identified a secondary fireball that occurred (approximately 100 milliseconds) after the intended shot fireball.
	A Q-cleared firefighter and the chamber operator entered B801A to perform an initial sweep of B801A. Personnel were wearing powered air purifying respirators (PAPR) as personal protective equipment (PPE). The FD then turned B801A over to ES&H to manage re-entries.
	The chamber operator completed his sweep of B801A. He went into the gray area and secured the chamber, went into the VTR to shut off power to the Photon Doppler Velocimetry (PDV) laser and associated equipment, pin diagnostics, and cameras and then secured the VTR, locked the security key for the chamber area, and gathered items (e.g., computers, car keys, etc.) from the Scorpion Room inside the bunker door of B801A. The chamber operator brought a camera with him and identified black soot on both the long chase's east and west doors into the VTR. The chamber operator had an E120 meter and read 200 counts on both doors. The chamber operator confirmed before removing PPE that his PPE was clean and not contaminated.
~11:20 p.m.	The ES&H technician scanned all items brought out of the Scorpion Room using an Alpha Meter for release. Nothing was detectable above background.
	ES&H technicians secured signs on the building and main entry points to the area as Radiological Buffer Areas and Beryllium Materials Areas (BMA). The main entry points included the gate on Table Road, the personnel gate up the stairs to the upper parking lot, and the door going into the lower control room of B801A.

WHEN	WHAT
SHOT DAY–6/10/2021 (Cont.)	
11:30 p.m.	All remaining personnel left the area.
6/11/2021	No one was onsite at B801. Personnel at S300 work four 10-hour days, with Friday off.
6/11/2021, 2:30 p.m.	The event at the CFF was categorized as an "occurrence report"–a facility operational event. Verbal notifications were completed. Note that it was determined that no reportable quantities per 40 CFR 302 nor environmental criteria were exceeded.
6/11/2021	The ES&H technical services SME reported this incident to the San Joaquin County Office of Emergency Services due to Hazardous Materials Business Plan reporting requirements. Specifically, immediate reporting is required if there is reasonable belief that the release or threatened release poses significant present or potential hazard to human health and safety, property, or the environment.
6/14/2021	Request issued for bioassays for the 16 individuals in the VTR/CDU. Note that an additional worker that was around B801 also requested a bioassay, with a total of 17 bioassays requested/fulfilled. Over half of the affected employees provided bioassay samples and the first batch was entered into the electronic system.
	Affected personnel were offered an appointment at the S300 health services.
6/14/2021, 8:30 a.m.	Fact finding meeting held.
6/14/2021	Sample plans began; swipes were prioritized on a scale of 1-5 for different areas in B801A.
	Direct surveys within the VTR discovered 10,062 dpm/100 cm^2 alpha on the floor at the point of breach. The VTR was posted as a Contamination Area/Radiological Buffer Area (RBA).
	ES&H technicians entered B801A to retrieve the sample cassettes from the air samplers used to confirm if Be and/or rad leaked into surrounding areas because of the event. The employee wore a full-face air-purifying respirator (APR) with P100 filters with an assigned protection factor (APF) of 50. Technicians also accessed the roof of B801A and collected the sample cassette from the air sampler for the chamber stack exhaust.
6/15/2021	First batch of bioassay samples went to the lab at S200 and were moved to the top of the priority list.
	Priority 1 and 2 swipes were collected. The employee wore a PAPR hood with P100 filters and APF of 1000.
6/16/2021	Last batch of bioassay samples were sent to the lab for analysis (by 1:30 p.m.).
	Three separate entries were made into B801A to collect the priority 3-5 swipes. The employee wore a PAPR hood with P100 filters and APF of 1000.

WHEN	WHAT
6/16/2021	Be swipe results were received for priority 1 areas. The following areas were released from Be controls: • Lower control room and Scorpion Room; • Flash radiography (FXR) corridor and corridor 1; • R113-R119, R2034, R2029-R2032, R2036; • Chamber tech area (R2002); • HST office (R2003); and • Men's and women's restrooms (R2020 and R2007).
	Be air sample results were received for the area samplers located around B801A. Detectable levels of Be were identified in the camera room, short chase, CDU room, VTR, and men's bathroom.
6/17/2021	Be swipe results were received for priority 2 and 3 areas. The following areas were released from Be controls: • R150, • R155 Mezzanine, • East and west half of the CDU room, and • The VTR (excluding the platform to the long chase and east end). The following areas were posted as Beryllium Work Areas (BWA): • East end of VTR, • Platform to the long chase in the VTR, and • Camera room (129).
	Personal air sampling results were received for the ES&H technicians performing sample collection in 801A. Results were below the analytical limit of detection for all entries. Respiratory protection controls were downgraded for work in the temporary BWAs.
6/17/2021	Radiation survey results for priority 1 and 2 areas in B801A were received. Areas within priority 1 were released from RBA controls. This includes the first floor, office areas, and hallways. Third floor areas remained as an RBA along with the CDU, VTR, and gray area. Some areas within the VTR were also CAs.
6/18/2021	Be swipe results were received for priority 4 and 5 areas and the following areas were released from Be controls: • Outside the buffer area in R2018, • FXR High Bay (R125), • Mechanical rooms 201-202 and 2012, • Scrubber room 2004, and • HEPA and HVAC rooms (3001 and 3002). Buffer area in gray area (2018) continued to be a BWA.
	Air monitoring results received from the stack–Be, copper, and lead were detected in the stack exhaust following the event. It should be noted that this air sample can only be used to confirm the presence of metals. The sample results cannot be used to accurately quantify the concentration of any contaminants in the stack exhaust.
6/18/2021 2:00 p.m.	Data was successfully recovered from the VTR. Some equipment was also turned off during entry into the VTR.

WHEN	WHAT
6/21/2021	Radiation survey results show that the only areas that remained as an RBA were the CDU room, camera room, and the west side of the gray area. The VTR also maintained its RBA and CA postings.
6/21/2021	New sample cassettes were placed on the area samplers to determine if the vent and purge of the firing chamber would introduce any new contamination into the adjacent areas.
6/21/2021 p.m.	The CDU room and VTR were posted as both an RBA and a BWA prior the purging the chamber. The chamber purge was completed (minimum 10 air exchanges).
6/22/2021 a.m.	Sample cassettes were placed to monitor the impacts of the purge were retrieved and were submitted to the lab.
6/22/2021 a.m.	The chamber was entered by chamber operators in appropriate PPE. The explosive all clear was determined and the accidental detonation hazard zone was dropped. Chamber operators took pictures of the scene for the IA team while the scene was being preserved.
6/22/2021 p.m.	The chamber was re-entered and the image plates removed from the chamber once the IA team was able to view the pictures and determined that enough information of the undisturbed scene was captured.
6/23/2021	The results of the chamber purge were received. Airborne Be was not detected in any of the area samples pre- and post-purging of the chamber. The following areas were downgraded from respiratory protection: VTR, CDU room, and camera room. The following areas in the VTR continued as BWAs: the east side of the VTR and the platform to the long chase. The rest of the VTR and the CDU room were released from Be controls.
6/24/2021	Radiation swipes and air samples showed that the VTR, CDU room, and gray area did not require respirators. The RBA postings and the CA remained in the VTR.
6/25/2021	A written occurrence report was submitted to the occurrence reporting processing system (ORPS).
6/28/2021	Bioassay results were received. There was no indication of an uptake of Depleted Uranium for the 17 individuals.

Immediate and/or mitigating actions taken in response to the event

All personnel present in B801 evacuated the area. The evacuation from the VTR and the CDU room was described by affected personnel as organized and not rushed. Building occupants assembled at the assembly point located west of the B801 facilities near the cooling tower, which was upwind. All personnel were accounted for by way of a head count. The FD arrived at the B801 complex and moved personnel to a secondary assembly point located at the entrance gate to the B801 complex further west of the facility.

The main concern for affected personnel upon exiting the facility was potential exposure to radiation and Be contamination released from the experiment. Once workers were relocated from the main assembly point to the secondary assembly point near the main road, ES&H representatives/trained workers performed Alpha Meter scans of the 15 personnel who were in the VTR and the one person who was in the CDU room at the time of the shot. The scans detected no contamination.

Once it was determined that the areas around B801D were safe to approach, the methane bottles outside of B801D were shut off. B801A was entered by a Q-cleared firefighter and one of the chamber operators; both workers were wearing PPE. The chamber was secured; the power shut off to the PDV, pin diagnostics, and cameras; and the VTR was secured. The security key for the chamber was locked. Personal belongings were retrieved from B801 and were scanned prior to release; no contamination was detected. Close to midnight, all remaining personnel were released and left the site.

Background

Located at LLNL's Site 300, the CFF and Building 801 complex were constructed in 2000 to enable the continued testing of hydrodynamic experiments while mitigating the impacts of experimentation with potentially hazardous materials. The B801 complex consists of B801A, B801B, and B801D. Room 2023 within B801A, (Figure 1) is the CFF's chamber. (b) (7)(F) (b) (7)(F) B801D and B801B consist of mainly office space.

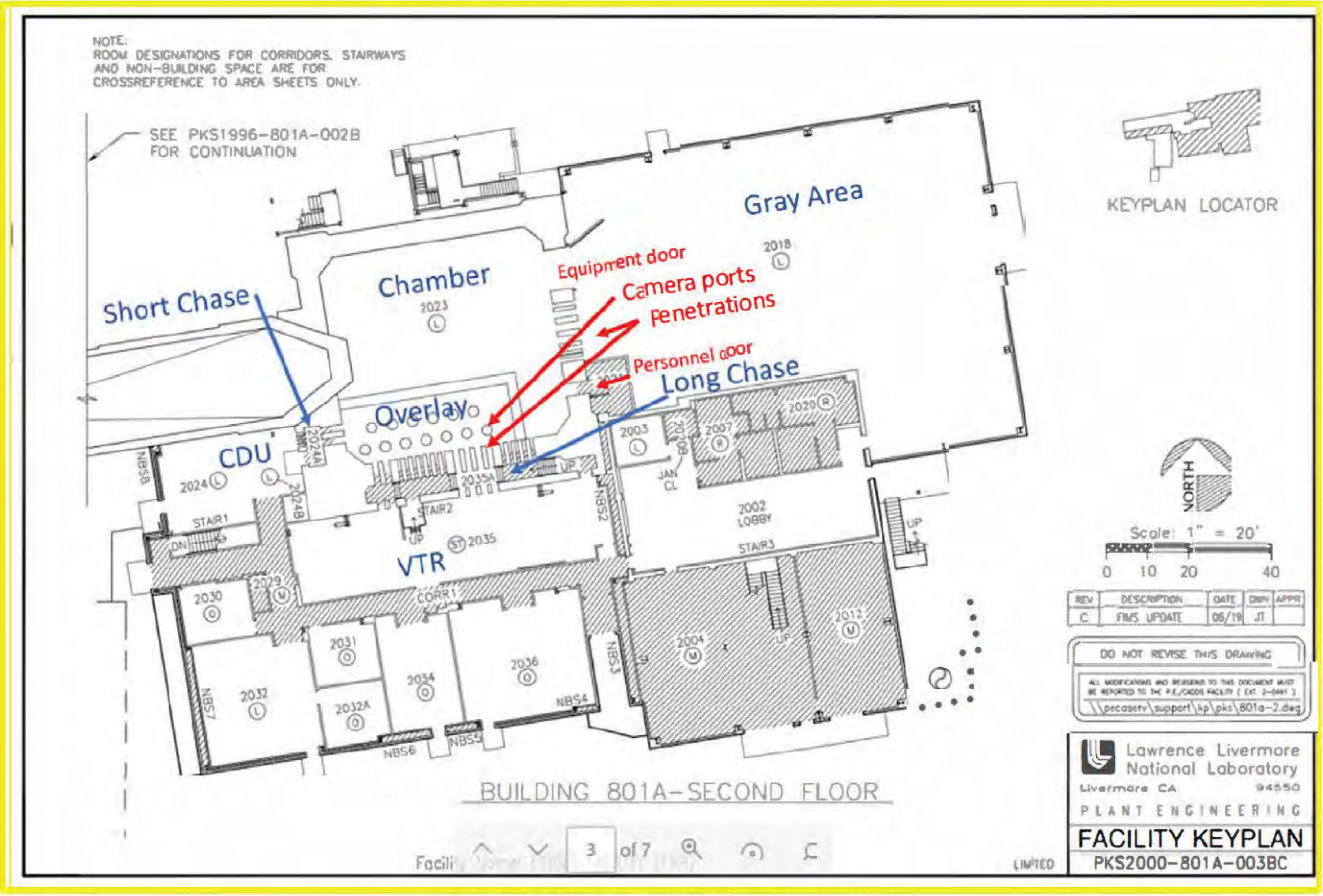


Figure 1: Facility keyplan of the 2nd floor of B801A.

The chamber is of unique construction designed to contain a detonation of up to 206 pounds of explosives and all its explosive effects, including resultant quasi-static pressures, within its walls. Designed in accordance with Army Technical Manual (TM) 5-1300, "Structures to Resist the Effects of Accidental Explosions," later superseded by Unified Facilities Criteria (UFC) 3-340-02, "Structures to Resist the Effects of Accidental Explosions," the chamber was constructed with rebar-reinforced concrete directly over the existing camera room and the FXR building that were previously in existence. The concrete structure of the chamber was then outfitted with a pressure liner consisting of mild steel plates affixed to the ceiling and walls and welded together to form a solid steel layer over the concrete. This pressure liner terminates at the floor, sealing to the concrete of the chamber floor as well as to the overlay and serves as the main barrier in ensuring a 32 psi quasi-static design pressure limit can be maintained. As a result of the chamber construction occurring over existing structures, special considerations were made to mitigate negative interactions between structures that could potentially compromise the chamber's ability to remain sealed. This consideration necessitated a design called the overlay to be constructed over the existing camera room, creating an additional sealing location. To qualify the chamber, it was over tested to 125% (75kg) of the operational weight limit of 60kg and was originally utilized for singular explosive device experiments. Over the current life of the facility, the CFF has been used for a variety of experimental configurations. Most recently, it has been utilized for multiple explosive devices simultaneously present and detonated within the chamber ensuring independent and cumulative explosive masses are below limit thresholds.

During any experiment where the detonation or deflagration of energetic material occurs, emissions are generated in the firing chamber, and therefore LLNL has an air permit with the San Joaquin Valley Unified Air Pollution Control District to permit these activities. Integrated into building design and identified in the air permit, B801A is equipped with a 100-gallon-per-minute sodium hydroxide scrubber that is used to remove acids, primarily hydrochloric acid and hydrofluoric acid, from gaseous experimental by-products. These acids are known by-products resulting from detonations of explosives, which contain the precursors of the acids in their binders. After passing through the scrubber, these by-products continue through High-Efficiency Particulate Air (HEPA) filtration and filter out particulates with 99.97% efficiency or better before being released outside the facility through the stack. These systems are designed to prevent any hazardous material and experimental by-products from exiting the building.

To better provide facility operators and personnel an indication of the status of the chamber and surrounding areas post-experimental execution, B801A is equipped with pressure and temperature monitoring capabilities within the chamber as well as 17 carbon monoxide (CO) monitors located throughout the facility. Operators monitor and document these readings and indications for various purposes. Temperature and pressure monitors provide operators vital information for operation of scrubber and HEPA systems while CO monitors provide an indication of potential release of experimental by-products. Pressure and temperature monitors are located within the chamber venting flow path, and CO monitors are divided into 10 primary and seven secondary monitors across all three floors of the building. Primary monitors are in areas that are unoccupied by personnel during experiment execution, and secondary monitors are located in areas where personnel may be present, forming a defense-in-depth notification approach.

This experiment included two types of HE-driven experiments comprised of three individual explosive charges, denote (b) (7)(F) was the primary experiment, a thermally cooled experiment. The (b) (7)(F) were secondary experiments using soft capture experiments locate (b) (7)(F) (b) (7)(F) There was also a fragment collection experiment known as the environmental addons from Figure 2. The environment addons included water stacks and foam fragment catchers to capture fragments for analyses; it did not include hazardous materials, but the foam catchers were a major source of hydrogen cyanide during this event.

LLNL has been in the design process of experiment setup for the (b) (7)(F) Reviews of previous similar experiments and discussions with colleagues about lessons learned generated from previous experiments with similar thermal controls and multiplexed digitizer systems functioned as a guide for experiment execution. Although a common experimental configuration, th(b) (7)(F) ncluded implementation of a multiplexing system and use of a new diagnostic, the M9a portable Linatron X-ray source, used for obtaining high resolution radiographs while the device is environmentally conditioned in situ. The M9a diagnostic captures part dimensional changes to document the actual internal configuration as fired while the device cools to a desired temperature. Adding the M9a diagnostic required a suite of functionals to be successfully performed in the facility before utilization. The(b) (7)(F) included use of (b) (7)(F) (b) (7)(F) omponent as part of the design. The(b) (7)(F) vas setup in a standard location within the CFF's chamber, as shown in Figure 1, within a thermal box made up of 51-71 kg of foam 10 meters from the FXR source (the source is recessed about two feet into the bull nose). A radiographic image pack was placed two meters beyond the setup of the(b) (7)(F) to capture X-ray images. Four additional plastic garbage cans containing approximately 832 kg of water were placed on the overlay to protect a port above the overlay from damage.

The(b) (7)(F) utilized a standard soft capture mechanism and were set up in the northwest corner of the chamber, closer to the exterior walls than typical.

The environmental addon included water stacks, noted as white squares in Figure 1, and three blocks of foam, noted as purple squares in Figure 2, and were placed aroun(b) (7)(F) There were approximately 2,280 gallons of water in the water stacks. The three foam blocks, intended to capture fragments without deforming them, consisted of approximately 7,015 pounds of foam total. The foam bundles were layered with different densities of foam ranging from 5 lb/ft^3 to 40 lb/ft^3 to sufficiently slow fragments without significant deformation or mass loss. Two of the three foam bundles were full-frame bundles (4 ft wide x 4 ft deep x 8 ft high) and included Kevlar layered in the bottom or top half of the bundle in a pre-prescribed fashion. The third bundle was half the height of the other bundles (4 ft wide x 4 ft deep x 4 ft high) elevated on a stand between th(b) (7)(F) and FXR bullnose and included a Kevlar layer only adjacent to the highest density foam. All bundles included a make screen (time of arrival diagnostic) of copper foil facing the(b) (7)(F)

(b) (7)(F)

Figure 3 denotes the actual configuration in the chamber on shot day. The differences from the configuration in the EAR (Figure 2) and that in the chamber on shot day (Figure 3) were:

- Water in the plastic trash cans that were originally planned to be placed around the (b) (7)(F) vere placed on the overlay to protect that area from shrapnel.
- An additional water stack was added to the west side of th (b) (7)(F) o prevent experimental cross talk. It was added due to the inability to move the water tank already in the chamber and intended for that location because of concerns of the stability while on the forklift.
- One of the four steel plates that was originally going to be placed around the (b) (7)(F) was placed between the (b) (7)(F) to protect the wall from fragments.

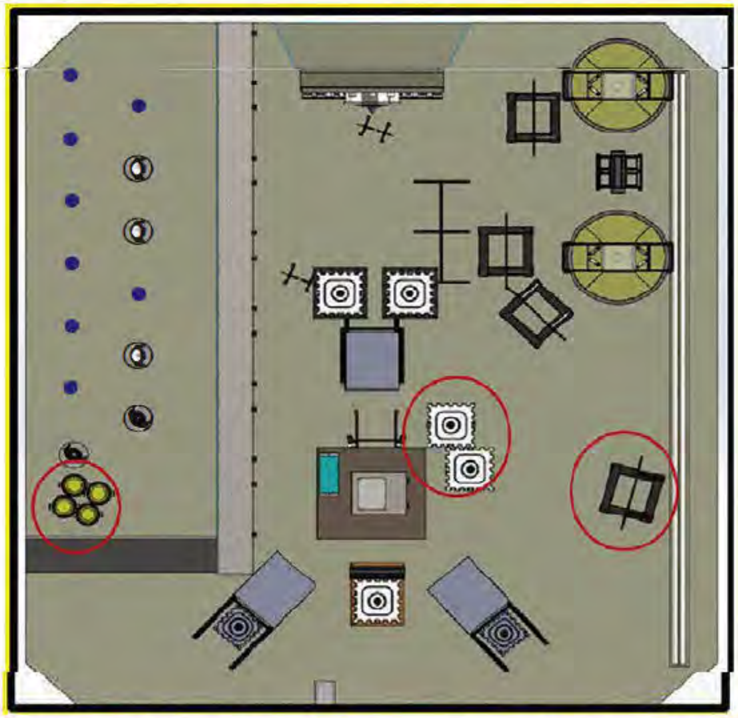


Figure 3: The actual shot configuration of the experiments in the chamber on June 10, 2021.

Several processes were reviewed and evaluated as part of the change analysis. Some of the processes briefly introduced in this section include design reviews, the *Site 300 Firing operations Experiment Workflow,* bunker scheduling request, chamber protection review, and the EAR.

Engineering design reviews were completed for the two energetic experiments, the 663G and the 671s, and the environmental addon experiment was integrated in the FDR for the 663G experiment.

The LLNL Defense Technologies Engineering Division (DTED) has a design review policy that "establishes an expectation for conducting and documenting design reviews for work under the auspices of the Weapon Technologies and Engineering Program." There are three main technical reviews, but not all are required: the preliminary design review (PDR), intermediate design review (IDR), and final design review (FDR). This document describes the scope of the engineering PDR to include "general concepts, scope definition, requirements (programmatic, quality assurance, ES&H, and Security), interface definition, safety basis, cost or schedule constraints, risk/risk mitigation (e.g., Failure Modes and Effects Analysis), mapping of requirements to design/implementation/ verification." The scope of the engineering IDR includes "progress as measured against scope, schedule and budget, progress of safety documents, risk identification and mitigation strategies, review of interfaces, and material handoffs." The scope of the engineering FDR includes "assurance that actions from previous reviews are closed; safety documentation has been written, reviewed, and approved; interfaces are defined; assembly procedures and test plans, risk/risk mitigations, and start-up plans and procedures have been written and approved."

S300 firing operations utilize a *Site 300 Firing Operations Experiment Workflow* procedure that "provides clarity on how experiments or shots are initiated and fielded at the WCI Site 300 firing operations facilities." Many of the following processes are described in more detail in this procedure, the EAR, chamber protection review, and the bunker scheduling request. It also defines roles and responsibilities for key roles such as the bunker supervisor, Ramrod, and lead engineer. This procedure provides a flow chart of tasks and roles from the start of the experiment, initiation of the bunker scheduling request, through the shot day, and closeout of the experiment.

The bunker scheduling request packet submitted by the Ramrod includes the estimated amount of HE, desired diagnostics, toxic materials to be used in the experiment and resources required such as radiography needed. For this experiment, the bunker scheduling request estimated a total of (b) (7)(F) both the (b) (7)(F) experiments, well under the 132 pounds maximum weight limit of the CFF's chamber listed in the S300 Firing Facility safety plan (FSP). The toxic materials listed for the (b) (7)(F) were DepU (henceforth noted as Rad D38 per bunker schedule request), Be, and LiH. For the (b) (7)(F) the toxic material listed was Rad D38. The bunker scheduling request packet was sent to the bunker supervisor and provided to various disciplines, facility, and RHWM personnel for review.

The chamber protection review is an evaluation performed by a mechanical engineer for protection inside of the chamber for designated experiments. Topics of this review include fragment and temperature effects; blast pressures; port, door, overlay, FXR bullnose, and diagnostics protection; multiple experiment interactions; HE types and chemistry; and anvil loading. It was communicated that the chamber protection review is a fairly new process improvement that was developed after the Monster shot that occurred in 2017 where contamination leaked into an unoccupied area. The Monster shot included several experiments in the chamber during execution of the experiment. The chamber protection review process was created to evaluate the effect of multiple shots in the chamber at one time and their interactions.

The EAR is a document prepared by the Ramrod and includes the design layout of all components and experiments in the chamber, including the shot stand assembly and setup, M9a setup, shielding zones, radiography plan, timing, camera allocations, fragment alley, field mirror setup, special instructions, and a listing of required materials. The EAR functions as the pre-shot, record of experimental setup, and as the vehicle for peer review. The EAR was reviewed by various disciplines and program representatives. Feedback was provided on the workflow, restrictions, optimization, diagnostic limitation, and diagnostic improvements, etc. Comments were incorporated, and the EAR was internally peer reviewed by the Ramrod group with feedback provided. The EAR was approved by two principal investigators, the Ramrod group leader and the explosives experiment fielding supervisor.

There are several other procedures related to firing operations, and many of these procedures are completed during execution of an experiment and then become a record. All the procedures/records were reviewed as part of this analysis, and some were analyzed further as part of the change analysis process. Two processes worth introducing in this section are the Methane Utility Manifold Assembly (MUMA) process and penetration checklists. The MUMA is a methane gas delivery system attached to an explosive device/experiment within the CFF that some experiments utilize. Firing operations follow the MUMA operations procedure, which provides the typical gas manifold that might be used. There is also a process for reviewing penetrations in the chamber to ensure they are closed and torqued prior to the shot. There are two penetration checklists, the *Bunker 801*

Chamber Penetration Checklist and the *Chamber Penetration Checklist for FXR Operation Beaming into the Chamber.*

Work Planning and Control (WP&C) is an activity-level implementation of the core functions and guiding principles of LLNL's Integrated Safety Management System (ISMS). This system provides a standard set of expectations, procedures, tools, and training that are applied consistently to the planning, control, and conduct of work and is implemented through policy document POL-2010, "Work Planning and Control" and DES-2012, "The LLNL Work Planning and Control Program." The WP&C system produces a work control document (WCD) or work package that bounds the work scope, identifies the hazards, and specifies the controls for work activities. WCDs are written to provide clear, concise direction for the workers performing those work activities. There are several WCDs related to experimental execution and post experimental clean-up used for this experiment:

- WP&C document No. 100133, "Firing Areas Laser Diagnostics Operations and Maintenance";
- WP&C document No. 100146, "Firing Area Camera Diagnostics and Maintenance";
- WP&C document No. 100336, "Firing Areas Post Experiment or Maintenance Recovery";
- WP&C document No. 100451, "Firing Areas Electronics Operations";
- WP&C document No. 100712, "Firing Areas Radiography Operations";
- WP&C document No. 100852, "Firing Area Chamber and Table Operations and Maintenance."

All WCDs were reviewed for applicability, but only relevant WCDs and associated tasks are documented as analyzed in the change analysis.

LLNL has an institutional peer review process for risk management of explosives-related experiments that is covered in ES&H Manual Document 17.1, Explosives. Peer reviews are performed for experimental explosives work to ensure that factors adversely affecting the success or safety of the experiment are identified/mitigated and controlled prior to performing this work. The peer review is a process that is a thorough and objective review by designated experts that involves new processes, experimental conditions, materials, or work that is otherwise required by FSPs. Peer reviews examine the physics, chemistry, and engineering aspects of the process. LLNL uses peer reviews as a tool to assure that an explosives experiment can be safely executed. Peer reviews do not specify new safety controls; however, if they are needed, they shall be addressed in the appropriate safety document that controls the operation (i.e., WCD). The peer review process begins when an individual initiates the work by submitting a completed a peer review form with supporting documentation describing the work. Peer reviewers examine these documents for completeness, accuracy, and potential safety concerns. Peer reviews are valid for up to one year and kept on file.

Analysis and Results

The issue for analysis is combustion products and contamination were released from the CFF's chamber soon after an experiment was initiated, releasing material into nearby rooms where personnel were present.

Interviews were performed with over 30 personnel and included the following roles (listed alphabetically):

- Assembly personnel,
- Associate DTED leader for operations,
- Bunker supervisors (including acting),
- Chamber operators,
- Conducts of operations subject matter expert (SME),
- Console operators,
- Engineers including engineers for each of the experiments,
- ES&H representatives including the IH and the HP,
- Explosive experiment fielding supervisor,
- Facility Manager,
- Firing operations personnel,
- Peer reviewers from approved peer review groups,
- Personnel located in the VTR and CDU areas during the event,
- Principal investigators for each of the experiments, and
- S300 Ramrods.

Barrier and change analyses were performed to analyze for apparent causes. Failed barriers and differences in process steps were analyzed to determine if they impacted the issue for analysis and if so, were determined to be apparent causes. Those differences that did not impact the outcome or event, were determined to be observations. Apparent causes identified from the failed barriers and/or differences in process steps were then analyzed further using the why/because methodology to determine root causes. HPI analysis was also considered and provides context for each why/because analysis.

A substitution-like test or mock peer review was also performed to determine how effective a peer review in the areas of physics, engineering, and chemistry may have been in the planning phases of these experiments. Peer reviewers from the approved peer review list were selected, specifically those that knew little about the event and had expertise in several the peer review groups recognized by the LLNL Explosive Safety Committee, process, physics, and materials. The IA team presented the experiment, including design information, the EAR, the chamber protection review, and the Materials Database to the mock peer reviewers. The IA team then fielded several questions from the mock peer reviewers.

A series of sub-scale experiments were designed and performed in the High Explosives Application Facility (HEAF) to support the TA team. These experiments were designed to determine if any of the flammable materials or combinations of materials could be identified as the primary contributor to the incident. The IA and TA teams came up with five hypotheses to test the myriad flammable materials that were in the chamber during the experiment. One noteworthy material that has not been used in this amount and position in a hydrodynamic test in the chamber was ABS, a known flammable plastic. Because of the known flammability and lack of history of using ABS in a hydrodynamic experiment in the chamber it was of particular interest. Other materials that had been used in the chamber in various quantities throughout the history of the CFF that were still of interest as flammable mass included:

- Blue insulating foam in thermal conditioning box, DOW®, Styrofoam™ (extruded polystyrene foam insulation);
- LAST-A-FOAM® flame-retardant (FR-series) ridged polyurethane foam, various densities, used in various locations;
- Low density polyethylene (water barrels and water tanks);
- 3D-printed ABS plastic (Stratasys FDM thermoplastic ABS-M30 TM).

Tests aimed to provide insight and answers to the following questions:

1. Were any materials in the chamber susceptible to continued burning when exposed to a flame?
2. Were any materials in the chamber susceptible to continued burning when exposed to radiant heating?
3. Does 3D-printed ABS plastic pulverize from a detonation driven shock?
4. Does pulverized, dispersed ABS plastic easily initiate into a fire from a spark/ignition source?
5. Did th (b) (7) (F) geometry and conditions lead to an ABS fuel-air mixture leading to a late-time explosion? (This would be considered as a final recreation of the shocked and dispersion conditions of the ABS.)

The experimental setup, analysis, and results are discussed in Appendix B of this report.

Barrier Analysis

The barrier analysis included physical barriers related to the chamber and chamber components. Administrative barriers, or processes, are analyzed in the change analysis. The barrier analysis includes four columns: a description of the barrier, a determination of how it performed (successful or failed), if it failed, why it failed, and a description of the effect of that failed barrier on the issue. If the failed barrier had an effect on the issue, then the failure is considered an apparent cause. Otherwise, the failure is considered an observation.

Table 2: Barrier Analysis.

BARRIER	PERFORMED	WHY FAILED	EFFECT ON THE ISSUE
Engineering design pressure constraints of the chamber	Failed	This experiment exceeded the quasi-static pressure of 32 psi, a chamber design constraint, intended to hold for an extended duration.	Physical barriers failed.
	Performed	The total amount of HE used in all experiments, (b) (7)(F) was well under the 132-pound maximum weight limit of the CFF's chamber listed in the S300 firing FSP.	N/A
Overlay seals	Failed. See why/because analysis for more information.	The overlay seals allowed combustion product and contamination to bypass it and leak into adjoining areas, the camera room, the long chase, and the VTR. Three holes were identified in the overlay seal.	Combustion product and contamination leaked into multiple areas without filtration, including the VTR where personnel were present.
Equipment and personnel door seals	Failed. See why/because analysis for more information.	All three seals on the personnel and equipment doors, the fire rope, face, and o-ring seals allowed combustion product and contamination to leak through both doors.	Combustion product and contamination leaked into areas without filtration, but no personnel were present.

