WIPP Site Incident Independent Review (WSIIR) Team

Final Report

December 2017

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Summary

The WIPP Site Incident Independent Review Team formed in December 2014 at the request of the Department of Energy. Our charge was to perform an independent and transparent review of the events surrounding the February 14, 2014 drum breach at the WIPP Site. In this final report we summarize our work and share information and conclusions concerning the prior investigations by the Technical Assessment Team and Los Alamos National Laboratories (LANL) as well as the drum testing performed at LANL. We also summarize the remediation plans in place by LANL and share the corrective action strategy shaping the future of LANL's waste processing and the WIPP facility.

Introduction

This document provides a final summary and analysis of the WIPP Site Incident Independent Review (WSIIR) team's analysis and conclusions of the February 14, 2014 breaching of Drum 68660 at the WIPP site.

Our eight-person team was led by Principal Investigator, Dr. Van Romero, Vice President for Research and Economic Development at New Mexico Tech. Members include faculty and staff with expertise in the areas of physics, chemistry, mineral engineering, explosives engineering, and technical communication. (Short biographies of the team are available in

Appendix A: WSIIR Team Brief Biographies).

Our team's work began in December 2014, and since then we have read the reports and available documentation surrounding the event and discussed the incident thoroughly in multiple meetings. The documentation we have reviewed includes the information on the DOE WIPP Recovery Site including the Accident Investigation Board (AIB) investigation reports (found on the DOE WIPP Recovery Site), the resources available via the WIPP Waste Information System Public Inquiry Site, the Carlsbad Environmental Monitoring & Research Center (CEMRC) Site, WIPP Monitoring Site, and the EPA's Review of WIPP Incident Site.

In addition, we have met with representatives from the Technical Assessment Team (TAT) who conducted an earlier review of the incident and presented their investigation's findings. At our request, the TAT responded to our in-depth questions concerning the overall methods they applied, the modeling techniques and software codes used, as well as their presentation and interpretation of results (see **Appendix B: Technical Assessment Team Responses to WSIIR Questions**) and delivered a second presentation to allow for clarification and discussion. We have also met three times with LANL staff to learn about their analysis of the incident and understand their methods and hear the results of their series of full-scale drum tests. From our meetings with LANL staff we have also learned about their corrective action plan and intended path forward for remediation.

To uphold the WSIIR team's mission of a transparent review, we have shared copies of our interim report and status updates on our website: http://www.nmt.edu/wsiir as well as information about our team's members, and links to resources about the WIPP incident. Also included on our website are documents from LANL and the TAT regarding drum testing, remediation plans, and corrective actions. Our team has met with members of the Carlsbad community during our February 2016 Town Hall presentation, and the previous February we met with Southwest Research and Information Center Director Don Hancock to better understand that organization's concerns regarding the WIPP incident. We have used these meetings as an opportunity to communicate our team's mission, scope of work, and preliminary analysis.

In this final report we summarize our team's analysis of the events that contributed to the breaching of Drum 68660. Our focus is on the information we've received and reviewed since submitting our interim report in Fall 2015. We begin with background information concerning the circumstances leading up to the event. Following this background, we provide a detailed account of all of our tasks and links to our documents presenting our prior analyses. We conclude with our analysis of LANL's remediation plans and corrective action strategy. Throughout this document we reference reports shared by LANL and the TAT. We include hyperlinks of those reports for the benefit of readers viewing electronically, and those reports are also available within the Reports section of the WSIIR website: https://www.nmt.edu/reports

Background

The Waste Isolation Pilot Project (WIPP) Site began receiving nuclear waste in 1999 and operated for 15 years with no reportable releases of radioactivity. In February of 2014, two separate events happened, halting WIPP operations. The first incident, an underground salt haul truck fire, occurred on February 5th and resulted in six workers being treated for smoke inhalation. Lab tests showed zero release of radiological material during the fire; however, since underground air monitoring equipment was affected by the fire, there was uncertainty surrounding these conclusions.

The second incident occurred the evening of February 14th when a drum barrel located in Room 7, Panel 7 breached. Air monitors at the WIPP facility detected unusually high radiation levels. While there were no workers underground at the time of the incident, trace amounts of airborne radiation consisting of americium and plutonium particles were discovered by aboveground monitors about a half mile away from the WIPP site. On February 26, 2014, the DOE announced that 13 WIPP aboveground workers had tested positively for radiation exposure (DOE/NWP Press Release). Since February 2014 the WIPP Site has been closed to waste shipments.

Two Accident Investigation Boards were established by the DOE to assess WIPP safety procedures. Included in these investigations have been "analysis of training and qualifications, maintenance, and emergency management response to the events" (WIPP Recovery homepage).

In addition, an independent Technical Assessment Team (TAT) was created by the DOE "to determine the mechanisms and chemical reactions that may have contributed to the failure of the waste drum" (WIPP Recovery Plans and Reports).

For a separate independent review, the WIPP Site Incident Independent Review (WSIIR) team was formed in December 2014 at the request of the DOE. WSIIR's timeline and key tasks are outlined in the following section.

Summary of WSIIR's Work

The following timeline summarizes our team's work on this project, with links to documents available on the WSIIR team's website.

December 2014- May 2015

- In December 2014 TAT representatives came to New Mexico Tech to meet with our group and present the preliminary findings of their investigation. While their written report was not yet published, they shared their own summary and analysis of the February 05, 2014 truck fire and their analysis of the February 14, 2014 breach of Drum 68660 through a detailed PowerPoint presentation.
- Southwest Research and Information Center Director Don Hancock met with our group at New Mexico Tech in February 2015 to better understand our mission and the scope of our review.

- Once the TAT published and released their written report in March 2015, our team performed an in-depth review of it. We generated questions regarding the TAT's overall approach, analytical techniques, modeling and experimental results. The TAT's written response to our questions is included in **Appendix B: Technical Assessment Team Responses to WSIIR Questions**.

August 2015-October 2015

- In August 2015 our team traveled to Los Alamos National Laboratories (LANL) to meet with LANL staff tasked with conducting their own review of the WIPP Site incident. At this meeting, we heard extensive and detailed information about LANL's thorough investigation. At this time we also learned about their ongoing drum tests, with preliminary results shared.
- Later in August 2015 our group met with the TAT in Albuquerque. During this meeting, members of the TAT explained in greater detail their answers to our questions as well as answered additional questions from our team.
- In September 2015 our team published an Interim report presenting our summary and analysis of findings. This report is available on the homepage of our website: http://www.nmt.edu/wsiir
- In October 2015 we again met with LANL (this time in Santa Fe). The LANL group presented further results of their ongoing drum tests and shared their plans for remediation as well as corrective action procedures.

November 2015-February 2016

- In November and December 2015 our team reviewed the information provided by LANL concerning their ongoing drum tests, remediation plans, and corrective action procedures.
- In January 2016 our team began preparing for a Town Hall presentation in Carlsbad.
- On February 17th, 2016 our team traveled to Carlsbad to participate in a Town Hall meeting attended by current and former WIPP Site personnel, Carlsbad citizens, and local media. We delivered a presentation about our team's scope and work and answered questions from those in attendance. The presentation slides are available on the homepage of our website: www.nmt.edu/wsiir . While the meeting was recorded and streamed live, we learned later that the audio quality was poor.

