Office of Oversight
Environment, Safety and Health

Type A Accident Investigation
of the December 8, 1999

Multiple Injury Accident Resulting from the Sodium-Potassium Explosion in Building 9201-5 at the Y-12 Plant

February 2000

PROLOGUE

The December 8, 1999 chemical explosion at the Y-12 Plant that injured 11 workers, three of whom required hospitalization, could have been prevented. The explosion resulted from the failure of the many barriers that we count on to prevent or mitigate such accidents, and in particular, the failure of the site to implement Integrated Safety Management.

This Type A accident investigation shows that there were failures associated with Integrated Safety Management within the DOE Oak Ridge Operations Office and at every level of the Lockheed Martin Energy Systems management chain. These failures caused numerous missed opportunities to prevent the inadvertent spill and spraying of NaK and the consequent explosion. I am especially concerned with the lack of understanding and appreciation for the chemical hazard involved and the failure to pursue additional information or expertise in the face of unusual or unexpected conditions.

Integrated Safety Management is not a paper exercise; it is not a philosophy. ISM must be a way of doing business every day, for both management and workers. This accident highlights the importance of an integrated and standards-based approach to safety that stresses implementation of the five core functions of integrated safety management by all levels of an organization.

Significant and prompt senior DOE and Lockheed Martin management attention is needed to better protect workers by improving the way ISM and management systems are implemented. Lockheed Martin must take a comprehensive look at how it implements existing requirements so that the integrated approach to safety management is effective. Lockheed Martin must examine the clarity of roles, responsibilities, authority and accountability for implementing ISM. DOE-Oak Ridge, including the Y-12 Site Office, needs to strengthen its management oversight and field presence to provide feedback on the adequacy of ISM implementation.

David Michaels, PhD, MPH
Assistant Secretary
Environment, Safety and Health

On December 9, 1999, I established a Type A Accident Investigation Board to investigate the December 8, 1999, multiple injury accident resulting from the explosion involving a sodium-potassium alloy at Building 9201-5 at the Y-12 Plant, in Oak Ridge, Tennessee. The Board's responsibilities have been completed with respect to this investigation. The analysis, identification of contributing and root causes, and judgments of need reached during the investigation were performed in accordance with DOE Order 225.1A, *Accident Investigations*.

I accept the findings of the Board and authorize the release of this report for general distribution.

David Michaels, PhD, MPH
Assistant Secretary
Office of Environment, Safety and Health

2/24/2000
Date

This report is an independent product of the Type A Accident Investigation Board appointed by Dr. David Michaels, Assistant Secretary for Environment, Safety and Health (EH-1).

The Board was appointed to perform a Type A Investigation of this accident and to prepare an investigation report in accordance with DOE 225.1A, *Accident Investigations*.

The discussion of facts, as determined by the Board, and the views expressed in the report do not assume and are not intended to establish the existence of any duty at law on the part of the U.S. Government, its employees or agents, contractors, their employees or agents, or subcontractors at any tier, or any other party.

This report neither determines nor implies liability.

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OVERSIGHT

Executive Summary

Accident

On December 8, 1999, at 9:35 a.m., a chemical explosion occurred within the skull caster furnace section of the Building 9201-5 at the Y-12 Plant in Oak Ridge, Tennessee. The explosion injured 11 workers, three of whom required hospitalization. One worker had third-degree burns on 17 percent of his body and was flown to the Erlanger Burn Center in Chattanooga, Tennessee. The worker was initially considered to be in critical condition and received a number of skin grafts before leaving the hospital on December 21, 1999.

On Thursday, December 9, 1999, the Department of Energy (DOE) Assistant Secretary for Environment, Safety and Health chartered a Type A investigation board to investigate the accident. The Board arrived on site on Friday, December 10, and completed the investigation in January 2000.

Background

On December 1, 1999, Depleted Uranium Operations (DUO) workers in Building 9201-5 were changing out the crucible in the skull caster furnace. This crucible is cooled by a sodium-potassium liquid metal alloy (NaK). The crucible was last changed out in 1993, and the workers were using a new procedure for the activity. When workers removed a flexible argon purge hose from the crucible, several gallons of NaK sprayed out through an open isolation valve into the furnace.

Over the next several days, the workers monitored conditions in Building 9201-5 and intermittently purged the furnace with argon in an attempt to minimize further oxidation. Facility management developed a recovery plan outlining the process for cleaning up the NaK spill. On Friday, December 3, the workers observed unusual and unexpected conditions in the furnace, including a yellow color and abnormal configuration of the material. Mineral oil was sprayed on the deposits to minimize oxidation.

On December 8, the explosion occurred while the workers were attempting to clean up the NaK using a vacuum probe and metal rod, having sprayed additional mineral oil. The direct cause of the explosion was the impact of a metal tool on a shock-sensitive mixture of potassium superoxide (KO_2) and mineral oil.

Results and Analysis

Some aspects of the emergency response to this accident were effective. For example, the workers promptly assisted the most severely injured workers to the safety showers. In addition, the fire department and radiation control personnel responded promptly and effectively to transport the injured personnel and prevent the spread of contamination. However, the accident highlighted deficiencies in numerous aspects of safety management at the Y-12 Plant.

The December 1 NaK spill resulted from numerous deficiencies in the new procedure for crucible changeout. During this work activity, the workers made pen and ink changes without stopping to obtain proper review and approval of the changes. A key step requiring opening of the dump valve to drain the crucible NaK piping had been inadvertently deleted from the procedure, resulting in a failure to open the valve and trapping the remaining NaK under argon pressure. When workers observed an unexpected NaK level in the sump, they did not stop to analyze the system configuration or seek assistance before repeating parts of the procedure. A worker climbed into the furnace to disconnect the argon purge hose. When the hose was disconnected, the trapped NaK sprayed out under pressure into the furnace through an open isolation valve that was also incorrectly aligned because of procedural deficiencies.

In addition to other deficiencies, the changeout procedure was designated Category 3, which does not require verbatim step-by-step compliance. However, the hazards of the work merited a Category 1 procedure, which would have required steps to be followed in sequence, signoffs for key steps, and management review of any changes prior to implementation.

After the spill, facility management stopped work to develop a recovery plan for cleaning it up. The plan was developed in one week using a team approach, including personnel from safety engineering and the industrial safety/hygiene organization. However, the personnel who developed the recovery plan did not adequately understand the hazards associated with superoxide explosions and the use of mineral oil. Further, the recovery plan did not conform to authorized Y-12 Plant mechanisms for controlling hazardous activities. The process did not include a hazard screen or job hazard analysis, and the plan was not subjected to any management or technical review or approval beyond the core group that developed it. The plan failed to address the necessary personal protective equipment (PPE) for the workers engaged in the hazardous NaK recovery; such equipment could have mitigated or prevented the injuries that were incurred.

The crucible changeout procedure and recovery plan did not identify or control the explosion hazard associated with potassium superoxide in the presence of organic materials, such as mineral oil. The explosion hazard is clearly identified in the NaK Material Safety Data Sheets required by the Occupational Safety and Health Administration and in many other documents and publications available on site, including the safety analysis for another Y-12 Plant facility. The recovery plan directed workers to spray the NaK spill with mineral oil and to mechanically break up NaK that could not be vacuumed out. These very actions and conditions caused the explosion and worker injuries.

In both crucible changeout and NaK spill recovery, facility management indicated to the Board that they were attempting to implement the DOE integrated safety management (ISM) policy. The development of a detailed crucible changeout procedure and the use of a multi-disciplined planning group are positive indications of this intent. In both activities, however, the actual implementation of ISM was significantly deficient, indicating a lack of understanding of the policy, a failure to adhere to established procedures, and a continuing reliance on informal, expert-based approaches to work and hazard control. Senior facility management was not adequately involved in the development, categorization, review, validation, or modification of procedures and plans. In addition, although the DUO organization has made progress in implementing ISM, it has not effectively utilized the lessons learned from other events and accidents at Y-12 and throughout the DOE complex, indicating continuing weaknesses in the understanding, acceptance, and implementation of improved safety management programs and processes.

Management at all levels and safety professionals, such as industrial hygienists, did not maintain an adequate level of knowledge on the well-documented hazards associated with NaK. Because previous NaK spills and events had not caused serious injuries, management and work planners apparently developed a level of confidence in their familiarity with NaK and did not seek outside expertise. Inadequate understanding of the hazard, as well as failure to follow the contractor's ISM work control processes, resulted in a hazard analysis and hazard controls that were ineffective in preventing or mitigating the accident.