BARRIER	PERFORMED	WHY FAILED	EFFECT ON THE ISSUE
Camera port seals	Unknown	It is unknown if the camera port seals failed. As a result of multiple leak paths, water and contamination leaked into the camera room. It cannot be determined if the leak paths were the camera port seals.	Possibly allowed combustion product and contamination to leak into areas without filtration, but no personnel were present.
Port feedthrough seals	Unknown	It is unknown if the port feedthroughs seals failed. If they failed, the seals would have allowed combustion product and contamination to bypass it and leak into the two chases. This same by-product and contamination may have leaked into the CDU and VTR, but the actual leak path is unknown.	Possibly allowed combustion product and contamination to leak past them into long/short chase and then into the VTR where personnel were present.
Rox seal from the long chase to the VTR	Unknown	It is unknown if the rox seal failed. Based on pictures, it looks like the rox seal is still intact, but it has not been physically reviewed or analyzed.	Possibly allowed combustion product and contamination to leak past it into the VTR without filtration with personnel present.
Structure (doors, wall, FXR bullnose)	Performed	No visible or proof of damage to chamber door, etc.	N/A
Overlay/frag plates to protect the overlay seal	Performed	Overall, the overlay plates mitigated the entire overlay seal from becoming compromised. In one instance where there was a hole in the overlay seal, it is thought that one of the spacers installed on an overlay plate potentially punctured the overlay seal causing the hole.	Overlay seal was compromised.
Overlay/frag plates to protect the overlay structure	Performed	N/A	N/A

BARRIER	PERFORMED	WHY FAILED	EFFECT ON THE ISSUE
Firing chamber ventilation	Performed	N/A	N/A
Long chase and short chase ventilation	Performed as designed	N/A	N/A
Sodium hydroxide wet scrubber employed to remove acids that are by-products resulting from detonations of explosives.	Expect would have performed if the exhaust valve was opened.	Combustion products bypassed the scrubber and HEPA by circumventing the ventilation system as configured (i.e., the exhaust valve was never opened before evacuation).	N/A
HEPA filter bank used to filter all explosive testing emissions from the firing chamber.			N/A
Interlocks on doors where known hazards are present during a shot (e.g., camera room, gray area, FXR high bay).	Performed	N/A	N/A
Interlock to vent chamber	Performed	N/A	N/A

Change Analysis

The change analysis includes a review of several existing processes related to firing operations. It includes the "ideal" process step (step from the procedure), what actually occurred, the differences between the ideal and actual (if existing), and the effect that difference had on the event. If there is an effect, the difference is considered an apparent cause; otherwise, the difference is considered an observation. The reference of the ideal step is provided as well in the ideal column. In many cases the ideal and actual steps were the same and therefore no difference, cause, or observation is noted.

The design review process was analyzed, but it is not reflected in the change analysis table. It was determined after review and discussions with interviewees, that the design review process is not a process that could have changed the outcome of this event due to its intended focus. Design reviews are conducted for individual experiments, not a collection of experiments, and the focus is on the design and whether the design will provide the desired data. Therefore, this process is not documented as part of the change analysis. There are other processes that occur after the design review to analyze and review all experiments collectively.

Table 3: Change Analysis

SOURCE	IDEAL PROCESS STEP	ACTUAL PROCESS STEP	DIFFERENCE	EFFECT ON THE ISSUE
Experimental Kick-off	Experimental kick-off meeting verifies work authorization and allows for early planning and preparation for the experiment (ref. workflow).	Meeting occurred on 3/22/21; EAR was fully presented. It is also referred to as the EAR or pre-EAR briefing. Invitees included Bunker 801 personnel, Ramrods, IT personnel, the FM, PIs, ES&H technician, engineer, chamber operators, bunker supervisor, etc.	The IH, HP, and explosive safety SME were not listed as attendees on the invite to the experimental kick-off meeting. The presenter is not positive that all points from the workflow procedure were covered in this meeting. **[Other Observation]**	No effect. Meeting is an opportunity for attendees to voice concerns; it is not the formal "peer review." By the time this meeting happens, the official peer review has already occurred.

SOURCE	IDEAL PROCESS STEP	ACTUAL PROCESS STEP	DIFFERENCE	EFFECT ON THE ISSUE
EAR	EAR is developed and includes layout (ref. workflow).	EAR was developed and included the layout of the experiment. The layout in the EAR shows (b) (7)(F) (b) (7)(F) [redacted]	Final layout in the chamber did not match the proposed final setup of th (b) (7)(F) [redacted] designated in the EAR. There were three differences: (1) four water barrels were moved to the overlay, (2) one of the steel plates around the (b) (7) (F) [redacted] was moved between the (b) (7) (F) [redacted] (b) (7)(F) [redacted] prevent interaction of the two experiments, and (3) an additional double stack of water was added to (b) (7)(F) (b) (7)(F) [redacted] **[Other Observation]**	None of the changes had an effect. For (3), a water stack was always planned for that location. It was only added since the intended stack already in the chamber could not be easily moved. TA team determined that the additional water did not have an effect with all the water that was already present.
	EAR is developed and includes diagnostics (ref. workflow).	Same as ideal	N/A	N/A
	EAR is developed and includes timing (ref. workflow).	Same as ideal	N/A	N/A
	EAR is developed and includes a description of hazardous operations and hazardous materials (MUMA, M9a, LiH, DepU) (ref. workflow).	The EAR was developed and included information on the layout, diagnostics, timing, information on the shot stand, hazards related to the experiment (DU, HE, Be) etc. It also included hazardous operations and materials related to the M9a.	The EAR does not include a description of all hazardous operations and materials related to experiment fielding (e.g., MUMA, materials in device, etc.). **[Other Observation]**	No effec

SOURCE	IDEAL PROCESS STEP	ACTUAL PROCESS STEP	DIFFERENCE	EFFECT ON THE ISSUE
EAR (cont.)	Ramrod review of the EAR.	A group of Ramrods peer reviewed the EAR. Their comments/concerns were mainly focused on structural stability of the half-pack fragment catcher, lighter weight foam to be used, the disposal of the water tanks, and labor involved in that effort.	No difference	N/A
	EAR approval from bunker supervisor.	EAR was approved by the PIs, the Ramrod group, and the S300 operations representative.	The bunker supervisor did not sign the EAR, due to some needed training. The Explosive Experiment Fielding Supervisor, a qualified bunker supervisor, signed the EAR representing the bunker supervisor role. The bunker supervisor communicated that he did have an opportunity to provide feedback, comments, or concerns.	No effect
WORK CONTROL DOC	Task 5: Operate MUMA system.	There is a MUMA procedure, and it is linked to the WCD. The MUMA procedure permits manifold assembly.	The WCD bounds out modifications to the system and does not cover fabrication or creation. **[Other Observation]**	Possible gap in training and allowed tasks. In this case the fabricating individual was trained for this activity.
	Task 13: Thermal conditioning of experiment.	Experiment utilized TCU to cool the device to a desired temperature.	No difference	N/A

SOURCE	IDEAL PROCESS STEP	ACTUAL PROCESS STEP	DIFFERENCE	EFFECT ON THE ISSUE
MUMA PROCEDURE	Recording deviation/deficiencies are found while completing the procedure.	Adjustment was made to redirect the methane flow within the manifold to maintain system operability. It is noted on the form that retesting is required; retested by and date fields were blank on the form. Verifications of deviations and deficiencies addressed was signed and dated on August 4, 2021 (after the event).	The adjustment made to redirect the methane flow was verified as acceptable a few months after the experiment as noted in *MUMA Operation Procedure.* Also, it appears that retesting did not occur based on a lack of signature under the box, "Actions Taken to Correct Deviations/Deficiencies." **[Other Observation]**	The amount of flow of methane was unknown. However, based on the technical team's review, it is speculated that the maximum possible amount of methane flow did not contribute to the event.

SOURCE	IDEAL PROCESS STEP	ACTUAL PROCESS STEP	DIFFERENCE	EFFECT ON THE ISSUE
MUMA PROCEDURE	MUMA components are properly identified, installed, calibrated, and approved for use with methane gas.	Componentry to support the MUMA included a vacuum pump that was used to pump down atmosphere, a precision gas mass flow meter, vacuum gauges that use hot filament, a flow controller calibrated for nitrogen, and several regulators.	Issues were identified with componentry that supports the MUMA: • The vacuum pump for the MUMA is not rated for flammable gases, • The flow meters are not calibrated for methane, • The vacuum gauges are not rated for use with flammable gases, • The flow controller is not calibrated for methane, • There are redundant regulators (possibly not calibrated for flammable gases) and are not rated for pressure/vacuum, • A pressure and instrument diagram (P&ID) is not present for the entire system. **[Other Observation]**	No effect on this event based on discussions with the TA team. Vacuum pump–Potential to ignite flammable gases within the gray area. Flow meters–Potential to inaccurately convey system status information pertinent to experimental execution resulting in an unknown quantity of methane gas. Vacuum gauges–Potential to ignite methane gas during abnormal operating conditions while preparing for the shot. Flow controller–Potential to introduce unknown quantities of methane gas into the device. Regulators–Inability to properly evacuate up to the methane source resulting in an unknown mixture of air and methane. P&ID–Confusion on system componentry location, componentry correlation to operational procedure, and omission of component labeling.
	A SME evaluates the MUMA for the need of a Mechanical Engineering Safety Note (MESN) as a result of system pressure and constituents.	MUMA system evaluation was completed by operation personnel that was not an engineering SME during the WP&C document creation process, and it was determined that an MESN was not needed.	The evaluation was performed, but an MESN was incorrectly determined (based on conversation with LLNL SMEs) to not be needed and therefore was not created. This determination was not made by the appropriate SME or designee. **[Other Observation]**	The componentry used to flow the flammable gas was not properly evaluated. Technical team determined this had no effect on the event.

SOURCE	IDEAL PROCESS STEP	ACTUAL PROCESS STEP	DIFFERENCE	EFFECT ON THE ISSUE
WORK PACKAGE	Assembly of work package 4-6 weeks before experiment (ref. workflow).	Work package approved April 21, 2021 (six weeks before the experiment).	No difference	N/A
	Work package contains cover sheet with signatures from the bunker supervisor and FM.	Same as ideal	N/A	N/A
	Work package includes the bunker schedule request that defines what they are going to do (ref. workflow).	The bunker schedule request includes the classification of the experiment, toxic and hazardous materials present, immediate safety considerations, WCD, and diagnostics required to execute.	No difference	N/A
	Work package includes shot folder contents checklist that entails what procedures are required to be retained for the experiment (ref. workflow).	Same as ideal	N/A	N/A
	Work package includes work assignment sheet that defines RI for designated areas/ diagnostics and is used as the invite or distribution list for meetings/mailings involving the experiment (ref. workflow).	Same as ideal	N/A	N/A
	Work package includes training objectives and identifies the trainer (ref. workflow).	N/A	N/A	N/A
	Work package includes the Materials Database (an unclassified version) and the initial task list (ref. workflow).	Same as ideal	N/A	N/A
	Work package is approved and signed by FM, logged, and made available for team. (ref. workflow).	Same as ideal	N/A	N/A

SOURCE	IDEAL PROCESS STEP	ACTUAL PROCESS STEP	DIFFERENCE	EFFECT ON THE ISSUE
WORK PACKAGE (cont.)	The work package must be updated and re-submitted for approval to the FM if there are changes to its components that substantively alter: i) Hazards and/or controls, ii) Scheduled range of execution (ref. workflow).	Same as ideal	N/A	N/A
	The FM must be notified if there are changes that alter: i) Resources required to perform work, ii) Amount and/or type of classified materials/info, iii) Any potential changes that affect the safety envelope, iv) Any change to the amount or type of hazardous materials on the Materials Database (ref. workflow).	Same as ideal	N/A	N/A
MATERIALS DATABASE	The Materials Database defines materials used and is needed for reporting purposes and ensuring proper hazards are adequately controlled (ref. workflow).	Materials related to all experiments identifies Be, asbestos, DepU, LiH is mentioned in the comment of the unclassified Materials Database for disposal and is listed as a line item on the classified Materials Database LiH was also annotated on the bunker schedule request for (b) (7)(F)	LiH was not listed as a line item on the unclassified version of the Materials Database, it is listed in the classified version. It is annotated on the bunker schedule request for (b) (7)(F) It was also added under the comment field on the Materials Database. [Other Observation]	No effect on the outcome; however, there was decreased transparency with SMEs, and their input may have been valuable.
	The Materials Database is reviewed and approved by RHWM (ref. workflow).	Same as ideal	N/A Note that multiple revisions of the Materials Database form were used.	N/A

f)

SOURCE	IDEAL PROCESS STEP	ACTUAL PROCESS STEP	DIFFERENCE	EFFECT ON THE ISSUE
MATERIALS DATABASE (cont.)	The FM must be notified if there are any change to the amount or type of hazardous materials on the Materials Database (ref. workflow).	There were no changes.	No difference	N/A
CHAMBER PROTECTION REVIEW	Evaluate the chamber protection in its totality from the effects of the experiment. Items covered (not limited to): (1) fragmentation effects (ref. workflow).	Fragment effects for individual experiments were evaluated in the chamber protection review, with the focus on the 671s. It is understood that the Ramrod group and/or PIs did consider fragmentation effects/pyrophoric fragments by their selection of foam densities for use.	The chamber protection review did not evaluate secondary fragment interactions for pyrophoric fragments. [APPARENT]	A possible effect on the outcome of this event cannot be ruled out. Flaming fragments were projected into foam catchers (i.e., environments experiment) without an evaluated outcome considering all materials in the chamber. Evaluation for fragmentation effects may have been an indicator for further analysis.
	Evaluate the chamber protection in its entirety from the effects of the experiment. Items covered (not limited to): (2) Temperature effects (ref. workflow).	Overall–A review of chamber protection was conducted as documented in a memo dated April 19, 2021.	The chamber protection review did not evaluate for temperature effects. [APPARENT]	The potential for material used in these experiments that could combust or pyrolyze as a result of the high temperature environment was not understood.

SOURCE	IDEAL PROCESS STEP	ACTUAL PROCESS STEP	DIFFERENCE	EFFECT ON THE ISSUE
CHAMBER PROTECTION REVIEW (cont.)	Evaluate the chamber protection in its entirety from the effects of the experiment. Items covered (not limited to): (3) Blast pressures (ref. workflow).	Individual blast effects were looked at for experiments containing explosives in the chamber protection review. It was communicated to the IA team that blast interactions between experiments was evaluated to ensure diagnostic success.	(1) Based on a lack of documentation, the chamber protection review did not evaluate combined blast effects. [APPARENT] (2) Based on a lack of documentation, the chamber protection review did not evaluate blast impulse effects for non-energetic components (the environment experiment). [APPARENT]	For (1), there is a potential effect; the evaluation of combined blast effects may have been an indicator for further analysis. The calculated time delay for the air shock to traverse the distance between the (b)(7)(F) s on the time scale consistent with the high-speed videos reviewed potentially creating an environment with increased mixing, fuel sources and agitation of the fuel air mixture. This is supported by observations from video footage. Note that an absolute time basis has yet to be determined. If the time basis was known, it could be more accurately determined if this was a major/minor contributor. For (2), the lack of the evaluation resulted in foam on the floor of the chamber, which could have affected the combustion process and potentially damaged to the chamber.

SOURCE	IDEAL PROCESS STEP	ACTUAL PROCESS STEP	DIFFERENCE	EFFECT ON THE ISSUE
CHAMBER PROTECTION REVIEW (cont.)	Evaluate the chamber protection in its entirety from the effects of the experiment. Items covered (not limited to): (4) Port protection, (7) Diagnostics port protection (ref. workflow).	Port protection (including diagnostic ports) was discussed: - Three water barrels are noted for placement on the overlay to protect the ports. Protection of the FXR bullnose was noted. - Two water tanks were placed to protect the bullnose.	No difference	N/A
	Evaluate the chamber protection in its entirety from the effects of the experiment. Items covered (not limited to): (5) Door protection (equipment and personnel) (ref. workflow).	Door protection was considered - An additional plate was to be added if necessary.	No difference	N/A
	Evaluate the chamber protection in its entirety from the effects of the experiment. Items covered (not limited to): (6) FXR Bullnose protection (ref. workflow).	Protection of the bullnose was analyzed for (b) (7)(F) the experiment in direct line to the bullnose.	No difference	N/A
	Evaluate the chamber protection in its entirety from the effects of the experiment. Items covered (not limited to): (8) Multiple experiment interaction (ref. workflow).	Int actions between (b) (7)(F) (b) (7)(F) were evaluated for blast and agment effects as part of the chamber protection review. Assessed experiments and their interactions were considered as part of the process to ensure that requested data was obtainable.	Based on a lack of documentation, the chamber protection review did not evaluate interactions for simultaneous initiation of the (b) (7)(F) (b) (7)(F) or did it evaluate in s between the environment experiment and the (b) (7)(F) for attribute of combined blast effects, blast impulse effects, estimated resultant temperature, and secondary fragments effects (i.e., ignition source). [APPARENT]	Foam catchers from the environment's interacting with the (b) (7)(F) may have provided additional combustible fuel. Placement of the water in relation to the (b) (7)(F) may have resulted in an unintended rapid reaction.
	Evaluate the chamber protection in its entirety from the effects of the experiment. Items covered (not limited to): (9) HE type and chemistry (ref. workflow).	HE type and chemistry were evaluated for all experiments with explosives.	No difference	N/A

SOURCE	IDEAL PROCESS STEP	ACTUAL PROCESS STEP	DIFFERENCE	EFFECT ON THE ISSUE
CHAMBER PROTECTION REVIEW (cont.)	Evaluate the chamber protection in its entirety from the effects of the experiment. Items covered (not limited to): (10) Anvil loading (ref. workflow).	The location of experiments in respective anvil and loading zones were evaluated for all explosive experiments.	No difference	N/A
	Ensure no variances in actual chamber setup versus what is described in the total chamber protection memo and revise/re-issue if necessary. Bunker supervisor may initiate a work pause to address the issue (ref. workflow).	The final shot configuration had four plastic garbage cans of water on the overlay, and the chamber protection review memo noted three. The additional garbage can was discussed with at least the Ramrod.	The chamber protection review memo was not revised/re-issued to reflect the final shot setup nor was a work pause initiated to address any differences. This implies that the evaluation process for chamber protection was not conducted for the final shot setup. **[Other Observation]**	No effect
	Prior to every experiment in the chamber, a chamber protection review is conducted and reviewed by the explosives experiment fielding supervisor and approved by Associate Program Director for Hydrodynamic and Subcritical Experiments (ref. Firing FSP).	The chamber protection review was sent to the Associate Program Director for Hydrodynamic and Subcritical Experiments and approved by the explosives experiment fielding supervisor.	The chamber protection review was not approved by the Associate Program Director for Hydrodynamic and Subcritical Experiments as required by the S300 Firing Facilities FSP, nor is there a signature line for approval by this role. **[Other Observation]**	No effect
	Chamber protection review is reviewed by peers and/or other knowledgeable technical personnel with experience in mitigating experimental effects (ref. review section of the chamber protection review).	The chamber protection review was reviewed by key operational fielding, programmatic, and facility personnel.	Personnel that reviewed the chamber protection review did not have all the technical background and expertise needed in experimental effects mitigation to better advise the chamber protection review preparer. **[APPARENT]**	Process does not encompass the opportunity to receive technically relevant feedback that may have influenced the layout of mitigation and experiments in the chamber.

SOURCE	IDEAL PROCESS STEP	ACTUAL PROCESS STEP	DIFFERENCE	EFFECT ON THE ISSUE
PEER REVIEW	The ESC appoints scientists and engineers to serve as peer reviewers, to implement the peer review process as described in ES&H Manual Document 17.1, Explosives (ref. ESC Charter).	ESC appointed two groups of S300 personnel as designated peer reviewers. Additional groups include other peer reviewer groups for process, physics, materials, synthesis, directed energy, and large charge reviews.	No difference	N/A
	The peer review process is a thorough and objective review by designated experts, of explosives work that involves new processes, experimental conditions, materials, or work that is otherwise required by facility safety plans and procedures to undergo a peer review (ref. 17.1).	EAR was sent to the designated group of S300 personnel for peer review. The section related to the peer review was approved by reviewers who are listed as approved explosives peer reviewers on the Feb. 2019 version of the approved explosives peer reviewer list.	The groups designated as peer reviewers for S300 may not be experts in all three required areas for examination as part of a peer review that are listed in ES&H Manual Document 17.1, Physics, Chemistry, and Engineering. **[APPARENT]**	The potential chemical interactions were not thoroughly analyzed.
		Peer review is required for all EARs, as stated in the FSP. It is also required in certain instances when lasers are used to illuminate certain types of explosives.	Work that is otherwise required to undergo a peer review is not defined in the Firing FSP, other than for all EARs and in certain instances when using lasers for illumination. **[Other Observation]**	No effect
	The individual proposing the explosives work initiates the peer review process by completing a peer review form (various versions are in use, as specified by individual FSPs) and attaching supporting documents describing the scope of the work (ref. 17.1).	Peer review is required for all EARs, as stated in the FSP. The EAR was the document provided to the peer reviewers for review.	All information pertaining to experiments and associated materials (e.g., plastics used) and all materials present in the final setup in the chamber (e.g., foam, water, other combustibles) was not provided to the peer reviewers in one cohesive package. **[APPARENT]**	An effect only if peer review included an SME review of chemical interactions of all experiments and materials in the chamber.

SOURCE	IDEAL PROCESS STEP	ACTUAL PROCESS STEP	DIFFERENCE	EFFECT ON THE ISSUE
PEER REVIEW (CONT.)	To ensure the quality and objectivity of the peer review, the following shall apply to all peer reviews: • Peer reviewers (PRs) shall not be directly involved in the subject work. • PRs shall have current expertise in the subject area. • The concurrence signatures for all applicable peer review groups shall be obtained prior to executing the experiment. • PRs shall be chosen from a list of individuals maintained by LLNL ESC. • Completed peer reviews shall be retained as specified in the relevant FSP (ref. 17.1).	There were two peer reviewers for this experiment that signed the EAR. Both were on the ESC list as peer reviewers under the S300 groups. They were not directly involved in the subject work. Their expertise was in physics and fielding experiments and had some experience with engineering and design. Experts in physics and engineering participated in all design reviews. EARs are retained as part of the shot record.	The groups designated as peer reviewers for S300 may not be experts in all three required areas for examination as part of a peer review that are listed in ES&H Manual Document 17.1, Physics, Chemistry, and Engineering. **[APPARENT]**	The potential chemical interactions were not thoroughly analyzed.

SOURCE	IDEAL PROCESS STEP	ACTUAL PROCESS STEP	DIFFERENCE	EFFECT ON THE ISSUE
PEER REVIEW (CONT.)	Since there are many interrelated variables associated with such work, each proposed explosives experiment is examined with respect to the physics, chemistry, and engineering of the process (expected contents of peer review) (ref. 17.1).	- The physics of th (b) (7)(F) (b) (7)(F) experiments were considered as part of the design review process. - Engineering of the (b) (7)(F) (b) (7)(F) and environmental addon experiments were considered as part of the design review process and the chamber protection review. The chamber protection review is an agenda item on the EAR review meeting. - The S300 peer reviewer group with expertise in physics peer reviewed the EAR; this group also has some background in chemistry. The experiment is reviewed as part of the chamber protection review for engineering.	All experiments in the chamber, (b) (7)(F) and the environmental addons were not examined with respect to chemistry, as required by ES&H Manual Document 17.1. The engineering analysis conducted did not include a chemistry SME review for combustible products. **[APPARENT]**	There was too much fuel in the chamber that could lead to a fire, increasing the internal energy of the chamber which increases the pressure in the chamber. Material changes in the (b) (7)(F) and materials in the environments experiment were not questioned by independent reviewers as part of the peer review.
	- RIs or work supervisors shall determine whether operations require peer review based on the requirements of the facility at which operations will be performed. - The FSP shall contain the criteria for initiating mandatory peer reviews. - The FSP shall address the subject areas to be reviewed and specify the peer review's life span. Areas to be reviewed may include process, physics, materials, synthesis, directed energy, large charge operations, or firing operations, as appropriate (ref. 17.1).	A peer review is required for all EARs, as stated in the FSP.	There is no graded approach for when a peer review is required for firing operations. Known hazards or subject areas that would trigger certain peer reviews have not been defined for review as part of the peer review process within the Firing Facility's FSP. The criterion that exists for initiating a peer review includes all experiments that have an EAR and in certain instances when lasers are used to illuminate certain types of explosives. **[APPARENT]**	Peer reviewers and the experimental fielding team perform a cursory and routine review of the potential hazardous outcomes from the experiments.

SOURCE	IDEAL PROCESS STEP	ACTUAL PROCESS STEP	DIFFERENCE	EFFECT ON THE ISSUE
PEER REVIEW (CONT.)	Each peer review is documented as part of the standard EAR package (ref. Firing FSP).	The signature page of the EAR includes a section for peer reviewers. For this experiment, this section was signed by two of the approved S300 peer reviewers. There was also an EAR review meeting.	No difference	No effect
	The positions of explosives charges are evaluated as part of the peer review process per the EAR (ref. Firing FSP).	Positions of explosive charges within the chamber are noted in the EAR and evaluated as part of the chamber protection review. The chamber protection review is noted as an agenda item in the EAR review meeting that takes place after the peer review.	It does not appear that the peer review included an evaluation of positions of explosive charges (e.g., three water barrels on overlay included in chamber protection review that were not included on the EAR). It is unknown if the chamber protection review was a focused conversation in the EAR review meeting. **[Other Observation]**	No effect–the end result of this review may have been movement of the (b) (7) (F) which had little to no effect on the outcome.
	Program or facility management may request a peer review of any operation regardless of whether the operation meets the criteria (ref. 17.1).	Peer review of the EAR was completed.	No difference	N/A
	The individual proposing the explosives work initiates the peer review process by completing a peer review form (various versions are in use, as specified by individual FSPs) and attaching supporting documents describing the scope of the work (ref. 17.1).	The EAR includes a signature page where the peer reviewers approve the EAR.	There does not appear to be a peer review form separate from the EAR. There is no documentation in the EAR that supports that the three areas for peer review, physics, engineering, and chemistry were evaluated. **[Other Observation]**	No effect–this is a documentation/records retention issue.
Chamber Penetration Checklist	Before securing the firing chamber a visual check is done on all penetrations of the firing chamber to validate that the penetrations are closed and the grates as applicable are installed.	All floor penetrations; ceiling and upper haunch penetrations; and north, east, west, and south wall penetrations were checked and documented on the penetration checklist.	No difference	N/A

SOURCE	IDEAL PROCESS STEP	ACTUAL PROCESS STEP	DIFFERENCE	EFFECT ON THE ISSUE
	The verification check is to be accomplished by someone with understanding and knowledge of chamber penetrations as determined by the bunker supervisor and must be other than the individual that closed/secured them.	Verification was completed by a trained chamber operator.	No difference	N/A
	In the case of no deviations or deficiencies, the executing technician will be responsible to sign, date, and give the procedure to the quality control document specialist to file.	No deviations or deficiencies were noted. The technician signed and dated the checklist on 6/10/21.	No difference	N/A
CFF Firing Operations Checklist	Complete sequence of operations steps.	Same as ideal	N/A	N/A
	Complete final chamber check steps.	Same as ideal	N/A	N/A
	Complete pre-experiment execution steps.	Same as ideal	N/A	N/A
	Complete experiment and post-experiment execution steps.	Section was completed; high pressure and CO readings documented in this section.	No difference	N/A

The barrier and change analyses identified the following differences or failed barriers that are considered apparent causes:

- Physical Barriers:
    - The overlay seal allowed combustion product and contamination to bypass it and leak into adjoining areas, the camera room, the long chase, and the VTR. Three holes were identified in the overlay seal.
    - All three seals on the personnel and equipment doors, the fire rope, face, and o-ring seals allowed combustion product and contamination to leak through both doors.
- Administrative Barriers/Processes:
    - This experiment exceeded the quasi-static operational pressure limit of 32 psi, intended to maintain pressure for an extended duration.
    - Based on a lack of documentation, the chamber protection review process did not collectively evaluate the following elements that relate to potential mechanisms enabling mass combustion and fire: blast impulse effects on non-energetic experiments (i.e., the environment experiment) and combined blast interactions for simultaneously executed (b) (7)(F) Additionally, the inert material experiments and all energetic experiments present were not evaluated for interactions such as combined blast effects, total resultant temperature, and secondary fragment interactions for pyrophoric fragments. It is noted that the chamber protection review is a new process improvement, and the recognition of the need for this process after the Monster shot is commended.
    - Personnel that reviewed the chamber protection review did not have all the technical background and expertise needed in experimental effects mitigation to better advise the chamber protection review preparer.
    - All experiments in the chamber (b) (7)(F) and the environmental addons were not examined with respect to chemistry. The engineering analysis conducted did not include a comprehensive chemistry SME review for combustible products.
    - The groups designated as peer reviewers for S300 may not be experts in all three required areas for examination as part of a peer review that are listed in ES&H Manual Document 17.1, Physics, Chemistry, and Engineering.
    - All information pertaining to experiments and associated materials (e.g., plastics used) and all materials present in the final setup in the chamber (e.g., foam, water, other combustibles) was not provided to the peer reviewers in one cohesive package.
    - There is no graded approach for when a peer review is required for firing operations. Known hazards or subject areas that would trigger certain peer reviews have not been defined for review as part of the peer review process within the Firing Facility's FSP. The criterion that exists for initiating a peer review includes all experiments that have an EAR.

The barrier and change analyses also identified differences and failed barriers that were determined to not have an effect on the outcome of this event and are therefore considered observations, not causes. These observations are listed below:

- The IH, HP, and explosive safety SME were not listed as attendees on the invite to the experimental kick-off meeting. The presenter is not positive that all points from the workflow procedure were covered in this meeting.
- The EAR does not include a description of all hazardous operations and materials related to experiment fielding (e.g., MUMA, materials in device, etc.).
- Final layout in the chamber did not match the proposed final setup of the (b) (7)(F) designated in the EAR: (1) four water barrels were moved to the overlay; (2) one of the steel plates around th (b) (7)(F) was moved between the (b) (7)(F) to prevent interaction of the two experiments; and (3) an additional double stack of water was added to the west side of th (b) (7)(F) to mitigate interactions between th (b) (7)(F)
- The WCD bounds out modifications to the MUMA system and does not cover fabrication or creation of the MUMA system.
- The adjustment made to redirect the methane flow was verified as acceptable a few months after the experiment as noted in *MUMA Operation Procedure*. Also, it appears that retesting did not occur based on a lack of signature under the box "Actions Taken to Correct Deviations/Deficiencies."
- Issues were identified with componentry that supports the MUMA: the vacuum pump for the MUMA is not rated for flammable gases; the flow meters are not calibrated for methane; the vacuum gauges are not rated for use with flammable gases; the flow controller is not calibrated for methane; there are redundant regulators (possibly not calibrated for flammable gases) and are not rated for pressure/vacuum; and a pressure and instrument diagram (P&ID) is not present for the entire system.
- An evaluation of whether a MESN was needed for the MUMA system was performed, but it was incorrectly determined to not be needed and therefore was not created. This determination was not made by the appropriate SME, or designee.
- LiH was not listed as a line item on the unclassified version of the Materials Database, it is listed in the classified version. It is annotated on the bunker schedule request for (b) (7)(F) It was also added under the comment field on the Materials Database.
- The chamber protection review memo was not revised/re-issued to reflect the final shot setup nor was a work pause initiated to address the differences between the final shot setup and the chamber protection review. This implies that the evaluation process for chamber protection was not conducted for the final shot setup.
- The chamber protection review was not approved by the Associate Program Director for Hydrodynamic and Subcritical Experiments as required by the Firing FSP, nor is there a signature line for approval by this role.
- Work that is otherwise required to undergo a peer review is not defined in the S300 Firing Facilities FSP, other than for all EARs and in certain instances when using lasers for illumination. Note that this observation is addressed by recommendations to the root cause related to the peer review and will not be included as a separate observation.

- It does not appear that the peer review included an evaluation of positions of explosive charges (e.g., three water barrels on overlay included in chamber protection review that were not included on the EAR). It is unknown if the chamber protection review was a focused conversation in the EAR review meeting.
- There does not appear to be a peer review form separate from the EAR. There is no documentation in the EAR that supports that the three areas for peer review, physics, engineering, and chemistry were evaluated.

Why/Because Analysis

The why/because analysis supplements both the change and barrier analysis to help identify root causes related to each apparent cause. Each apparent cause from both the barrier and change analyses are analyzed by asking "why" the failed barrier or difference in process exists. Sometimes this analysis leads to a root cause and sometimes the "why" leads to a stopping point. This section also includes HPI analysis. The HPI analysis paired with the why/because analysis provides context to some of the "whys" to better understand the human factors involved. Each header represents an apparent cause from either the barrier or change analysis.