March 2016-July 2016

- The WSIIR team requested and was granted a no-cost extension to extend this project to December 2016, to coincide with the anticipated reopening date of the WIPP Site.
- Throughout the remainder of the Spring, we conducted further reviews relative to the WIPP facility and identified additional information we wanted presented to us by LANL.

In particular, we identified the results of LANL's drum tests and their remediation plans as information we wanted shared.
- In July 2016 we met with Dave Funk from LANL in Santa Fe to learn about the LANL group's updated results and final conclusions regarding their full-scale drum testing. Several documents were shared with the WSIIR group at that meeting. These documents are all available on our website: https://www.nmt.edu/reports

August 2016-December 2016

- The WSIIR team compiled our findings in a final report.

January 2017-December 2017

- Two individuals continued working on the project through a no-cost extension.
- Tasks included responding to requests from the New Mexico Congressional delegation and the media to provide details regarding our team's review of the 2014 incident.
- The final report was updated.
- The team website was maintained and updated.

In the next section of this final report, we provide detailed information concerning LANL's drum testing and our group's analysis of the tests and LANL's conclusions. LANL also presented their strategy to resume waste treatment options with the remaining drums at LANL as well as the 114 drums located in Andrews, Texas at Waste Control Specialists. At this meeting we also discussed LANL's corrective action plan.

Full-Scale Drum Testing at LANL

During our meeting with LANL in Santa Fe on July 6, 2016, Dave Funk shared slides that he had already presented to Texas Commission on Environmental Quality (TCEQ), the regulator for Waste Control Specialists in Andrews, TX (which has the 114 drums that also contain Swheat and therefore have potential of breaching). Some key summary points (mentioned up front) included:

- LANL's main conclusion is that the cause of Drum 68660 breaching was a thermal runaway reaction involving the nitrate salts of the waste and the Swheat used to absorb liquids and biological factors were not involved.
- The truck fire on February 5, 2014 was not related to the drum breach.
- With Comsol modeling, LANL concluded the higher the oxidizer concentration in the drum, the lower the onset temperature.
- Only chemical processes were involved; there was no need to invoke nuclear processes in order to recreate a breach event.
- LANL discovered that by heating complex mixtures of nitrate salts, they evolved NO_2 to levels of increased reactivity.

Detailed Results of LANL's Final Drum Tests

With their full-scale drum testing, LANL performed the following actions:

- Tested ladder of plausible exothermic reactions
- Diagnosed thermal response of drums
- Evaluated effect of pressure and venting
- Performed headspace gas analysis
- Recorded audio and video of drum contents' behavior
- Replicated drum contents as closely as possible (nitrate salts ,Swheat, no radioactive components, Pb, Liquid neutralized w/ Kolorsafe Spifyter, Bismuth gloves—segmented into 3 layers
- Conducted a test matrix of 4 drums (A,B,C,D) from nominal (vented) to accelerated (worst case—heated and sealed)

Following are the summarized results of LANL's full-scale drum tests. Further information can be found in LANL's Nitrate Salt Disposition presentation, available via: Nitrate Salt Presentation Dropbox File *(electronic dropbox link due to large file size).*

Drum A: (25°C vented) After 3 days at 60°C contents began to self heat, but quenched. The pressure didn't do much (.5 psi). The lid was intact. The bag slightly yellowed, and contents were heterogeneous and damp. After 94 days upon heating to 60°C, self-heating began showing that reactive potential remained. However, even these reactions quenched. When LANL heated the drum (at the end) to 200°C, it did react with a sudden breach of the drum and dispersal of glowing embers (as shown on a video LANL presented).

Drum B (25°C sealed): This drum represents a drum stored under normal conditions in WIPP but explores the possibility of the vent becoming blocked. The temperature increased to 34°C and the maximum gas pressure was 25 psi but then it quenched. On day 12 LANL saw the onset of self-heating and increased rate of pressurization, followed by quench. Twelve days is the approximate duration that the Drum 68660 was in the WIPP. The condition of this drum was stable for 75 days; then the facility power was lost and the controller was reset to 160°C. When examined by LANL they saw the lid was bulged and the lid seal failed. The bag reddened and thermally damaged contents were homogenous, dry and sooty; the material had slumped. This drum provides a lot of insight, with the takeaway lesson being that reactivity and self-heating occurs at 25°C.

Drum C: (60°C vented): This drum exhibited a runaway quench event. When pressure was relieved, runaway was quenched at 115°C (which surprised LANL) even though signs of bulging were observed. Flow restriction of the vent may be necessary for runaway to occur. (Also, the vent failed on this drum, but that vent failure allowed more gas to escape and the maximum gas pressure to be controlled at about 14 psi which was lower than 30 psi pressure needed to breach the drum). LANL hypothesizes that Drum 68660's vent was blocked by an internal plastic bag. The hottest location was in the top layer, with high headspace gas temperature (which is also evidence for the importance of gas-phase reactants).

Drum D (60°C sealed): With this drum the lid seal failed in a controlled manner at 32 psi and started leaking. The top layer started the runaway. The pressure burst happened after 3 days and the breaching was driven by chemistry. Event precursors included noticeable bulging of the drum lid and base prior to the burst, as well as considerable fumes. No flame was observed and no blackening was seen on the drum. Orange vapor was evidence for NO_2 production.

Questions and Conclusions

When asked why Drums A and B (those drums closest to WIPP conditions) didn't' behave in the same manner as #68660, LANL's explanation was that while this question cannot be answered definitively, drums are all extremely variable and not uniformly mixed. There could have been more water in one drum.

Drum D did not have MgO sacks weighing down the lid as those in the WIPP facility do; thus the reaction was quenched when the lid blew off. LANL cannot say for certain what would have happened if the lid had been held in place.

Based on their full-scale drum tests, LANL drew the following conclusions:

- Thermal runaway w/ plausible surrogate was replicated by their full scale drum tests meaning only chemical processes need be considered as the cause of Drum 68660's breaching
- Pressurization is required for runaway
- Reactant concentrations for the low temperature chemistry can be diminished with sufficient time at ambient temperature
- Accident prevention strategies include: elimination of potential for pressurization, reduce temperature where stored

LANL's assessment of what happened with Drum 68660 is as follows: When you mix a saturated salt mixture with a neutralizing agent that is itself an organic material (Triethanolamine in this case) together with Swheat it reacts and may cause a thermal runaway.

The WSIIR team's analysis is that the physical full-scale drum tests on surrogate material conducted by LANL demonstrate the cause of thermal runaway. Their test results show the importance of the venting system on each drum. Fortunately, new drums now have a pressure release valve in addition to a filter to increase the safety of the drums against the internal pressure buildup and possible breaching. Regarding simulation of drum kinetics, LANL's analysis supports the hypothesis of drum behavior—which is that safety increases with decreased reaction potential over time, barring upset conditions and also supports the idea that the remaining drums with this mixture can be safely opened at low temperatures and the waste remediated.

The WSIIR team concludes that while it is not reasonable for the exact trigger of Drum 68660's breach to be definitively identified, circumstances that led to Drum 68660 breaching are as understandable as they can be without a direct examination of 68660. The WSIIR team does not recommend additional testing. We also believe modeling tests show the truck fire that occurred at WIPP on February 5, 2014 was unrelated to the drum breach. We believe chemical processes were the only processes that needed to be studied and tested; as referenced in LA-UR-15-22393, prior work and "…recent radiolysis calculations, suggest that gas generation and heating from radiolysis should be minor based on the radionuclide inventory of Drum 68660, especially over the short, several month time-frame (ca. 75 days) between packaging at LANL and radiological release from Drum 68660 at WIPP" (LANL Chemical, pg. 9). Based on the conclusions drawn from the results of LANL's drum tests, there is no need to invoke nuclear chemistry or nuclear physics processes in drum testing.