This accident highlighted weaknesses in programs and processes essential to safety, such as procedure quality, use, and change control; system configuration control; unreviewed safety question determinations; and training. These weaknesses persist, in part, because of a lack of management involvement in safety and weaknesses in the contractor's independent quality assurance function, line management self-assessment programs, and DOE oversight. Further, the December 1 spill was not reported to contractor senior management, safety engineering, the DOE Facility Representative, or the DOE Occurrence Reporting and Processing System as required.

At the activity level, workers involved in crucible changeout and NaK spill cleanup demonstrated a lack of understanding of ISM requirements and a continuing heavy reliance on informal work controls and skill of the craft. When procedures did not work as written, they were changed in process without management review or approval. When workers encountered unusual or unexpected conditions, they continued their activities, including spraying oil, without stopping to obtain appropriate management or technical assistance. ISM would require, as a minimum, revisiting the hazard analysis and reconsidering the hazard controls when, for instance, workers encountered a low NaK sump level or observed unusual conditions and suspected superoxides in the furnace. Given the long history of uneventful use of mineral oil and the level of confidence in its use, it is not clear what would have prompted the DUO workers to stop work and seek guidance. The willingness to stop work and obtain management and technical assistance when procedures or instructions do not work, or when unusual or unexpected conditions arise, is fundamental to effective safety management. Failures in the safety management system contributed to the accident and indicate that Y-12 has not yet developed a standards-based safety culture.

The Board determined that the contractor, Lockheed Martin Energy Systems (LMES), has not effectively incorporated the lessons learned from previous events and accidents, thereby missing a number of opportunities to prevent this accident. In 1992, an NaK release at this same facility prompted corrective actions that involved specific PPE requirements for workers who could come in contact with NaK—requirements not incorporated in the NaK spill cleanup plan. In 1994, LMES generated a lessons-learned document based on a sodium explosion in France that killed one worker and injured four. The facility's response to that document was inadequate, and neither workers nor management questioned its adequacy. In 1997, when an NaK drum and a small reactor containing NaK were discovered in another Y-12 facility, management recognized that the facility safety analysis report did not address these hazards. As a result, the facility filed an unusual occurrence report and performed a hazard screening evaluation that clearly identified the explosion hazard and the chemical reaction that would cause an accident like the one that later occurred in Building 9201-5. However, this hazard information was not effectively communicated to or utilized by workers or planners in Building 9201-5.

In the last five years, Lockheed Martin has experienced six serious accidents resulting in Type A investigations at the Oak Ridge and Idaho National Engineering and Environmental Laboratory facilities it manages for DOE. These accidents included three fatalities and several serious injuries. In each of the two most recent accidents, ten or more workers were exposed to hazardous materials. Similar deficiencies led to these accidents: inadequate procedures or procedure use; overreliance on skill of the craft; informal or inadequate hazard identification, analysis, or control, particularly for work that was considered routine; lack of management involvement and supervision; and inadequate training or competence. Until these systemic deficiencies are corrected, undesired events and accidents are likely to continue, and LMES will not be able to implement ISM fully and effectively.

Conclusions

The Board concludes that this accident and the resulting injuries were preventable. The line managers and work planners responsible for the workers' safety did not understand the imminent hazard of the interaction of the materials and therefore did not provide appropriate hazard controls or worker protection. The deficient level of control resulted from inadequate hazard analysis and unreviewed safety question screening, and from overreliance on past practices and skill of the craft.

LMES needs to expedite full and effective implementation of the DOE ISM policy at DUO and in its non-nuclear facilities. To do so, LMES will need to significantly strengthen the supporting infrastructure and processes, including procedure quality and adherence; the authorization basis and unreviewed safety question determination processes; hazard identification and analysis; quality assurance; and training. In addition, LMES and DOE need to increase their presence in the field to promote and provide training in the tenets of ISM and to provide feedback on progress and lessons learned.

Table ES-1. Root Causes and Summary of Judgments of Need*

Judgments of Need	Root Causes
#1: Strengthen the training and competence for workers and for managers, engineers, and safety and health professionals responsible for worker safety.	LMES failed to establish, seek, or maintain an adequate level of knowledge and competence on the hazards associated with NaK, including the formation of superoxide, the incompatibility of superoxide and organics, and the explosive sensitivity of the mixture to impact or shock.
#2: Strengthen the implementation of the ISM core functions and existing LMES processes to assure that all potentially hazardous work and activities are subjected to effective, formal, and documented hazard analysis.	LMES's implementation of the hazard analysis and control processes failed to identify, prevent, or mitigate the explosive interaction of potassium superoxide, mineral oil, and impact. The NaK Material Safety Data Sheet was not used.
#3: Strengthen the identification and implementation of engineering, administrative, and worker protection controls for potentially hazardous work and activities.	LMES management systems and processes did not assure adequate procedures or controls to prevent the loss of system configuration control resulting in an NaK spill or to preclude the addition of mineral oil and impact in the presence of potassium superoxide during NaK spill recovery.
#4: Strengthen the implementation of the ISM feedback process through improved sharing of technical expertise and information and through use and appropriate application of lessons learned from events, accidents, and near misses.	LMES management failed to effectively communicate or utilize information from the hazard screening evaluation, lessons learned, previous events and accidents, studies, analyses, and publications in planning and controlling this work and the associated hazards to worker health and safety. Knowledge of this hazard and expertise to address it were readily available at the Oak Ridge Reservation and other DOE sites.
#5: Expedite the understanding, acceptance, and implementation of the ISM core functions through improved use of and adherence to work and hazard controls, including procedures.	OR, YSO, and LMES have not established or assured a safety culture that implements an ISM process in which workers are consistently held accountable for adherence to procedures and hazard controls and are willing to stop work and seek management and technical assistance when procedures do not work or abnormal conditions are encountered.
#6: Improve the identification, availability, and use of appropriate personal protective equipment to protect workers against work-related hazards. (NOTE: This provision has been a factor in the last three Oak Ridge Type A accident investigations.)	LMES management systems and processes were not effective in assuring the provisions for and use of appropriate personal protective equipment for working with a pyrophoric liquid metal and protecting against thermal and caustic chemical burns and the inhalation of toxic and radioactive smoke.

* More detailed judgments of need are delineated in Section 4 of this report.

1.0 Introduction

On December 8, 1999, an explosion at the Y-12 Plant injured 11 workers, three of whom required hospitalization for burns. On December 9, 1999, Dr. David Michaels, Assistant Secretary for Environment, Safety and Health (EH), U.S. Department of Energy (DOE), appointed a Type A accident investigation board (referred to as “the Board”) to investigate the accident in accordance with DOE Order 225.1A, *Accident Investigations* (see Appendix A). This report documents the results and conclusions of the accident investigation board.

1.1 Facility Description

The Y-12 Plant, located in Oak Ridge, Tennessee, encompasses 600 acres within the fenced complex, with an additional 3000 acres of buffer zone. The primary mission of the Y-12 Plant is nuclear weapons stockpile maintenance. Secondary missions include research and development, as well as management of facilities that are no longer needed for defense missions while they undergo or await decontamination and decommissioning.

Building 9201-5, also referred to as Alpha-5, was constructed in the early 1940s. It is a large (about 530,500 square foot of floor space) clay block and concrete block structure that has a high bay. The activities in Building 9201-5 are part of the Y-12 Plant depleted uranium operations (DUO) program, which encompasses processing of depleted uranium for use in stockpile maintenance. Within the DUO program, the Y-12 Arc Melt Operations Division operates various process equipment in Building 9201-5.

The accident occurred in the skull caster furnace, which is located in the Building 9201-5 high bay and is used to melt depleted uranium and niobium to form a uranium-niobium alloy needed for manufacturing nuclear weapons parts. The skull caster furnace is an inert atmosphere electric, vacuum arc-melt furnace that uses an alloy of sodium (chemical symbol Na) and potassium (chemical symbol K). The alloy (NaK) is used to cool the furnace crucible, which contains the molten metal.

Contractor activities at the Y-12 Plant are managed by the DOE Oak Ridge Operations Office (OR). The facility in which the accident occurred is under the cognizance of the Office of Defense Programs (DP). Lockheed Martin Energy Systems (LMES) is the management and operating contractor for the Y-12 Plant.