1. *Why did the combined experiments exceed the quasi-static operational pressure for the chamber of 32 psi?*

The combined experiments exceeded the 32-psi because:

- See Appendix A–Technical Team Analysis.
- The operational 32 psi pressure limit is not a well-known limit, which is necessary to estimate expected quasi-static pressure of experiments and stay within the bounds of the limit. Interviewees lacked awareness of the 32 psi limit and the understanding of operational conditions that contributed to an elevated quasi-static pressure [Error Precursor–Lack of Knowledge].
  - This lack of knowledge of the operations 32 psi pressure limit is because:
    - **There was a lack of communication in readily available mechanisms such as training, procedures, plans, etc. of the chamber's 32 psi operational limit for key facility and operator positions [ROOT].** The 32 psi limit was difficult to find in documentation. The IA team was able to find information on this limit in a conceptual design document in the VTR, and for weeks the team was unsure if there was a final design document. Later, the IA team located the final design document that also communicated the 32 psi limit. If this limit was communicated in facility documents and/or training, it would be more available to personnel who need to know of the limit for the process of fielding experiments. For example, the chamber operators have the role of logging the quasi-static pressure on the *Bunker 801/CFF Sequence of Firing Operations Procedure* form and could be the conduit of communication if the pressure seen is close to or exceeds the 32 psi limit. The receiver of this information would need to understand what actions to take if the pressure limit is exceeded such as some evaluation of the chamber, etc. The chamber operators have a training plan that includes on-the-job training, practical training, and required reading. One of the competencies is listed as "Trainee demonstrates and understands chamber limits during HE operations." The allowable limit of HE was well understood by most, if not all, personnel interviewed. However, the pressure limit does not appear to be incorporated or flowed into the chamber operators' training plan. In obtaining the history of shot records for the CFF, there was a shot in 2014 that exceeded the 32 psi limit, but it does not appear that any analysis was

conducted. However, if this limit is not understood, the pressure seen in an experiment loses its meaning to the person capturing that data. The FSP could also be a way of communicating the pressure limit as it communicates the allowable limit of HE in the chamber. However, this limit is not currently flowed in the FSP to then be accessible by all personnel who need to know it.

- There is a lack of understanding of operational conditions that contributed to circumstances permitting an elevated quasi-static pressure resultant from the lack of a combustible material evaluation. See Appendix A for the technical team's analysis and why/because analysis 3.

2. Why were the overlay seal and personnel and equipment door seals bypassed?

The seals were bypassed because:

- The post-experiment environment within the chamber resulted in pressures above 50 psi (gauge limit as read on the control panel chamber pressure gauge) exposing all seals to pressures above design ratings. Note that the 50 psi reading is the highest pressure the instrumentation is capable of, the true maximum pressure the chamber experienced because of this incident is unknown but has been estimated by the TA team and documented in Appendix A. This exceeds the chambers operational quasi-static limit of 32 psi.
    - Why were the seals exposed to increased pressure? See Appendix A–Technical Team Analysis.
- The seals were potentially exposed to elevated temperatures (greater than 660 ˚C) beyond rated material capabilities. There is an area where the overlay seal is unprotected via overlay plates, and it is estimated that the upper two thirds of the chamber saw temperatures greater than 660 ˚C evidenced by aluminum in this region melting.
    - Why were the seals exposed to elevated temperatures? See Appendix A–Technical Team Analysis.
- Operational practices do not reference engineered analysis for the chamber sealing limitations and configurations to ensure adequate margins of safety for impulse and that quasi-static pressure loading are maintained.
    - Why is there no referenced engineered analysis ensuring proper safety margins? There is a lack of knowledge and understanding of the limitations of the chamber pressure boundary and assessment criteria for sealing as well as pressure failure mechanisms of the chamber as engineered, rather than as experienced.
        - Why is there a lack of knowledge/understanding?
            - **There was a lack of communication in readily available mechanism for the chamber pressure boundary limits, assessment criteria for sealing, pressure failure mechanism [ROOT].**
            - There is a lack of knowledge/understanding because of the lack of detailed analysis/evaluation as discussed in why/because analysis 3.
- The seal may have already been weakened from previous shots.
    - Why may the overlay seal have been weakened from previous shots? **There is no record of inspection or maintenance of the overlay seal nor is there a process or schedule defined for the inspection/maintenance of the overlay seal [POTENTIAL ROOT].** The overlay seal was reviewed and some of it replaced after the Monster shot in 2017. However, some of the seal is over a decade old. The DOE STD 1212, *Explosives Safety,* has a requirement for periodic inspection of the containment apparatus: "Qualified engineering personnel shall periodically inspect the containment apparatus to verify that its structural integrity is maintained after repeated detonations. (Section 30.10.5)." The overlay seal is not easily accessible because it is protected by steel overlay plates. These plates are difficult to move for an inspection of the seal, as described in the HPI Analysis. Since there is no record

of inspection/maintenance and the last inspection was in 2017, it cannot be confirmed that the overlay seal was in good condition prior to this experiment. Therefore, the lack of an inspection/maintenance process for the overlay seal is considered a potential root cause.

- Why may the door seals have been weakened from previous shots? There is no record of inspection or maintenance of the door seals nor is there a process or schedule defined for the inspection/maintenance of the door seals [POTENTIAL ROOT]. It was described in interviews that the door seals are visually inspected post-shots. One interviewee noted that the strips on the bottom of the doors have been replaced and two of the three seals have been completely replaced all the way around the doors. The firing operations checklist includes steps to review the door seals. One step states, "Verify chamber equipment door threshold is installed." It is likely that the door seals were in good condition since they are easy to visually inspect after a shot; however, there is no way of knowing for certain without a record of inspection.

3. Why didn't the chamber protection review process evaluate for blast impulse effects on non-energetic experiments, combined blast interactions for simultaneously executed (b) (7)(F) ***interactions for combined blast effects, total resultant temperature, and secondary interactions for pyrophoric fragments between inert material experiments and all energetic experiments?***

These areas were not evaluated because of historical knowledge and utilization of the CFF and what has been observed (or not observed) during experiments. There are some specific reasons that will be discussed for why some of these areas were not fully evaluated. However, the overarching root cause is the initial process to analyze and assess experiments in the CFF, via the chamber protection review, was defined to encompass a broad spectrum of experimental effects but is currently implemented based on a narrow interpretation of the predominant post-detonation experimental hazards. Additionally, current implementation of the chamber protection review process to analyze and assess defined criteria for experimental effects within the CFF has not evolved over time to coincide with the changes to CFF utilization. The analysis and assessment of experiments in the CFF does not

- Require or include expertise in all areas of physics, chemistry/chemical combustion, and engineering, as part of the analysis and review process, including other knowledgeable personnel with technical expertise in designing experimental mitigation to participate and advise;
- Include an evaluation of combustible material within the fireball, combustion products, off-gassing constituents, combustible interactions with pyrophoric materials, and general chemical interactions between the device and all other materials present in the chamber [ROOT].

For some context, additional information is provided below.

Combined blast effects–Historically, combined blast effects have not been perceived as an issue. Experiments are under the total chamber explosives limit and within their blast loading map. Experiments usually include a large and small device so the combined blast effect is perceived to be negligible. Historically, one experiment was conducted in the chamber at a time, but in recent years, more combined experiments have been conducted simultaneously in the chamber. Even with high pressures noted in the history of the chamber, most (if not all) did not result in a failure impacting occupied areas.

Blast impulse effects on non-energetic experiments–Most of the non-energetic components in hydrodynamic experiments are data driven, are not traditionally combustible materials, and are not thought of as one of the primary hazards associated with an experiment.

Temperature effects–Materials in the chamber with the potential to combust or pyrolyze are not considered a major contributing factor to the loading condition (i.e., pressure, temperature, and environmental emissions) of the chamber.

Secondary interactions for pyrophoric fragments–Secondary interactions for pyrophoric fragments have not been perceived as an issue that differs from fragments in general. With certain materials used in an experiment, a fire is expected and usually self-extinguishes. It was expected to be no different in this experiment.

Multiple experiment interactions–Historically, this has not been necessary since one experiment would be executed at a time in the chamber. The number of experiments executed within the chamber concurrently has increased over the last two decades, since initial facility qualification.

4. Why did personnel that reviewed the chamber protection review not have technical background/expertise to better advise the chamber protection review preparer?

Personnel currently integrated into the chamber protection review process did not have the technical background/expertise to better advise the chamber protection review preparer because reviewers with this expertise were not perceived as necessary for the chamber protection review. The chamber protection review is a fairly new process, implemented after the Monster shot in 2017. This expertise is probably thought to be unnecessary due to a historical lack of visual indicators and events in the chamber and expertise of fielding personnel. This why/because analysis aligns with the root cause from why/because analysis 3, related to inclusion of expertise in all areas defined in ES&H Manual Document 17.1. for the review process.

5. Why were all experiments not examined with respect to chemistry and a chemistry SME included in the engineering analysis?

All experiments were not examined with respect to chemistry because the designated peer reviewers for this experiment have some knowledge of potential chemical interactions but are not SMEs in chemistry.

- Why is there no SME for chemistry as part of the peer review process? There are SMEs in the area of chemistry that are designated by the chair of the Explosive Safety Committee (ESC) and are part of the overall peer review process for LLNL as trained peer reviewers appointed to group I (Process), group III (Materials), and group IV (Synthesis). However, peer reviewers with expertise in chemistry as part of groups I-IV are not included in the S300 peer review process. The S300 peer review groups were added to the LLNL ESC's approved explosive peer reviews list in late 2018/early 2019 at the request of operations personnel. However, **the S300 peer review process does not incorporate experts in chemistry [ROOT].** Peer reviewers in defined peer review groups I-IV were trained as peer reviewers and acknowledged as approved peer reviewers in a memo from the Chair of the Peer Reviewer Training Committee to the Chair of the Explosive Safety Committee (dated January 29, 2016). The peer reviewer training includes attending instructor led courses, a practical training course, and a mentorship or on-the-job training of the trainee reviewing/signing at least two peer reviews with concurrence from an approved peer reviewer. The S300 peer reviewers have not been through the peer review training but are listed as approved peer reviewers **[Other Observation].** This appears to be an observation and not a causal factor because even if they were trained, an expert in chemistry is still not included as part of the process.

6. Why did the peer reviewers for this experiment not include expertise in all three areas of physics, chemistry, and engineering?

See why/because analysis 3 and 5.

7. Why is all information pertaining to experiments and associated materials not provided to the peer reviewers in one cohesive package (e.g., the EAR, chamber protection review, and ENG and physics FDRs)?

All information was not provided in one cohesive package because historic and current processes did not require the consolidation of all information pertaining to the experiments and associated materials, including materials used in the experiments/device, other materials to be used in the chamber, and the quantification of how much will be used [ROOT]. It is thought that the EAR has all the information needed for an independent review and this may be true for the peer reviewers that are reviewing firing operations at S300. However, with a review of chemistry incorporated in the process, more information needs to be provided to the peer reviewers. For example, for this experiment a peer reviewer with expertise in chemistry looking for potential chemical interactions would need detailed information on how much foam, water, and plastic was used in the chamber and understand that ABS plastic and LiH were part of the main experiment. The point of a peer review is for independent experts to ask questions that those close to the experiments did not consider when designing the experiment. For this to be effective, peer reviewers need to know what materials are included in each experiment, what and how much material is included in the chamber, and the configuration of the experiments and location of everything in the chamber. In this instance, it is most likely that the ABS plastic used in the experiment would not have raised concern, but with peer reviewers with expertise in physics, engineering, and chemistry, they may have tried to quantify the amount of combustibles used in the chamber to then question the total amount.

8. Why is there no graded approach for when a peer review is required?

There is no graded approach because the peer review process for S300 firing operations as documented in the Firing Facility FSP does not permit a graded approach [ROOT]. Due to the complexity and periodicity of experiments at the CFF, facility and operational personnel did not understand how to integrate a graded approach into operations that would be value added. Note also that aside from seeing chamber pressures in the 18 psi, 20 psi, and 40 psi ranges, there has been no other significant breach of the chamber besides this event and the Monster shot in 2017. Historically, it appears that experiments have been mostly contained by the chamber. However, with that historical perspective and by requiring a peer review for all experiments with an EAR, the purpose of that review is undervalued.

Human Performance Improvement (HPI) Analysis

HPI is the concept that humans make errors, but HPI methodology and tools can help reduce the severity of consequence of human error. In this event, there was no active error that occurred on the day of the experiment that caused the unexpected outcome. The latent error, the error that occurred prior to shot day and in all the preparation and planning of these experiments, is that the complexity of the materials and fuel source interactions in all experiments were not considered a potential issue.

There are several conditions or error precursors that surround the issue that are discussed as context in the why/because analysis and are also summarized here. Note that the "Error Precursor" header groupings in this section are defined categories of error precursors from the DOE *Standard Human Performance Improvement Handbook*.

Error Precursor–Inaccurate Risk Perception

There was an overall *inaccurate risk perception* that the chamber would contain the experiments because the explosives and LiH were well below the limit and the experiments were within the loading zones. Chemical interactions were considered at a cursory level. It is known that LiH and water can react and produce hydrogen gas, which is extremely flammable and can easily result in a fire, but the perception is that the reaction is mitigated by waiting to vent the chamber. Historically, residual LiH is typically present in the chamber after an experiment, meaning not all of it reacts during the shot and contributes to the inaccurate perception of minimal risk when using LiH and water in the chamber. In this experiment, there was no such LiH left over after the shot. Along with this inaccurate risk perception is the assumption that the greatest hazard in the chamber is the explosives and that any fire as a result of an experiment would self-extinguish.

Another *inaccurate risk perception* was the change to using (b) (7)(F) final design. This material change was made after the initial design review and before the final engineering design review. This change in material was not thought to have any negative impact on the experiment or other experiments present in the chamber.

Error Precursor–Unexpected Equipment (or Material) Condition

The post-experiment reaction between materials was an *unexpected equipment (or material) condition.* The addition of water in the chamber is seen as a mitigating factor for the Be hazard and is used to consume the LiH, but in this case, the additional water initially contributed to the event. The use of the foam box was also a change many years ago from using a plywood box that was seen as hazardous; however, the foam box was also a major contributor to this event as discussed in Appendix A.

In the previous Monster shot experiment from 2017 where contamination leaked into an unoccupied area, the mechanism of failure was different from the June 10, 2021, event. In the Monster shot, the contamination was due to the initial explosion rather than a post-experimental reaction, which was the case in the June 10, 2021, event. Although minor leaks have occurred in the past, usually around the chamber doors, the Monster shot was the first time that contamination exited the chamber into the camera room, an area free of contamination. Since the historical example of contamination exiting the chamber was during the initial explosion, the post-experiment reaction in this event was unexpected and therefore not considered during planning/analysis phases.

Error Precursor–Lack of Knowledge

There is a *lack of knowledge* regarding the chamber's quasi-static operational pressure limit of 32 psi. This lack of knowledge contributes to an *inaccurate risk perception.* High pressures from previous experiments such as the one from 2014 with a pressure reading of approximately 42 psi were not considered or thought to require additional review or action because that quasi-static pressure limit is not well known. As stated in the why/because analysis, this limit was not easy for the IA team to find. It is not flowed into documents that employees read such as the FSP, nor is it incorporated into training plans of key roles that could initiate action by knowing the pressure limit. The limit was buried in a conceptual design document located in the VTR, and the final design document took weeks for the IA team to locate. It was thought for many weeks that a final design document did not exist.

As discussed in the why/because analysis, there is a *lack of knowledge* and understanding of the limitations of the chamber pressure boundary and assessment criteria for sealing as well as pressure failure mechanisms of the chamber as engineered, rather than as experienced. The documentation to support the chamber pressure boundary and assessment criteria is not readily available. The IA team has had to consult multiple institutional resources and retirees who were at LLNL during initial building construction and certification.

There is also a *lack of knowledge* among peer reviewers in chemistry and chemical combustion as discussed in the why/because analysis.

Error Precursor–Lack of an Alternate Indication

Historically, there is a *lack of an alternate indication* precursor, meaning no shot executions that resulted in potential exposure to personnel, nor contamination in areas that are occupied. There has been no indication that more in-depth analysis was needed beyond what was already built into the process. In 2017, contamination leaked from the chamber into the camera room after the Monster shot; however, the area with contamination was a non-occupied area. There have been previous pressure readings close to and one above the 32 psi operational pressure limit. However, since the quasi-static operational pressure limit is not well known and there were no visual indications of issues from any of those shots, it is thought that there was no issue with materials used inside the chamber.

Error Precursor–Pressure (to Complete Experiments)

The IA team heard from several interviewees about actual or perceived *pressure* to complete experiments. It was communicated by interviewees that the CFF used to have one experiment in the chamber at a time, but that over time, more experiments would be simultaneously executed in the chamber. There was also a perception among staff that there was an increased emphasis to conduct simultaneous experiments to catch up as a result of COVID delays. Others perceived that there has been a push in more recent years to execute simultaneous experiments. Interviewees stated that certain roles are stressed and overloaded with how many more cameras, diagnostics and associated cables, and items are involved in some experiments. Interviewees also noted that Ramrods are fielding multiple experiments at a time, making them less available to those with questions. As an example of this work pressure, interviewees noted that a week after the CFF event there was a shot executed at the Outdoor Firing Facility, and some perceived this to be rushed given the severity of the event at the CFF. The operations personnel perceived the shot deadline to be 7:30 p.m. at the B851 Outdoor Firing Facility, and the shot was fired at 7:31 p.m. Note that there is no fixed shot deadline–limits and deadlines are based on cumulative hours worked with HE and government agency (such as the Federal Aviation Administration) activity authorization time windows. It was also shared that there is preventative maintenance that workers want to perform in the chamber, but it is hard to schedule this due to the shot schedule. Note that the maintenance discussed was not part of a formal maintenance schedule and that some maintenance would be difficult to perform such as removing the overlay plates to clean behind them and to review the overlay seal. It was also communicated that there is a lot of work with the LEPs and stockpile stewardship that needs to utilize the capabilities of the chamber which contributes to the pressure. It is understood that work needs to get done. This discussion does not suggest missing LEP and stockpile deliverables, but rather suggests finding a better balance between developing the schedule at the CFF–including experiment fielding/execution, maintenance, experiment fielding setup and reviews–and allocating time to analyze more complicated experiments. However, it is also recognized that there are safety concerns related to experiment execution. For example, sometimes, it is safer to proceed rather than disassemble to a safe state as disassembly requires more people to be exposed to hazardous conditions, as in the case when the shot is connected to the detonator and ready to fire. In this instance, stopping for the day at this point would require disconnecting the detonator from the fire-set and then setting it back up to restart the test sequence the following day.

Mock Peer Review

A mock peer review was held with peer reviewers trained and approved as peer reviewers by the LLNL Explosive Safety Committee. During presentation of experimental information, which included the design of the (b) (7)(F) EAR, and chamber protection review, the mock peer reviewers asked many questions:

- What is the print density of the (b) (7)(F) experiment?
- Is it typical to execute multiple experiments at a time?
- What is the ceiling protection?
- How tall are the water stacks?
- Are the hubcaps typically placed so close to the walls?
- Is anything different that has not been done before?
- How much do the foam bundles weigh?
- What is the limit for combustibles for the chamber?
- What is the total mass of all materials?
- What went into creating the loa (b) (7)(F)
- What else supports putting the (not sure where calculations came from)?

The mock peer reviewers had two main concerns in their review: the number of combustibles involved in all experiments and the placement of the (b) (7)(F) Peer reviewers wanted to know the total amount of combustible materials in these experiments to compare that number to the limit of combustibles allowed in the chamber. When peer reviewers were told there was no defined limit of combustibles, they were surprised and concerned that without a limit, a reviewer or experimentalist would not know when there were too many combustibles or when further analysis was needed. Peer reviewers also wanted more information of the analysis and associated calculations that were performed to determine that the location of the (b) (7)(F) was not a matter of concern. The mock peer reviewers were also surprised that facility personnel were not part of the original peer review.

The mock peer reviewers were not concerned with the amount of water that was involved in these experiments nor the presence of LiH and its potential reaction with the water.

Overall, this effort helped the IA team conclude that an improved peer review of this experiment might have had a positive effect on the overall outcome of this experiment by asking questions that were not considered, specifically questions about combustibles and what was different in this experiment vs. others. A peer review is only as good as the information that is shared, and the breadth of knowledge and experiences the peer reviewers can contribute to analysis of the information. These two reasons are why the causes and associated improvements for the peer review process include providing reviewers with a cohesive package of information that goes beyond the information in the EAR and involving peer reviewers with expertise in all areas of concern.

Event Response

This section includes several lessons learned related to event response including the immediate response and in the days following the event. LLNL has not seen an event of this magnitude with several workers affected in several years. These lessons are opportunities for organizations to learn and improve so that affected workers and organizations are well informed of steps preceding any potential future events of this magnitude.

Building 801 has a formal procedure for abnormal events which was executed as written for immediate event response. It was communicated by interviewees that the evacuation from the B801 to the assigned assembly point went smoothly. The CO sensors were monitored at the control panel along with pressure readings, and based on those readings, the entire facility evacuation was announced over the building's paging system. It is noted that workers started evacuating the facility as soon as they saw smoke. Personnel followed all evacuation announcements, alarms, and instructions provided at the assembly point, and the Fire Department (FD) arrived onsite. Although the run card database included current information, the physical run card used by the FD for B801 was outdated and included a retired employee's contact information **[Observation].**

A muster role call was performed at the assembly point, and all personnel were accounted for. Many affected personnel commented that there were too many people in the VTR that did not need to be there. Interviewees offered perspective based on their roles, stating that only a handful of personnel determined by diagnostic complexity were needed in the VTR to perform their work, but others present during this experiment were observers/visitors **[Observation].** Note that the Firing Operations Management does carefully consider who can be present in the VTR during experiments.

Soon after evacuation, the Incident Commander relocated personnel to the B801 gravel staging area for personnel safety due to the run card information regarding explosives, which requires a larger evacuation zone. The HAZMAT Fire Response (ALCO HAZMAT) was dispatched to the scene. Personnel were segregated based on potential exposure to contamination based on their location within B01A. An LLNL ES&H technician and radiation worker screened potentially contaminated personnel for radiological contamination at the second assembly point using FD instruments. It was noted that the FD was not familiar with use of the instruments for screening contamination **[Observation].** LLNL's instruments were in a truck in an area that personnel were not allowed to access due to the evacuation zone required for the FD response.

ALCO HAZMAT arrived on scene. Once the screening showed no personnel contamination, the segregated personnel were reintegrated with all other personnel. A concern was raised for the timing of the screening; workers were not screened immediately upon evacuation at the first assembly point before moving around. **[Observation].** This was due to a lack of instrumentation. LLNL had instrumentation in a vehicle at B801, but the vehicle was in an area where the FD was not allowing access.

T8021 was opened for personnel to gather. Some personnel with personal belongings on hand were permitted to depart S300; some remained for voluntary data recovery/security protocols; and personnel with belongings still in B801A remained until re-entry was approved for belongings to be recovered.

Once B801D was released by ALCO, remaining personnel relocated to B801D for shelter, potential data recovery, and to stage for personnel belonging retrieval. A re-entry plan to secure systems and rooms and to recover personal belongings was developed; all areas in B801A were treated as contaminated, and upon re-entry, personnel wore appropriate PPE based on this assumption. The PPE needed for reentry in B801A was not easy to retrieve. The necessary GVP respirators were stored in B801A, and Tyvek® PPE was in the storage area of B867, just outside of B801D. The procedure for abnormal events in B801 states that personnel should "stage at least four sets of PPE as described in WCD 100366 in B801D for emergency use during execution of experiments." It appears that this step was not completely performed **[Observation].** Note that one worker had a set of PPE in his vehicle that was accessed and utilized for reentry.

ALCO FD relinquished IC responsibility to WCI facilities personnel. The ALCO HAZMAT/Fire departed S300 (~9:30 pm). A plan was developed and executed for the recovery of personnel's personal belongings while data recovery efforts in B851A occurred. Personal belongings were recovered and surveyed for radiological contamination. When no contamination was detected, personal belongings were released to their owners, and personnel left S300. Restricted access signs (Radiological Buffer Area and BMA) were posted (~11:00 p.m.) and remaining personnel departed S300. There was concern that so many personal belongings (keys, phones etc.) were in affected areas and if they could not be retrieved, it was unknown how personnel would leave the site and/or get home **[Observation]**.

After the event on Thursday, June 10, 2021, affected personnel stated that they received little communication as to the next steps **[Observation].** For example, personnel were unsure if they should go see their doctor, report to Health Services, and/or were not sure if they should ask for medical testing and if so, what kind of tests. Some personnel communicated that they contacted their doctor, but their own doctor was unable to help due to LLNL's contract with Kaiser. The lack of communication appears to be a result of confusion as to who or what role and/or organization oversaw event response and follow-up with workers.

Personnel were concerned that the S300 nurse practitioner was not immediately aware of what had occurred. **[Observation]**. Upon learning about the incident, the nurse practitioner asked for a list of affected employees and stated that all employees needed to be seen. The nurse practitioner also inquired as to why she was not told about this incident. Once she was made aware, the S300 nurse practitioner facilitated testing for affected personnel such as chest X-rays. It was communicated to the IA team that ES&H personnel told affected personnel that if they felt any symptoms such as irritation in their throat or had difficulty breathing that they should contact either the LLNL Health Services Department or their personal physician. Affected personnel were told when their names were collected that they would be contacted for bioassay monitoring. However, it is thought that the shock of events that occurred that evening prevented personnel from retaining what was communicated to them.

On the night of the event, it was unknown if there were any potential Be exposures. Since radiation contamination screening showed no contamination greater than background, it was initially thought that radiation and Be contamination would be correlated. There is no laboratory with equipment at S300 or a trained analyst to prepare the samples for rapid Be analysis like at other facilities at LLNL.

Personnel stated that they would have liked to have had someone to talk to about what happened. Some personnel communicated that they received a phone call soon after the event by someone checking in on them and they greatly appreciated that effort.

On Monday, June 14, 2021 following the event, affected personnel came to work as normal and were somewhat surprised that there was no safety stand-down, pause of work, or hot wash of some sort to talk about the event that occurred on June 10, 2021. A portion of the Firing Facilities staff reported to B851 to assist in preparations for the upcoming shot at B851. The rest of the staff reported to B801D to start recovery of B801A. ES&H had peer reviewed sampling plans ready to be initiated. Survey and samples were taken to begin the release/recovery of 801A.

A fact finding meeting was held after the event on Monday morning, June 14, 2021. Invitees to the fact finding included some affected personnel along with operations and facility personnel who could offer insight into processes that took place prior, during, and after the event to establish a comprehensive timeline. All affected workers were not invited to attend the initial fact finding meeting. This may have been appropriate; however, the other affected workers were also not afforded the opportunity to communicate what happened in some venue soon after the event so information was not lost or forgotten. **[Observation].** With so many affected workers, there was a need for interviews shortly after the fact finding discussions or for one longer discussion focused on the development of a timeline and testimonies from affected workers while the information was fresh.

Also on June 14, 2021, affected personnel were requested to provide a bioassay sample for analysis; nine of the 16 samples were provided on June 14, 2021 and entered into the associated database for processing. Before samples can be entered into the database, a unique exposure area number must be assigned to each individual. This information comes from internal dosimetry after the HP submits the request. It was noted that it was difficult to determine who the non-S300-resident-affected workers (visitors in the VTR at the time of the experiment) were to then request a bioassay sample.

It was also communicated that program management or matrixed organizations were not aware of the event that their employees were involved in and were surprised to see an injury/illness report come from the eCAR system **[Observation].**

On Tuesday morning, June 15, 2021, the nine bioassay samples provided on June 14, 2021 were driven to the S200 bioassay laboratory for processing. The samples were placed in the urgent/rush status because they were categorized as abnormal. Some affected workers were told that the samples would be analyzed in one large batch instead of as they were provided **[Observation].** This upset some workers who had rushed to provide their bioassay samples. This appears to have been a miscommunication. There were some promises of results made without a full understanding of the process to submit and analyze bioassay samples. An internal dosimetrist talked with some personnel and provided them with a pamphlet explaining the process. The bioassay samples were ultimately provided in two different batches, the first batch on Tuesday, June 15, 2021 and the remaining samples on Wednesday, June 16, 2021. By early afternoon of June 16, 2021, all bioassay samples were collected and sent to the analytical lab.

After progress with the bioassay samples, it took several days for workers to understand that they could ask for a blood test for the potential Be exposure, but LLNL does not use the same mechanism as bioassays to perform mass collection after an incident **[Observation].**

On Thursday, June 17, 2021, a shot was executed at 7:31 p.m. at S300's Outdoor Firing Facility, beyond the perceived cutoff time of 7:30 p.m. Some personnel perceived this execution as rushed due to the timing of the shot and given the event that occurred a week prior at the CFF. It was communicated that at a certain point in execution of a shot it is more hazardous for HE handlers to stop progress on shot execution and move the shot to another day than to finish the process. Once HE handlers reach a certain point in the process and "det-up" or set up the detonator(s), it is hazardous for HE handlers to short-out the detonator and perform a task not routinely performed. Explosives cannot be left on the firing table over the weekend, and as it gets later in the day, the lighting to conduct a shot is too low since there is no outdoor lighting due potential damage from shrapnel.

Judgments of Need/Recommended Corrective Action

All causes from analyses above, the barrier, change, and why/because analyses are summarized in Table 4 below. Apparent cause and their associated root causes (if applicable) are included as one line item, with associated judgements of need or recommended corrective actions corresponding to each. The conclusions from the technical team's analysis, summarized in Appendix A, are also included in Table 4. All observations that are not considered causes, and their associated recommendations are summarized in Table 5.

Table 4: Summary of Causes and Recommended Actions.

ROOT CAUSE	JONs/RECOMMENDED ACTION
Cause of loss of containment at CFF during the (b) (7)(F) experiments was a combustion-induced over-pressurization. Ample fuel sources for sustaining the observed combustion were present, as well as at least one likely ignition source. [Direct Cause–TA team]	1. Develop a team to work through some of the process action below and include representation from Explosive Safety Office and/or Explosive Safety Committee, expertise in chemical combustion, Ramrod group, experimental fielding personnel, and expertise in engineering analysis. [COMPLETE–A CFF Improvement Team was chartered–effective 10/11/2021.] 2. The team from action 1 to develop a "Combustion and Energetic Materials Loading" worksheet indicating pressure rise greater than half the chamber's pressure limit if 100% of combustion of materials present occurred (worksheet 1). See the technical team's analysis in Appendix A for what to include in the worksheet. Incorporate all identified pressure limits. 3. The team from action 1 to develop a worksheet that addresses type and mass of explosives, explosive effects, temperature effects, pyrophoric fragment interactions, and multiple experiment interactions (worksheet 2). Note that this worksheet can be combined with worksheet 1. 4. The team from action 1 to develop a process flow that includes decisions based on the analytical data from developed worksheets 1 and 2 to determine what is required for analysis of chemistry, physics, and engineering for peer review(s) and a new Chamber Energetic and Combustibles Materials (CECM) review. This process flow should include: a. Decisions that trigger a CECM review based on worksheet 1. • CECM reviewers include experts in energetic material chemistry (HE and otherwise) and combustion. • The CECM is to take place before the FDR for engineering and with reviewers present at both the FDR for engineering and the chamber protection review.
[ROOT 1] The initial process to analyze and assess experiments in the chamber, via the chamber protection review, was defined to encompass a broad spectrum of experimental effects but is currently implemented based on a narrow interpretation of the predominant post-detonation experimental hazards. Additionally, current implementation of the chamber protection review process to analyze, assess, and review defined criteria for experimental effects within the chamber has not evolved over time to coincide with the changes to chamber utilization. The complete analysis and assessment of experiments in the chamber does not:	

ROOT CAUSE	JONs/RECOMMENDED ACTION
• Require or include expertise in all areas of physics, chemistry/chemical combustion, and engineering as part of the analysis and review process, including other knowledgeable personnel with technical expertise in designing experimental mitigation to participate and advise. • Include an evaluation of combustible material within the fireball, combustion products, off-gassing constituents, combustible interactions with pyrophoric materials, and general chemical interactions between the device and all other materials present in the chamber.	b. Decisions that encompass the type and mass of explosives, explosive effects, temperature effects, pyrophoric fragment interactions, multiple experiment interactions, and other relevant information to ensure experiments are within the design constraints of the chamber (worksheet 2). c. Use of industry-accepted or LLNL-developed tools and software for the evaluation of various experimental interactions, states, and outcomes. For example, expected resultant chamber temperature and pressure, potential thermal gradients, secondary burn effect, etc. d. Incorporation of lessons learned from experiments into the process flow to continuously improve. e. A change control section to track what lessons learned were incorporated over time. 5. Re-evaluate the chamber protection review process to include technical peers and appropriate stakeholders to participate and advice the mitigation strategy proposed. 6. Identify a person with combustion and chemical expertise to be regularly consulted during the experimental design process. 7. Institute practices in both design and execution phases to avoid the use of combustible materials in CFF experiments, especially in combination with materials that can cause a significant exothermic energy release such as LiH. It is recognized that this will not always be possible. 8. Redesign the thermal box with non-combustible insulation or reduce, to the extent possible, the combustible mass in the design of the thermal box. 9. Facility and experimental team to collaborate and evaluate adequacy of environmental mitigation equipment (i.e., scrubber and HEPA) for current configuration of chamber use (i.e., multiple experiments, mass, and scale of constituents).