LANL's remediation plans for existing drums w/ Swheat

To treat the existing drums that originated from the same waste stream as #68660, LANL has developed remediation plans. As part of their remediation plan process, LANL established in-depth criteria for reviewing options, involved multiple peer reviewers, and conducted a full engineering options assessment.

Processing Drums at LANL

Drums at LANL requiring processing include 29 of the original containers which are categorized as unremediated nitrate salt (UNS) drums and 60 remediated nitrate salt (RNS) drums that contain remediated, absorbed, and repackaged nitrate salt wastes. For further information regarding LANL's inventory of waste composition, refer to the RNS Engineering Options LA-UR-28900 report page 14.

Four process options were presented by LANL and are briefly summarized below. Peer reviews of LANL's remediation plans are presented in reports by Savannah River National Laboratory experts in report SRNL-MS-2016-00035 and a Technical Advisory Panel (TAP) including experts in nuclear waste processing, environmental remediation, and environmental management from several agencies (TAP Report Options for Processing RNS and UNS).

1. Batch blending: simple, but slower than drum blending.
- Zeolite introduced in daughter drum
- Operators will get more of a radiation dose compared to drum blending
- Only a 60 drum campaign for RNS and quality of process easily verified.

2. Drum blending is easiest, fastest option
- Concerns related to quality of blend and verification of mix quality
- Time to prove-in likely extensive

3. Cementing in a drum tumbler
- Eliminates adding cement in the glovebox
- Still requires dissolution and pH adjustment in drum

4. Cementing in glovebox is most difficult option
- Add cement in glovebox
- Mix cement in glovebox
- Sacrificial agitator

Of the above four options, the TAP considered the batch blending option (#1 above) to be the best candidate (TAP, pg. 18). At our meeting with LANL in July 2016 they indicated that they had already tested the batch blending process on surrogate drums located in Andrews, TX and the burn test indicated this option works. As part of this batch blending process multiple tests of adding different levels of zeolites were conducted, and all were effective.

In addition to investigating different techniques, LANL also investigated several location options for the processing of the waste. The Waste Characterization, Reduction, and Repackaging Facility (WCRRF) glovebox was the leading candidate. The drums will be processed in order of increasing consequence. Per their contract, LANL's processing must occur before the end of the 2017 fiscal year. LANL noted that they are working hard to accelerate that schedule to eliminate the hazard as early as possible.

The WSIIR team concludes that LANL's plans to remediate their drums on site are the most viable path forward.

Processing Drums in Andrews, Texas

To treat the 114 drums with the Swheat mixture contained in Andrews, Texas, at a facility managed by Waste Control Specialists, LANL has considered a range of options. They have concluded the best option is to bring a portable facility to Texas to treat the drums on site. Two modular systems exist: MObile Visual Evaluation and Repack (MOVER) and Mobile Repack (MORK). LANL noted that this process will be a lengthy one, estimating it could take five years. Once these drums are processed they will be taken to WIPP.

Next Steps: Corrective Actions by LANL

LANL's Corrective Action Plan resulted from the Accident Investigation Board's (April 2014) Phase I report citing 40 judgments of need and 17 required corrective actions. This plan is summarized in LA-UR-15-29568CAP, a PowerPoint presentation delivered to the New Mexico

Environment Department (NMED) in December 2015 (file also available in Reports section of WSIIR website: https://www.nmt.edu/reports).

Following were the different types of corrective actions included in LANL's plan:

- addressing systemic issues
- improving requirements definition
- improving implementations
- ensuring compliance

To develop their path forward to address corrective actions, LANL established an Integrated Corrective Actions Team as well as an Institutional Management Review Board. In addition LANL's Corrective Action Plan presentation noted "Federal counterparts have been engaged throughout the CAP development process" (LANS Corrective Action Plan Slide 3). LANL presented each of the required corrective actions and their strategies for addressing them. They acknowledged that the safety culture at LANL had deteriorated and management failed to effectively respond to workers' issues regarding unexpected conditions. Questioning attitudes were not welcomed by management, and many potential hazards did not appear to be readily recognized by site personnel. Included in this presentation was information concerning their new process engineering group and details about the enhanced rigor in their procedures. **Prior to the incident, LANL lacked a process engineering approach and did not use a formal engineering change control process to develop modifications.**

Conclusion

While our team's work has focused on reviewing all of the information and independent investigations pertaining to the February 14, 2014 breaching of drum #68660 at WIPP, in our final analysis we have also identified a combination of complacency and external pressure as provoking the incident. WIPP operated for 15 years with no major safety incidents and no reportable releases of radioactivity. During WIPP's lengthy period of no major accidents, it is likely that a sense of complacency surrounded procedures and operations of both WIPP and the originator of the waste, LANL.

Safety literature recognizes complacency as an established problem "frequently observed in a wide range of industries" (Marais et al., 2006, p. 573). Complacency has been identified as a pattern that can become present as "the perceived level of safety increases," with the temptation being "to redirect investments away from safety measures and towards improving system performance" (Rasmussen, 1997, quoted in Marais et al. 2006, p. 570). Numerous examples where complacency has contributed to accidents are cited in the literature, including the Challenger (Vaughn, 1990) and Columbia Shuttle disasters (Garner, J.T., 2006), the Union Carbide chemical plant in Bhopal, India (Rasmussen, 1997), the American Airlines B-757 crash in Columbia (Leveson, 2004, p. 242), as well as multiple other aviation examples (Kontogiannis and Malakis, 2012).

Coupled with complacency was external pressure. As noted by safety literature, “Pressure for increased performance (e.g., shorter delivery times…) can make it difficult to remain focused on safety goals” (Marais et al., 2006, p. 573). Following the 2012 Las Conchas wildfire, LANL was under pressure to move waste located at AREA G (an area close to where the fires had burned). The anticipation of another hot and dry summer likely increased LANL’s urgency to process waste by the state-mandated deadline of June 2014 (Villagran and Oswald 2015). Among the conditions cited in the AIB’s Phase 2 report as contributing to drum #68660’s packaging as noncompliant, was “High-load work schedule to complete the waste remediation campaign” (U.S. DOE Accident Investigation Report 2014, p. 200). As included in the AIB’s report, a “get-it-done-at-all-costs” attitude was cited in LANL’s own Safety Conscious Work Environment Self-Assessment”, issued in 2013 prior to the WIPP incident (U.S. DOE Accident Investigation Report 2014, p. 207). LANL’s failure to follow proper procedures when packaging waste is consistent with a phenomenon the safety literature has noted in numerous examples: work load and timing constraints have repeatedly provoked modifications of instructions and violations of procedure (Rasmussen, 1997 187).

From LANL’s corrective action plan, the WSIIR team believes there are appropriate process enhancements in place, allowing LANL to avoid complacency and equipping them to be better about monitoring risk and determining appropriate oversight procedures. With their corrective action plan directly addressing each of the multiple judgments of need identified by the AIB, we view the successful integration of this plan as the key to improvements in engineering discipline and rigor at LANL.