1.2 Scope, Purpose, and Methodology

The Board began its investigation on December 10, 1999, completed the onsite phase of its investigation on January 14, 2000, and submitted its report to the Assistant Secretary for Environment, Safety and Health on February 10, 2000. The scope of the Board’s investigation was to review and analyze the circumstances of the accident to determine its causes. The Board also evaluated the adequacy of safety management systems and work control practices of OR and the Y-12 Plant, as they relate to the accident.

The purposes of this investigation were to determine the causes of the accident and to assist DOE in understanding lessons learned to improve safety and reduce the potential for similar accidents at the Y-12 Plant and across the DOE complex. The Board conducted its investigation using the following methodology:

- Inspecting and photographing the accident scene and individual items of evidence related to the accident
- Gathering facts through interviews, document and evidence reviews, and walkdowns of the area
- Reviewing the emergency and medical response
- Analyzing facts and identifying causal factors through events and causal factors charting and analysis, barrier analysis, and change analysis to correlate and analyze facts and identify the accident’s causes (see box on page 6)

ANALYSIS METHODS

A **causal factor** is an event or condition in the accident sequence that contributes to the unwanted result. There are three types of causal factors: direct cause**,** which is the immediate event(s) or condition(s) that caused the accident; root causes, which is (are) the causal factor(s) that, if corrected, would prevent recurrence of the accident; and contributing causes, which are causal factors that collectively with other causes increase the likelihood of an accident, but that individually did not cause the accident.

Events and causal factors analysis includes charting, which depicts the logical sequence of events and conditions (causal factors) that allowed the event to occur, and the use of deductive reasoning to determine events or conditions that contributed to the accident.

Barrier analysis reviews hazards, the targets (people or objects) of the hazards, and the controls or barriers that management systems put in place to separate the hazards from the targets. Barriers may be administrative, physical, or supervisory/management.

Change analysis is a systematic approach that examines failures in barriers and controls that result from planned or unplanned changes in a system.

- Developing judgments of need for corrective actions to prevent recurrence, based on analysis of the information gathered.

1.3. Report Organization

Section 2 of this report describes the accident and the response to the accident. In Section 3, the accident investigation team presents its analysis of the Y-12 Plant processes and systems that are intended to ensure safety, such as hazard analysis, conduct of operations, procedures, worker safety processes, training, emergency response, facility design, and work planning and management systems. This analysis leads to the identification of the contributing and root causes of the accident. Section 4 presents the accident investigation board's conclusions and judgments of need, which are areas where improvements are needed to prevent recurrence of similar accidents. Appendix A provides the appointment memorandum for this Type A accident investigation. Appendix B presents the application of analysis methods and tools.

2.0 The Accident

2.1 Overview

On December 8, 1999, ten Y-12 Plant workers were engaged in cleaning up a December 1, 1999, spill of NaK. The NaK spill occurred while workers were replacing the furnace crucible on the skull caster furnace in Building 9201-5, which uses NaK as a coolant. NaK is pyrophoric. NaK and its oxides are highly reactive and can be explosive under certain circumstances (e.g., when exposed to air it can form a potassium superoxide that is shock-sensitive and explosive when combined with hydrocarbons, such as mineral oil). On December 1, 1999, incorrect positioning of valves resulted in an inadvertent spraying of NaK into the furnace. From December 1 through December 8, the Building 9201-5 personnel planned for the removal of the spilled NaK and NaK oxides. On December 8, at about 9:30 a.m., the Y-12 Plant operators began using a steel rod and vacuum probe to remove residual NaK from the furnace (see Exhibit #1). Shortly after starting to use the steel rod, an explosion occurred in the furnace, resulting in a blast, fireball, smoke, and a shower of highly-reactive hot NaK particles. The explosion, smoke, and NaK particles caused burns and other injuries (eye injuries, ringing in ears, hearing degradation, respiratory irritation, contusions, muscle strains) in varying degrees to nine of the ten workers and one other person in the building who responded to assist after the explosion. The most seriously injured worker received third-degree burns to about 17 percent of his body.

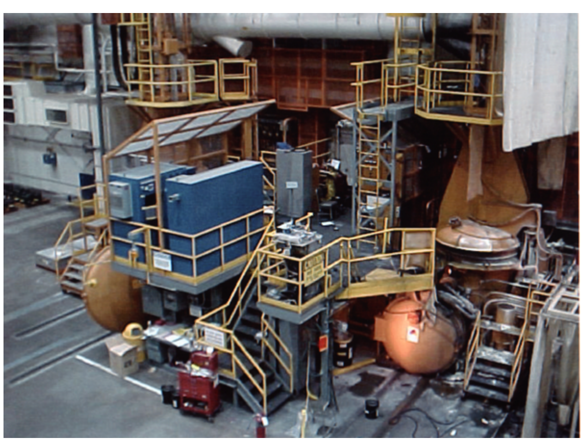


Exhibit #1. Skull Caster Furnace and Accident Scene

2.2 Sodium-Potassium Alloy (NaK) Properties and Hazards

The mixture of sodium and potassium metals, commonly called NaK, is a highly reactive material that has been used in industry for decades because of its excellent high-temperature thermal and hydraulic properties. NaK is an extremely reactive and pyrophoric alloy, composed of 78 percent potassium and 22 percent sodium, that is a liquid at room temperature. Because it is extremely reactive with water, moist air, and oxygen, NaK must be used and stored in an inert atmosphere (e.g., dry argon or nitrogen).

The primary hazards associated with NaK are fires, explosions, and release of caustic fumes. When exposed to water, NaK reacts violently, producing fire, small explosions, release of caustic fumes, and spattering of hot, reactive particles of NaK and combustion compounds. NaK reacts to a lesser degree with air, causing fires and caustic fumes of potassium oxide and sodium oxide. Hydrogen can also be produced by NaK reactions with the water vapor in air. An NaK fire produces caustic white smoke (consisting of oxides and hydroxides of potassium and sodium). The smoke made up of these combustion products can attack the skin and mucous membranes and can cause irritation and chemical burns. According to the Material Safety Data Sheet (MSDS), the long-term health effects of exposure to NaK fumes have not been fully investigated and are not well known.

Under certain conditions, the potassium present in NaK can form an explosive compound. Specifically, potassium oxide (K_2O) forms when potassium is exposed to air. The potassium oxide can then react with oxygen in the air to form potassium superoxide (KO_2). The conversion of the oxide to a superoxide is more efficient if the oxide is heated. A shock-sensitive explosive compound can result when a surface layer of potassium superoxide interacts with acids, halogens, or organic compounds (e.g., mineral oil). The explosive compound is similar to a Class 1 explosive (i.e., it is sensitive to detonation by pressure and small sparks) and has about 40 percent of the explosive energy of TNT (2200 joules per gram for the potassium superoxide-oil and 4680 joules per gram for TNT).

2.3 Accident Description and Chronology

Although the explosion and injuries occurred on December 8, the circumstances that led to the accident occurred on December 1, 1999, when NaK was inadvertently released during preparation for crucible changeout. This section describes the chronology of events leading up to the accident, the response to the accident, and the personnel injuries resulting from the accident. The event timeline is shown in Figure 1.