ROOT CAUSE	JONs/ RECOMMENDED ACTIONS
[ROOT 2] There is a lack of communication of the 32 psi chamber operating limit for key facility and operator positions, such as in the Firing FSP and the training plan for chamber operators. Note that current processes acknowledge CFF anvil loading zones and associated HE limits.	10. CFF ARWG to communicate the chamber's interim design pressure limitations (if a phased approach is used) and importance of limitations to all firing operations personnel. 11. CFF ARWG to communicate the chamber's final design pressure limitations (if a phased approached is used) and importance of limitations to all firing operations personnel. 12. Create a team to assess, identify, research, recommend, and document solutions to reactivate the CFF. **[COMPLETE**–A CFF Assessment and Recertification Working Group (ARWG) was chartered–effective 8/2/2021.] 13. CFF ARWG to analyze all failure mechanisms associated with the chamber to define operational criteria including pressure and temperature. Analyze preferred failure modes: Is it undesirable to strengthen the seals such that a similar event could lead to higher chamber pressure and a more catastrophic failure? Could the seals be engineered to fail first in unoccupied areas? 14. Define a trigger pressure for action or additional review below the designed pressure limit; and define the action to take when that trigger is met. 15. Include the chamber's pressure limit in the S300 Firing Facilities FSP. 16. Determine roles that are required to understand chamber pressure limits. At a minimum, this must include the chamber operators. 17. Update associated training plans for roles defined from action 7 (determine roles) to include the chamber operator's training plan. Include in those plans the chamber's relevant pressure limitations, the trigger pressure and additional actions, and design information such as chamber design, how it was built, etc. 18. In the *Bunker 801/CFF Sequence of Firing Operations Procedure,* include the established pressure limit(s) triggering actions to take as part of step 26.
[ROOT 3] There was a lack of communication in readily available mechanisms for the chamber pressure boundary limits, assessment criteria for sealing, and pressure failure mechanisms.	
[ROOT 4] There is no record of inspection or maintenance of the overlay seal or the door seals, nor is there a process or schedule defined for the inspection/maintenance of the seals.	19. CFF ARWG to assess the existing design of the overlay seal and determine proper sealing method. 20. CFF ARWG to assess the existing design of the door seals and provide recommendations. 21. Develop an inspection process and schedule for the overlay seal and the door seals on both the equipment and personnel doors. 22. CFF ARWG to assess the design of the overlay plates that protect the overlay seal and provide recommendations.

ROOT CAUSE	JONS/ RECOMMENDED ACTIONS
Port feedthrough seals, camera port seals and the rox seal between the long chase and VTR may have failed–it is unknown. Note that this difference was not analyzed via the why/because methodology since their performance is unknown.	23. Review port feedthroughs and develop or establish a documented maximum pressure design limit for each feedthrough. 24. Establish a documented inspection and maintenance program for the port feedthroughs. 25. Evaluate other chamber penetrations and determined if a documented inspection and maintenance program are needed. 26. Inspect camera port seals and take appropriate action if any issues are identified. 27. Inspect the rox seal and take appropriate action if any issues are identified.
[ROOT 5] Weaknesses were identified with the S300 firing operations experimental explosives peer review process as documented in the S300 Firing Facilities FSP. The process does not: • Incorporate experts in chemistry as part of the review; • Provide all information pertaining to the experiments/device and associated materials in one cohesive package to include or materials used in the experiments and other materials that will be used in the chamber, nor does it quantify how much will be used; • Include a graded approach for when a peer review or a certain type of peer review is required.	See action 4 to address this cause. 28. Modify the current firing operations experimental explosives peer review process and document it in the Firing Facilities FSP or applicable controlled document. The process is to include: a. Process flow from action 4. b. Peer reviewers that are experts in physics, engineering, and chemistry and are approved via the defined training program, as approved peer reviewers by the LLNL Explosive Safety Committee. c. A comprehensive list of information to provide to peer reviewers to include: • Experimental design information and materials for all experiments/devices and materials and their associated amounts that will be in the chamber during the experiment, as deemed necessary by peer reviewers for sufficient review. d. All worksheets from action 1 (including the combustible loading CECM worksheet).

Other Observations

In performing the change analysis, where process steps are reviewed and compared to actual steps taken in relation to this event, differences were identified that were determined to have had no effect on the outcome of this event (i.e., are not causes). These differences that need action, are summarized in the Table 5 below. Observations are also included below from the event response section.

Table 5: Summary of Observations and Recommended Actions.

OBSERVATIONS	RECOMMENDED ACTIONS
The history of pressure rise in CFF experiments is incomplete due to loss of such records from some of the earlier experiments. However, the existing data for similar hydrodynamic experiments points to a strong correlation between the presence of fuel and an ignition source (LiH and water) being associated with pressure rise higher than configurations without the presence of fuel and an ignition source.	1. Implement chart recording of post-shot chamber pressure and temperature. 2. Evaluate the use and installation of in-chamber temperatures sensors and implement if feasible. 3. Digitally archive chamber pressure and temperature data along with other shot data. Note that no additional action is needed. Firing operations currently have a formal record-keeping process documented in *Site 300 Records Management (S300-WCIOPS-024).*
The IH, HP, and explosive safety SME were not listed as attendees on the invite to the experimental kick-off meeting. The presenter is not positive that all points from the workflow procedure were covered in this meeting.	4. Document and communicate roles required to attend the experimental kick-off meeting (or EAR briefing), even as a simple checklist to ensure all needed members are included. This could be incorporated into the experimental workflow procedure as a guide for organizer.
The EAR does not include a description of hazardous operations and materials related to experiment fielding, other than the M9a (e.g., MUMA, materials in device, etc.)	5. Remind those responsible for developing EARs to include a description of hazardous operations and materials.

OBSERVATIONS	RECOMMENDED ACTIONS
Final layout in the chamber did not match the proposed final setup of the (b) (7)(F) designated in the EAR: (1) four water barrels were moved to the overlay, (2) one of the steel plates around the (b) (7)(F) was moved (b) (7)(F) to prevent interaction of the two experiments, and (3) an additional double stack of water was added to the west side of the (b) (7)(F) to mitigate interactions between the (b) (7)(F) and (b) (7)(F)	6. Establish a threshold of changes that require a re-review via the chamber protection review, EAR, and/or peer review process. Include addition or movement of combustible products as a change requiring re-review.
The WCD bounds out modifications to the MUMA system and does not cover fabrication or creation of the MUMA system.	7. Include modification to the MUMA system as part of the WCD and ensure this task is analyzed and properly controlled, or create a WCD for assembly and fabrication of the MUMA system.
The chamber protection review was not approved by the Associate Program Director for Hydrodynamic and Subcritical Experiments, nor is there a signature line for approval by this role. The chamber protection review was not revised/re-issued to reflect the final shot setup, nor was a work pause initiated to address the differences between the final shot setup and the chamber protection review. This implies that the evaluation process for chamber protection was not conducted for the final shot setup.	8. Re-evaluate approval and review of the chamber protection review to ensure that stakeholder needs are appropriately met and oversight/approval is appropriately aligned with key active stakeholders. 9. Include defined chamber protection review approvers as part of the approval process for the review.

OBSERVATIONS	**RECOMMENDED ACTIONS**
The following issues were identified with the MUMA process: • Verification that the adjustment was acceptable was performed a few months after the experiment. Also, it appears that retesting did not occur based on a lack of signature. • Issues were identified with componentry that supports the MUMA: the vacuum pump for the MUMA is not rated for flammable gases, the flow meters are not calibrated for methane, the vacuum gauges are not rated for use with flammable gases, the flow controller is not calibrated for methane, there are redundant regulators (possibly not calibrated for flammable gases) and are not rated for pressure/vacuum, a pressure and instrument diagram (P&ID) is not present for the entire system. • An evaluation of whether a MESN was needed was performed, but it was incorrectly determined (based on conversations with LLNL SMEs) to not be needed and therefore was not created. This determination was not made by the appropriate SME, or designee.	10. IA team to present MUMA assessment observations to firing operations personnel. 11. Resolve questions/concerns documented in the memo from the WCI Explosive Operations Manager to the Experimental Ramrod, mechanical engineer, and the Experimental Fielding Supervisor dated August 3, 2021. These questions/concerns in action form include: a. Consult with Associate DTED leader for operations and the LLNL pressure safety expert to determine what is required for an MESN. If the MESN is determined necessary, create an MESN for the MUMA system at B801. b. Reconfigure and verify non-consumable components of the MUMA system are (1) compatible with methane, (2) have an accurate P&ID, (3) are calibrated for flow and pressure measurement for methane, (4) calibration is documented on a periodic schedule (or done prior to needing the MUMA system), and (5) resolve the redundant regulator issue. c. Install proper rated gauges on consumable MUMA manifold and calibrate the consumable MUMA manifold flow meter. 12. WCI Conduct of Operations Manager to perform an informal management observation focused on the *MUMA Operation Procedure* and process.
LiH was not listed as a line item on the unclassified version of the Materials Database, it is listed in the classified version. It is annotated on the bunker schedule request fo(b) (7) (F) It was also added under the comment field on the Materials Database. Note that this issue was identified for other experiments where the unclassified and classified versions did not match.	13. Immediate action taken–Responsible employee became aware of the omission the night of the event when reviewing documents with first responders. 14. Evaluate the unclassified and classified forms of the materials database to ensure consistent revision use and materials present.
There does not appear to be a peer review form separate from the EAR. There is no documentation in the EAR that states the peer review meets the criteria of the three areas for review: physics, engineering, and chemistry.	15. Develop a comprehensive approval sheet for the peer review process to include signatures for physics, engineering, and chemistry.

OBSERVATIONS	RECOMMENDED ACTIONS
The S300 peer reviewers have not been through the peer review training but are listed as approved peer reviewers.	16. Train S300 peer reviewers as approved by the ESC and/or remove them from the list as approved peer reviewers.
The following is a general observation from interviewees that is not discussed elsewhere: Some of the key roles did not have all the information needed about the experiments and associated materials involved to perform their job. For example, ES&H and the chamber operators were not aware that LiH was used in this experiment. The chamber operators no longer receive the Materials Database. They use this information for several reasons, one being how many dog washes are needed. The chamber operators were also surprised by how much foam was being used; they saw the foam when the stands were being filled a few weeks before the experiment.	17. Work with the chamber operators to determine what information they need regarding an experiment. Document the information provided in the appropriate location. 18. Work with ES&H to determine what information they need regarding an experiment. Document the information provided in the appropriate location.
Several observations were identified with the response to the B801 event: • There were too many non-essential people in the VTR during the event. • Although the run card database included current information, the physical run card used by the FD for B801 was out of date and included a retired employee's contact information. • FD was not familiar with use of the instruments for screening for contamination. • The contamination screening did not take place immediately after evacuation, and personnel were not kept segregated prior to moving to the second assembly point. • PPE was not where it was supposed to be in 801D as specified in the prerequisites of the *Procedure for Abnormal Events at 801*. Since B801D was initially in the evacuation zone, any PPE stored in B801D would have been difficult to retrieve. • Personnel's personal belongings (keys, phones etc.) were in affected areas and were not easily retrievable for cleared personnel to leave the area.	19. Develop comprehensive Lessons Learned that identifies all continuous improvement items. 20. Consider if remote operations are possible, otherwise, limit who is in the VTR/CDU rooms during shots to only essential personnel. 21. Immediate action–The run card was updated with current information [COMPLETE]. 22. ES&H to work with the FD to familiarize them with the instruments for contamination screening [COMPLETE]. 23. Work with the LLNL training coordinator for the FD to coordinate a recurring training schedule to familiarize the FD with the instruments for contamination screening. 24. Determine a better location to store PPE and other needed supplies during execution of a shot at B801. Add a step to the CFF firing operations checklist to stage at least four sets of PPE (as described the *Procedure for Abnormal Events in B801*), including respirators, in the new location. 25. Review WCD 100336 and determine if the *Procedure for Abnormal Events in B801* needs to be referenced based on the expectation of

OBSERVATIONS	RECOMMENDED ACTIONS
• When bioassays were collected from affected workers, they were planned to be sent for analysis in one large batch, vs. as they were received.	staging PPE in B801D for emergency use during execution of experiments. 26. Evaluate if firing operations personnel can be full-face respirator approved. 27. Determined better location for personnel's personal belongings including possible movement of cars to lower parking lots on shot days. Note that it was communicated by affected personnel that requiring the use of an N95 respirator for those present in the VTR/CDU in future shots may be a good idea. In consultation with ES&H, it was determined that the N95 respirator is only rated with a protection factor if it is fit-tested and the N95 respirator is only good with particulate, not other hazards that can be released.
Days following the event, there was little communication to affected workers regarding the path forward: • Workers were unclear as to the potential health effects, were not told if any tests were needed (e.g., blood tests, bioassays, etc.), and/or if they should contact a health professional. • Not all affected workers were afforded the opportunity to communicate what happened in some venue soon after the event so that information was not lost or forgotten. • Workers were unaware of someone they could speak to about what happened.	28. LLNL to evaluate existing procedures/processes (e.g., DES-0080) to determine if an additional process is needed for follow-up after an event with many collocated workers affected by the event in which they were not directly involved. Include in this evaluation a discussion of the process outlined in DES-0080 related to injury/illness response (e.g., reporting to supervisor, going to HSD). 29. WCI Assurance Office to work with MAS to ensure affected workers are contacted sooner in the event response process. Determine if process updates are needed or if a Lessons Learned bulletin is sufficient. 30. Communicate LLNL services offered for personnel to talk with someone [COMPLETE]. 31. Determine if a post-event communication plan is necessary to ensure affected workers' needs are met and information is adequately provided.

OBSERVATIONS	RECOMMENDED ACTIONS
There was little to no communication to matrixed organizations that their employees were affected by the event that occurred at B801.	32. WCI Assurance Office to develop a strategy to notify affected organizations of matrixed personnel involved in WCI owned events.
The nurse practitioner supporting S300 was unaware of the event.	33. Better document/define that workers potentially exposed to an adverse event need to be seen by HSD within 24 hours. Determine if DES-0080 needs revision. 34. Communicate action 33 in appropriate means such as Newsline, Lessons Learned, etc. 35. Review the communication process to and from HSD from ES&H and the LEDO so everyone is clear on notification procedures, specifically for potential exposures.
In looking for loading zones for the chamber in the FSP, it was discovered that information that used to be in Appendix D of the Firing Facility FSP has been removed from the FSP; however, additional procedures have not been created to capture that important information.	36. Review Appendix D from the previous version of the FSP and create any new documents if the information is not covered in other documents.

Lessons Learned

The WCI Assurance Office has an action documented in this report to develop a Lessons Learned related to this event to summarize, at a high level, overall lessons learned. The intent of this Lessons Learned is not only to communicate the lessons soon, but also to serve as a short summary of lessons learned for employees to have access to years from now if needed.

Appendix A–Technical Team Analysis

As described in the Executive Summary, it is the judgement of the technical team, in collaboration with the IA team, that the overarching cause of loss of containment at CFF during th (b) (7)(F) experiments was a combustion-induced over-pressure that exceeded the capability of the chamber seals on doors and other openings to withstand. High temperatures were also present, but the loss of containment was most likely due to the high pressure. Smoke and gases containing combustion products and other post-experiment material leaked into the environment as a result.

Pressure rise data in the CFF chamber is key to understanding the nature of the event, although detailed time histories were not recorded (pressure was measured at a gauge in piping outside the chamber, but relevant time scales are long compared to the propagation of pressure waves, so pressure equilibrium between chamber and gauge is a reasonable assumption). An approximate reconstruction of the time history, based on eyewitness accounts of technicians observing the gauge is sketched in Figure A1. The pressure was observed to rise rapidly to about 4 psi above ambient, as is typical from the release of HE energy in the chamber. The bulk of the pressure rise, however, occurred over tens of seconds implying that chemical reactions, including combustion, caused most of the pressure rise rather than the prompt energy release from the HE. The peak pressure is unknown, having reached the maximum the gauge is capable of measuring (50 psi) after a period of approximately 30 seconds. After 60 seconds, the gauge dropped below 50 psi again. The leakage due to breached seals was audible once 40 psi was reached. These details place important constraints on what could have occurred in the chamber, as discussed in detail below.

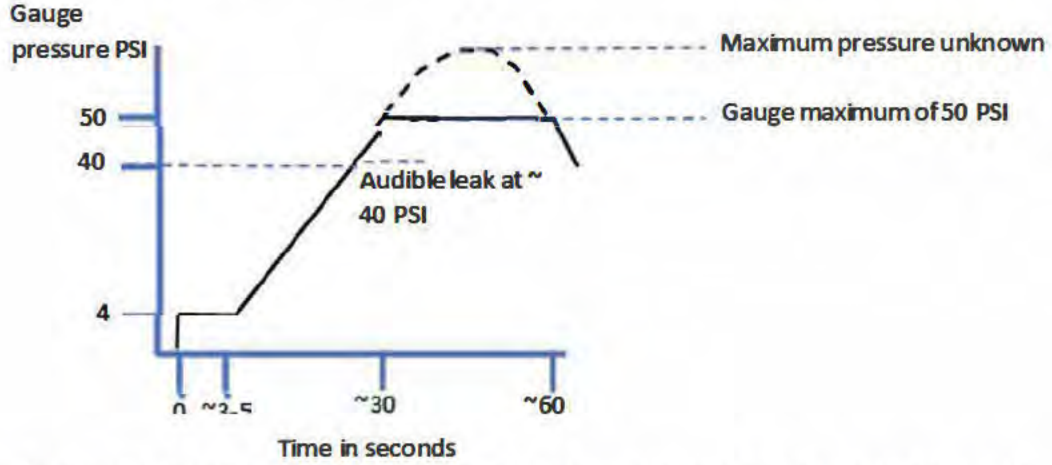


Figure A1. Inferred pressure-time history from several eye-witness accounts.

Having identified that chemical reactions over an extended period, likely including combustion, must have been the source of the pressure rise, the next tasks are to identify the chemical energy and fuel sources that were present during the experiment as well as ignition sources that could have triggered combustion. This information can be combined with data from the history of similar experiments at CFF where an unusual pressure rise was observed to help create a consistent picture. The layout of the chamber is shown in Figure A2. The FXR bullnose is to the upper right, and the overlay with ports for optical diagnostics is on the upper left. The (b) (7)(F) hydrodynamic experiment contained in a foam thermal box is labeled, along with the (b) (7)(F) addon experiments. The HE energy release was dominated by (b) (7) (F) Other items of note are the large gray blocks of flame retardant polyurethane frag catcher foams as an additional addon experiment, the stacked plastic water towers, water-filled polyethylene garbage cans on the overlay and the large plastic water tanks associated with the (b) (7)(F) experiments. The large quantities of plastics, foam and otherwise, constitute a large potential fuel source as called out in Figure A3.

(b) (7)(F)

[redacted]

can contribute to the ignition of the fue (b) (7)(F) (b) (7)(F) E gases reach high temperatures but rapidly undergo expansion cooling due to the large volume change of the explosion, especially for the insensitive HE types employed, converting most of the energy to hydrodynamic work so the prompt energy release is ineffective at igniting material that is not in close proximity. Uranium fragments are known to be pyrophoric and can ignite other materials; however, both the (b) (7)(F) periments were designed to be consistent with long experience (e.g., by using flame retardant foams of sufficient density) to resist ignition by either prompt HE products or uranium fragments. The frag capture addon used similar materials. The thermal box surrounding (b) (7) s the most problematic item with regard to these "traditional" ignition sources. It is composed of bot (F) ensity Styrofoam™ on the interior and flame retardant foam pieces for structural support. The first hydro experiment in the CFF in 2002 employed a thermal box composed of Styrofoam™ and plywood and caused a high-pressure excursion of 24 psi, compared to the typical pressure rise of less than 10 psi observed from HE energy release. Notes by the shot Ramrod indicated concern that the thermal box would ignite and burn, as appears to be consistent with the pressure rise. Subsequent shots replaced the plywood with flame retardant foam. As noted in Appendix B on experiments supporting the analysis of this incident, all the plastic and foam materials present are readily pyrolyzed to produce flammable gases at temperatures of 400 to 500 degrees centigrade, but the flame retardant foams do not show sustained burn once a heat source is removed. That result is consistent with their use in avoiding ignition from transient sources, but also shows that with sustained high temperature heating they are a ready source of fuel.

The (b) (7) (F) experiment contained two less common ignition sources: LiH, and ABS plastic. In principle, both are capable of producing sustained high temperatures since the large volume change and expansion cooling that occurs with HE products are not applicable in these cases. The ABS was unique to this experiment and was additively manufactured, resulting in a material with significant porosity. One hypothesis is that the ABS was reduced to small particles by an HE-driven shock, which were then susceptible to a rapid fuel-air burn in the dispersed cloud of particles. Tests described in Appendix B show that for fine enough particles, the ABS plastic is indeed capable of such a burn. n experiment described in Appendix B, dubbed "Icepick," that subjected a sample of ABS manufactured by the same technique as in 663G, to similar hydrodynamic loading and at similar initial temperature shows that the ABS was indeed a likely contributor to ignition of fuel in CFF's chamber. Pressure rise in the HEAF chamber, using similar analysis methods to those described below, showed unequivocal evidence of combustion of both ABS and TPX plastics in the Icepick experiment. LiH has been present in a number of CFF hydrodynamic experiments where it is also subjected to HE-driven shock loading. When pulverized, LiH is known to spontaneously ignite in moist air and reacts violently with water. The reaction sequence of concern is first the highly exothermic $LiH + H_2O \rightarrow LiOH + H_2$, followed by the combustion of hydrogen, $2H_2 + O_2 \rightarrow 2H_2O$ that can result in high temperature hydrogen fire with an adiabatic (ideal) flame temperature of 2,400 K at atmospheric pressure. Large quantities of water were present in the CFF chamber in close proximity to th (b) (7)(F) evice, providing a high likelihood of the interaction of LiH fragments with water.

Given the previous extensive experience with HE products and uranium fragments, it appears most likely that the large-scale ignition and burn was initiated by either or both the interaction of LiH with water and the fuel-air combustion of ABS plastic. The distribution of materials that could contribute to ignition are shown in Figure A4. As shown below, the energy present in these sources is insufficient to account for the observed pressure rise, but they likely played a key role in triggering large-scale combustion of the available fuel.

(b) (7)(F)

[redacted]

The history of hydrodynamic experiments at the CFF suggests a correlation between the presence of LiH, water, and a thermal box as a fuel source with regard to large pressure excursions. Table A1 shows a "stoplight chart" for shots where pressure data was found. Five characteristics of the experiment are noted, along with the observed pressure rise: (1) the presence of LiH; (2) water sources located within three meters of the device; (3) water sources located at greater than three meters; (4) the presence of a thermal box and whether the experiment was hotter/colder than ambient; and (5) significant additional amounts of foam located within three meters of the device. With the exception of the first shot and its plywood thermal box, every experiment that exceeded a pressure rise of 20 psi (highlighted in yellow) was positive for the first four indicators. The last experiment on the list, the 663G experiment, was positive for all five indicators.

The state of the CFF chamber post-shot supports the picture of widespread combustion. Figure A5 shows one of the frag catcher foam assemblies that are extensively charred on the exterior, indicating surrounding temperatures of at least 400-500 °C based on the experiments described in Appendix B. The second image in Figure A5 shows an individual slab of foam from the frag catcher with both edge-charring and penetrations from device fragments clearly evident. The upper ends of the aluminum struts are partially melted, indicating a temperature exceeding the melting point of aluminum at elevations above about three meters (total chamber height is 9.45 m), suggesting the upper two-thirds of the chamber reached temperatures exceeding 660 °C. In the absence of other flows, buoyancy should establish some temperature stratification in the chamber on a time scale of a few seconds. All the other potential fuel sources shown in Figure A3 showed evidence of complete or partial combustion. The water-filled garbage cans appear to have been completely consumed. The water-filled towers and 671 water tanks showed extensive burning, pyrolysis, and melting down to the level at which water remained in some of the vessels.

Table A1: Hydrodynamic experiment history for CFF where pressure data exists.

Date Fired	LiH	Water < 3m	Water>3m	Temp	Foam<3m	ΔP (psi)
6/20/2002	🟩	🟩	🟩	🟥 Cold	🟩	24
5/6/2003	🟥	🟩	🟩	🟥 Hot	🟩	18.91
9/9/2003	🟩	🟩	🟩	🟩	🟩	18.47
7/9/2012	🟩	🟩	🟩	🟩	🟩	3.83
12/12/2012	🟩	🟩	🟩	🟩	🟩	9.74
10/31/2013	🟩	🟩	🟩	🟩	🟩	5.08
1/31/2014	🟥	🟥	🟥	🟥 Cold	🟩	41.86
7/30/2015	🟥	🟥	🟥	🟩	🟩	7.1
12/3/2015	🟥	🟩	🟥	🟩	🟩	4.95
4/6/2016	🟩	🟩	🟩	🟥 cook off	🟩	0.16
7/6/2016	🟩	🟩	🟩	🟥 cook off	🟩	0.13
4/6/2017	🟥	🟥	🟥	🟥 Cold	🟩	28
7/20/2017	🟥	🟩	🟥	🟩	🟩	3.5
3/21/2018	🟥	🟥	🟥	🟥 Hot	🟩	23.53
8/9/2018	🟥	🟥	🟥	🟩	🟩	4.2
11/4/2018	🟩	🟩	🟩	🟩	🟥	7.89
7/25/2019	🟩	🟩	🟩	🟩	🟩	13.6
8/28/2019	🟩	🟩	🟩	🟩	🟩	11.2
6/9/2021	🟥	🟥	🟥	🟥 Cold	🟥	50
	red for LiH present	red for water +LiH	red for water +LiH	red for thermal box	red for large foam close to shot	

Figure A5: Post-shot images showing charred frag catcher foam and aluminum stand.

The magnitude of the pressure rise can be related to the energy released in the chamber. The inventory of the available energy sources, the known volume of the CFF chamber, and the equation of state of the hot gases allows the pressure rise to be estimated. Table A2 gives approximate masses for the various energy-releasing materials in the chamber along with the energy per unit mass due to combustion or other chemical reactions and the total energy release possible in the case of complete reaction/combustion of the material. The HE energy release is divided into two portions: the prompt release that occurs during the explosion phase and the total energy release if the explosion products were completely oxidized. For LiH, the energy release includes the exothermic reaction with water to form lithium hydroxide and the energy of combustion of the resulting hydrogen. The foam box is composed of different types of plastic, so a mass-averaged energy release is used.

Table A2: Masses and energy release potential for materials in the CFF chamber, calculated with an accuracy of two significant figures.

	Mass kG	MJ/kG	MJ
HE (prompt)	(b) (7)(F)	4.2	110
HE (total)		11.7	300
LiH	2.4	55.5	130
ABS	5.9	40	240
Foam box	51-71	33	1,700-2,300
Foam frag catchers	3,182	25.5	81,000
Burned F.C. foam	15-24	25.5	380-610
Garbage cans	44	47.7	2,100
Other plastic burned	>10	41-46	>410
Trash can water	832	-2.57	-2,100

Total water excluding 671	8,631	-2.57	-22,000

The energy per unit mass values in Table A2 are drawn from LLNL explosive databases, and references below [Smith and Miser (1963) for LiH properties; Lyon, et. al., (1998) for polymers; and Kao and Duh (2020) for ABS plastic]. For the foam frag catchers both the total mass and the estimated mass burned (from post-shot analysis by the shot Ramrod) are given in Table A2. Although the foam blocks show extensive charring, that appearance is due to the large volume change that occurs as it chars (like a marshmallow held over a fire), and only a small fraction was actually consumed.

Table A2 makes it clear that combustible materials constitute a much larger potential source of energy than either the HE or ignition sources. Although the water present likely contributed to ignition, the large quantity indicated in Table A2 may also have helped limit net energy release and pressure rise through the latent heat of vaporization. Video taken during the experiment shows large quantities of water droplets in flight following the explosion. Aside from straightforward combustion and vaporization, a complex array of reactions (both endothermic and exothermic) between hydrocarbon pyrolyzed gases, combustion products, and steam were undoubtedly occurring in the high temperature environment within the chamber. For the purpose of approximate estimates and because the exact quantities of constituents present in the chamber atmosphere are unknown, such reactions are ignored in this analysis.

For pressures less than 10 atmospheres and temperatures between room temperature and a few thousand degrees centigrade, the gases within the chamber should obey the ideal gas law to reasonable precision,

$$PV = nRT$$

eq. A1

where *P* is the pressure, *V* is the chamber volume, *n* is the number of moles of gas present, *T* is the absolute temperature, and *R* is the gas constant. Additionally, the internal energy of the gas can be related to the pressure and volume through equation A2:

$$U = PV/(\gamma - 1)$$

eq. A2

where *U* is internal energy, and γ is the adiabatic index or ratio of specific heats $\gamma = Cp/Cv$. Equation A2 applies only in the case where γ is independent of pressure and temperature, which is not strictly true for the range of condition present in the CFF chamber. On the other hand, γ is likely to vary over a fairly small range between the cool, diatomic gases in room temperature air with γ=1.4, and high temperature combustion products including triatomic gases and molecules in excited states with γ~1.3. For estimates with ~20% accuracy, equation A2 is used since it allows a direct connection between energy release and pressure rise without needing to know the detailed molar constituents, and γ is adjusted to an average value appropriate for the case at hand.

Ignoring energy losses for the moment, energy releases such as those given in Table A2 would appear over a multi-second time scale predominantly as internal energy of the gases within the chamber. This is because the chamber has a fixed volume preventing *PdV* energy exchange and the time scales are much longer than the sound transit across the chamber, limiting the coupling to flow energy of the gas and enforcing near spatial uniformity of the pressure. Equation A2 then gives a connection between a chemical/combustion energy release, *ΔE* and pressure rise, *ΔP* given in equation A3:

$$\Delta P_{psi} = 0.0612(\gamma - 1)\Delta E_{MJ}$$

eq. A3

In deriving equation A3, the CFF chamber volume V=2.37 x 10^3 m^3 has been taken into account. Making use of equation A3, we can arrive at estimates for the cumulative pressure rise, shown in Table A3 below, due to the various energy sources given in Table A2.

Table A3: Estimated pressure rise due to energy release in the CFF chamber, calculated with an accuracy of two significant figures.

	MJ	γ□	ΔP_{psi}
HE prompt	110	1.4	2.7
HE prompt+LiH	240	1.4	5.9
HE total +LiH	440	1.4	11
HE total +LiH+ ABS	670	1.35	16
HE total +LiH+ ABS+Foam Box	2,400-3,000	1.35	50-65
HE total +LiH+ ABS+Foam Box+Burned F.C.	2,700-3,600	1.35	59-78
HE total +LiH+ ABS+Foam Box+Burned F.C.+30kG plastic	4,000-5,000	1.35	85-110

From Table A3, it is clear that most of the pressure rise was due to combustion rather than the HE or the ignition sources. Note that the predicted prompt rise due to the HE (2.7 psi) is of similar magnitude to the observed prompt rise (4 psi). Pressure differences of 1 psi or less are not significant due to accuracy of the gauge. Given the presence of ample fuel sources well beyond those included in Table A3, it appears that the combustion within the chamber was on a path to consume all the available oxygen in the room (711 kG). If that much oxygen were combined with ~200 kG of hydrocarbons, then approximately 8,000 MJ of energy would be liberated, resulting in a peak pressure of ~170 psi if the average γ is 1.35.