The AIB for both the truck fire and the radiological release events indicate a number of contributing causes. Both of the AIB investigations cited a lack of effective maintenance practices and proper adherence to procedures. The Mine Safety and Health Administration (MSHA) was created to promote “safe and healthful workplaces” for workers in mining environments (US Dept. of Labor MSHA). MSHA requires comprehensive maintenance, training and adherence programs. Since its creation in 1977, adherence to MSHA regulations have resulted in significant improvements to underground operations of mining activities. In the past, WIPP was never subject to rigorous inspection by MSHA and only loosely followed MSHA regulations. It is the conclusion of the WSIIR team that adherence to MSHA requirements could have prevented the truck fire and could have minimized the effect of the radiological release event.

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Appendix A: WSIIR Team Brief Biographies

Van Romero, Ph.D.: Project Lead

Dr. Romero is currently the Vice President for Research and Economic Development, Professor of Physics and serves as the Chief Operating Officer of the New Mexico Institute of Mining and Technology (New Mexico Tech). Dr. Romero is widely known as an explosives expert, supervises graduate students researching improvised explosive devices and was the former director of the Energetic Materials Research and Testing Center at New Mexico Tech. Prior to joining New Mexico Tech, Dr. Romero worked at four DOE laboratories and spent 15 years working in the Naval Reactors program. While working for Naval Reactors, Dr. Romero was responsible for radiation transport calculations and radiation measurements in and around reactor compartments. After leaving the Naval Reactors program, he joined the Superconducting Super Collider (SSC) where he was responsible for the SSC's radiation protection program. At the SSC his specific area of focus was groundwater contamination.

Jeff Altig

Dr. Altig is Associate Professor of Chemistry at New Mexico Tech. He is a physical chemist with expertise in the modeling of chemical and physical systems, and he runs New Mexico Tech's Molecular Modeling Lab. His recent research projects concern modeling the binding of small organic molecules to biomolecules to study the effects of new drugs with anticancer potential. He has extensive teaching experience at both undergraduate levels and graduate levels and is heavily involved with curriculum design. Prior projects involve developing a Living Learning Community on the topic of sustainability for first-year students, as part of a Department of Education grant. He has an extensive background in computer programming, with prior work experience for Edkey and Tech Seven Systems Inc., both Portland-based companies.

Melissa Candelaria- Lyons

Melissa Candelaria- Lyons worked as a Research Chemist at the Energetic Materials Research and Testing Center and is a Ph.D. student in Materials Engineering with an emphasis in Explosive Chemistry. She was part of the WSIIR team until April 2016 when she accepted a position as Explosives Characterization Specialist and Project Manager with K2 Constructions Consultants, Inc.

Gina Chavez

Gina Chavez is the Administrative Assistant for New Mexico Tech's Office of Research and Economic Development.

Ali Fakhimi

Dr. Fakhimi received his PhD in Civil Engineering from the University of Minnesota in 1992 and is currently a professor in the Mineral Engineering Department at New Mexico Tech. He has more than thirty years of experience dealing with both physical and numerical testing of geomaterials. In particular, he has developed two computer programs called CA2 and CA3 for two and three dimensional analysis of geomechanical problems. These computer codes are hybrid discrete-finite element programs for solving large deformation, dynamic and coupled problems. Dr. Fakhimi worked for several years in stability analysis of underground excavations and dam foundations. In 2002, he joined the Mineral Engineering Department at New Mexico Tech. During the last 15 years at Tech, in addition to teaching, he has been involved with several projects from research agencies and industry. His work for DTRA was related to crack propagation and shear banding of rock under dynamic loading. In the Questa project, the time-dependent stability of waste rock piles in Questa mine, New Mexico was studied. Dr. Fakhimi was in charge of the design of a large shear box and in situ shear testing. In addition, he served as the member of the geotechnical and numerical analysis teams in this multidisciplinary project. His role on the WSIIR team has included reviewing the modeling practices conducted by LANL and the TAT in their investigations.

Julie Ford

Dr. Ford is Professor of Technical Communication at New Mexico Tech, housed within the Mechanical Engineering department. Along with teaching both undergraduate and graduate communication courses to Mechanical Engineering students, Dr. Ford coordinates the Junior and Senior Capstone Design Clinics for the Mechanical Engineering department, interfacing with industrial sponsors for 20 student teams. She has served as the Communication Specialist on the WSIIR team, ensuring that information is presented to the public in a clear and transparent manner. Dr. Ford's research involves engineering communication, organizational communication, and knowledge transfer. She has published and presented widely including work in the *IEEE Transactions on Professional Communication, Journal of Engineering Education, the Journal of STEM Education: Innovations and Research, the Journal of Technical Writing and Communication, Technical Communication* and *Technical Communication Quarterly*. Prior to joining the faculty at New Mexico Tech, Dr. Ford worked as a communications consultant and researcher with McCulley/Cuppan LLC, providing documentation training to clients within the pharmaceutical industry.

Michael Hensley

Dr. Hensley is Director of Strategic Research Initiatives for the Research and Economic Development Division at the New Mexico Institute of Mining and Technology. During the past eleven years, he has managed projects funded by the Department of Energy, the Department of State, and the Department of Homeland Security. At New Mexico Tech, Hensley has performed in many senior leader positions. He was Director of the USDOS International Law Enforcement Academy Graduate School for six years, Deputy Director of the USDOE National Training Center at Kirtland AFB, NM for three years, and Principal of the New Mexico Center for Energy Policy, co-located in Hobbs and Socorro, NM for the past four years. He has overseen energy research and project development and was the co-investigator for a $3.7m USDOE grant to develop a water cleaning system that is now commercially deployed in the New Mexico and Texas oil fields. Earlier in his career, Hensley was also Director of the Virginia Tech Economic Development Center and an Assistant Professor in the School of Urban Affairs and Planning. He was appointed as a Senior Community Builder Fellow by President Clinton and served primarily as an energy education and economic development advisor for the United States Department of Housing and Urban Development. He has spent four years as the Deputy Director of the New Mexico State University Solar Energy Institute and two years as the Director of the Noble Center for Advanced Technology at Oklahoma State University. Hensley received his Ed.D. in Technology Education from Virginia Tech and did post-doctoral study in Organizational Communications at the John F. Kennedy School at Harvard University.

Navid Mojtabai

Dr. Mojtabai has a BS (1984) and MS (1984) in Mining Engineering from New Mexico Institute of Mining and Technology and a PhD (1990) in Mining Engineering from University of Arizona. Both the MS and PhD degrees were with specialization in blasting and explosive engineering. Dr. Mojtabai has over 25 years of teaching and research in various fields of mining engineering. Most of his activities have been in the areas of surface and underground mine design and operations, drilling and blasting applied to mining and construction, applied geomechanics in surface and underground excavations. Dr. Mojtabai has been involved in research activities in underground potash mines in Carlsbad New Mexico. One project concerned studying surface subsidence from mining, field measurements and computer modeling. This project was funded by WIPP. Another project included monitoring underground closure rates and computer modeling of roof and pillar behavior in an underground Potash mine. This work was supported by Mosaic Mining Company. Several of Dr. Mojtabai's research projects have related to rock fragmentation, studying damage from blasting, and ground vibration. Other areas of research have pertained to environmental issues such as studying tailings dam design and analysis. A current ongoing project is focused on abandoned mines in New Mexico and is supported by the Environmental division of State of New Mexico and Abandoned Mine Land office.