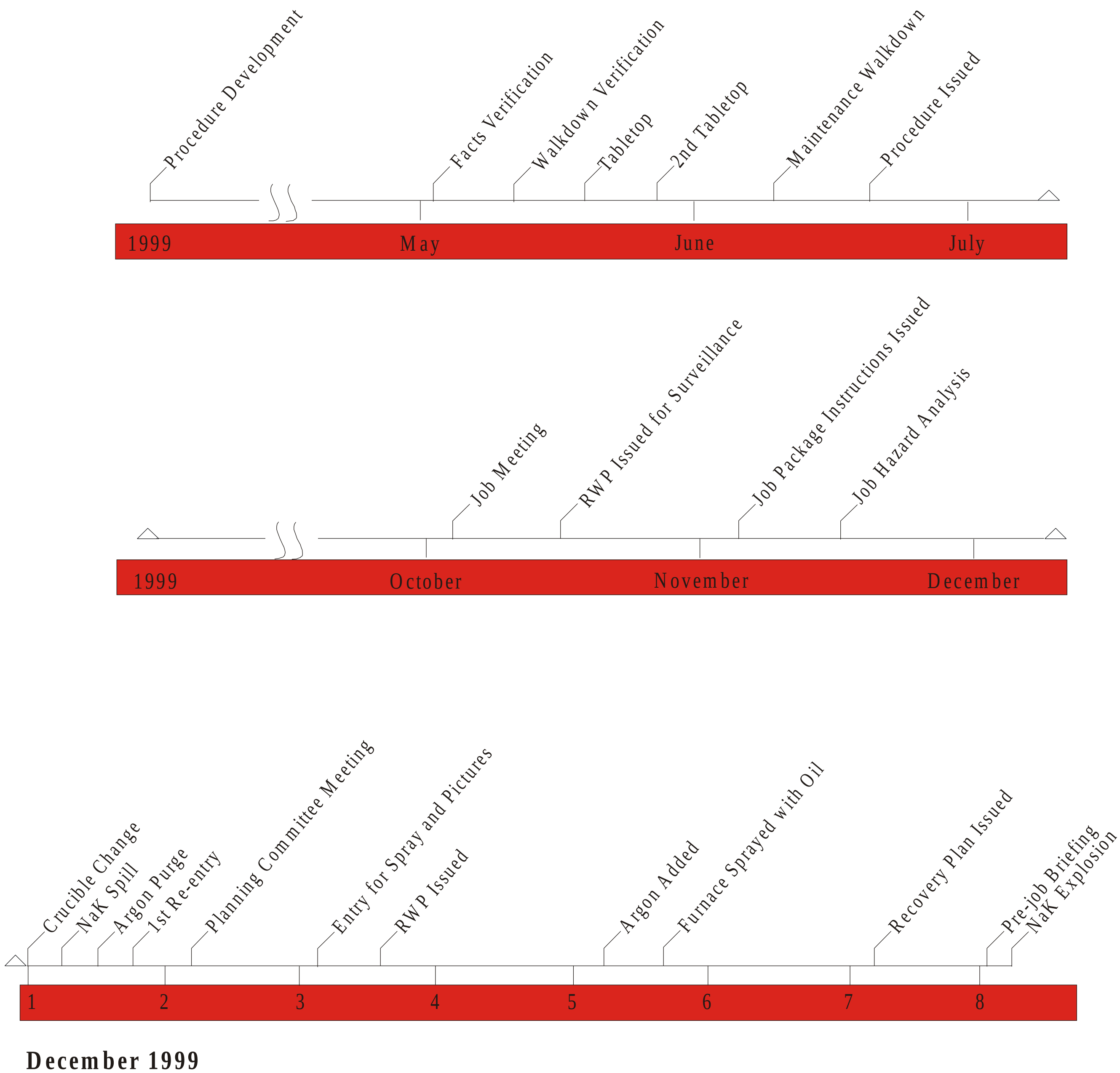


Figure 1. Activities Related to Development of the Crucible Changeout Procedure

Work Planning and Preparation for Crucible Changeout (January–November 1999)

In early 1999, Y-12 Plant management began planning to replace the steel crucible of the skull caster furnace (Figure 2). These crucibles experience heat stress during the arc melting process and need to be replaced (typically after about 70 melting cycles) to reduce the likelihood of a crucible failure during operations. The last crucible change occurred in 1993.

The crucible changeout procedure was finalized and issued in June 1999. In October 1999, an informal meeting was held to discuss the job and the potential hazards. Also in October 1999, a radiological work permit (RWP) was issued for surveillances in the area that established personal protective equipment (PPE) requirements. The job package instructions were issued and a job hazard analysis was completed in November 1999.

Crucible Changeout and NaK Spill (December 1, 1999)

The crucible changeout work began on December 1, 1999, at about 7:30 a.m. with a pre-job briefing. A simplified schematic of the NaK system is shown in Figure 3 (see page 10). The first portions of the procedure involved heating the NaK system to about 200 F to improve flow characteristics and then draining the expansion tank through the dump valve.

After the tank was drained, the dump valve was closed in accordance with the procedure. An engineer was marking up a copy of the procedure as it was being performed. Next, the crucible annulus was pressurized with argon to force NaK from the crucible annulus to the sump tank. The sump level was then measured and a four-inch discrepancy was noted, indicating to the operators that the crucible had not been fully drained. At this point, the supervisor, along with others present, decided to repeat the procedure steps involving heating the NaK. The supervisor then directed the pipefitter to close the argon isolation valve and remove the argon purge hose. The pipefitter removed the hose without closing the valve.

A combination of procedural errors (as discussed in Section 3.2) resulted in NaK spraying out the vent line. The spray of argon and NaK continued until the operators closed the NaK crucible isolation valves outside the furnace. Operators also closed the furnace lid and added argon to minimize the exposure of NaK to air. Oxides coated the walls and outside surfaces of the piping and furnace internals. Y-12 Plant personnel estimate that about three to ten gallons of NaK were spilled (although the estimates vary considerably).