Although data beyond the peak gauge pressure of 50 psi is unavailable, it is unlikely that the chamber reached pressures as high as 170 psi. As the oxygen in the room is consumed, the burn rate slows until energy and mass losses, neglected up to this point, become competitive. Ignoring leaks and other losses and at an initial burn rate of ν_1, the number of oxygen atoms in the room, N, with initial number N_0, would be expected to vary in time as given in equation A4:

$$\frac{dN}{dt} = -v_1 N \rightarrow N = N_0 e^{-v\ t}$$

eq. A4

The pressure would rise proportional to energy release, hence as given in equation A5:

$$\frac{dP}{dt} = v_1 \frac{P_{max}}{N_0} N \rightarrow P = P_{max}(1 - e^{-v\ t})$$

eq. A5

Where P_{max} ~170 psi would be appropriate for the chamber as discussed above. Now include a particle leak rate ν_2, which modifies the equation for the number of oxygen atoms to equation A6:

$$\frac{dN}{dt} = -v_1 N - v_2 N \rightarrow N = N_0 e^{-(v \;\; +v_2)t}$$

eq. A6

Energy loss is associated with the leaks, which modifies the pressure equation to equation A7 (the extra factor of γ comes from the *PdV* work associated with the outflow). Allowance for additional energy loss (e.g. through convective cooling) can be accommodated through a third rate ν_3,

$$\frac{dP}{dt} = v_1 \frac{P_{max}}{N_0} N - (\gamma v_2 + v_3) P$$

eq. A7

The solution to equation A7 for pressure starting at 0 psi at time t=0 seconds is given in equation A8:

$$P = P_{max} \frac{v_1}{v_1 + (1-\gamma) v_2 - v_3} \left(e^{-(\gamma v_2 + v_3)t} - e^{-(v \;\; +v_2)t} \right)$$

eq. A8

Unless ν_2 and ν_3 are small compared to ν_1, the pressure will peak well below the maximum. The observed time history, as qualitative as it is, places constraints on these rates. Additionally, there is pressure-time history data from some of the early CFF experiments that constrains the chamber cooling rate, ν_3. Figure A6 shows a chart record for chamber pressure from the first shot in Table A1.

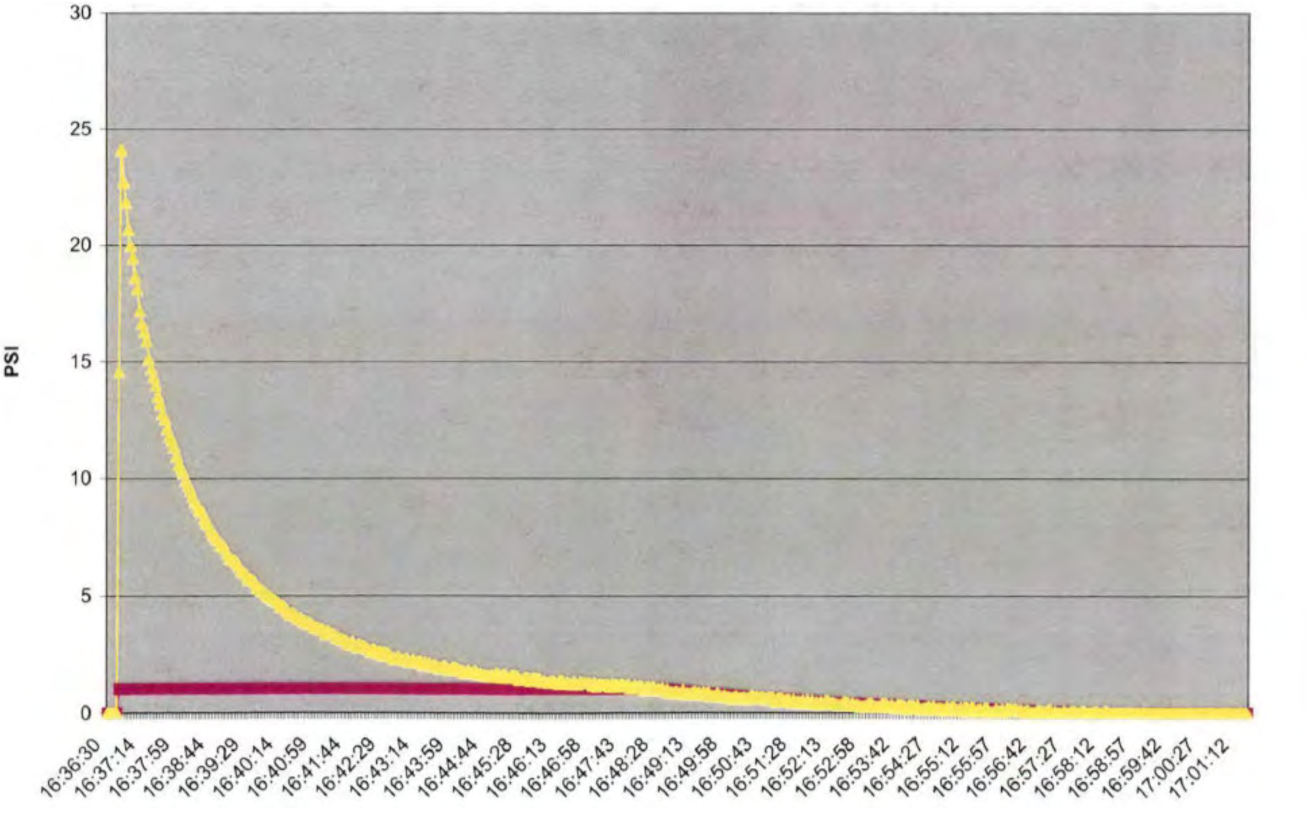


Figure A6: Chamber pressure history for a CFF experiment performed 6/20/2002.

The data in Figure A6 gives an approximate cooling time $t_3 = 1/v_3$ of 98 seconds. Over different shots t_3 ranged from 80 to 100 seconds. These time scales are consistent with what could be expected from convective cooling, with cooling times varying inversely with the surface to volume ratio for the chamber and an empirical heat transfer coefficient that depends relatively weakly on the convection velocity, expected to be in the range of ~10 m/s due to the buoyancy of heated gases.

Although the pressure observations as pictured in Figure A1 are too qualitative to accurately constrain the other rates necessary for equation A8, they do allow some additional semi-quantitative insights. If the cooling rate is taken from the earlier data and the solution must rise to 50 psi in 30 seconds, then fall below 50 psi again at 60 seconds, a consistent set of rates would be

$$\upsilon_1 = \frac{1}{52} sec^{-1}, \quad \upsilon_2 = \frac{1}{148} sec^{-1}, \quad \upsilon_3 = \frac{1}{90} sec^{-1}$$

with the corresponding pressure/time history from equation A8 shown as the lower curve in Figure A7. A key point is that the pressure dropping below 50 psi in 60 seconds forces the solution to reach pressures only modestly above the maximum gauge pressure as opposed to approaching the theoretical maximum of 170 psi. Another interesting point is that if the leak term is neglected, as shown in the upper curve in Figure A7, the decay rate due to convection alone is too slow to bring the pressure below 50 psi at 60 seconds. This suggests that leakage from the chamber was a significant player in limiting pressure rise.

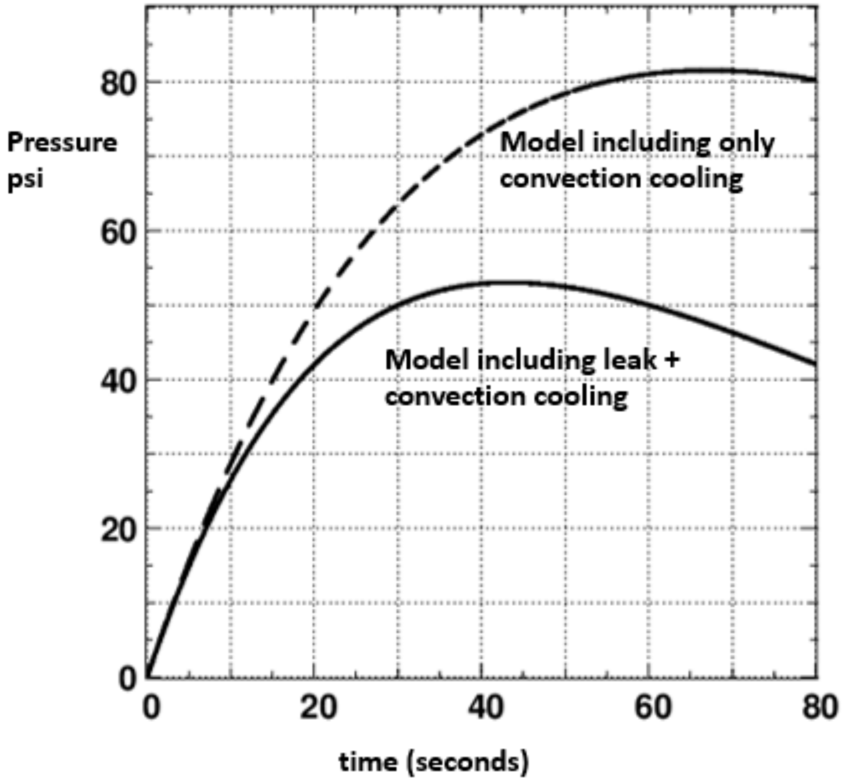


Figure A7: Models of chamber pressure versus time.

Finally, we can use ignition source energy estimates and the properties of gases to examine how the ignition process itself occurred. We can estimate the volume of hot gas from an ignition source, in the approximation that it burns at nearly constant pressure, using the relation for enthalpy given in equation A9:

$$\Delta H \quad \frac{\gamma P V_{hot}}{\gamma - 1}$$

eq. A9

Where ΔH is the enthalpy release, approximately equal to the energy of combustion, and V_{hot} is the volume of hot gas, with an ideal flame temperature >2,000 K for the LiH-driven process. Taking γ=1.3, P=19 psi following the HE explosion, and ΔH=130 MJ for LiH from Table A2, we can solve for V_{hot}:

$$V_{hot} = 234\ m^3 \approx 10\%\ CFF\ Volume$$

In practice, convective mixing of the hot gas will increase the volume of heated gas, with the temperature dropping according to the ideal gas relation, equation A1 (i.e., the temperature varies inversely with the number of moles of gas in the hot cloud at a given pressure). For the example of LiH above, mixing by a factor of three or more in molecular number could reduce the gas cloud temperature below the 400 °C necessary to pyrolyze plastics.

We can get an idea of the flow field and mixing rate in the chamber from idealized 3D hydrodynamic simulations of the 663G experiment with the ARES code shown if Figure A8a-c. The simulation mocks up the (b) (7)(F)
(b) (7)(F)
[redacted]

(b) (7)(F)

[redacted]

Figure A8.a: Initial configuration of 3D simulation.

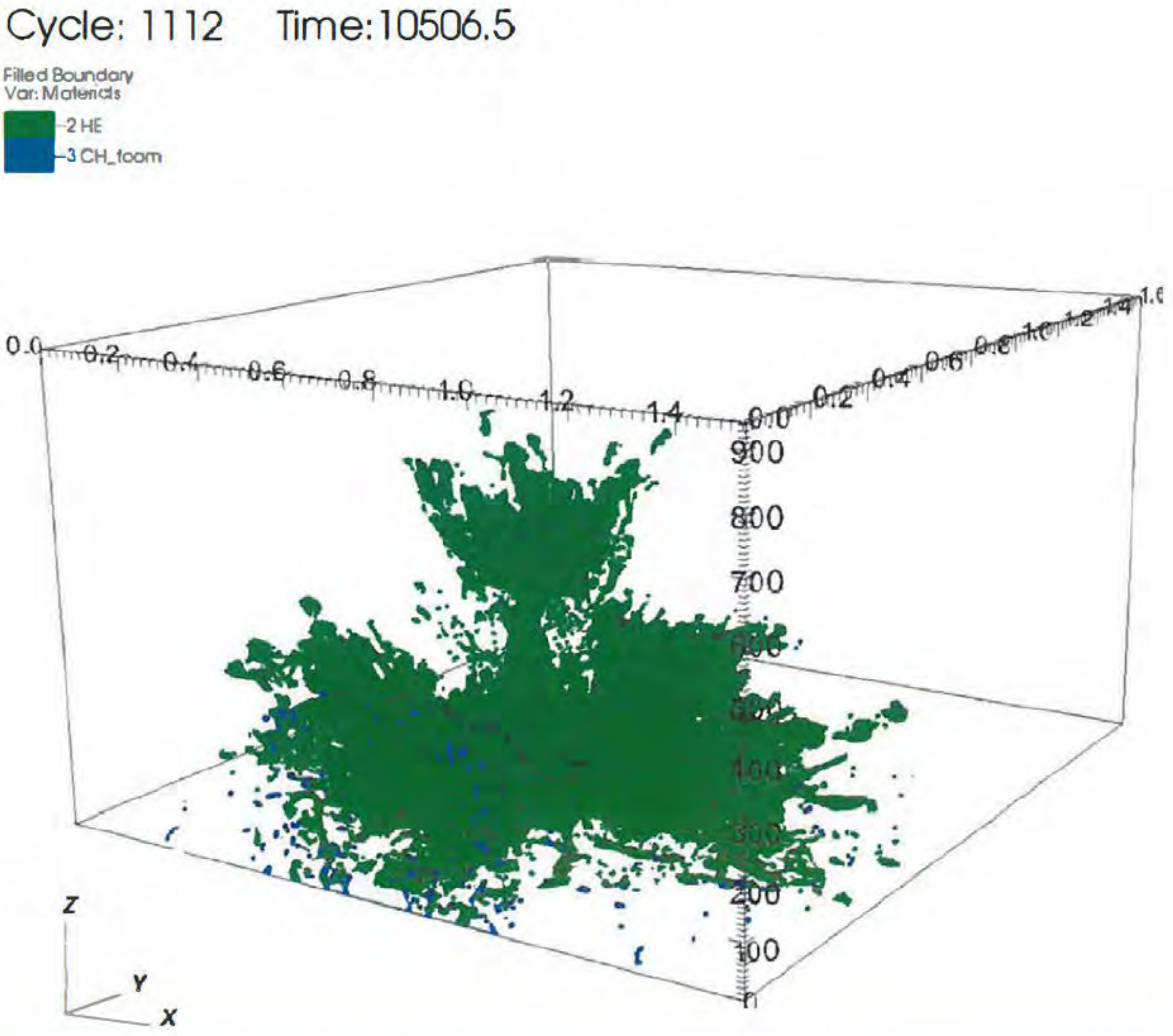


Figure A8.b: 3D simulation showing distribution of HE products and foam box debris at ~10.5 ms after detonation.

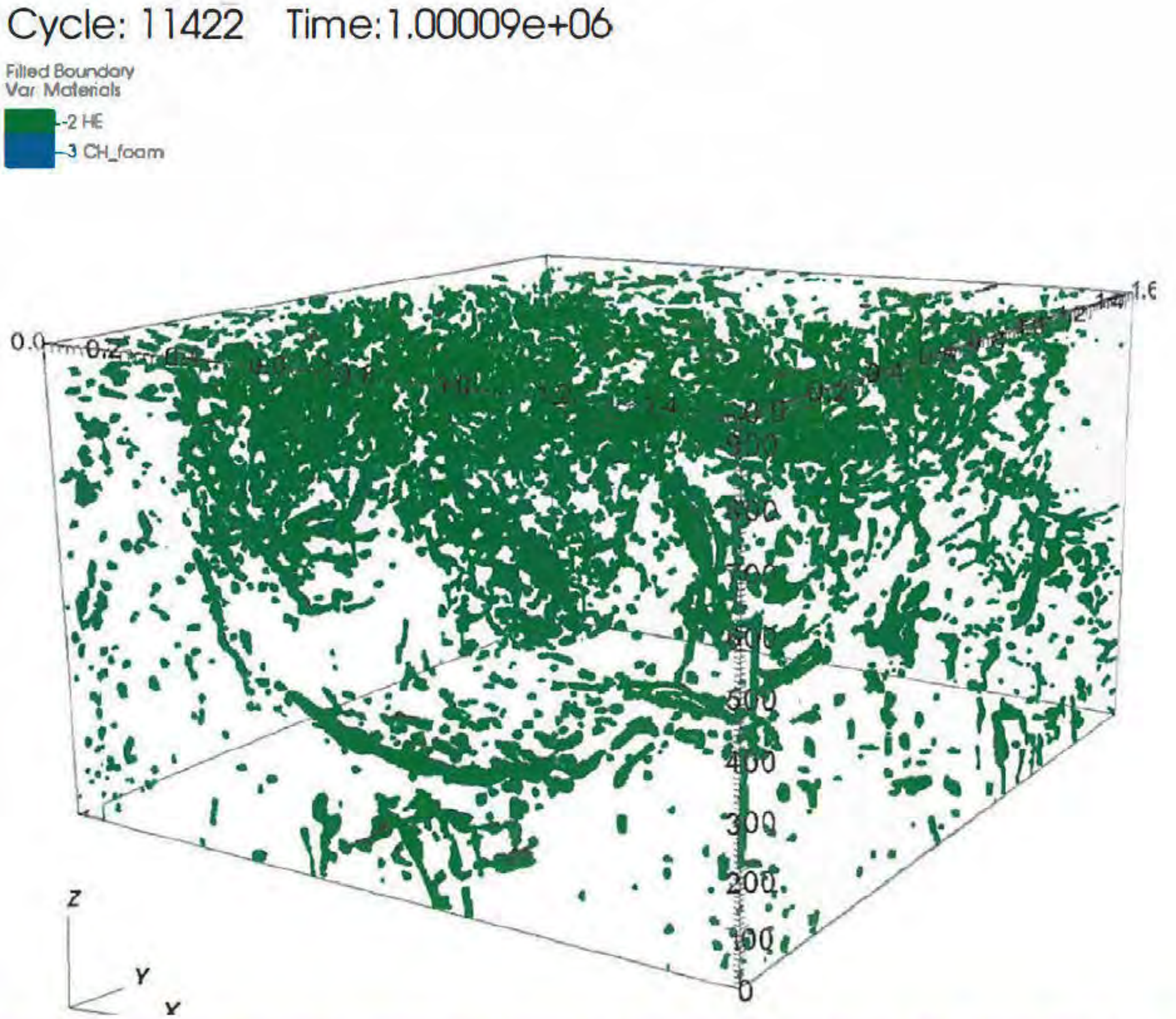


Figure A8.c: 3D simulation showing distribution of HE products and foam box debris at ~1 second after detonation

The calculations suggest that significant mixing of a gas cloud hundreds of cubic meters in scale is unlikely to be significant until times greater than about a second, as indicated in Figure A9. The mean velocity in Figure A9 is derived from the time-dependent kinetic energy in the simulation, corrected by adding in buoyancy driven flow, estimated as $v_{Buoyancy} = \sqrt{2gh}$, with *g* the acceleration of gravity and *h* the height of the chamber (9.4 m), since both gravity and additional heat sources were neglected in the simulation. The characteristic mixing time for the gas cloud is taken to be the height of the chamber divided by the mean velocity. Additionally, video from the chamber shows a strong brightening of light in the chamber, emanating from the direction of the (b) (7)(F) experiment, occurring many milliseconds after the HE explosion that is likely associated with the ignition event.

Mean gas velocity inside CFF chamber

Characteristic mixing time

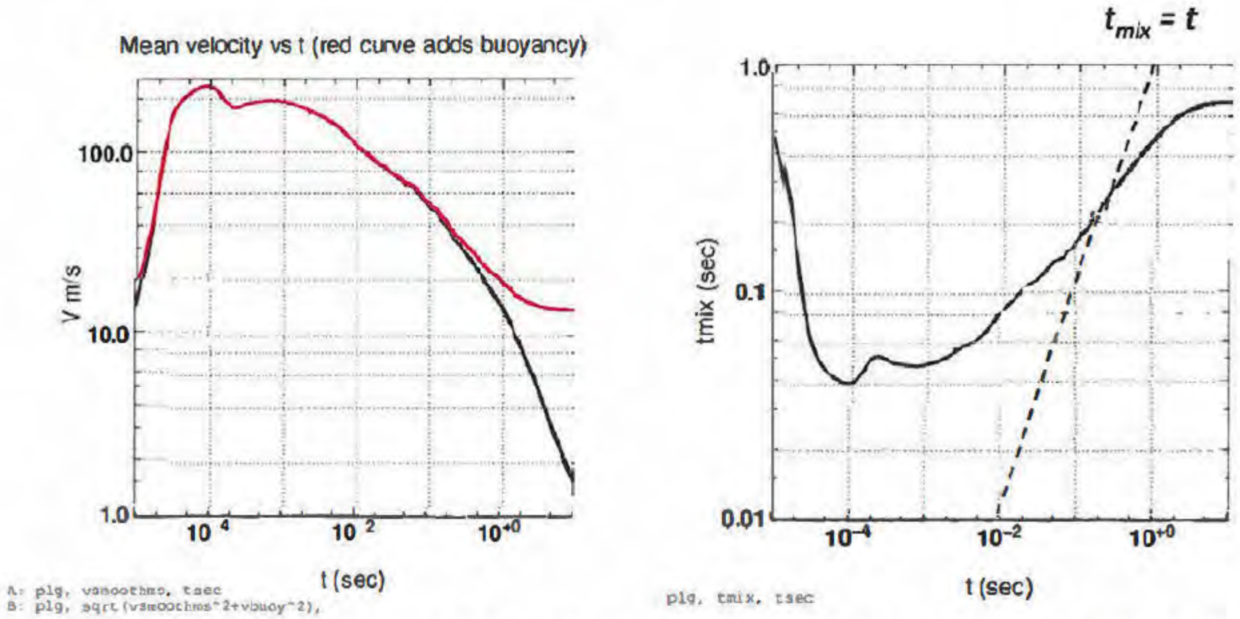


Figure A9: Mean flow velocity in the chamber and corresponding mixing time scale from 3D simulation.

The simulations also suggest that the debris from the foam box will be distributed roughly uniformly through the chamber by a few tenths of a second. Under the assumption that mixing is not significantly increasing the volume of ignition-source hot gas (i.e., it fills about 10% of the CFF chamber), then it is reasonable to expect about 10% of the foam box debris, or 5-7 kG, from Table A2, to be co-located with the hot cloud above the ignition temperature of the plastic foam. From Table A2, ignition of that material would lead to an energy release of 170 to 230 MJ that would more than double the original energy release. If mixing did increase the initial gas volume, it will increase the "second generation" energy release as long as the cloud temperature remains above the ignition temperature. Convective mixing over a few seconds' time scale could be expected to bring the more energetic hot gas cloud augmented with burned foam box debris into contact with even more foam box debris and other fuel, leading to continued growth toward a chamber-filling conflagration. As the pressure rises, the volume of hot gas produced by each new energy release decreases according to equation A9. However, the total volume could be expected to grow until the chamber is entirely filled given the available fuel and oxygen. The observed time scale for the pressure rise of ~30 seconds is consistent with this scenario.

Conclusions

Multiple lines of evidence point to runaway combustion of fuel sources within the chamber as the source of overpressure and breaching of chamber seals in the (b) (7)(F) experiment. High temperatures were reached in the chamber during the event–sufficient to melt aluminum in the upper two-thirds of the chamber (> 660 °C), consistent with combustion causing the pressure rise. Tests on materials present in the chamber confirm they are readily pyrolyzed and burned in the conditions that were present.

Quantitative analysis shows the overpressure was likely limited by available oxygen within the CFF chamber, along with energy loss processes including leakage from the chamber through breached seals, convective cooling to the chamber walls, and the latent heat of vaporization of the large amount of water present.

Further indications suggesting consistency of this picture can be found in the history of CFF hydrodynamic experiments. The history of pressure rise in CFF experiments is incomplete due to loss of such records from some of the earlier experiments. However, the existing data for similar hydrodynamic experiments points to a strong correlation between the presence of fuel and an ignition source (LiH and water) being associated with unusually high pressure rise. The experiment had an additional potential ignition source, an additively manufactured ABS plastic part which follow-on experiments strongly suggest played an important role.

These observations on the cause of the event along with examination of existing processes have led both the IA and technical teams to the conclusion that a more robust review process for combustible materials is needed. As described in the recommendations within the body of the IA report, a "Combustion Energetic Materials Loading" worksheet should be completed by the experimental team in the process of defining the experimental configuration. The essential elements of the worksheet would be (1) the equivalent of Table A2, employing the full mass of any explosive, reactive, and combustible material in the chamber and (2) use of equation A3 to estimate the magnitude of potential pressure rise. Equation A3 may not rigorously apply if the inferred energy release exceeds the available oxygen in the chamber, but in that circumstance the review would be triggered regardless. If the worksheet indicates the potential for high pressure in the chamber, meaning a pressure rise greater than half the rating for the chamber, a "Chamber Energetic and Combustible Materials Review" process would be triggered including appropriate experts in the chemistry of combustion and energetic materials. It is understood that many experiments would require this type of review. One possible mitigation that could remove limits on combustible materials is to replace all the 83,000 cubic feet of air in the chamber with nitrogen or other inert gas for the experiment, although that would introduce its own set of safety concerns.

In returning the chamber to experimental operation, the teams believe significant engineering effort should be applied to the analysis of preferred failure modes in the event of future over-pressure excursions. For instance, it is not clear that the uniform strengthening of seals is desirable in that containment of higher pressures might cause greater damage to the facility, although avoiding failure of seals that potentially cause exposure to personnel is clearly a top priority.

Appendix B–Sub-Scale Experiment Methodology, Analysis, and Results

Introduction

Based on the event that occurred on June 10, 2021 and deducing unlikely explanations based on the similarity to many previous experiments that have taken place in the chamber, a series of sub-scale experiments were designed and performed. These experiments were designed to determine if any of the flammable materials or combinations of materials could be identified as the primary culprit of the incident. The IA team and technical team came up with five circumstances to test the myriad flammable materials that were in the chamber during the experiment. One noteworthy material that has not historically been used in a hydrodynamic test in close proximity to HE in the chamber was ABS, a known flammable plastic. Because of the known flammability and lack of history of using ABS in a hydrodynamic experiment in the chamber, it was of particular interest. Other materials that had been used in the chamber in various quantities throughout the history of the CFF that were still of interest as flammable mass include (1) blue insulating foam in thermal conditioning box, DOW®, Styrofoam™ extruded polystyrene foam insulation; (2) LAST-A-FOAM® flame-retardant (FR-series, FR-3703 and FR-4515) ridged polyurethane foam of various densities, used in various locations; (3) low-density polyethylene (water barrels and water tanks); and (4) 3D-printed ABS plastic (Stratasys FDM thermoplastic ABS-M30™). These interests led to the following five questions testing aimed to answer:

1. Were the materials in the chamber susceptible to continued burning when exposed to a flame?
2. Were the materials in the chamber susceptible to continued burning when exposed to radiant heating?
3. Do pulverized, dispersed ABS plastic, or other materials easily initiate into a fire from a spark/ignition source?
4. Does 3D-printed ABS plastic pulverize from a detonation driven shock?
5. Can the (b)(7)(F) geometry and conditions lead to an ABS fuel-air mixture leading to a late time explosion? (This would be considered as a final recreation of the shocked and dispersion conditions of the ABS.) This test was named Icepick.

Experimental

The experimental setup for the experiments conducted to test the above questions are described below.

Materials: All materials tested in these experiments were provided by the B801 operations staff and were identical to materials utilized in the chamber during the experiment. Materials were tested as received.

Thermal-gravimetric-analysis (TGA): Thermal-gravimetric-analysis (TGA) was performed on a TA instruments discovery TGA purged with 50 mL min^{-1} UHP $N_2(g)$. Experimental runs were performed in precleaned TA instruments platinum pan. Experiments on all five materials, cut from bulk samples, were run in duplicate and sample masses ranged between 3.00-11.45 mg depending on density. Experimental runs started at room temperature (ca. 22 °C) and ramped to 700 °C at a heating rate of 10 °C min ^{1}.

Flame-heating ignition and combustion testing: Samples of each material (25-50 mm × 25-50 mm × material thickness, 1-5 g in mass depending on density) were held with a flexible arm affixed to a rigid metal stand. The sample was then inundated with a hand-held propane fueled torch. Experiments were filmed at 120 fps, 720 pixels using a Canon EOS 5D Mark IV digital SLR camera with a 24-105 mm lens. Using this method, two experiments were performed: (1) torch was held on a sample until it was entirely consumed or until the flame returned to the blue propane flame color, and (2) torch was held on a sample until it was on fire and then the torch was removed to see if the material would burn to completion or would quench combustion. Finally, materials that did not burn to completion were burned until the flame returned to the characteristic propane blue color with a mass taken before and after burning to quantify mass loss from the material.

Radiant-heating ignition and combustion testing: Samples of each material (25-50 mm × 25-50 mm × material thickness, 1-5 g in mass depending on density) were held with a thin wire into the middle (height and diameter) of a 457 mm-diameter steel cylinder, 559 mm tall, on 225 mm tall legs with a window (159 mm × 82.6 mm) cut into one side about halfway down the center of the cylinder. The cylinder was used to reduce conductive and convective energy losses. Inside the steel cylinder were three tungsten filament (2,250 °C) radiant heaters (StripIR® heaters, model# 5306B-10-2000-00-00, λ=1,159 nm, power=18.81 W cm ^{2}) spaced radially apart ~120°. The heaters were controlled with two thermocouple (Omega™ part KMQSS-020G-12 K-type, grounded, stainless steel, 0.020-inch diameter) feedbacks where the measurement end of the thermocouple was located as close as possible to the surface of the sample. Schematic of the experimental setup is shown in Figure B1.

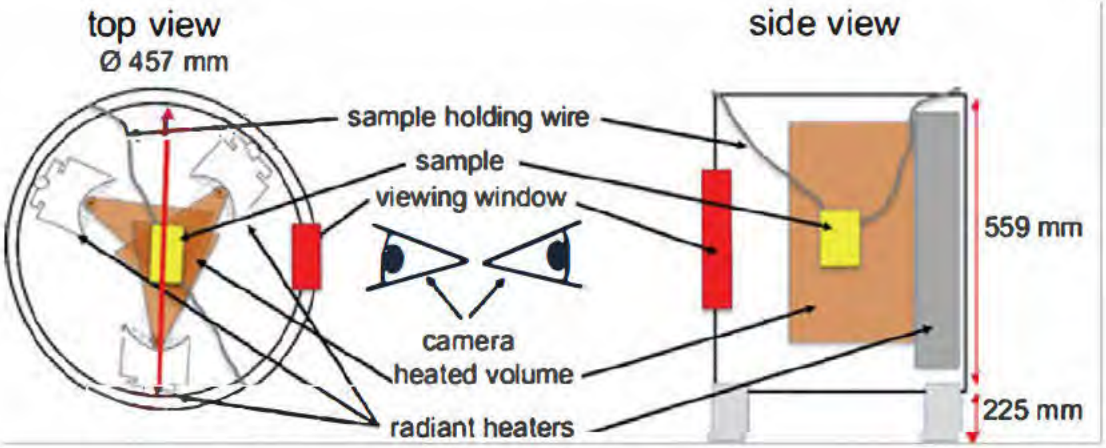


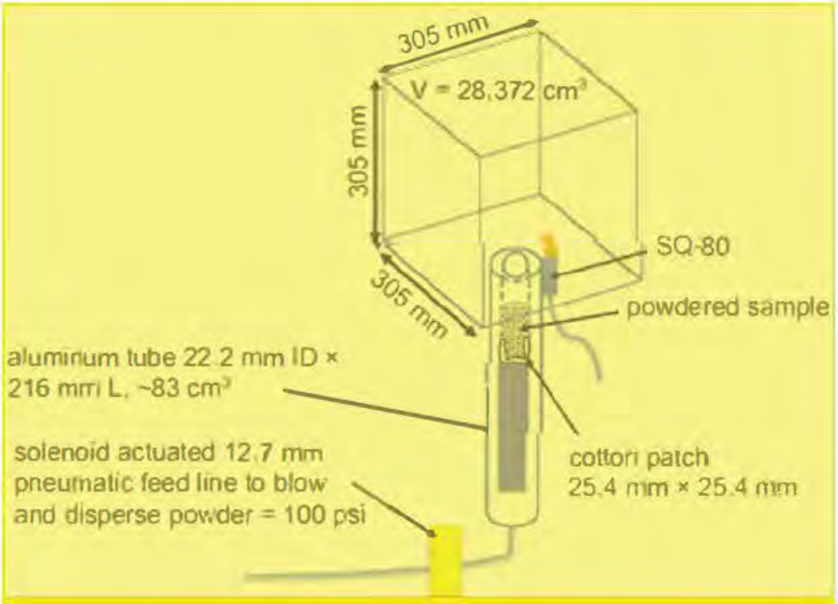
Figure B1: Experimental setup of radiant heating tests. Thermocouples on surface and inside sample are not shown for clarity. Each sample having unique, size, shape, material properties resulted in the thermocouple placement moving to accommodate the sample

Experiments were filmed at 24 fps (4k) using a Canon EOS 5D Mark IV digital SLR camera with a 24-105 mm lens. Two types of experiments were performed: (1) all five materials were heated at ~10 °C min^{-1} meant to mimic the TGA experiments, and (2) the ABS plastic and the FR-3703 foam was also heated as fast as the heaters could heat. Additionally, the flame-retardant foams were also weighed before and after heating to quantify mass loss.