Appendix B: Technical Assessment Team Responses to WSIIR Questions

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Waste Isolation Pilot Plant Technical Assessment Team Response to WIPP Site Incident Independent Review Team Questions

July 10, 2015

SRNL-MS-2015-00098

Lawrence Livermore National Laboratory

Oak Ridge National Laboratory

Pacific Northwest National Laboratory

Sandia National Laboratories

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CONTENTS

LIST OF ACRONYMS AND ABBREVIATIONS

AIB	Accident Investigation Board
APTAC	Automatic Pressure Tracking Adiabatic Calorimetry
atm	atmosphere
DOE	Department of Energy
DSC	differential scanning calorimetry
EM	[Office of] Environmental Management
ESD	electrostatic discharge
GC	gas chromatography
IC	ion chromatography
ICP	inductively coupled plasma
INL	Idaho National Laboratory
LANL	Los Alamos National Laboratory
LC	liquid chromatography
LLNL	Lawrence Livermore National Laboratory
MS	mass spectrometry
NASA	National Aeronautics and Space Administration
NMT	New Mexico Tech
OES	Optical emission spectrometry
ORNL	Oak Ridge National Laboratory
P7R7	Panel 7 Room 7
PNNL	Pacific Northwest National Laboratory
Pu	plutonium
R&D	research and development
SEM-EDS	scanning electron microscopy-energy dispersive x-ray fluorescence spectroscopy
SITI	Sandia Instrumented Thermal Ignition
SNL	Sandia National Laboratories
SRNL	Savannah River National Laboratory
TAM	Thermal Activity Monitor
TAT	Technical Assessment Team
TEA	triethanolamine
TG-MS	thermogravimetric- mass spectroscopy analysis
WIPP	Waste Isolation Pilot Plant
WSIIR	WIPP Site Incident Investigation Review
XRD	x-ray diffraction [spectroscopy]
XRF	x-ray fluorescence

1.0 INTRODUCTION

PURPOSE

This document provides the responses of the Waste Isolation Pilot Plant (WIPP) Technical Assessment Team (TAT) to questions asked by the WIPP Site Incident Independent Review (WSIIR) team about the WIPP TAT report released in March 2015. The WIPP TAT responses address both the general inquiries regarding the TAT's overall approach and the specific questions about analytical techniques and modeling and experimental results. The responses are arranged in the same order as the questions received. At the request of the WSIIR team, WIPP TAT representatives will participate in the WSIIR team's meeting scheduled for August to discuss the WIPP TAT responses.

BACKGROUND

WIPP Radioactive Material Release Event

On February 14, 2014, an incident in the WIPP underground repository resulted in the release of radioactive material into the environment. No personnel were determined to have received external contamination; however, twenty-one individuals were identified through bioassay to have low-level amounts of internal contamination, and trace amounts of radioactive material were detected off-site following the incident. [AIB, April 2014]

WIPP Accident Investigation Board

The Department of Energy (DOE) Office of Environmental Management (EM) expanded the scope of the Accident Investigation Board (AIB) that had been established to investigate the February 5, 2014 salt-hauling truck fire in the WIPP underground to include investigation of the WIPP radiological release. The scope of the AIB's investigation is broad and includes identifying all relevant facts; determining direct, contributing, and root causes; developing conclusions; and determining measures to prevent recurrence. [Moury, March 2014]

The AIB's Phase 1 Investigation Report released in April 2014 concludes that the direct cause of the event was the "breach of at least one transuranic (TRU) waste container in the underground which resulted in airborne radioactivity escaping to the environment downstream of the HEPA filters." The Phase 1 Investigation Report notes that "the exact mechanism of container failure . . . is unknown at this time and must be determined once access to the underground is restored. This will be investigated in Phase 2." [AIB, April 2014]

WIPP Technical Assessment Team

To complement the AIB investigation, DOE established the WIPP TAT to determine to the extent feasible the particular mechanism(s) and chemical reactions that may have resulted in the failure of the waste drum and release of material in WIPP. This narrowly defined scope allowed the TAT to confine its investigation to the technical aspects of the release while the AIB conducted its broader investigation.

The TAT was chaired by the Savannah River National Laboratory (SRNL) and composed of members from SRNL and Lawrence Livermore National Laboratory (LLNL), Oak Ridge National Laboratory (ORNL), Pacific Northwest National Laboratory (PNNL), and Sandia National Laboratories (SNL). The TAT's national-laboratory team approach provided scientific and technical rigor and credibility needed to assess the event and support DOE's implementation of a WIPP recovery plan.

The TAT undertook an extensive process of historical data review, sample collection and analysis, laboratory testing, and computational modeling to understand the release event in WIPP. Investigative constraints, such as incomplete documentation of the processes used to create the drum that breached and the physical inaccessibility of the breached drum in WIPP, created uncertainties, which made collection and interpretation of scientific data alone insufficient to reconstruct the event fully. However, the TAT evaluated the uncertainties and utilized expert assessments of available information and analytical data to fulfill its charter.

Using this strategy, the TAT reached its overarching conclusion and five associated key judgments. (*Waste Isolation Pilot Plant Technical Assessment Team Report*. March 17, 2015. Savannah River National Laboratory. SRNL-RP-2014-01198. http://energy.gov/em/downloads/technical-assessment-team-report)

WIPP Site Incident Independent Review (WSIIR) Team

The WSIIR is an independent review team established by the State of New Mexico to review the events leading up to the closure of WIPP and recommend changes needed to resume operations.

The WSIIR team is composed of faculty, administrators, and staff of New Mexico Tech (NMT) and is led by NMT's Vice President for Research and Economic Development.

In addition to examining the circumstances that led to the rupture of the waste containment drum in WIPP and defining the magnitude of the reaction, the WSIIR will conduct open-to-the-public meetings in the Carlsbad area to collect and understand public concerns regarding WIPP operations. The information gained from these meetings will aid the team in developing recommendations for future operations.

The expected result of this work will be a more resilient, safe, and robust program that will restore credibility with and support from the community and state.

As part of their mission to conduct a transparent review, all WSIIR work is documented and available to the public. Beginning in August 2015, the WSIIR team will publish quarterly reports accessible to the public. (http://www2.nmt.edu/wsiir)

2.0 WIPP TAT RESPONSES TO WSIIR TEAM QUESTIONS

2.1 METHODS

1. With what criteria were the methods used by TAT decided upon?

   Approaches and methods used by the WIPP TAT were selected to answer questions that were central to gaining an understanding of the underlying cause(s) of the breach of LANL Drum 68660. The WIPP TAT relied on historical records, visual observations, chemical analyses, small-scale testing, and modeling to characterize the release event and answer questions about the nature and causes of the release. This strategy was dictated in part because the site of the release was inaccessible, precluding direct examination and collection of samples for analysis. The TAT used accepted principles of forensic science, analytical and radioanalytical chemistry, and thermochemical and mechanical modeling as well as tractability, quality control and assurance, and peer review to guide the selection and use of methods of inquiry. Proposed methods were discussed, vetted and approved by the WIPP TAT prior to implementation.

2. Were there additional methods considered but not used, and if so, why?

   Yes, additional methods were considered for application to sample analysis, modeling, material characterization, and sub-scale drum testing, but not used. In some cases this was because methods changed based on sample condition and availability or evolving TAT understanding of WIPP conditions and waste characteristics. In general, methods that were considered but not used may have refined elements of the TAT's understanding of the event but were not expected to substantially affect its conclusions.