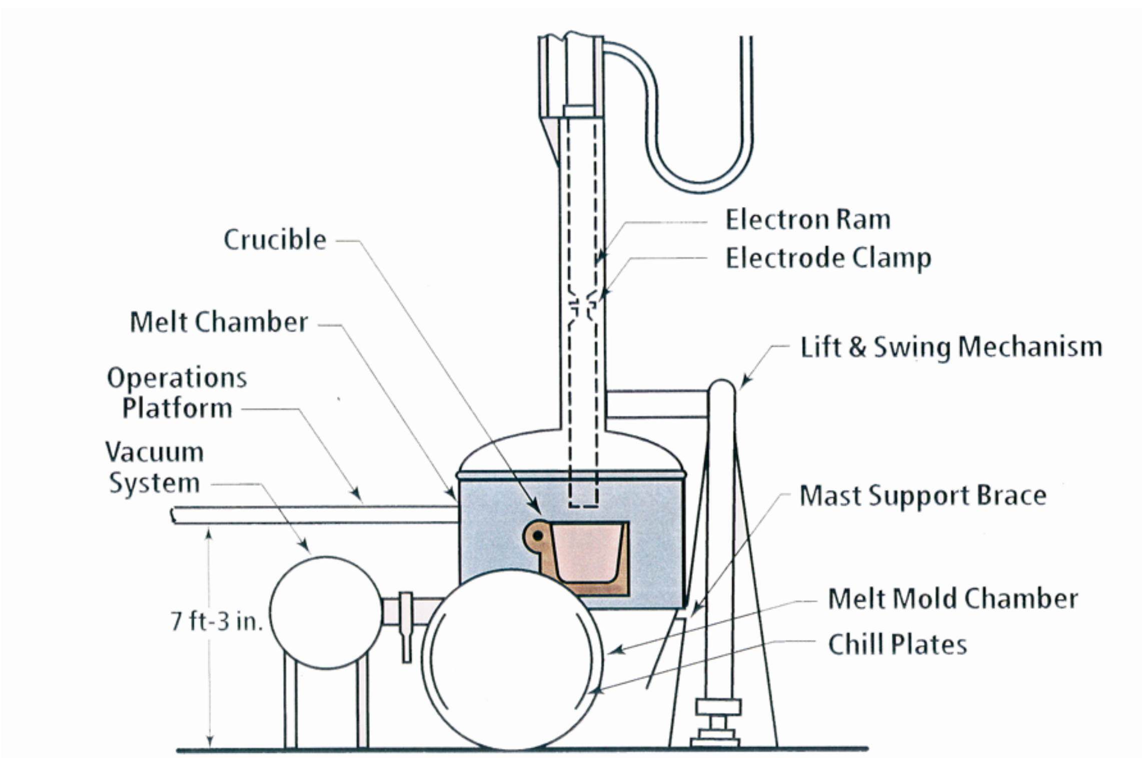


Figure 2. Skull Caster Furnace

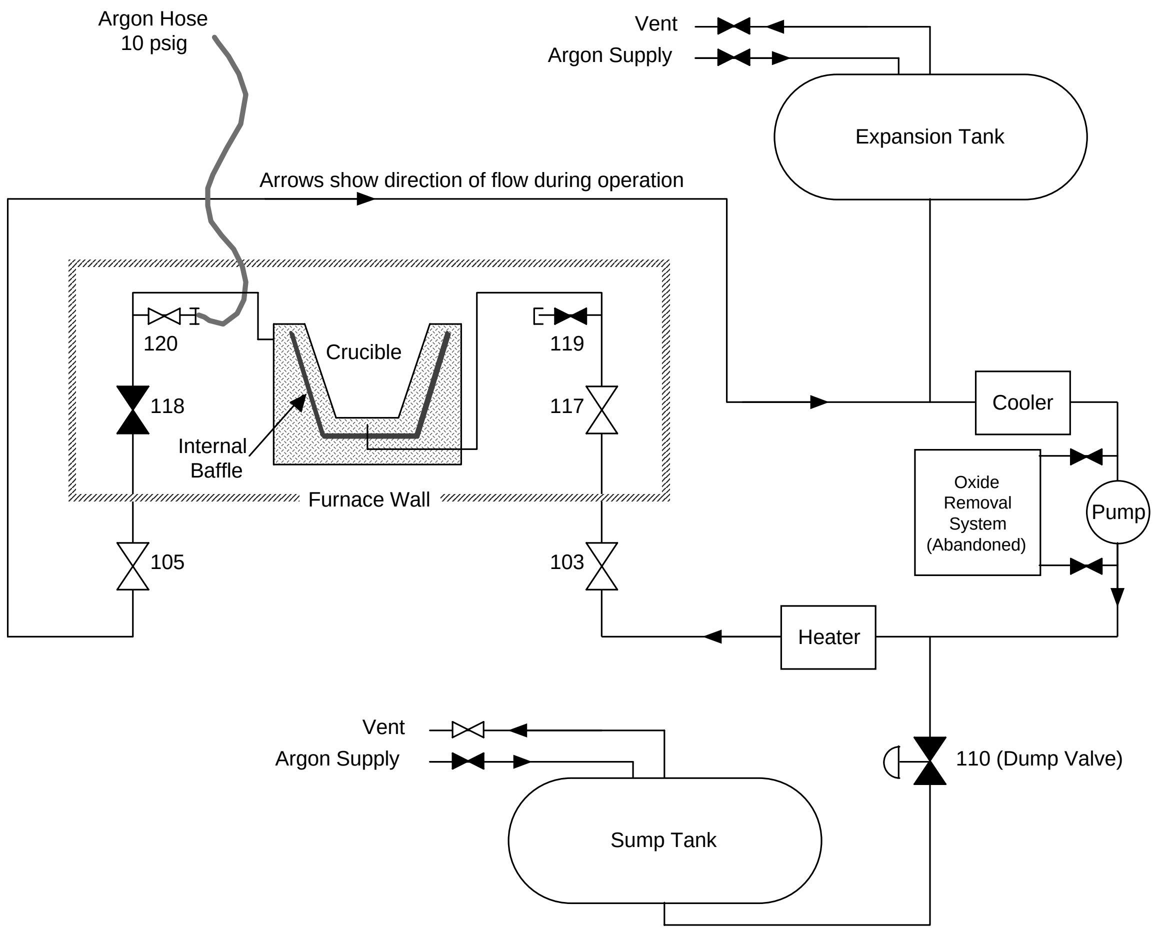


Figure 3. Simplified NaK System Schematic

The spill generated a large amount of hazardous smoke. The pipefitter, who was not wearing appropriate PPE, saw the leak and exited the furnace immediately. All personnel left the area. Fire Protection Engineering was notified to open the roof-mounted smoke dampers in the facility to permit clearing of the smoke.

Later that day, a management review was held to review the spill incident. The main corrective action from the management review was to develop a recovery plan for the NaK spill. After that meeting, two Y-12 Plant staff reentered the area to observe conditions. They opened the furnace cover and saw "a white flaky powder."

Development of a Recovery Plan (December 2-7, 1999)

The next day, facility personnel began planning to clean up the spill. They established a planning committee, which held its first meeting on Thursday, December 2, 1999. The planning committee held two additional meetings (December 3 and 6) and refined the recovery plan, which was finalized and approved by the operations manager on December 7, 1999. An RWP was also developed and issued on December 3, 1999. As part of the recovery plan, facility personnel assembled a vacuum system that was intended to remove liquid NaK.

During December 2 through 7, Y-12 Plant personnel entered the area several times to observe conditions and add argon. On December 3, workers took pictures (Exhibit #2) of the furnace and observed a "fine white snow." On this entry, the process engineer indicated that the NaK "did not look right" and that he saw things that he "hadn't seen before." The process engineer suspected potassium superoxide because of the yellow color observed on the surface of the NaK. He directed the furnace surface to be sprayed with mineral oil in an attempt to minimize further oxidation, which again caused reactions, noise, and generation of significant quantities of black and white smoke. On Monday, December 6, the furnace cover was lifted and the task of spraying the entire furnace with mineral oil was completed. During these recovery activities, the workers wore lab coats, booties, and gloves for PPE.

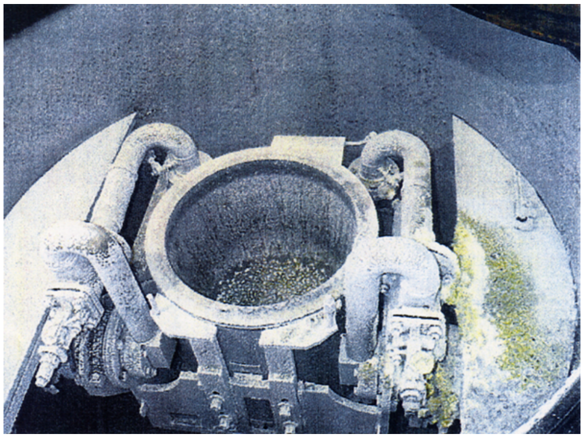


Exhibit #2. Skull Caster Furnace and Crucible on December 3, Showing NaK and Yellow Potassium Superoxide

The Explosion (December 8, 1999)

On Wednesday, December 8, 1999, ten DUO workers were involved in the effort to remove NaK from the crucible in accordance with the recovery plan. The ten positions are listed in the box, along with a designator that will be used in the remainder of this report to identify the workers.

Position	Designator
Building 9201-5 Operations Manager	OM-1
Process Engineer	PE-1
Front-line Supervisors	FS-1, FS-2
Process Support Engineer	PS-1
Industrial Hygienist	IH-1
Chemical Operators	CO-1,CO-2, CO-3, CO-4

The recovery team met at about 7:15 a.m., proceeded to the process area, and held a pre-work briefing, which ended about 7:50 a.m. The team entered the skull caster furnace area at about 8:00 a.m., at which time questions arose about where operators could don respirators. Three individuals were sent back to don respirators. The team re-signed the RWP and assembled at the platform about 9:00 a.m. Three of the workers, two of whom were on the platform, wore standard anti-contamination coveralls, booties, gloves, cloth hoods, and respirators, while the other workers wore only lab coats or coveralls, booties, and gloves. None of the workers wore NaK suits or flame-retardant coveralls.

At about 9:15 a.m., the recovery team opened the cover approximately one-fourth of the way to gain access to the furnace. They began to use the vacuum rig to probe under the crust to determine whether they could siphon off any liquid NaK. One individual was spraying mineral oil into the area being probed. Using the vacuum rig, they were only able to collect a small quantity (about half a cup) of oxides. They drained the glass flask containing the oxide into the bucket containing mineral oil. They then washed the vacuum probe with mineral oil and placed it in the holding area.

The industrial hygiene representative (IH-1)and the process engineer (PE-1) report having a short conversation among themselves at about 9:25 a.m., in which they discussed the importance of "not letting their guard down" because NaK was a hazardous material with a potential for explosions involving superoxides and/or hydrogen.

At about 9:30 a.m., the recovery team opened the cover further (about half open) and then began to use a stainless steel rod in an attempt to break up the NaK crust. The operator (CO-1) believed that this tool was too short because he had to bend over the furnace to reach the NaK with the rod. The operator then tried another lift tool (one fitted with a flat scraper on the end), but it was flimsy and could not break through the hard crust that had formed. The operator again began to use the steel rod to lift the crust in an attempt to determine whether unreacted NaK could be seen. Two of the operators then left to find materials to make a longer probe (see Exhibit #3).