Dust-flammability ignition and combustion (DFIC) testing: Samples were broken down/pulverized from bulk materials in various ways based on material properties. Foams were broken down with a wire wheel or frozen with dry ice and crushed; 3D-printed ABS was frozen with dry ice and broken down with a hammer and sieved or further crushed in a clean/new coffee grinder and sieved. Sieved samples were sieved through a 16 mesh (<1.18 mm) sieve and collected. 3D-printed ABS was also broken down in a cryomill (Retsch CryoMill) in batches of 10 g of roughly broken-down ABS in a 50 mL stainless steel grinding jar with eight stainless steel grinding balls, each Ø 12 mm. The process was five cycles per batch with a precooling stage to a grinding temperature of −180 °C (LN$_2$ coolant), 5 Hz for three minutes, grinding cycle of 30 Hz for three minutes, and an intermediate cooling stage of 5 Hz for one minute. Images of the pre-cryomilled ABS, post-cryomilled ABS, and crushed/ground and sieved ABS are showing in Figure B2.

Figure B2: ABS powder prepared for the dust explosion experiments by different grinding and sieving procedures. Left: Roughly ground 3D-printed ABS in grinding jar with Ø 12 mm stainless steel (before cryomilling). Right: Collected cryomilled 3D-printed ABS (for scale the vial is ~Ø 25 mm).

Dust-flammability experiments were performed in an aluminum framed box (305 mm × 305 mm × 305 mm, 28,372 cm^3) with 6.35 mm thick PMMA shielding on all sides and an aluminum tube (22.2 mm inner diameter × 216 mm long, ~83 cm^3 volume) coming up through the center base attached to a solenoid actuated pressure line with 100 psi gas pressure (house compressed air, filtered and dried) to disperse the powder. The powder was loaded into the tube on top of a 25.4 mm × 25.4 mm square cotton patch and lightly tamped. To the side of the launch tube was affixed a Teledyne RISI SQ-80 igniter with strip of Nashua 357 tape. A schematic of the experimental setup is shown in Figure B3, and an image of one of the experiments prior to testing is also shown in Figure B3. Firing of the SQ-80 igniter was due to delayed varying times from the opening of the air pressure line solenoid valve based on the dispersibility and settling characteristics of the sample. Samples ranged in mass from 1.76 g to 28 g based on density of powdered material and level of tamping.



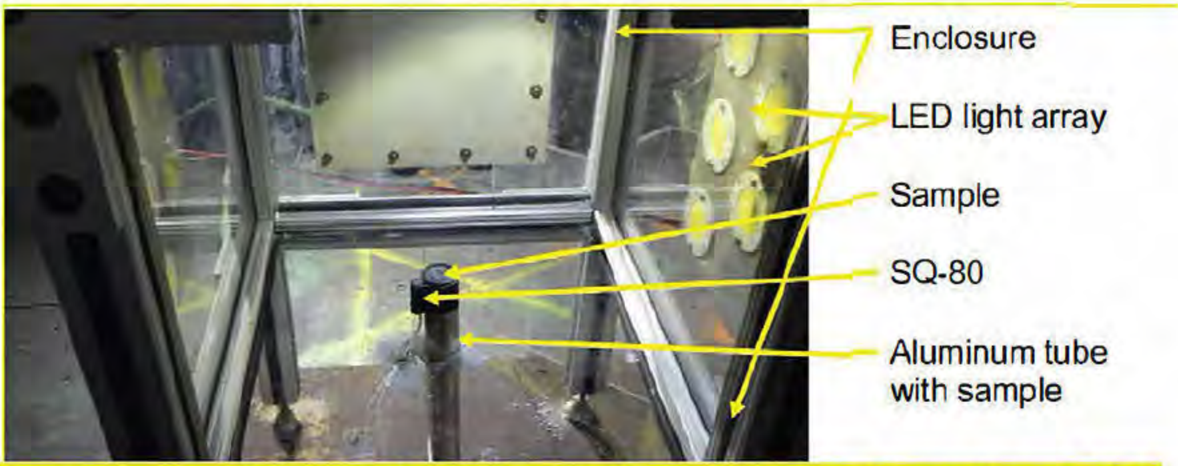


Figure B3: Top: Schematic of experimental setup for dust-flammability tests. Bottom: Image of dust flammability ignition and combustion (DFIC) experimental setup for cryo-milled 3D-printed ABS plastic.

Experiments were tracked by high-speed imaging (Phantom TMX-7510) front-lit with continuous lighting from an LED array. Experiments were imaged at 4,000 frames s ^{1} (250 µs per frame).

Detonation shock pulverization of 3D-printed ABS plastic. Detonation setup of the control experiment: initiated with a Teledyne RISI RP-1 detonator (b) (7)(F) (b) (7)(F) (b) (7)(F) Detonation setup of the pulverization experiment: initiated with a Teledyne RISI RP-1 detonator, LX-10 booster, (b) (7)(F) (b) (7)(F) encased in 3D-printed ABS (Stratasys ABS-M30) Ø 76.2 mm × 187.3 mm with Ø 51.05 mm × 172.2 mm bore. Schematics are shown in Figure B4 along with the actual images take of the charges prior to detonation. (b) (7)(F) (b) (7) (F) (b) (7)(F) All explosive interfaces were bonded with cyanoacrylate adhesive (Eastman (Permabond™) 910) and allowed to fully cure. The RP-1 detonator was threaded into a 3D-printed PMMA adaptor that was also bonded to the end of the LX-10 booster with cyanoacrylate adhesive. The bonding served to hold the parts fixed to one another without additional encasing or tamping mass and to minimize airgaps at interfaces.

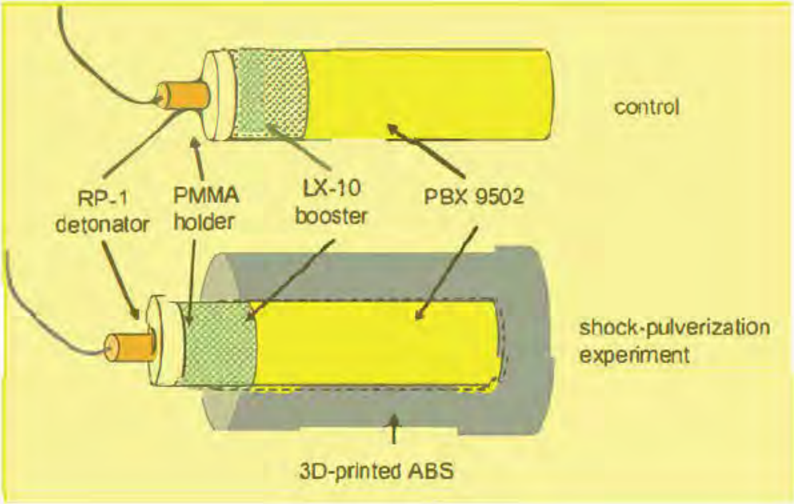


Figure B4: Top: Experimental setup for detonation shock-pulverization of ABS experiment and the control experiment. Bottom: Images of actual setups for control and shock pulverization experiment.

Experiments were tracked by high-speed imaging (Phantom v2511), front-lit with electrical flash lamps (giga-lumen flashlamp capacitor bank with xenon flashlamps (Genesis Lamp, GN-34), which provides a 960 µs continuous light pulse with ~100 µs rise and fall time, 860 µs of usable light). Imaging speed was 99,000 fps (10.09 µs per frame).

Shock and thermal treatment of 3D-printed ABS, Icepick: Icepick is intended to create specific pressure, temperature for a specific duration to see if the 3D-printed ABS plastic will pulverize to a sufficiently small size creating the conditions for a potential dust explosion. If the test results in a dust cloud of ABS but not in a fireball, the result is still an indication that the pressure and temperature conditions were appropriate to generate such a cloud of ABS. The experimental scale, confinement, material selection, and configuration were informed by hydrodynamic modeling to ensure the 3D-printed ABS plastic was exposed to the appropriate input pressure.

The various components and their geometries are shown below in Figure B5. Detonation was initiated with a Teledyne RISI RP-1 detonator into a Ø 30 mm (b) (7)(F) [redacted] potted (APC 2.5) into (b) (7)(F) [redacted] (b) (7)(F) [redacted] The charge- and pressure-attenuating parts were encased in a 3.0 mm thick stainless steel cylinder, and all interfaces were coated with a thin film of silicone-based bubble-eating grease to minimize air voids at interfaces. Th(b) (7)(F) [redacted] and entire charge assembly were individually under a pre-load supplied by two pre-compressed springs to ensure no gaps would open and that the detonator would stay in intimate contact with the booster during cooling to the prescribed -54 °C. Time of arrival of the shock wave in the various materials was tracked with piezoelectric pins located on the external stainless-steel case at each material interface and at the aluminum end cap. A diagram of piezo pin locations relative to components is shown in Figure B6. The pin locations were determined considering the contraction of each component from room temperature to the -54 °C of the experiment. Highspeed imaging in two orientations using phantom v2511 camera (camera 1, 70,000 frames s^{-1}), and phantom v2511 camera, (camera 2, 70,000 frames s^{-1}) as illustrated in Figure B7. Camera 1 is imaging perpendicular to the direction of detonation being front lighted with the giga-lumen lighting system in front of a grip screen to observe any projected plastic or materials from Icepick. Camera 2 is imaging 45° into the tank looking at the end of the Icepick assembly as deep into the fragment catcher as possible, also front lighted with the giga-lumen lighting system. A small, real-time video camera was

also placed in the 10 kg spherical tank to observe late time combustion. Lighting was provided by a giga-lumen flash lighting system for a total of 860 µs.

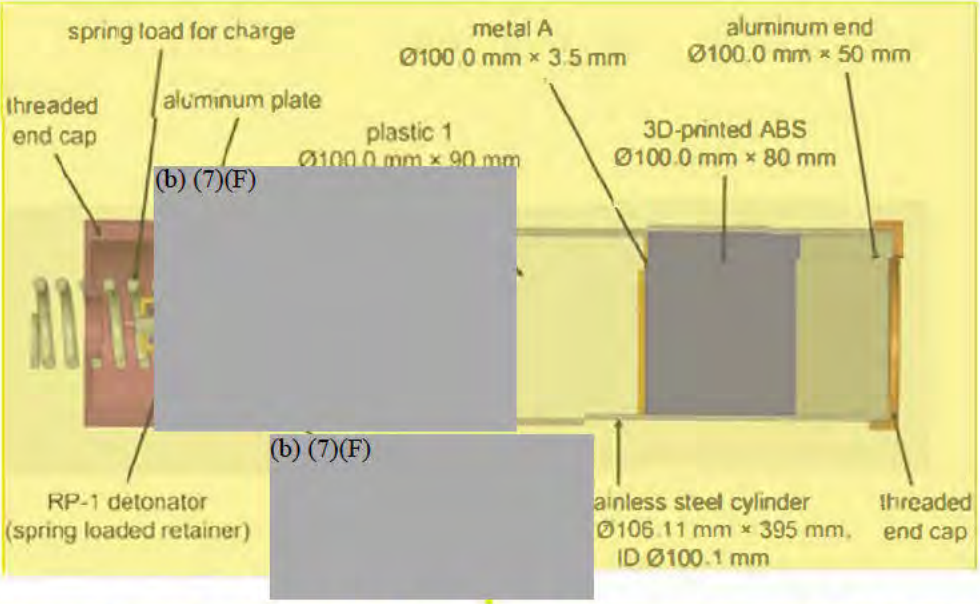


Figure B5: Experimental configuration for detonation shock-pulverization of ABS inundated with a specific input pressure at a specific temperature.

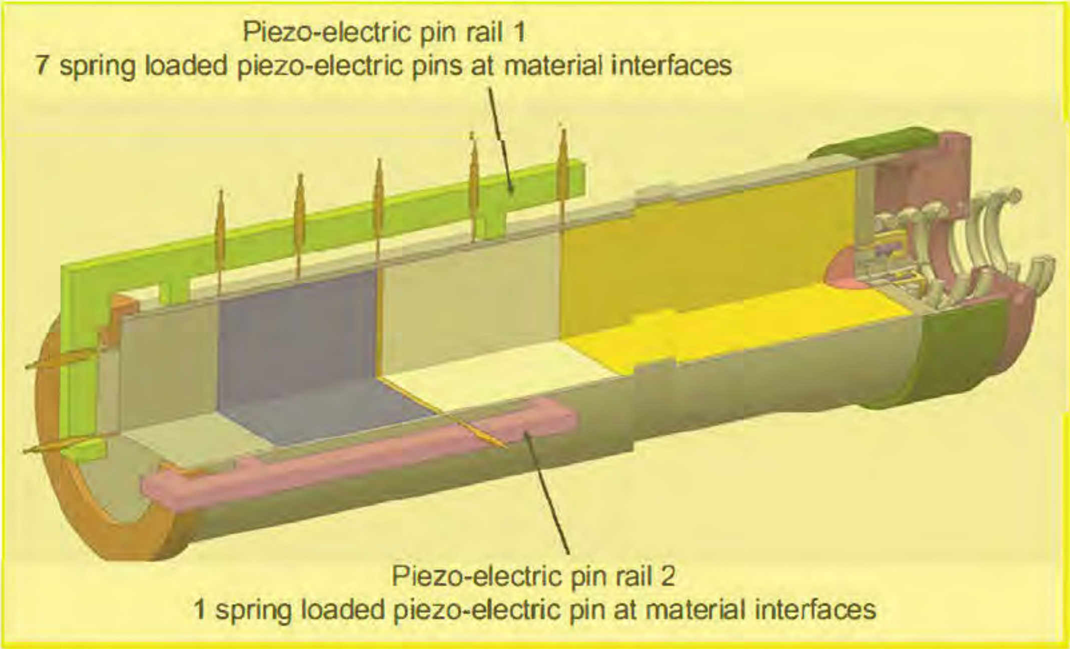


Figure B6: Experimental configuration for detonation shock-pulverization of ABS inundated with a specific input pressure at a specific temperature.

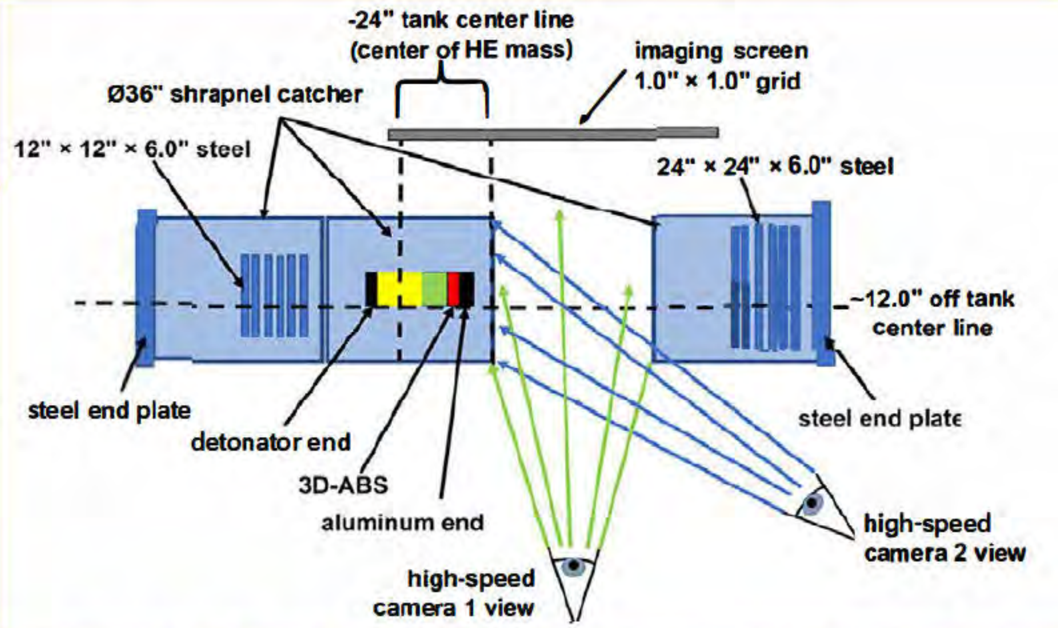


Figure B7: Experimental configuration for detonation shock-pulverization of ABS inundated with a specific input pressure at a specific temperature.

Results

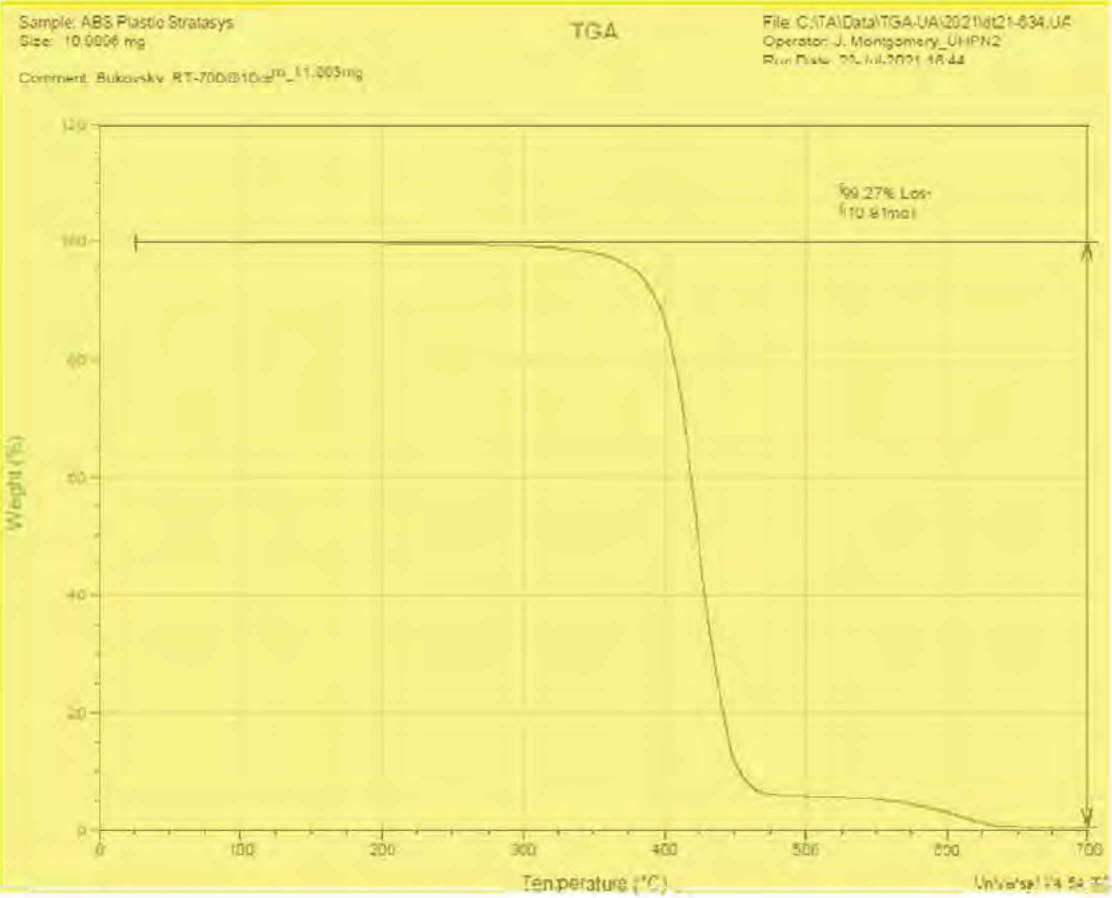
Thermal-gravimetric-analysis (TGA): The TGA experiments were very controlled radiant heating experiments in an inert gas environment to determine (1) the total mass each material evolves up to 700 °C, (2) the fastest mass loss, and (3) at what temperature the fastest mass loss occurs. The 3D-printed ABS, blue foam (polystyrene), and yellow trashcan (low-density polyethylene, LDPE) all exhibited decomposition to +99% mass loss up to 700 °C. The LAST-A-FOAM® FR-3703 (flame-retardant polyurethane foam, 3 lb/ft^{3}) had an average mass loss of 76.3%, and LAST-A-FOAM® FR-4515 (flame-retardant polyurethane foam, 15 lb/ft^{3}) had an average mass loss of 62.7% up to 700 °C. To quantify and compare the TGA data, the thermograms were analyzed to determine (1) temperature at 25% mass lost, (2) temperature at 50% mass lost, (3) temperature at 75% mass lost, (4) total mass loss at 700 °C, and (5) max mass loss rate and temperature at which that rate occurred. The data for each sample material, in duplicate, is shown in Table B1.

Table B1: TGA data for each sample. Temperature at mass loss of 25%, 50%, 75% and total mass lost at 700 °C.

Sample	Temp @25% mass loss (°C)	Temp @50% mass loss (°C)	Temp @75% mass loss (°C)	Total mass lost (%)	Max mass loss rate (mg min ^{1}, °C)
3D-ABS 1	410.7	423.8	437.7	99.3	23.4, 423.5
3D-ABS 2	410.8	423.9	437.7	99.2	21.3, 423.2
Blue foam 1	394.1	408.6	419.3	100.0	25.1, 414.9
Blue foam 2	396.0	409.1	418.6	100.0	27.8 412.4
FR-3703 1	305.7	328.7	663.5	75.7	19.5, 311.9
FR-3703 2	305.7	326.3	548.2	76.9	20.9, 311.8
FR-4515 1	323.9	421.3	—	62.3	8.40, 328.2
FR-4515 2	323.0	407.3	—	63.1	8.39, 327.5
Yellow trashcan 1	449.1	463.2	473.0	99.7	26.3, 471.6
Yellow trashcan 2	449.3	463.6	473.4	99.6	26.5, 472.5

The max mass loss rate quantifies the rate of mass loss; however, it is calculated by taking the derivative of mass with respect to temperature and finds the peak of the derivative curve. The resulting derivative curve can have some precipitous and sometimes non-physical behavior. Therefore, to get a qualitative understanding of the mass loss, it was also analyzed by comparison of temperatures when going from 25%, to 50% and 75% mass loss. If the mass loss rate is slow, those three temperatures will have a broad range, but if those three temperatures have a narrow range, the mass loss rate is fast.

Based on the data listed in Table B1, 3D-printed ABS, the blue foam (polystyrene), and yellow trashcan (LDPE) will decompose with almost no residue when heated to temperatures of 700 °C in the absence of oxygen gas ($O_2(g)$). All three materials rapidly decompose below 500 °C. With all three materials being comprised of organic-based (CHNO) polymers, there is a high likelihood the evolved mass has flammable CHNO fragments and would readily combust at these temperatures in the presence of $O_2(g)$. The FR-3703 and FR-4515 did exhibit lower total mass loss and a reduced mass loss rate during the TGA experiments. Since both FR foams are flame retardant, they did not evolve as much gas as the ABS, blue foam or LDPE, but between the FR foams there were quantifiable differences. The lower density FR-3703 exhibited an average of 13.6% more mass lost then the FR-4515 foam, and the FR-3703 reached 25% mass loss ~18 °C earlier than the FR-4515. Finally, the FR-3703 exhibited max mass loss rates that were over double the max mass loss rate of the FR-4515. Thermograms of 3D-printed ABS, FR-3703 and yellow trash can are shown in Figure B8 as examples.



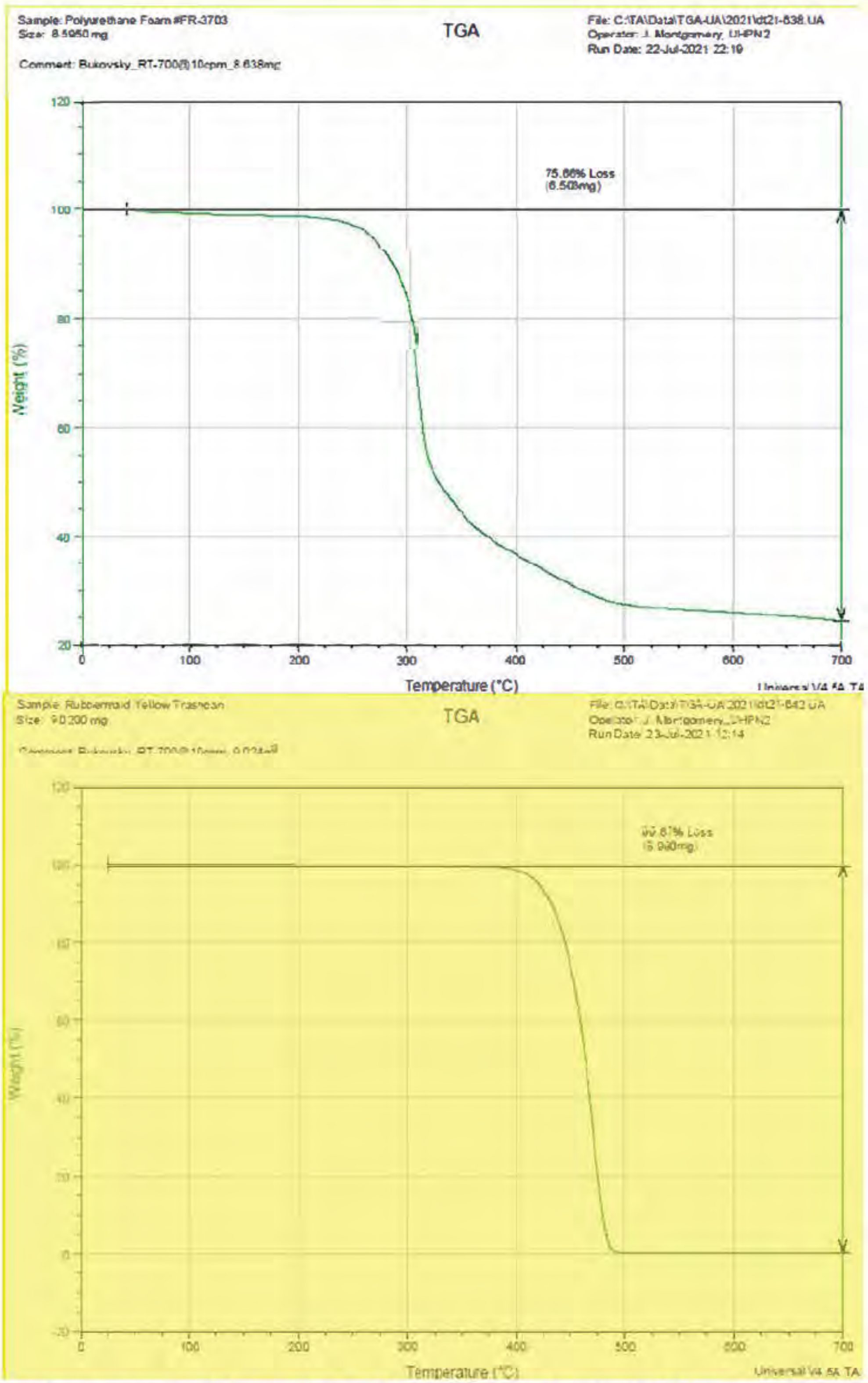


Figure B8: Example thermogravimetric analysis of three different materials from room temperature up to 700 °C at a heating rate of 10 °C min^{-1}. Top: 3D-printed ABS. Middle: polyurethane flame retardant foam FR-3703. Bottom: High density polyethylene (HDPE) yellow trash can. Note that in all three cases greater than 75% mass loss over this temperature range and that the FR foam has started to significantly lose mass at 300 °C.

Flame-heating ignition and combustion testing: The direct flame heating experiments were intended to understand how each material would behave if exposed to a low temperature flame. For the continuous burning experiments, the torch was held on a sample until full consumption or until the flame reverted to propane-only color and intensity. The color and intensity change of the propane flame from foam indicates that all materials when heated with a flame evolved mass (likely gaseous) that was also flammable and continued to burn.

In the continuous burning experiments for 3D-printed ABS, blue foam, yellow trashcan, and ABS-drain (a piece of black ABS drainpipe used as a control for ABS) all burned to completion, which aligns with the TGA results for those materials. Attempts to burn the FR foams to completion failed. After exposed to the torch flame long enough, the flame color and intensity returned to the original propane flame and the remaining charred material began to just heat and glow a dull red-orange color. Based on initial and final masses, the FR-3703 foam exhibited 84% mass loss and the FR-4515 foam exhibited 56% mass loss. These mass loss values were +7.7% for the FR-3703 foam and -6.7% for the FR-4515 foam compared to the TGA results.

The second type of flame heating experiment performed was to expose the sample to the flame until it was ignited and then remove the flame and see if the material continues to burn to completion or self-extinguishes. In these experiments the five materials yielded two basic results: the materials that continued to burn to completion and the ones that self-extinguished. The 3D-printed ABS, control ABS, yellow trashcan, and blue foam all continued to burn until completion after sufficiently burning once the torch was removed. An example of 3D-printed ABS is shown in Figure B7.

Figure B7: 3D-printed ABS in flame test. Left: prior to exposing the sample to direct flame. Middle: holding flame on sample (note that change in flame color and intensity indicates combustion other than propane). Right: 3D-printed ABS burning to completion after the flame was removed.

The two different densities of flame-retardant foam exhibited similar results, once the direct flame was removed the remaining flame emanating from the sample quickly diminished and then extinguished. An example of the FR-3703 foam is shown in Figure B10. The FR-3703 foam ignited easier and stayed burning longer than the FR-4515 foam.

Figure B10: Flame exposure test on FR-3703 where the flame is removed after ignition. Upper Left: torch igniting the FR-3703 foam (note the change in flame color and intensity indicating combustion other than propane). Upper right: Flame removed, sample continues to burn, but quickly diminishes in surface burning. Lower Left: Flame quickly extinguishes. Lower right: From the time the torch was removed to the time no flame was visible ranged from ~15-25 seconds.

All FR foams tested by removing the propane flame extinguished in a range of ~15-25 seconds.

Radiant-heating ignition and combustion testing: The radiant heating experiments were designed to determine if the materials would (1) spontaneously combust and/or (2) evolve gases or other mass that could be flammable upon exposure to intense radiant heating. None of the samples spontaneously combusted when heated at 10 °C min ^{1} or when heated as fast as possible. All samples did off-gas significant amounts of vaporous material. Again, the five samples were broken down into two basic results where the 3D-printed ABS, drainpipe-ABS, blue foam, and yellow trashcan all off-gassed and melted fast enough such that most of the material dripped out of the focus of the radiant heater and was not completely charred/decomposed. Examples of 3D-printed ABS and yellow trashcan, and blue foam are shown in Figure B11.

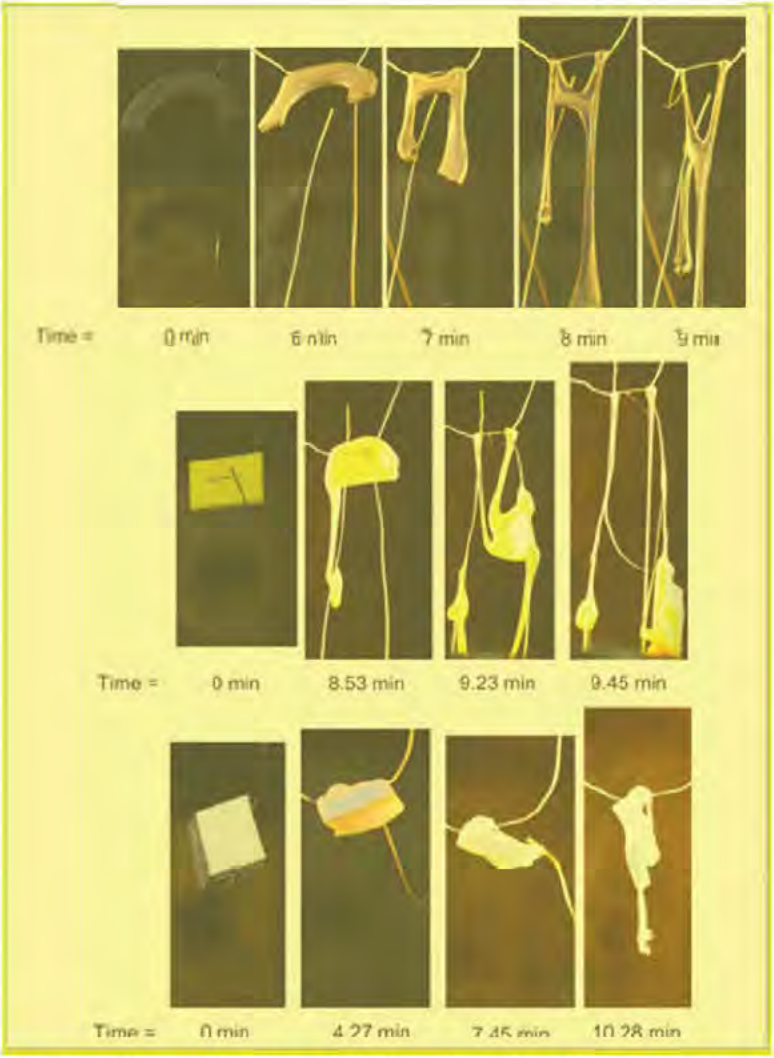


Figure B11: Images at various times of radiant heating 3D-printed ABS, yellow trashcan, and blue foam. Top: Radiant heating test on 3D-printed ABS. Middle: Radiant heating test on yellow trashcan. Bottom: Radiant heating test on blue foam. Samples were heated at 10 °C min^{-1}.