3. Did the TAT consider conducting any modeling or simulation on the sibling drum?

   No, modeling of drums other than 68660 was not considered. Modeling of a thermal runaway was conducted for Drum 68660 because it was the drum known to have breached at the time of the TAT study. The contents of sibling Drum 68685 (solid waste and a lead liner) are significantly different from the contents of Drum 68660 (which received the job waste and absorbed liquids). Thermal runaway modeling of Drum 68685 would not provide direct insight into the behavior of Drum 68660.

4. Page 40 refers to the TAT interfacing with LANL : "as they conducted small scale tests to evaluate potential reactivity within the MINO2 waste." What kind of tests were conducted by LANL and what is the MINo2 [sic] waste?

   The MIN02 is a waste stream generated by LANL in the 1970s and 1980s from the recovery and purification of Pu. Details are in Section 3.1 (p.17) and Appendix E (p. 150) of the WIPP TAT report. The process resulted in material consisting primarily of metal nitrate and oxalate salts. It is from this waste stream that the parent of Drum 68660, Drum S855793, was generated. Given knowledge of the MIN02 waste stream and the remediation processes that generated Drum 68660, assessments of potential mixtures within Drum 68660 could be determined for characterization of exothermic reactivity using small-scale testing. After the breached drum was established to contain MIN02 waste, LANL performed a number of bench-scale tests to evaluate the reactivity of mixtures of the components of the MIN02 waste stream, neutralizing agents and the Swheat Scoop®. These results were reported periodically to the TAT through presentations, reports, and teleconferences. LANL's testing included a wide range of surrogate waste mixtures using Differential Scanning Calorimetry (DSC), Automatic Pressure Tracking Adiabatic Calorimetry (APTAC), Thermal Activity Monitor (TAM), and explosive sensitivity tests (Impact, ESD, Friction, DSC, and Vacuum Stability). These findings, along with MIN02 waste stream characterization data, provided input to the deliberations of the TAT, which included independent bench-scale reactivity testing at SNL and PNNL. A summary report of the LANL reactivity testing is provided in the report authored by D.L. Clark and D.J. Funk, "Chemical

Reactivity and Recommended Remediation Strategy for Los Alamos Remediated Nitrate Salt (RNS) Wastes", LA-UR-15-22393, Feb. 17, 2015; cited in the TAT report as LA-CP-15-20082.

5. Did the TAT consider modeling a worst case scenario of all sibling drums being in the same room at the same time?

   No. Co-location or proximity of sibling drums is not believed to significantly affect the likelihood of ignition. However, an assessment of the effect of an igniting drum on a neighbor drum was made and is discussed in the "External heating" section (p. 81) of the report. Although this assessment showed that ignition of a drum due to external heating following ignition of another drum is possible, no evidence of additional drums breaching or having extensive discoloration was found.

2.2 CODE

6. Why was CTH-TIGER code used instead of Cheetah for modeling?

   Any equilibrium code would have been appropriate for the calculations conducted as long as an appropriate library of potential products was utilized. CTH-TIGER was chosen for this effort specifically as it has been shown to be more accurate when calculating equilibrium properties for reactants composed of a large number of atoms including metals. (Hobbs ML, Brundage AL, and Yarrington CD, "JCZS2i: An Improved JCZ Database for EOS Calculations at High Temperature and Pressure" 15th Int. Det. Symp, San Francisco, CA (2014))

7. What version of the computer code was used?

   CTH-TIGER is maintained by SNL. The most recent version of CTH-TIGER was used and committed to the SNL version control repository on August 30, 2014.

8. What input of the code was used?

   The input to CTH-TIGER included the reactant mass fractions and the product library. A good reference for the Jacob, Cowperthwaite, Zwisler, Sandia (JCZS) product library used is provided in Hobbs, ML, Baer MR., McGee BC, "JCZS: An Intermolecular Potential Database for Performing Accurate Detonation and Expansion Calculations," Propellants, Explosives, Pyrotechnics, 24, 269 (1999). This library uses the same product species found in the Joint Army, Navy, NASA, Air Force (JANNAF) tables found in Chase MW, Davies CA, Downey JR, Frurip DJ, McDonald RA, Syverud AN, JANNAF Thermochemical Tables, Third Edition, Journal of Physical and Chemical Reference Data, 14 (1985).

9. How did the TAT assure the code was running properly?

   The code has been extensively compared to detonation properties as well as to the NASA-CEC code for rarefied gas dynamics as shown in the paper by Hobbs et al. (2014), cited above, to validate its results. The code has also been used to reproduce the water phase diagram, water hugoniot, sound speed data, etc. It is recognized that the equation-of-state used in an equilibrium code impacts the results. Specific to this work, a check was conducted on the CTH-TIGER results. As a check, selected equilibrium points with both the NASA-CEC and the CTH-TIGER codes were conducted and demonstrated to provide similar results.

10. Page 28: It appears that the chemical simulation was conducted under a constant pressure of 1 atm. In reality, the pressure was variable. What would be the prediction of the CTH-TIGER code if pressure is considered variable?

In comparison to the calculations shown on page 28 which found the adiabatic flame temperature to be 618 °C at 1 atm, at 2 atm the adiabatic flame temperature is predicted to be 642°C. The pressure is believed to be limited to this range by a combination of the drum vent and the failure pressure of the drum lid closure.

2.3 MODELING

11. Page 29: It appears that two models have been utilized: 1) a chemical model under constant pressure, 2) a mechanical model that has gas pressure as input. Is that the case? Shouldn't the first chemical model be under variable pressure to get more realistic and consistent results?

There were three models used: 1) equilibrium calculations to determine the equilibrium products at given temperatures (CTH-TIGER), 2) a chemical kinetic model with three representative processes and associated kinetics, and 3) a mechanical model for the drum response to pressure. The chemical kinetic model was a "prescriptive model" as opposed to a "predictive model", in that it used kinetics intentionally adjusted to result in ignition in 70 days. Insufficient data were available to develop a pressure-dependent kinetics model, so the kinetics for this model were not pressure-dependent and therefore provided the same answer whether or not the gases were vented or remained sealed within the vessel. However, because the degree of reaction relates the heat released to the amount of gas generated, the kinetic model also predicts gas generation. The amount of gas formed can be converted to pressure depending on the assumed degree of confinement. This rate was used as a limiting condition for the drum mechanical model. After ignition, the dynamic burn and subsequent rapid pressurization were not calculated.

12. Page 31: The finite element model shows that runaway occurs after 70 days, exactly similar to what was observed in reality. Considering many approximations and assumptions in the model, such accurate prediction is very unlikely.

It is important to keep in mind that the model was prescribed to undergo thermal runaway at the time it did by adjustment of the activation energies used in the model. This was done to demonstrate the feasibility of the mechanism and to provide a tool for associated analyses. The detailed information required to develop a predictive model (i.e., identification of rate-determining processes and associated kinetics) does not exist and cannot be determined with any certainty given limitations in knowledge regarding the drum contents and their distribution. Therefore, the model is prescriptive rather than predictive. The kinetics used were adjusted to match the apparent 70-day ignition time but could be adjusted for ignition at any time. The main objective of this exercise was to determine if thermal runaway was an ignition mechanism, and the result was that the model was able to replicate ignition at 70 days with realistic kinetic parameters. In addition, the model provided a tool to conduct related analyses, e.g., estimation of the wall temperature at ignition, sensitivity to input parameters and boundary conditions, and sensitivity to external heating.