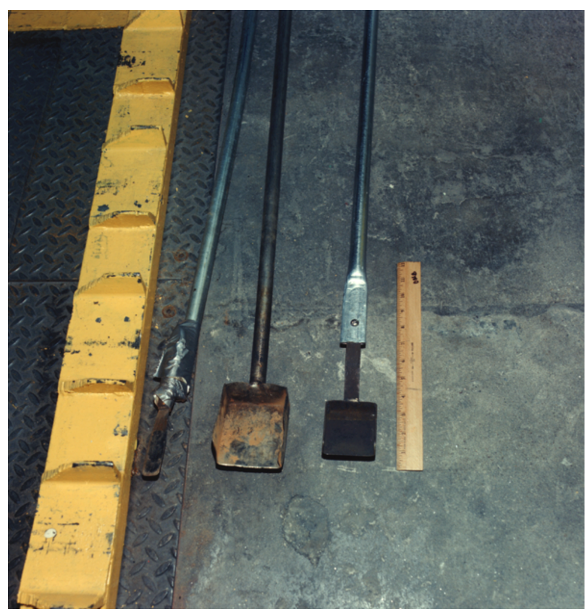


Exhibit #3. Metal Tools Used To Probe and Break Up the NaK Spill

The explosion occurred at about 9:35 a.m., while the operator (CO-1) was using the probe to break the crusted NaK after additional mineral oil was sprayed.

There were four workers on the platform around the top of the furnace. The explosion occurred with no warning and resulted in blast and a fireball. The sound of the explosion was described as "deafening." They noted a "yellow-orange-red ball of flame" accompanied by a large "whooshing" sound and "lots of smoke." The force of the explosion was directed toward the personnel on the platform and to the floor by the position and dome shape of the furnace lid. A shower of hot particles and "sparks" (burning NaK) fell on the workers (see Exhibits #4 and #5).

Direct Cause

The **direct cause** of the explosion and resulting injuries was disturbance (impact with a steel probe) of an unrecognized and unanalyzed shock-sensitive explosive compound (consisting of potassium superoxide and mineral oil) that was formed when mineral oil was inappropriately sprayed on a previous NaK spill.

The layout of Building 9201-5 is shown in Figure 4. At the time of the explosion, the ten workers were positioned as marked on Figure 5.

The operator who was using the probe (CO-1) was in the direct path of the explosion/fireball due to the furnace lip configuration; he was knocked over by the force of the explosion and severely burned. Four other workers (CO-2, CO-3, OM-1, and PE-1) also incurred

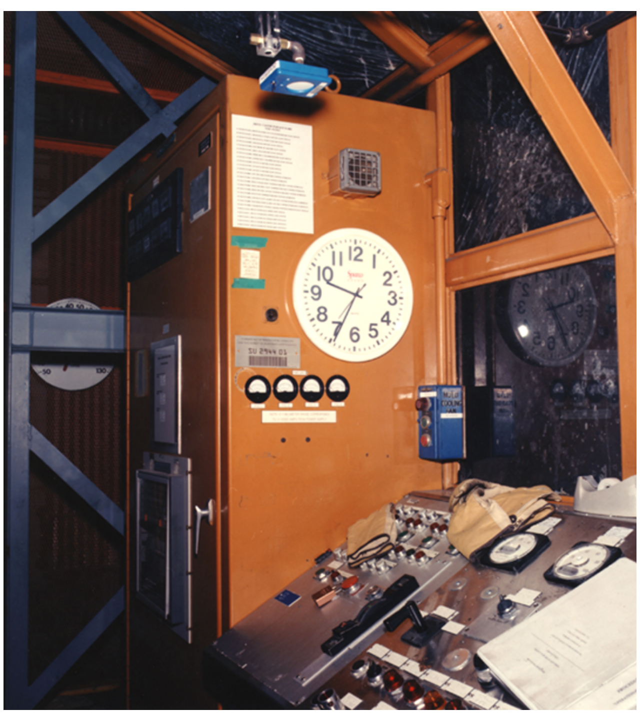


Exhibit #4. Skull Caster Furnace Control Panel Showing Clock Stopped as a Result of the Accident

Exhibit #5. Skull Caster Furnace Showing Explosion Damage and NaK Residue

burns from the initial fireball and/or the shower of particulates. Another worker (IH-1) was knocked to the ground and dazed by the force of the explosion.

The workers on the platform left as rapidly as possible. The operations manager (OM-1) helped the most severely injured worker (CO-1) off the platform and held him in an effort to smother his burning coveralls as they proceeded to the safety shower. Other workers discarded burning clothing as they left the area. The workers assisted the injured personnel and extinguished small fires. One worker (IH-1) exited the area and called 911, which connects to the Y-12 fire department dispatcher.

Although suffering from burns, three team members (OM-1, CO-3, and CO-4) returned to the furnace area to close the lid and extinguish small spot fires using dry chemical extinguishers. Another worker (FS-2) cleaned up water from the safety showers, which was accumulating on the floor (there are no berms or drains around the safety shower that is nearest the furnace). The water had spread in the direction of furnace and was reacting with NaK that had been dispersed onto the concrete floor by the explosion. Another DUO worker not involved in the recovery plan heard the noise and provided assistance when the accident occurred.