Both densities of flame retardant foam did not melt off the wire regardless of the rate of radiant heat exposure; however, they did lose significant mass through gas evolution resulting in visibly charred material on the surface. Example results of both FR foams are shown in Figure B12.

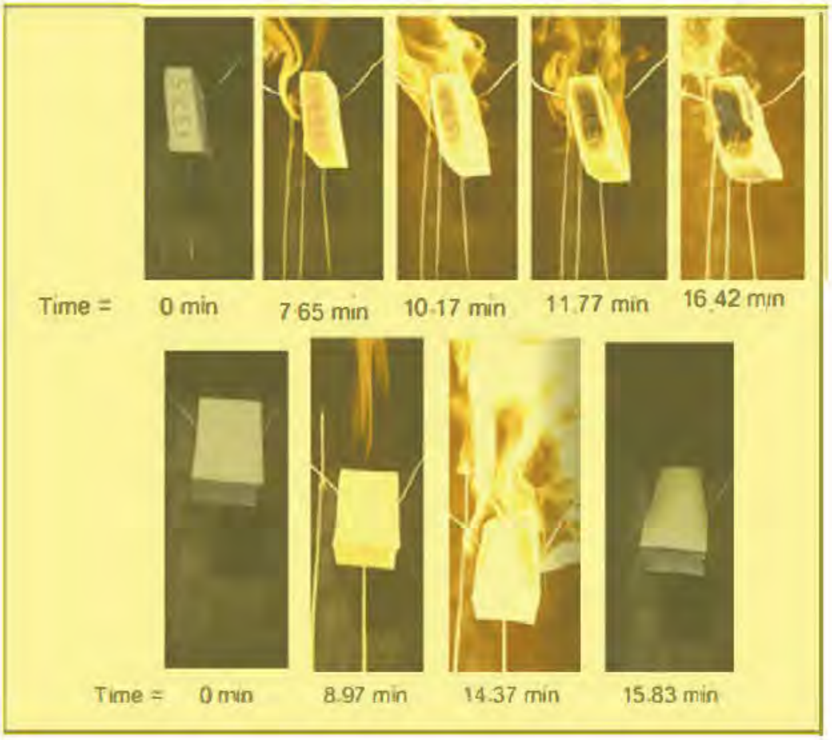


Figure B12: Images at various times of radiant heating flame retardant foam FR-3703 and FR-4515. Top: Radiant heating test on FR-3703 foam. Bottom: Radiant heating test FR-4515 foam. Samples were heated at 10 °C $\mathrm{min^{-1}}$.

Since the flame retardant foams did not melt off and continued to stay in the heated zone of the test chamber, total mass loss experiments were also performed. The FR-3703 foam lost 58% of its mass, while the FR-4515 foam lost 84% of its mass. It should be noted in both mass loss experiments the experiment was stopped before the samples stopped evolving gases, but these mass losses exemplify the potential for significant loss of likely flammable mass due to radiant heating only.

The 3D-printed ABS and FR-3703 foam were also heated as quickly as possible in the radiant heating experiments to see if spontaneous combustion would occur. The 3D-printed ABS part was larger in the hopes that it would not melt off the sample holder and move out of the radiant heated zone as quickly. It only stayed in the radiant heated zone for approximately 168 seconds. It did melt and evolve gases similar to the slower heating rate experiment with 3D-printed ABS. The FR-3703 foam evolved a lot of gas very quickly and exhibited significant surface charring. The sample was in the radiant heat (at full power) for 99 seconds. Progression of the experiment is shown in Figure B13. As the sample rapidly heated (from 10-30 seconds), solid particles were seen emanating from the surface before any significant gas evolution, which was not observed in the slower heating rate experiments. At 49 seconds, the sample began to evolve gases very quickly. The experiment was halted at 99 seconds because the radiant heaters were also visibly smoking.

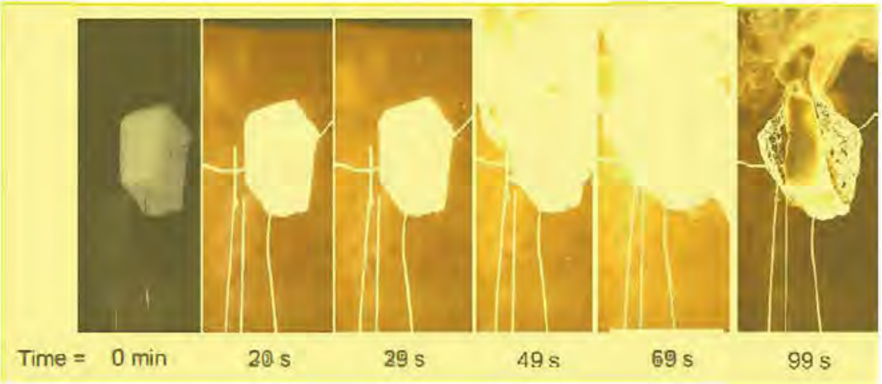


Figure B11: Images at various times of radiant heating flame retardant foam FR-3703. Solid particulate is seen ejecting from the sample in early time and then significant quantities of gas evolve until the heat is stopped at 99 seconds.

Finally, there was a dramatic increase in internal temperature compared to the surface temperature of the flame-retardant foam samples, an interesting result seen only in these samples partly because they were the only samples to remain intact with the internal thermocouple inside the sample throughout the heating experiment. Internal temperature vs. time curves for FR-3703 and FR-4515 both heated at 10 °C min^{-1} are shown in Figure B12 compared to the external air temperature thermocouple, the target temperature, and the heater output. In both experiments, there appears to be an induction time required before the internal temperature runs away from the external temperature. It is presently unknown the cause of the induction period or why it appears to be so different for both flame retardant foams.

A potential hypothesis to explain this observed result is the following: foams are "generally" intended to slow the transmission of conductive or convective heat by having a low thermal conductivity and low heat capacity. However, the radiant heat can penetrate the foam due to the wavelength of the radiant heat and in doing so transitions from radiant heat to heated mass inside the foam. The foam, effective at resisting conductive and convective heat flow, essentially traps the heat inside, and therefore, the continual incoming radiant heat can continue to heat the inside of the foam samples. This is not observed on the outside as the radiant heat heating the foam surface was being dissipated by air moving over the surface convectively cooling the surface.

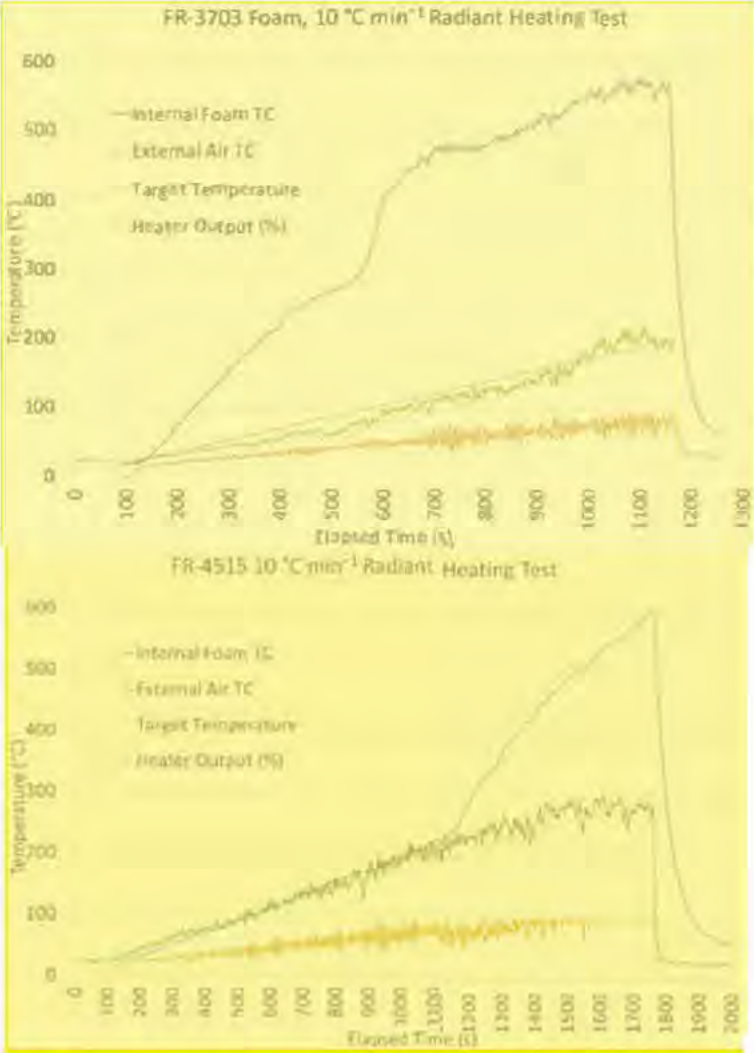


Figure B14: Temperature vs. time graphs for radiant heating experiments for FR-3703 and FR-4515 foams. Top: FR-3703 demonstrating the significant increase in internal temperature of the foam during the experiment. Bottom: FR-4515 also demonstrating the significant increase in internal temperature of the foam during the experiment.

Presuming the radiant heating hypothesis of the flame retardant foams is accurate and using the TGA data for the flame retardant foams, it would appear that significant heating of the foam from radiant heating could internally heat the foam liberating a significant mass of material that was demonstrated to be flammable in the flame experiments with the flame retardant foam.

Dust-flammability ignition and combustion testing: The dust-flammability ignition and combustion (DFIC) was performed to see if any of the sample materials were more probable to exhibit a dust-air explosion. This kind of flammability is sensitive to several variables such as particle size, morphology, surface area, particle distribution and density in air, combustion rate of each particle, heat evolved per unit mass during combustion, and more. These variables can require optimization of any or all of the aforementioned variables to achieve combustion and propagation of dispersed powders. Due to the high specificity of these kinds of reactions, any self-propagation observed under these simple, non-optimized conditions indicate that a dust reaction or explosion are plausible. Furthermore, self-propagation of the reaction beyond the time it takes to consume the squib (60-70 ms) was taken as an indication that a dust reaction or explosion are plausible.

Only the 3D-printed ABS (two grinding methods), blue foam, and two flame retardant foams were tested in the DFIC test. The yellow trashcan plastic was not tested since no credible mechanism could be conceived where the yellow trashcans, or other sources of LDPE in the chamber, would have been pulverized to a dust and dispersed.

The coarse and fine-powdered 3D-printed ABS exhibited some level of self-propagation with the finer particles (as expected) exhibiting significantly more reaction. The burn time of the fine 3D-printed ABS was ~255 ms and nearly filled the entire test chamber at one point, while the course exhibited a burn time of ~85 ms. Images of the high-speed imaging stills for the coarse and finely ground 3D-printed ABS are shown in Figure B15.

Coarse powdered 3D-ABS dust-flammability test

Fine powdered 3D-ABS dust-flammability test

Figure B15: Images taken from the DFIC experiments on different particle sizes of 3D-printed ABS. The initial image in each image set was artificially brightened to illustrate the powder cloud being dispersed. Top five frames: Coarse 3D-printed ABS (hand-ground/coffee grinder) exhibiting some self-propagation after the squib was consumed as indicated by the dull orange flame in the upper right-most and lower two frames. Bottom six frames: Fine 3D-printed ABS (cryomilled) exhibited

longer self-propagation after the squib was consumed. The flames spread through the powder so well it swept down the test-chamber walls and filled the entire volume for a short duration.

The blue foam was a coarser particle size and did not exhibit much, if any, self-propagation after the squib was consumed, as shown in Figure B16. Although it appears some combustion of the blue foam may have occurred, the blue foam did not ignite enough to sustain reaction beyond the burning of the squib.

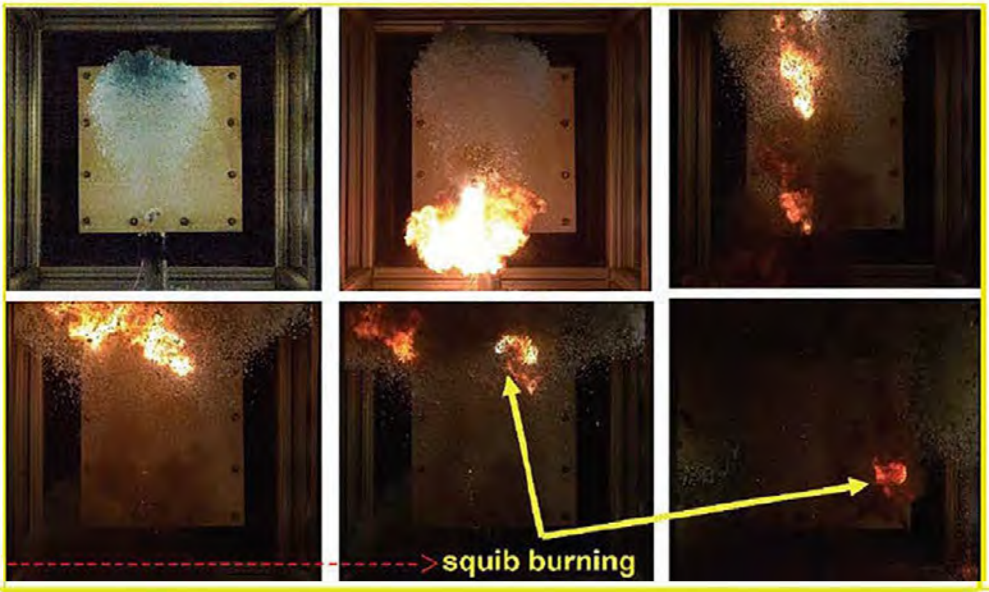


Figure B16: Images taken from the DFIC experiments on blue foam. The initial image (upper left) was artificially brightened to illustrate the powder cloud being dispersed. Very little, if any, reaction occurred, and no reaction propagation was observed longer than the squib consumption (60-70 ms).

Results from the DFIC of the FR-3703 and FR-4515 foams are shown in Figures B17 and B18 respectively. The FR-3703 foam did show some significant burning after the consumption of the squib, although it did not propagate to fill the test chamber like the fine 3D-printed ABS. The FR-4515 exhibited even less reaction propagation after the squib was consumed. Based on these DFIC experiments, the powdered flame retardant foams likely could have been better optimized to result in a longer reaction propagation, but that would increase the specificity of the conditions for a dust explosion.

Figure B17: Images taken from the DFIC experiments on FR-3703 foam. The initial two images (upper left images) were artificially brightened to illustrate the powder cloud being dispersed. Some self-propagating reaction was observed. The squib was fully consumed shortly after the upper right-most image, the remaining bottom four images are all thought to be self-propagating combustion reaction.

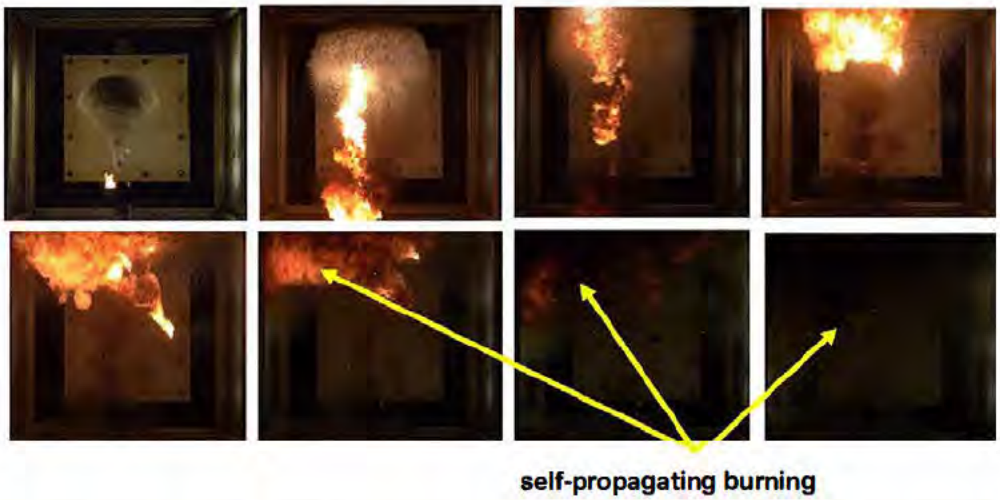


Figure B18: Images taken from the DFIC experiments on FR-4515 foam. The initial image (upper left) was artificially brightened to illustrate the powder cloud being dispersed. Some self-propagating reaction was observed. The squib was fully consumed shortly after the lower left-most image, the remaining bottom three images are all thought to be self-propagating combustion reaction.

Detonation shock pulverization of 3D-printed ABS plastic: The shock pulverization of 3D-printed ABS resulted in a positive reaction of ABS as evidenced by the increase in post-shot tank pressure. The difference in tank pressure was also a quantifiable way to estimate the extent of 3D-printed ABS combustion that occurred. The experiment of the bare LX-10 and PBX-9502 (776.6 g combined HE mass) resulted in a tank pressure=Δ6.2 psig and a tank temperature=Δ33.1 °C. Still frames from the high-speed video (20 µs apart) are shown in Figure B19.

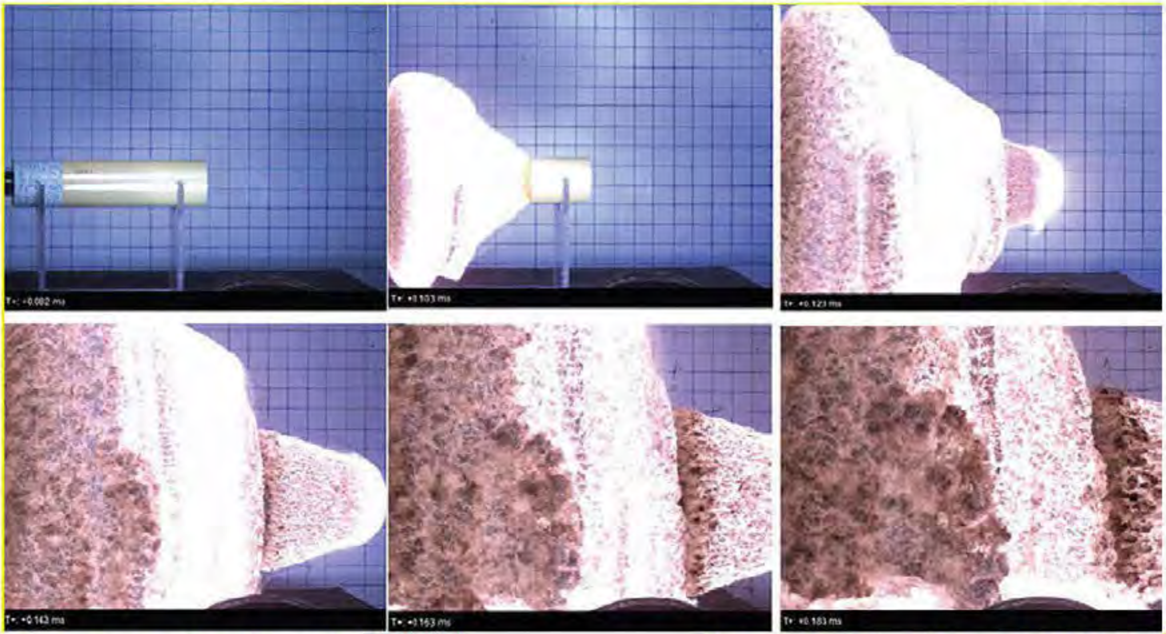


Figure B19: Images taken from the (b) (7)(F) detonation experiment in HEAF 10 kg spherical tank. Charge was front lit pulse totaling 890 µs. Images are 20 µs spaced in time.

The 3D-printed ABS (484.9 g ABS) encased explosive (b) (7)(F) 776.6 g combined HE mass) resulted tank pressure=Δ14.85 psig and tank temperature=Δ54.6 °C. Still frames from the high-speed video (20 µs apart) are shown in Figure B20. Notice the highly fragmented 3D-printed ABS as detonation proceeds along the charge axis from left to right.

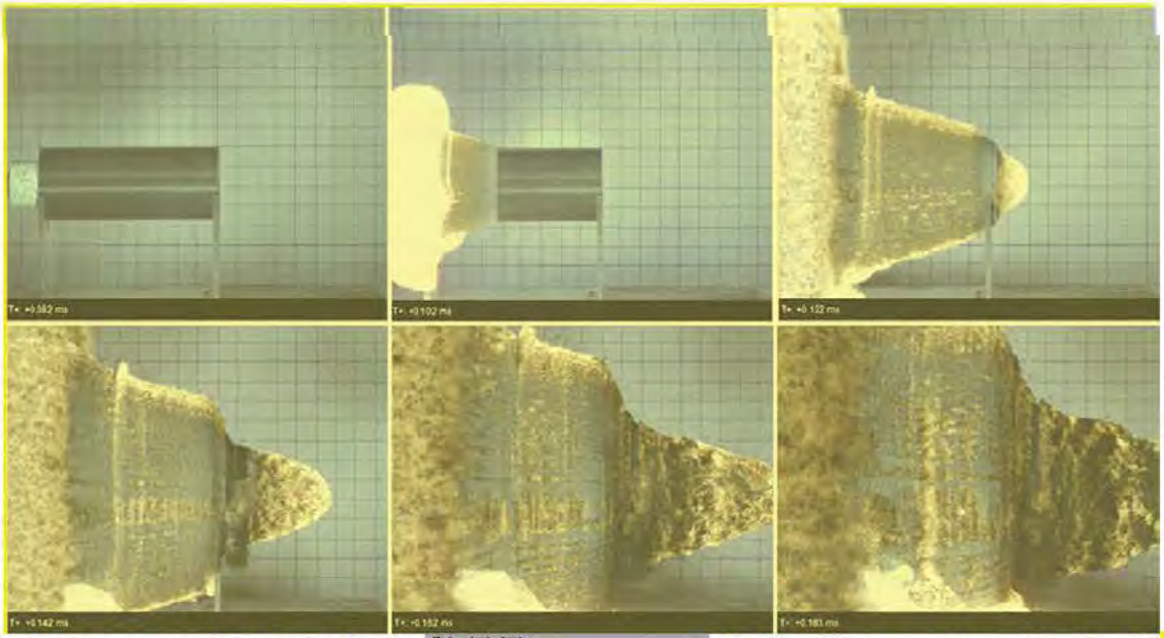


Figure B20: Images taken from the ba(b) (7)(F) detonation experiment in HEAF 10 kg spherical tank. Charge was front lighted with high intensity light pulse totaling 890 µs. Images are 20 µs spaced in time.

Estimations of the amount of 3D-printed ABS consumed can be determined by calculations of the pressure changes at constant volume assuming the volume of the tank does not change, which is reasonable, and assuming that the detonation product gases are not a significant increase to the total moles of gas in the tank. The tank temperature is not wholly reliable as there is a considerable time lag for the tank to fully equilibrate temperature without active mixing, allowing for considerable heat losses due to conduction into the steel tank wall. Based on the tank volume (62.21 m^3), the mass of gas in the tank at 20 °C and 14.7 psi (1.204 kg m^{-3}) is ~74.9 kg. The total explosive and ABS mass in the encased experiment is 1.26 kg, which is only 1.7% of the tank gas mass and assumes all the solid mass is converted to moles of gas. Therefore, assuming the moles of gas are constant is reasonable.

To estimate the amount of 3D-printed ABS consumed, in the 3D-printed ABS encased experiment the combustion of the detonation products of the bare experiment must be considered. First, the total energy of detonation was found using heat of detonation estimates from Cheetah 8.0 for LX-10 (5.65 kJ g^{-1}) and PBX 9502 (3.99 kJ g ^{1}). Using the masses above, this translates to detonation energy of 3,419 kJ. Based on the volume of the 10 kg spherical tank at γ=1.3, and the Δ pressure for the bare charge, the total internal energy change ΔU=8,864 kJ. Therefore, approximately 5,445 kJ of energy was also released from post-detonation combustion of the explosives from the bare charge experiment.

Following the same logic for the 3D-printed ABS encased, the detonation energy from the charge is still 3,419 kJ (almost identical charge masses). The total internal energy change ΔU=21,231 kJ equates to a surplus of energy of 17,813 kJ greater than the detonation energy from the (b) (7)(F) alone. Assuming the combustion of the post-detonation products is the same (5,445 kJ), the remaining energy (12,367 kJ) must come from combustion of the 3D-printed ABS or some combination of 3D-printed ABS combustion and post-detonation product combustion/reaction. Using a Cheetah 8.0 estimated value for the combustion of ABS (41.48 kJ g^{-1}) results in an estimate of 298.1 g of 3D-printed ABS were fully combusted during this experiment, which equates to ~61.5% of the original mass.

It should be noted that this result is somewhat surprising given the experimental configuration. While the detonation was expanding into the 3D-printed ABS encasing, both shocking and heating the 3D-printed ABS, there was no other confinement or other means driving the temperature of the 3D-printed ABS to significantly increase. This indicates that the moderate flame temperatures c(b) (7)(F) (Cheetah 8.0 predicts CJ temperature=2,272 °C) for short durations, are sufficient to initiate significant combustion/reaction of 3D-printed ABS. Like most cased explosives the 3D-printed ABS could have simply fractured and been projected outward with minimal reaction or charring, a result that happens consistently with machined PMMA encased explosives. Fragmentation of the 3D-printed ABS did certainly happen as evidenced by the high-speed video and image stills (Figure B18), but the dispersed ABS must have reacted rapidly to account for the observed pressure rise in the 10 kg spherical tank.

Shock and thermal treatment of 3D-printed ABS, Icepick: The detonation-shocked TPX (polymethylpentene) and ABS plastics confined in a steel tube also yielded a positive result indicating significant reaction of these two plastics when exposed to these rapid shock and heating conditions. The charge was slightly modified from the original design to aid in assembly and optimize experimental results. The first change was the addition of notch to the aluminum end plate (detonator side), a hole through the case wall, and a rigid steel pin to ensure that aluminum plate did not rotate during assembly by threading on the end cap and sleeve connector. The notch in the plate was open on the spring side, allowing the aluminum plate freedom to slide further into the case upon cooling-induced contraction. Friction from the spring on the aluminum end plate as the end cap and sleeve were threaded onto the case was further reduced by the addition of another thin aluminum plate and a sheet of Teflon® to act as a plate bearing. Next, an aluminum shield exterior of the case was added approximately at the end of the explosive charge to slow the fireball from obscuring the camera view towards the end of the charge. Finally, to verify the ABS reached the desired temperature, a Ø 1.60 mm hole was drilled to the center of the 3D

printed ABS for a thermocouple. The hole through the case wall was a larger diameter to ensure the 3D-printed ABS was not inhibited from moving upon contraction-induced cooling. The thermocouple was sealed into the 3D-printed ABS with Dow Corning® 732 RTV silicone sealant to ensure erroneous temperatures were not observed due to LN2 getting into the hole with the thermocouple. A picture of the final assembled charge is shown in Figure B21.

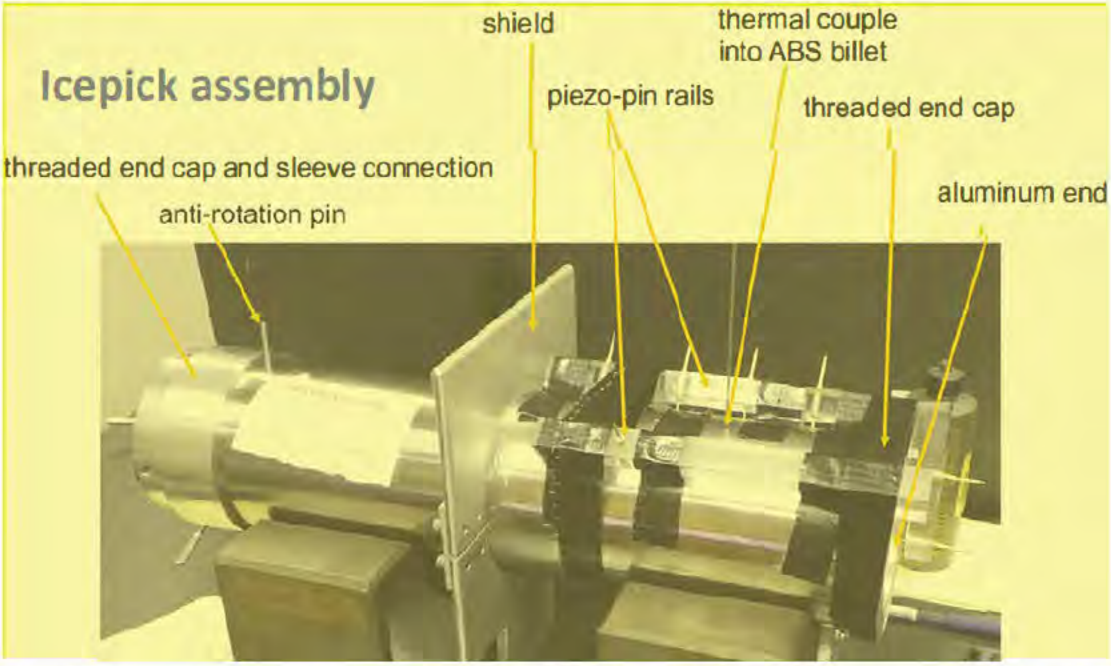


Figure B21. Icepick assembled in shot building room. Some visible components annotated to orient internal components.

The experiment was set up in thick steel cylindrical fragment catchers as described previously in the experimental section and shown schematically in Figure B7. Both ends of the charge set up in the fragment catchers are shown in Figure B22.

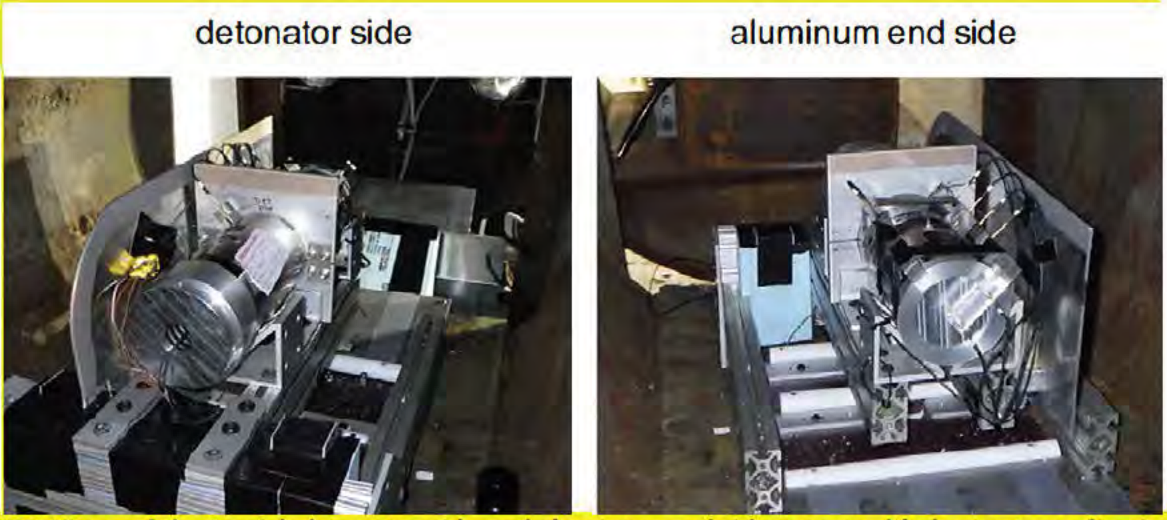


Figure B22. Views of the Icepick detonator side and aluminum end side as assembled prior to cooling in the fragment catcher.

To ensure the experiment cooled to the desired -54 °C, the entire shot assembly was encased in an insulating box comprised of rigid polystyrene insulating foam. The insulating foam box with the LN2 inlet tube is shown in Figure B23. This box was in place during cooling with LN2, but it was removed prior to the experiment to minimize the thermal load in the 10 kg spherical tank. Because of the time it would take to remove the box, close the tank, and be prepared to execute the experiment, the charge assembly was cooled to -64 °C based on the temperature in the center of the 3D-printed ABS. The shot was fired when the 3D-printed ABS thermocouple registered -53 °C.