13. Is the accurate prediction due to calibration of the model (e.g. by using heat sources of 0.12 Watt for nitrate salt and 0.17 Watt for neutralized and sorbed liquid layer) to get this very accurate result?

The kinetics in the thermal chemical model were prescribed as described previously. The constant heat sources are real numbers determined from the amount of radioactive decay in each layer. See Appendix E, Table E-9 (p. 160) of the WIPP TAT report. This is a very small source of energy. If we turned off this source, the ignition would have been delayed by about 5 days using the same kinetics. The point is that it was not because of the presence of radioactivity that the runaway occurred, which was an important question for the TAT. The thermal runaway would have occurred regardless of the radioactivity. More details of this assessment are discussed in Appendix D (page 82) of the WIPP TAT report.

14. Why is the assumed heat conductivity of the contents of Drum 68660 so low that in 70 days, almost no increase (only 1° C) in the drum body temperature was realized? This low increase in the temperature of the drum body is not consistent with temperature monitoring of other drums which are being monitored by LANL. Their monitoring shows increase in the body temperature.

    The thermal conductivity of surrogate waste mixtures was measured at SNL in the SITI apparatus using the methodologies discussed in Erikson WW, Cooper MA, Hobbs ML, Kaneshige MJ, Oliver MS, Snedigar S., "Determination of thermal diffusivity, conductivity, and energy release from the internal temperature profiles of energetic materials," International Journal of Heat and Mass Transfer, 79, 676 (2014) and was typical for non-metallic granular solids. Previous work has shown that the surface temperature of drum-scale thermally decomposing objects remains very close to ambient temperature up to ignition. We have not seen any temperature measurements on drums being monitored by LANL that indicate internal heating and would not expect such indications given how the measurements have been made, namely on the outside of waste boxes containing waste drums and empty drums.

15. Page 31: It appears that an uncoupled modeling has been used: 1) a chemical model and gas generation. 2) a mechanical model with gas pressure applied inside the drum. Was the drum vent part of the model? Isn't a full coupled model more realistic?

    The thermochemical model calculated the temperature profile within the drum over the 70 days leading to ignition. The mechanics model simulated the mechanical response of the drum after ignition, when significant pressurization occurred. Because the two models were used over different times and time scales, direct coupling was not attempted. Since coupling of the models would be primarily through pressure loading resulting from gas generation, as modified by losses through the drum vent, the vent was not part of either model.

    While a fully coupled model would have the potential to be more accurate and address certain scenarios such as a blocked vent, this was not necessary to meet the objectives of the TAT and would require significantly more information than was available.

16. Page 32: Is the stress analysis of the drum an elasto-plastic or visco-plastic model? What boundary conditions were applied to the drum lid? If the vent was not part of the model, why is it claimed that: "This slow pressurization was sufficient to overcome the drum vent"?

    The stress analysis of the drum used an elastic-plastic model.

    The boundary conditions applied to the drum lid were a) the material contact between the closure ring, the drum body, and the lid and b) the applied pressure condition. In addition, c) for some cases a pressure load consistent with the weight of the MgO was applied, and d) some cases were analyzed with a surrogate drum on top of the pressurized drum.

    The vent was not part of the mechanical model of the drum.

    It is claimed "This slow pressurization was sufficient to overcome the drum vent" because even the slower pressurization rate simulated in these mechanical analyses simulates a pressure generation event (ignition) that is fast enough to overcome any reduction due to a working vent. Two different pressurization rates were modeled to demonstrate what such an event might do to the drum. These were not specific to a certain event, but are considered within a regime of potential runaway type events.

17. Page 34: The air flow and change in temperature in P7R7 was modeled to find out the impact of the truck fire on Drum 68660. How was the heat source (burning of the truck) modeled in this situation?

A detailed model of the combustion was not used or deemed necessary. Rather, fires with constant thermal outputs of 5 or 10 MW deposited energy into the flows that were estimated for the mine air shafts. As indicated in the footnote on page 128, the 5 and 10 MW numbers were incorporated from AIB analyses. Flow conditions and other important factors at the time of the fire are poorly known. Inputs for more detailed models of the combustion cannot be specified with confidence. Consequently, as described in Appendix D, the analyses of the fire products flowing toward the distant P7R7 were handled parametrically both in terms of the fire's thermal output and the flow conditions. These analyses indicated only small temperature rises at P7R7.

More detailed analyses cannot be supported with reliable descriptions of required detailed boundary conditions, and these simpler energy balances consistent with first laws indicate that the fire's output could not reach the waste array. This conclusion was true even with conservative assumptions regarding the fire's energy deposition into the shaft air in the immediate vicinity of the truck.

18. Page 95: "The hardening curves from the test data were implemented in the analysis for the elastic-plastic model". How? Did the TAT try to simulate the uniaxial tensile tests? How about the softening? Did the TAT conduct a large deformation analysis?

The Sierra/Solid Mechanics model designated as "elastic_plastic" was used for the analyses that used the "original mechanical property estimate" (based on Ludwigsen, J. S., D. J. Ammerman, and H. D. Radloff. "Analysis in Support of Residues in the Pipe Overpack Container. 1998. SAND98-1003. Sandia National Laboratories. Albuquerque, NM). This model is an elastic-plastic, linear-hardening model. Linear hardening generally refers to the shape of a uniaxial stress-strain curve where the stress increases linearly with the plastic, or permanent, strain. The model used was the isotropic version.

The Sierra/Solid Mechanics model designated as "ml_ep_fail" was used for the analyses that were based on the mechanical tests from the sample drum lid and closure ring. This model is the multi-linear, elastic-plastic hardening model with failure. However, failure was not implemented. It is similar to a power-law hardening model (common in most finite element analysis codes) except that the hardening behavior is described with a piecewise-linear curve as opposed to a power law. For these analyses, the piecewise-linear curves were based on actual tensile tests performed on coupons from the sample lid and closure ring.

We did not simulate the uniaxial tensile tests. Mechanical properties are derived from the tests, and simulation of the tests is not necessary.

Softening was not included in the analysis.

The Sierra/Solid Mechanics analyses presented are all large deformation analyses.

19. Page 97: Second paragraph: Is our reading accurate that the computer program used did not model the drum content? Therefore, is it correct that no gas-drum interaction was modeled? A time varying pressure boundary condition was applied that was not affected by bulging of the drum?

It is correct that no "gas-drum" interaction was modeled. The pressure on the surface of the drum varied only as a function of time. The magnitude of the pressure did not vary as a function of the internal volume of the drum. The pressure was applied normal to the surfaces of application. So, as the surfaces deformed, the pressure direction remained normal to the surface.

20. Page 99-106: The yielding stress (also the stress contours) was either 29×103 or 40×103 psi. It does not seem hardening was modeled (even though it is claimed to be part of the model). Based on Figs. D10 and D11, steel can carry up to 50×103 psi Von-Mises stress, which is not the case in figures reported in pages 99-106.

    Hardening was modeled. The figures on pages 99-106 are plotted with a maximum contour limited to the yield value. So, anywhere in the figure that the color is fully red means that the Von-Mises stress is at the yield value or greater. The purpose of plotting the figures this way was to demonstrate as simply as possible the regions that are at or above yield.