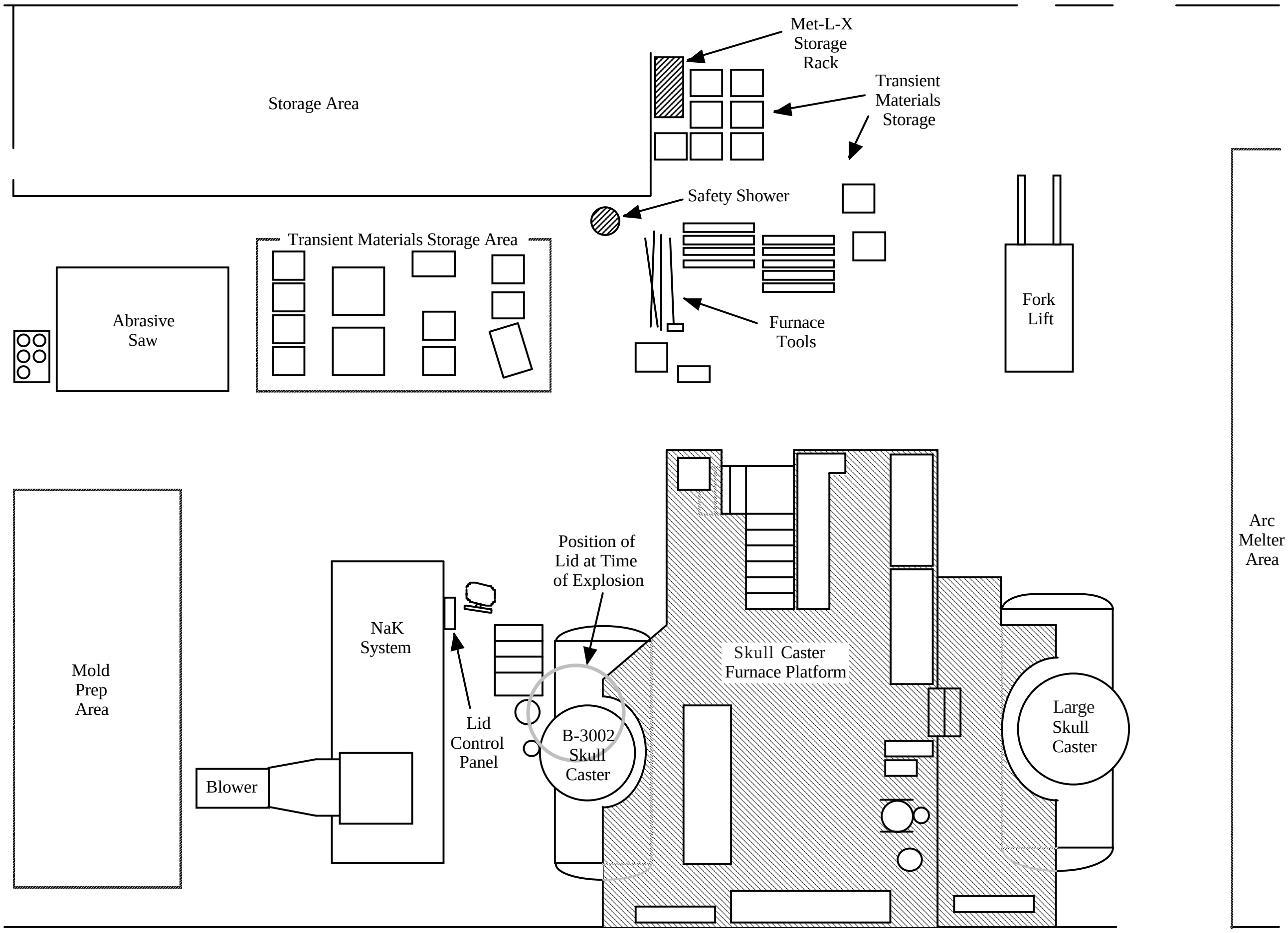


Figure 4. Skull Caster Furnace Area, Showing Position of Safety Showers

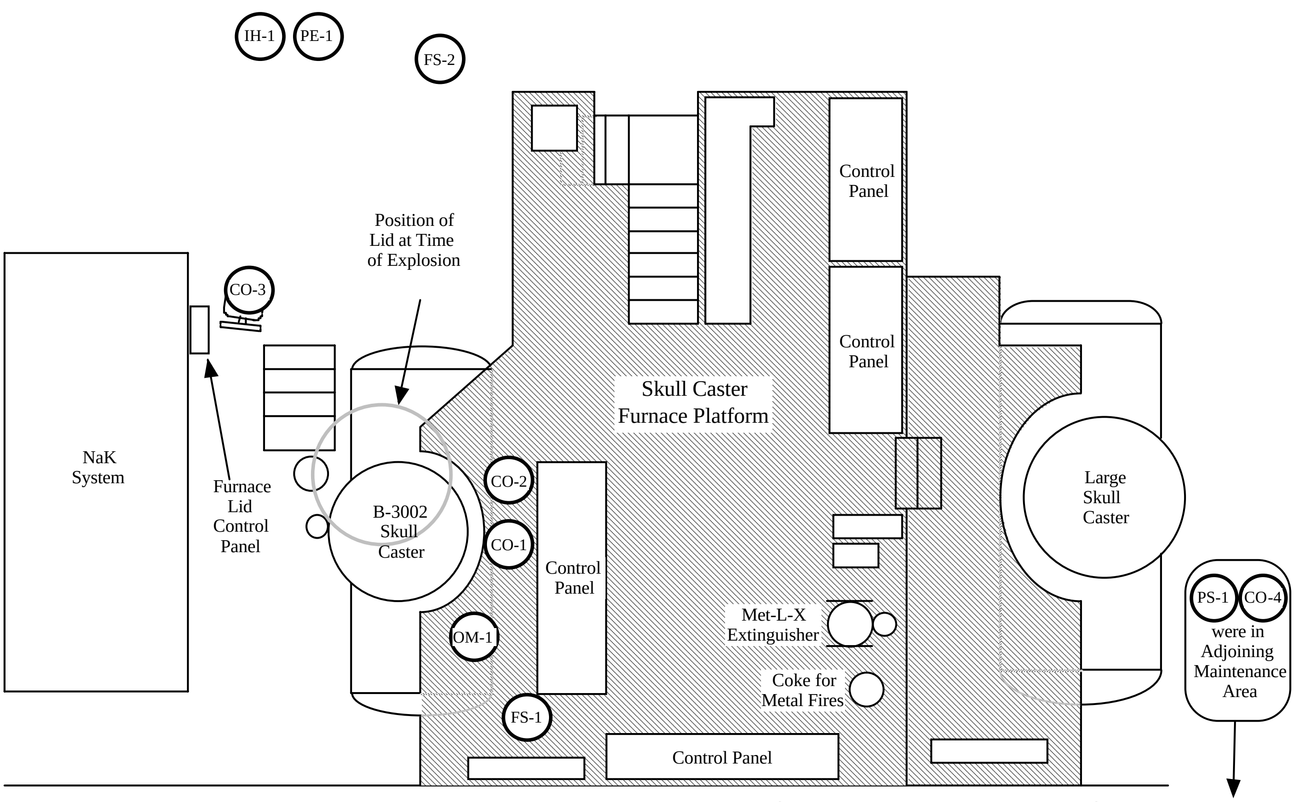


Figure 5. Skull Caster Furnace Area, Showing Positions of Workers at the Time of the Explosion

Current Status and Plans

As of the conclusion of the onsite phase of the accident investigation (January 14, 2000), the Y-12 Plant was in the process of developing an approach to stabilize and remove the remaining hazardous material. Y-12 Plant management indicated that their plan is to discontinue the use of NaK systems across the plant. They plan to collect and dispose of all NaK in the Y-12 Plant, including the material in Building 9201-5 and other areas at the Y-12 Plant.

In the interim, NaK remains in the furnace, in the sump, and in the buckets of oil at the accident scene. The Y-12 Plant is controlling access to the area and prohibiting disturbing the remaining NaK. Y-12 Plant management is evaluating a proposal by an outside contractor to perform the needed remediation and disposal activities.

Fire alarm functions had been removed from the skull caster furnace high bay in about 1969, leaving the high bay without a fire alarm function (discussed further in Section 3.6). Because of the lack of adequate fire detection alarms and the presence of a hazard (NaK cooling system, spill and potential superoxides), DUO management established a compensatory fire watch for the skull caster furnace area in response to the accident investigation board's concern. The fire watch will wear appropriate anti-contamination clothing and inspect the high bay area from the third floor mezzanine once every four hours until the hazard is abated. DUO management, in conjunction with fire protection engineering and the fire department, plans to evaluate the removal of fire alarm protection from that section of the building.

Until the hazard is stabilized and/or remediated, several conditions require further evaluation by Y-12 and compensatory or permanent corrective action:

- Potential unknown explosion damage to the NaK cooling system and piping inside the skull caster furnace
- The lack of fire alarm detection for the skull caster furnace high-bay area
- The lack of skull caster furnace integrity due to missing gaskets
- The presence of superoxide in the remaining material (confirmed by chemical testing)
- The presence of mineral oil in contact with superoxides inside the furnace
- Operability of the roof vents.

The combination of these conditions may require evaluation for an unreviewed safety question determination.

2.4 Emergency Response and Medical Treatment

Initial Emergency Response

The Plant Shift Superintendent's (PSS) office and the Y-12 fire department received the first call about the accident at 9:36 a.m. The Y-12 fire department was immediately dispatched and arrived at Building 9201-5 at 9:38 a.m. The fire department established an on-scene incident command post and secured the area around the building. Personnel in the accident area started to proceed to the Boundary Control Station where emergency response personnel assisted and prepared injured individuals for ambulance transport.

At 9:42 a.m., reports that the area was full of smoke prompted the PSS to direct an evacuation. Personnel evacuated to the assembly area on the west side of the building. The PSS declared an operational emergency and activated the Technical Support Center (TSC) at 9:43 a.m. DOE was notified of the accident at 9:49 a.m.

Building 9201-5 accountability was complete at 10:19 a.m. Radiological contamination surveys were taken at the Assembly Station, and by 10:45 a.m. all personnel were cleared.

Medical Transport and Contamination Control for Transported Victims

At 9:51 a.m., the most severely injured worker (CO-1) was transported by ambulance to the Y-12 Plant medical facility. Upon his arrival, Y-12 medical personnel immediately directed that the worker be transported to the Oak Ridge Methodist Medical Center (ORMMC) because of the severity of the injuries. This worker was subsequently air-lifted to the Erlanger Burn Unit in Chattanooga, Tennessee. The two ambulances with the other two severely burned individuals were also immediately sent to ORMMC and arrived there by 10:04 a.m.

A Y-12 Plant radiological control technician (RCT) accompanied CO-1 to the ORMMC and remained there to provide assistance with the other two workers when they arrived. The Radiation Emergency Assistance Center/Training Site (REAC/TS) was activated while the first ambulance was transporting the first individuals to the ORMMC. REAC/TS personnel met the ambulances when they arrived at the ORMMC, where they surveyed and decontaminated the victims.

The minimal external radiological contamination on the three victims transported offsite would not result in a radiological health hazard. (The highest level of contamination in the surveys at the ORMMC was about 1500 counts per minute.) The contamination was generally found in the hair or along the hairline. Most of the contamination-control PPE (lab coats, gloves, booties) worn by the three transported victims was removed immediately after the explosion (e.g., because of burn damage) or before transport to the hospital. Decontamination efforts (washing and shampooing of hair) were successful in reducing the contamination. The survey of CO-1 indicated some small areas of low-level contamination (50 to 100 counts per minute), which was removed from the individual at the burn center.

The Y-12 RCTs set up contamination control areas at the ORMMC and assisted the REAC/TS. Contaminated clothing was collected and returned to the site. A nurse's shoe was found to be contaminated and was returned to the site. Subsequent surveys of the accident responders, ambulances, gurneys, and ORMMC facilities showed no radioactive contamination resulting from treating the accident victims.