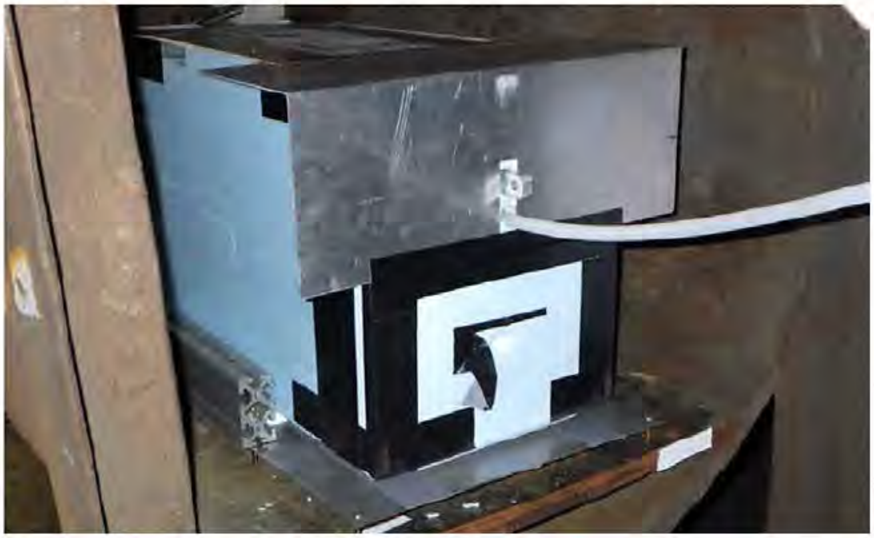
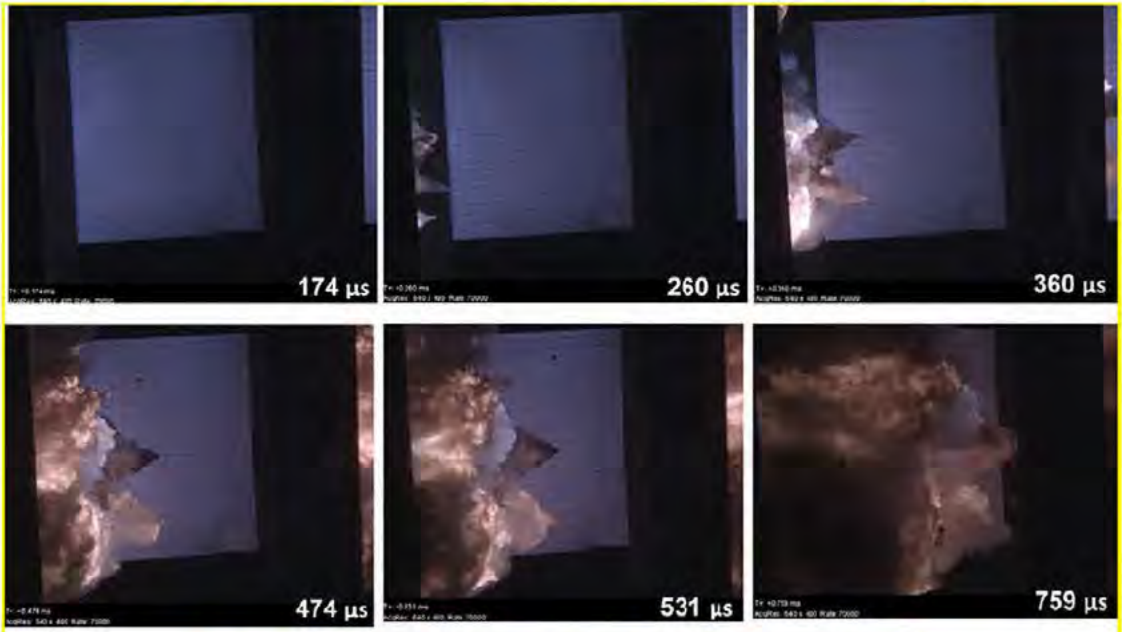


Figure B23. Ridged polystyrene foam box used to insulate the Icepick assembly while being cooled to -54 °C. The center of the 3D-printed ABS billet was monitored with a thermocouple. The entire charge was cooled to -64 °C, then the insulation was removed, and the tank closed. The shot occurred when the 3D-printed ABS thermocouple read -53 °C.

Both high speed cameras and the real-time camera collected date. High-speed camera 1 (side view) observed the initial detonation products moving across the grid-imaging paper for the entire time the giga-lumen lighting functioned, ~860 μs. High-speed camera 1 also captures a late time combustion event that started around 5,000 μs and continued until approximately 12,652 μs. Still images captured by camera 1 from the early time and late time events are shown in Figure B24.

Camera 1 early time (times listed on frames in microseconds)



Camera 1 late time (times listed on frames in microseconds)

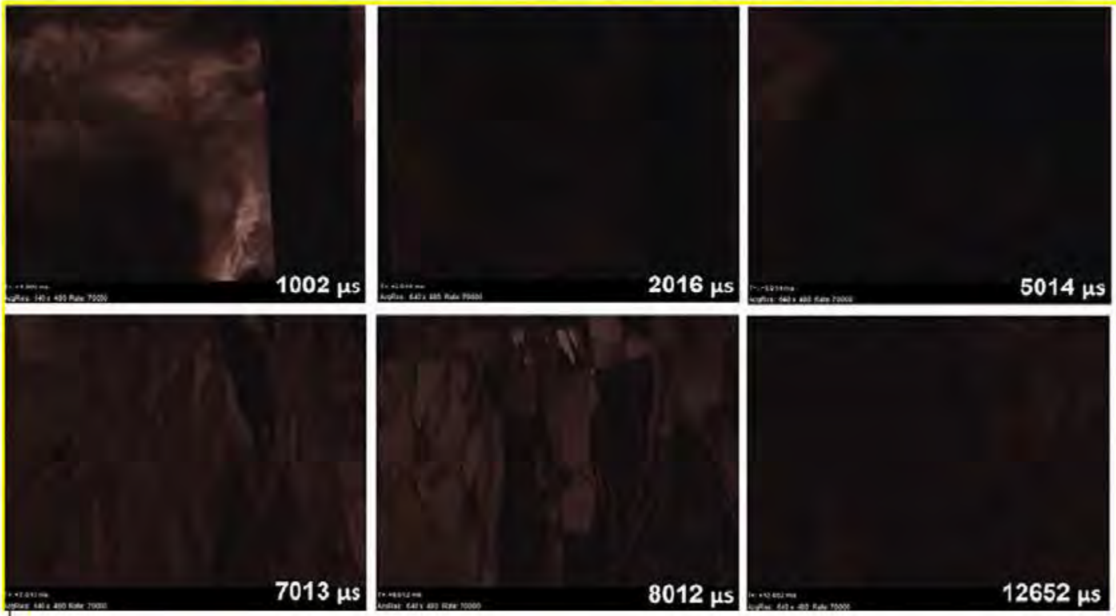


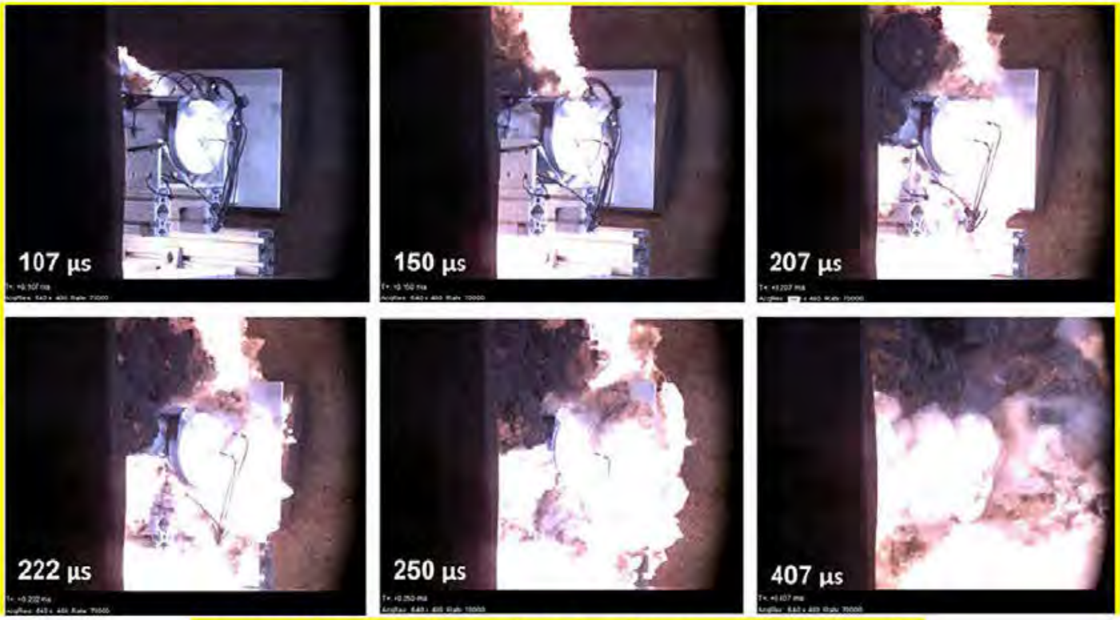
Figure B24. Still images from camera 1 (side view) high-speed imaging. Top: Early time detonation products moving (left to right) from charge in front of imaging paper. Note that there was no discernable plastic dust cloud or the aluminum end cap projected into the adjacent catcher tank. The early time was front-lit with the giga-lumen system for ~860 µs. Bottom: The fireball dies out for approximately 4,000 µs then reignites for approximately 7,600 µs.

The early time images did not observe any discernable plastic dust cloud or even the projection of the aluminum end plug from the steel case, only the blast cloud progressing from left to right on the images in the direction of detonation. The still images from the later time show what appears to be shards of broken glass. This was due to the two turning mirrors used to periscope the image over because the center of the two fragment catchers did

not end up in the center line of the camera one port. Around 5,000 µs a faint orange glow reappears and persists for approximately 7,600 µs.

As expected, camera two (45° off tank centerline) high speed images demonstrate similar results as camera 1. Camera 2 early time and late time images are shown in Figure B25.

Camera 2 early time (times listed on frames in microseconds)



Camera 2 late time (times listed on frames in microseconds)

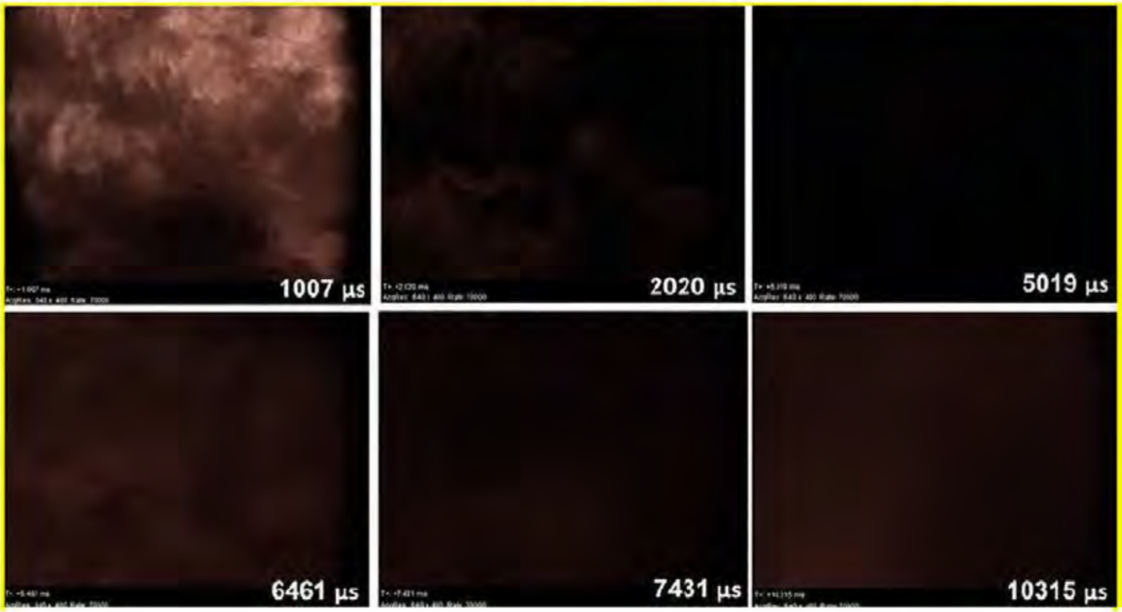


Figure B25. Still images from camera 2 (45° off tank centerline) high-speed imaging. Top: Early time detonation products moving angled towards the camera. Note that there was no discernable plastic dust cloud, or the aluminum end cap projected into the adjacent catcher tank. The early time is front lighted with

the giga-lumen system for approximately 860 μs. Bottom: The fireball dies out for approximately 3,000 μs, then reignites and persists for nearly 4,000 μs.

Following the same results as camera one, camera 2 did not show any powders, parts, or pieces projecting from the Icepick casing that were discernable from the fireball. Similarly, the fireball appears to extinguish around 2,000 μs and reignite around 6,000 μs, persisting for approximately 4,000 μs. The late-time fireball captured by both cameras makes physical sense when thinking about time required to disperse the plastic around the tank and mix with the oxygen available, then reignite by an adventitious source of ignition.

The images captured by the real-time video inside the 10 kg spherical tank also yielded interesting results. Right after the detonation event, the real-time camera observed burning fragments being scattered throughout the tank, even adhering to the tank wall with combustion persisting for seconds afterwards. Image stills from the real-time camera are shown in Figure B26.

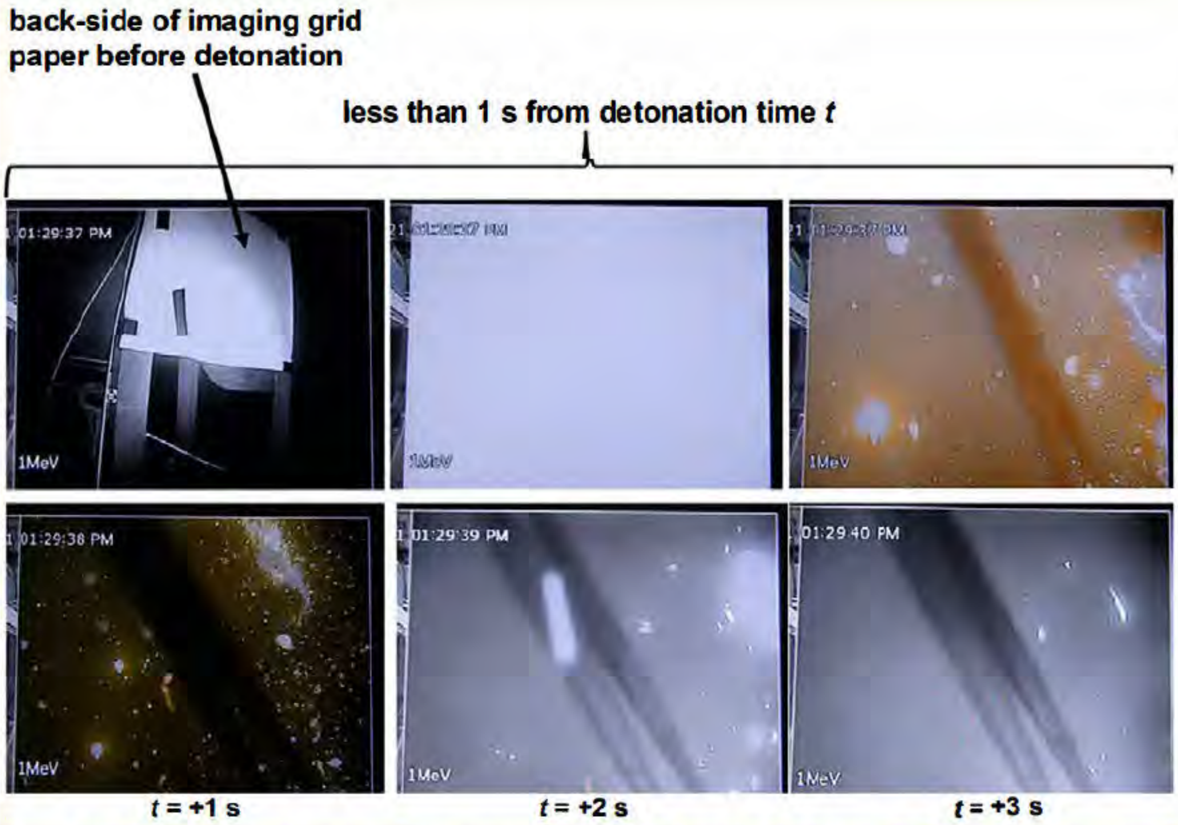


Figure B26. Still images from real-time camera inside 10 kg spherical tank. The top three images are within one second of the detonation event. The lower three images are increasing one second in time to demonstrate dispersion of flaming particulates and the continued combustion of those particulates.

All three camera still images demonstrate that combustion persisted after the detonation even on different time scales from *t*=0 (initiation of detonator). Time scales ranged from; detonation=*t* +18 μs, expansion of fireball to 400 mm (rough distance to inside surface of shrapnel catcher) =*t*~+1000 μs, gaseous combustion in tank=*t*~+5,000 μs to + 12,000 μs, late-time combustion of solids=*t*~>3,000,000 μs (3 seconds). All these combustion events are dependent on the fuel type, the fuel's proximity to the explosive during detonation, dispersion of fuel in the contained volume which depends on relative location of obstacles in the volume and flow paths, and the flammability of nearby objects, their susceptibility to ignition, and the flame temperature and persistence of the flaming debris landing on those nearby objects.

To estimate the mass of plastic consumed, the maximum pressure in the 10 kg spherical was again used to determine how much fuel (with known heats of combustion) would have been consumed to generate the observed pressure in the known volume. The tank reached a maximum pressure of 38.53 psig and temperature of 84.7 °C. Due to a faulty gasket on the 45° camera port, a leak formed after the experiment and some gas escaped (a very rare but known occurrence). The upper working pressure limit (quasi-static pressure) of the 10 kg spherical tank is 88 psig, so there was no concern of over pressurization of the 10 kg tank. Due to this, the total plastic consumed based on recovered mass was used to estimate a pressure, and similarly, working the problem from the other direction, the max pressure observed was used to determine the mass of plastic required to reach that pressure. The masses of the parts recovered after the experiment allow for more accurate estimates of heat generated to create the observed pressure. Table B2 lists the initial and final mass of combustible components in the Icepick experiment. No trace of either explosive or TPX was found after the experiment. Two large pieces of 3D-printed ABS totaling 323.3 g in mass were found behind the steel "catch" plates in the fragment catcher to the right of the Icepick charge in Figure B7. Based on the flammability that 3D-printed ABS exhibited in other experiments described, this is an interesting result. However, it is likely that being projected onto the other side of those catch plates in that fragment catcher protected those pieces from complete combustion.

Table B2: Beginning and recovered masses of combustible materials in the Icepick experiment.

Component	Initial mass (g)	Recovered mass (g)	Δ mass consumed (g)
(b) (7)(F)	(b) (7)(F)	0	(b) (7)(F)
		0	
ABS	608.2	323.3	284.9
TPX	586.3	0	586.3

The literature value for the heat of combustion of ABS is 39.84 kJ/g. A literature value for the heat of combustion for TPX was not found. However, TPX (polymethylpentene) has the formula unit $(C_6H_{12})_n$, which reduces to the same carbon and hydrogen ratio of 1:2 as does polypropylene $(C_3H_6)_n$. Therefore, the heat of combustion of polypropylene (45.8 kJ/g) was used as a reasonable estimate for this analysis.

Following a similar process and assumptions as described before for the detonation shock-pulverization of 3D-printed ABS experiment, the pressure and known materials and masses was used to determine how much of the pressure was generated by plastic combustion. To reiterate, the assumptions are (1) the volume of the tank does not change, and (2) the detonation product gases are not a significant increase to the total moles of gas in the tank. For the moles of gas, the mass of air inside the tank is 74.9 kg, and the total mass of HE and plastic that could combust was 78.0 kg. The mass of gas added by solid combustion would be 3.1 kg or about 4%. Therefore, the moles of gas being similar before and after detonation is still a reasonable assumption.

To estimate the amount of 3D-printed ABS and TPX consumed in the Icepick experiment the combustion of the detonation products must be considered. First the total energy of detonation was found using heat of detonation estimates from Cheetah 8.0 for LX-07 (5.37 kJ g^{-1}) and PBX 9502 (3.99 kJ g^{-1}). Using the masses of the explosives above this translates to a total energy of detonation 8,775 kJ. Based on the volume of the 10 kg spherical tank, a γ=1.3, and the Δ pressure for experiment, this results in 46,313 kJ of energy in excess of the total detonation energy. Using an average energy gained from combustion of all explosives determined from the bare LX-10 and PBX 9502 experiment, an estimated 15,475 kJ of energy could be contributed to combustion of the post-detonation products of (b) (7)(F) From detonation (8,775 kJ) and post-detonation combustion (15,475 kJ) of the explosives alone, the tank pressure should have only reached an estimated 17.0 psig. This leaves 30,838 kJ that must have come from combustion of 3D-printed ABS and TPX plastics.

Estimating the plastic consumed based on the maximum tank pressure observed is as follows. First, a mass weighted heat of combustion starting from the heats of combustion for each plastic and the initial mass of each plastic was found to be 42.77 kJ/g. Using this and the previously determined excess heat unaccounted for by detonation and combustion of the post-detonation products resulted in approximately 721.1 g of plastic being consumed. This is short by 150.1 g of the mass of plastic consumed; therefore, it is reasonable to presume that had the tank not vented, the pressure would have gone up further.

Estimating the max pressure that should have been observed is as follows. Using the above Δ mass consumed for each plastic and their heat of combustion yields a total energy based on mass of 38,203 kJ, 7,365 kJ greater than the residual energy calculated above. Based on this additional energy, the final tank pressure should have been 43.7 psig had the camera port gasket not vented

Based on this analysis, the TPX and 3D-printed ABS plastics collocated in the steel housing wit (b) (7)(F) (b) (7)(F) definitely had a significant increase on the total tank pressure shortly after detonation. It is interesting that the 3D-printed ABS was not fully consumed in the Icepick experiment, but a reasonable explanation of why the 3D-printed ABS was not fully consumed based on where the 3D-printed ABS pieces were recovered in the tank is justifiable. The TPX plastic was fully consumed as far as could be determined upon recovery.

Conclusions

The experiments performed and presented here demonstrate several crucial factors in the B801 over-pressurization event. First, all materials tested, polystyrene foam, low-density polyethylene (LDPE), ABS, and two densities of flame retardant polyurethane foams, used in the chamber will vaporize into flammable gases when heated to moderate temperatures of 300-500 °C. The polystyrene, LDPE, and 3D-printed ABS vaporized to completion in the absence of available oxygen for combustion reaction. Second, all five materials tested were susceptible to ignition by direct flame heating. The polystyrene, LDPE, and 3D-printed ABS burned to completion once sufficiently initiated. The flame retardant foams burned as long as they were exposed to flame but did self-extinguish after 5-10 seconds. The gases evolved during flame heating of the flame retardant foams were flammable and these foams lost 50-80% mass during heating. All five materials evolved vaporous products, when heated with radiant heat. While it was not directly tested, it is highly likely that the gases evolved during radiant heating were also flammable. As expected, most materials did not exhibit significant reaction in a dust-explosion-type test as such fuel-air reactions are dependent on many variables including particle size, dust density, distribution etc. However, tests on unoptimized dust-explosion experiments showed finely ground 3D-printed ABS resulted in a persistent combustion reaction, and surprisingly the low-density FR-3703 LAST-A-FOAM® also exhibited some persistent combustion.

The 3D-printed ABS and TPX were also tested in detonation experiments to determine their extent of combustion from a detonation type event. A well-controlled experiment subjected the 3D-printed ABS direct heating/pulverization via direct shocking from (b) (7)(F) detonation in the detonation shock pulverization of 3D-printed ABS plastic experiments. This demonstrated that 3D-printed ABS experienced significant combustion/reaction that more than doubled the tank pressure for the same mass and identity of HE. It should be noted in that experiment with 3D-printed ABS, the pressure more than doubled but the 3D-printed ABS was only 38.4% of the combustible mass in the tank during that experiment. Finally, in a combined experiment that had both TPX and 3D-printed ABS in a similar configuration to the B801 incident and was environmentally conditioned to -53 °C, both plastics exhibited significant reaction. The participation of the 3D-printed ABS and TPX based on recovered mass was such that the resulting tank pressure should have been approximately 43.7 psig; however, the observed maximum tank pressure was only 38.53 psig. Notably, the predicted tank pressure without any plastic participation would have been approximately 17.0 psig.

Overall, these experimental results support the findings of the IA and Technical Teams. There were a significant number of pathways that could have led to the B801 over-pressurization event, and without more information it is not possible to determine a direct cause pathway. Yet these experiments indicate there were many available flammable fuel sources in the chamber that exhibited varying levels of susceptibility to ignition and combustion. Furthermore, these experiments have demonstrated ignition and combustion over a range of timescales and initiation by a number of heat/ignition sources for these flammable materials. Therefore, none of the known flammable materials in the chamber, 3D-printed ABS, LDPE, TPX, polystyrene foam, or high- or low-density polystyrene flame-retardant foam (LAST-A-FOAM®) can be confidently ruled-out as not participating in the B801 over pressurization event.

Appendix C–MUMA Process and Procedure Review

As part of the IA, or root cause analysis, the IA team reviewed the B801 CFF MUMA system and associated procedure, *MUMA Operation Procedure*. The MUMA is a methane gas delivery system attached to an explosive device/experiment within the CFF's chamber. This system and process was reviewed to determine if the flow of methane had an effect on the outcome of this event. The WCI Conduct of Operations Manager was also asked to review the completed *MUMA Operation Procedure*, now a record for input from a Conduct of Operations perspective.

It was determined that although issues were identified with the MUMA system and associated procedure, none of these issues had an effect on the event and are therefore, not considered causes but observations.

Observations identified by the IA team are summarized below:

Per previous ES&H Manual Pressure Safety guidance and the current LLNL institutional RID 9282 Pressure Safety document, the CFF MUMA manifold did not have an LLNL approved/reviewed pressure safety note to operate or build a flammable methane gas manifold.

A gas specie-dependent Granville Phillps vacuum gauge was used on the MUMA manifold. When using a flammable gas manifold that is evacuated, LLNL pressure installer training specifically discusses the University of Hawaii event, and the use of proper gauges for use with proper gases. Further, when reading/using a vacuum gauge that is not properly calibrated for evacuating a gas other than nitrogen, vacuum pressure readings will vary significantly, and give false pressure readings.

Granville Phillps specifically discusses in their updated manual the risks of using this style vacuum gauge that was used in the MUMA manifold for the subject gas used. Granville Phillps manual states: "Do not operate in an explosive atmosphere. Do not operate the product in the presence of flammable gases or fumes." Because the gauge is not calibrated for use for any other gas other than nitrogen, even the smallest gas specie different from nitrogen will affect the gauge calibration giving the operator a false reading. Granville Phillps manual states; "operation of any electrical instrument in such an environment constitutes a definite safety hazard. Do not use the product to measure the pressure of explosive or combustible gases or gas mixtures." The sensor wire of the Convectron® gauge normally operates at only 125 °C, but it is possible that controller malfunction can raise the sensor temperature above the ignition temperature of combustible mixtures.

The Granville Philips manual states: "Convectron® Tube Mounting Position–If the gauge tube will be used to measure pressures greater than 1 Torr or 1 mbar, the tube must be mounted with its axis horizontal. Although the gauge tube will read correctly below 1 Torr when mounted in any position, erroneous readings will result at pressures above 1 Torr if the tube axis is not horizontal. Erroneous readings can result in over- or under-pressure conditions which may damage equipment and injure personnel." From the IA reviewers and the photo provided in the MUMA procedure, gauge orientation could not be discerned. Nor was any mention of gauge orientation discussed in the MUMA procedure that would have the operator orient the gauge properly.

Prior to the experiment detonation, when it was realized one flow path was plugged, the experiment Ramrod authorized an alternate flow path. It is unclear if the bunker supervisor made aware of the change at that point. Per procedure, "The bunker supervisor is responsible for ensuring this procedure is conducted as per experiment requirements with the approval of those specifications by the Ramrod, if there are any questions or discrepancies." On the completed procedure provided, the bunker supervisor signed the document roughly two months after the experiment. Note that at the time of the experiment, the bunker supervisor was not at the facility (on leave) and there was an acting bunker supervisor during the experimental time frame.

IA Committee observation: MUMA manifold was set up, used for several days prior to the experiment being detonated, and was used when individuals were in proximity of individuals setting up peripheral experimental apparatuses. The consequences of using the wrong gauge are unknown gauge pressure in the experimental device and a potential spark source for methane that is introduced and connected to experimental explosive device.

IA Committee observation: The MKS flow controller used was not calibrated for methane, but for nitrogen. Effect would be unknown gas flow through the device. MKS offers correction factors for different gases; it appears that bunker personnel are unaware of the MKS correction factors. Gas correction factor (GCF) is used to indicate the ratio of flow rates of different gases which will produce the same output voltage from a mass flow controller. The GCF is a function of specific heat, density, and the molecular structure of the gases. Since flow controllers are usually calibrated with nitrogen, nitrogen is used as the baseline gas (GCF=1). The GCF of any other gas is determined by using an equation.

IA Committee observation: The Alicat flow meter used directly on experimental device is calibrated for nitrogen. The MUMA operational procedure does not direct personnel to pick the right flow meter gas setting per the Alicat manual. The Alicat flow meter manual specially states how to use the instrument properly for different gases and gives a menu explaining how to correct the flow instrument for different gas species.

IA Committee observation: The actual MUMA methane pressure was unknown to the operator and Ramrod due to multiple regulators in the system. Redundant regulators in the CFF long chase are set for an unknown pressure. Nothing in the B801 MUMA procedure discusses the secondary CFF long chase regulator or its actual setting.

IA Committee observation: Viscosity of gases and temperature related effects–gas entered from a methane manifold exterior of the facility; which gas could be at X temperature then enters a device that is cooled to -54 °C. Depending on the amount of time the methane gas is in the device, the methane would get cooled to X °C and the gas would be affected by this cooling, and potentially the instruments around the device that measure gas pressure would need to be calibrated for temperature effects.

IA Committee observation: For approximately 45 minutes, methane was introduced (once the CFF chamber was closed) to a “leaky device/experiment” per personnel interviews. An unknown amount of methane was introduced into the CFF chamber.

IA Committee observation: Methane gas suppliers SDS has specific recommendations that have not been utilized by the CFF MUMA system items such as non-sparking tools and grounding the exterior Facility MUMA methane manifold.

IA Committee observation: Vacuum pump used for MUMA manifold operation manufacturer's operating manual states to never evacuate or pump toxic, explosive, flammable, corrosive gases, chemicals, solvents, or powders. Flowing substances can cause explosion or fire and can cause bodily injury.

The IA Committee asked the WCI Conduct of Operations (COO) Manager to review the *MUMA Operations Procedure* and associated record from the shot. The WCI COO Manager identified several conduct of operations elements that require further evaluation to include (1) technical accuracy of the *MUMA Operations Procedure* and whether it can be performed as written, (2) procedure change practices to include the use of pen and ink or page changes and complete reissues, and (3) procedural use/adherence. The WCI COO performed a preliminary review of the *MUMA Operations Procedure* and associated process and plans to perform a more detailed review via the management observation process.

Acronyms

ABS	Acrylonitrile Butadiene Styrene
ALCO	Alameda County
APF	Assigned Protection Factor
Be	Beryllium
BMA	Beryllium Materials Area
BWA	Beryllium Work Area
CA	Contamination Area
CDU	Capacitor Discharge Unit
CFF	Contained Firing Facility
CO	Carbon Monoxide
DTED	Defense Technologies Engineering Division
EAR	Experiment Activity Report
ES&H	Environment, Safety, and Health
FD	Fire Department
FDR	Final Design Review
FM	Facility Manager
FSP	Facility Safety Plan
FXR	Flash Radiography
HE	High Explosive
HEAF	High Explosives Application Facility
HEPA	High Efficiency Particulate Air
HF	Hydroflouric acid
HP	Health Physicist
IA	Incident Analysis
IC	Incident Commander
IH	Industrial Hygienist
IDR	Intermediate Design Review
ISMS	Integrated Safety Management System
LiH	Lithium Hydride
LLNL	Lawrence Livermore National Laboratory
MESN	Mechanical Engineering Safety Note
MXL	Multiplexed Alarm Reporting
MUMA	Methane Utility Manifold Assembly
ORPS	Occurrence Reporting Processing System
PAD	Principal Associate Director
PAPR	Powered Air Purifying Respirator
PDR	Preliminary Design Review
PDV	Photon Doppler Velocimetry
PPE	Personal Protective Equipment
RBA	Radiologic Buffer Area
SME	Subject Matter Expert
TA	Technical Analysis
TCU	Thermal Control Unit
VTR	Vault Type Room
WCD	Work Control Document
WCI	Weapons and Complex Integration
WP&C	Work Planning and Control

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