21. Page 107: It is noted that "the deformation of the lid might provide an indication of the rate of the pressurization." Have there been any attempts to see the actual deformed shape of the Drum 68660?

    Due to radiation hazards to personnel, no visual inspections of the room or breached drum were allowed other than the images obtained remotely by the Accident Investigation Board in May and then later in Project Reach. The TAT used the photographs available from these two exercises. However, it was difficult to see the actual shape of the lid because it was covered with MgO.

22. Page 108: "Without a better understanding of the strain in the closure ring, it was not felt it was advisable to pursue some of these issues. There is uncertainty regarding how consistent the closure ring strain is from drum to drum. An improved understanding of this is advisable prior to pursuing further mechanical modeling with respect to predicting opening pressure." Can strain gages be installed and used to measure the actual closure ring strain?

    Yes, strain gages could be installed and used to get some indication of the actual closure ring strain. However, there would still be some uncertainty with respect to how that related to Drum 68660. It would remain uncertain how the properties of any tested "sample" drum material might relate to drums that have already been put into service.

23. Page 109: It is noted that "No analyses showed the drum rupture on its sidewall and one would not expect that to happen from this type of a pressurized event." Was the model used capable of actually showing the rupture in the drum?

    No specific method was applied to the analyses to predict "rupture" of the metals. However, rupture in this material would most likely be preceded by very high strains concentrating locally. The model is capable of predicting such concentration of strains.

2.4 RESULTS

24. Page 19: Table 3-1 lists the samples collected. Why are samples 4 and 5 not listed or accounted for?

    Samples 4 and 5 were not collected. We were prepared to collect up to five samples from the surface of the drum stack at 15-5 and the lip of 16-4 in P7R7 if the constraints of the August 15, 2014 sampling operation allowed; we collected three samples from those locations during that operation. The chain-of-custody document received by the TAT lists those three samples (Samples 1, 2, and 3) from 15-5 and 16-4 as well as two samples of MgO (Samples 6 and 7). All were accounted for by the TAT. A copy of the chain-of-custody is available in *Sampling Report for August 15, 2014 WIPP Samples*, December 19, 2014, Forensic Science Center, Lawrence Livermore National Laboratory, LLNL-TR-667000.

25. Based on Fig. 4.2, almost all ingredients of Drum 68660 are lighter than water. Wouldn't this cause the material to mix up? The lighter material should gradually move upward and this especially is encouraged when the drum is shaken and moved, i.e. during its transportation.

    The densities listed in Figure 4-2 are the overall bulk density of each layer and not of the specific density of the material in the mixture. The bulk density includes any void volume that may have existed in each layer, which would decrease the bulk density with increasing void fraction. That being said, the TAT did not conduct experiments to evaluate the post-mixing and separation of materials, and associated kinetics, within the mixtures of each layer and amongst the individual layers that may have occurred in Drum 68660 due to handling and transport. This type of experiment would be helpful if a predictive thermal runaway model was pursued. The remediation process does entrain the free liquids and liquid in the salt with the Swheat Scoop® material. The water in Drum 68660 was absorbed by Swheat Scoop® as well as entrained in various hydrates and would not be expected to separate from the Swheat Scoop® and hydrates at the resident temperatures over the majority of the lifetime of the drum.

26. Page 27 (first and second paragraph): "The chemical and physical forms of these layers and interfaces are different in chemical reactivity and thermal conductivity. The degree of mixing between the layer of neutralized and sorbed liquid and the layer of nitrate-salt admixture is not known". "The physical configuration at the interface of the neutralized-and-sorbed liquid/Swheat Scoop and the nitrate-salt and mixture/Swheat Scoop layers may have formed a localized region of reactivity leading to the thermal-runway event". Based on our previous question about the materials shown in Fig. 4.2 mixing up, how certain are you about the existence of this localized region?

    There is no absolute certainty about the nature of the interfacial region between the admixture of TEA-neutralized free liquid and Swheat Scoop® and that of the moist nitrate salts and Swheat Scoop®. Bench scale testing indicated that the admixture of TEA-neutralized free liquid and Swheat Scoop® as well as that of the moist nitrate salts and Swheat Scoop® are both reactive. The TAT hypothesized that additional mixing of the two layers, beyond that which occurred during assembly of the drum, could have occurred during post-assembly handling and transport of Drum 68660. Such mixing, if it occurred, increases the possible range of chemical environments and conditions that would support a localized thermal runaway reaction. Note that the thermal chemical model was dependent upon the amount of energy contained in the system and not on the specific location for the initiation. However, the physics of a slow thermal runaway process is characterized by a localized region becoming increasingly reactive and progressing to the runaway condition, which makes one pay attention to areas that are candidates for localized reactivity, such as interfaces of two reactive admixtures.

27. Page 29: Fig. 4.3: The CTH-TIGER model shows localized high temperature after 70 days. Do you consider both heat conduction and convection in the model? Might the high temperature gradient observed in the model be due to unrealistic heat conduction/convection coefficient used?

    For clarity, the CTH-TIGER model was used for the equilibrium calculations and not the determination of the temperature profile in the drum as a function of time. The thermal/chemical model used was SIERRA/Thermal (sometimes referred to as ARIA). Yes, heat conduction, convection, and radiation are considered in the thermal/chemical model. The conductive energy equation with a source term was applied to the waste. Enclosure radiation and free convection were modeled in the head space. The exterior of the drum considered radiative heat loss as well as convective heat loss. Page 82 explains how a radiation boundary temperature of 300 K was used. In addition, a 300 K free convection boundary condition was applied. The conductivity was measured using a surrogate material for the nitrate salts mixed with Swheat Scoop®. The high temperature gradient at ignition is a result of energy being generated faster than the energy is dissipated. The exponential rise in reaction rates with temperature is a result of using temperature dependent Arrhenius-like reaction rates. Conduction/convection coefficients used were deemed realistic and comparable to other scenarios that have been modeled with the Sierra/Thermal code.

28. Page 77: 1st paragraph: The X-ray was used to observe the layer interfaces of different materials in Drum 68660. How did the TAT know the arrangement from top to bottom of these materials?

The TAT obtained a copy of the radiographic video of Drum 68660 produced at Los Alamos. This video documents the arrangement of the materials in Drum 68660 prior to shipment of the drum to WIPP, consistent with the waste logs and discussions with the operators. In addition to the video, the radiographer's commentary while performing the analysis was documented. The TAT requested the video to be analyzed by an expert at INL to obtain a second interpretation of the Drum 68660 radiographic video. Both interpretations are included in the report (see page 176). From the reports aligning still photographs captured from the video, the TAT was able to align the layers of materials from the bottom to the top of Drum 68660.

29. Page 80: Equation (17) considers the reaction heat sources and heat conduction. How about the convection process?

Equation (17) is the conductive energy equation and does not include internal convection. Internal convection was not considered relevant because the drum contents were primarily solids, and circulation of air and other free liquids would contribute minimally to heat transfer. However, external convection heat loss was included as part of the boundary conditions. We used a free convection boundary condition as well as a radiative boundary condition. The radiation temperatures as well as the bulk convective temperatures were assumed to be 300 K. The convection coefficient was assumed to be 50 W/m2K. The emissivity of the drum was assumed to be 0.9.

30. Page 94: Are the drum mechanical tests referred to in the literature numerical or physical tests or both?

The drum mechanical tests referred to in the literature are actual physical tests.

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