In addition to the three individuals transported offsite, eight others with less-serious injuries were transported to the Y-12 Plant medical facility. Two from this group were later transferred by automobile to the ORMMC for further evaluation. The remaining six were treated and sent home, with follow-up at the Y-12 medical facility. Site RCTs performed radiological surveys of these individuals and found several to have small areas of contamination, with the highest level being 33,000 counts per minute. All of the individuals were successfully decontaminated. Subsequent radiological surveys of the Y-12 medical facility indicated no contamination.

Radiological Exposure

Bioassay samples (urine and fecal) were collected from the workers on the spill recovery team, another DUO worker in the building who entered the area after the explosion to provide assistance, and emergency responders (fire department/ambulance). Bioassay samples were not yet available for the three individuals who were sent to the ORMMC.

The available bioassay results indicate that several of the workers received intakes of radioactive material resulting from the accident. Y-12 Plant personnel estimated the committed effective dose equivalent (CEDE), which is the expected dose that will occur over a 50-year period as a result of the intake, using the conservative assumption that the material was all Class Y uranium-234.

The highest internal dose was 507 millirem, which was incurred by an individual who was standing several feet from the bottom of the platform, without a respirator, and was in the direct path of the explosion. The estimated CEDE dose for the other 11 individuals who had bioasssay samples ranged from 110 millirem to zero millirem. The accident investigation team independently calculated doses based on urine and fecal samples for several of the individuals and obtained similar results. Although higher than expected for depleted uranium, the doses incurred by these individuals are below the threshold of concern for health effects and below the regulatory limit of 5000 millirem.

Chemical Exposure

The Y-12 Plant did not perform estimates or calculations of chemical exposures following the accident. However, based on worker reports of lingering respiratory irritation and evidence of clouds of smoke, workers were exposed to concentrations of sodium and potassium hydroxides and oxides. Based on an estimated release of three gallons of NaK and using the methodology described in the 9201-5 authorization basis, the Board believes that some workers may have been briefly exposed to concentrations of sodium and potassium oxides and hydroxides in excess of ceiling guidance levels and "immediately dangerous to life and health" levels as established by regulatory agencies.

Injuries and Medical Prognosis

A total of 11 personnel sustained injuries or health effects as a result of the explosion, including the ten members of the NaK spill recovery team and one other DUO worker. The injuries included thermal/chemical burns, respiratory irritation, bronchitis, and acoustic trauma affecting the hearing. Of the eight employees in the vicinity of the skull caster furnace at the time of the explosion, six sustained thermal and chemical burns; three of them were hospitalized. Two of the three hospitalized individuals were released from the hospital (December 10 and 15, respectively). One of these two has returned to work and the other is expected to return to work in mid January 2000.

The most severely burned employee (CO-1) was leaning on a platform directly over the vessel when the explosion occurred. The force and heat of the explosion burned off most of his clothing above the waist (see Exhibit #6). He sustained burns to 25 percent of his total body surface area, including third-degree burns to about 17 percent of his body. Burns were located mainly on the upper part of the front of the body, including the head, neck, chest, fronts of the arms, and backs of the hands. He also had burns on his left torso behind his left arm, extending from the shoulder to the buttock. A small amount of NaK or its oxide was embedded in the skin of the left upper chest and was surgically removed because it was producing localized, progressive tissue destruction. The explosion also forced the worker's respirator off his face, causing a corneal abrasion of the right eye and allowing caustic burns to both eyes. The respirator minimized further burns to the face. He also sustained caustic burns to the nostrils, lips, and palate. He received skin grafts and was released from the burn center on December 21, 1999. His treatment is continuing, including additional skin grafts.

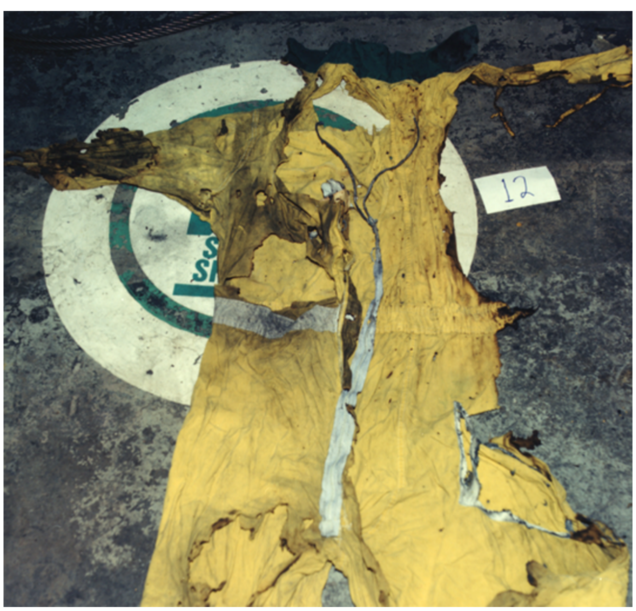


Exhibit #6. Standard Coveralls Burned During Explosion

Five employees experienced respiratory irritation following the explosion. Two of these five had not been in the vicinity of the skull caster at the time of the explosion, but entered the vicinity immediately after the explosion to provide assistance. Three employees developed bronchitis in the days following the explosion. Of these three, two had a prior history of asthma. In addition to burns and smoke inhalation, the explosion and/or physical trauma (e.g., falls) resulted in other injuries (eye injuries, ringing in ears, hearing degradation, contusions, and muscle strains) to varying degrees.

Several of the employees involved in the incident, or acquainted with those involved in the incident, suffered emotional upset and post-traumatic stress reactions. In addition to medical treatment, the Y-12 medical facility's psychologist and the Y-12 employee assistance program (EAP) director offered psychological support and education regarding the potential for trauma-induced stress reactions. Those involved in and responding to the accident, the family members of those injured, and co-workers in the building were contacted and invited to use these services.

Employees experiencing more serious burns (CO-1, CO-2, CO-3, and OM-1) may develop visible scars. Due to the severity of their neck burns, there is some concern that the two most seriously burned employees (CO-1 and CO-2) could develop neck scars that somewhat limit head movement. The most seriously burned worker (CO-1) may also develop a scar in the left armpit that could limit shoulder range of motion. It will be several months before it is known whether these complications have developed.

The prognosis for the other affected workers is good for a full recovery from most medical conditions resulting from the explosion, including minor burns, bronchitis, and acoustic trauma. However, the long-term effects of a short-term exposure to high concentrations of sodium and potassium oxides and hydroxides is not known, particularly for those with a prior history of asthma.

3.0 Analysis

3.1 Chemical Safety Hazard Analysis

Y-12 Plant chemical safety hazards analysis processes are intended to identify and control hazardous materials by means of the facility authorization basis, hazard identification, job hazard analysis, hazard screening, and hazard evaluations. These processes did not identify and communicate the hazards associated with a mixture of potassium superoxide and mineral oil and did not establish effective controls (e.g., prohibiting the use of mineral oil on NaK) to address the hazards. These processes failed even though the potential for superoxide explosions is documented and communicated in numerous technical and safety documents, including the MSDS for NaK, the Fire Protection Guide for Hazardous Materials, and the Sodium-NaK Handbook, all of which are readily available. In addition, the NaK MSDS and other technical documents clearly warn against the storage of metal under hydrocarbons (e.g., oil) or the addition of organics where superoxide is suspected. The MSDS, which can be accessed from any computer terminal within Y-12, also recommends that spills be cleaned up promptly using Met-L-X (which is a fire-fighting agent for liquid metal fires) or dry soda ash. Table 1 provides a sample of the technical information related to NaK and the superoxide/organic explosion hazards.

The Y-12 Plant has used mineral oil to isolate NaK from contact with air since the system was installed in 1969. Y-12 Plant personnel refer back to an undocumented analysis by a Y-12 Plant materials science specialist as a basis for this practice. Although mineral oil was commonly used during this era to cover NaK in storage, numerous publications as early as the 1950s warned of the hazards associated with organics (including oil) where potassium superoxides may have formed.

A 1997 hazard screening evaluation for reactive metals stored in a different Y-12 Plant facility (Building 9720-27) clearly identifies the hazards associated with superoxide/oil explosions. It states: "The potassium present in the NaK can react with atmospheric oxygen to form oxides, peroxides, and superoxides that form a crust over the NaK surface. These oxides can be shock sensitive and can react violently (even explosively) upon contact with acids, halogens, organics, and metallic potassium in NaK." This hazard screening evaluation was developed by the same department that is responsible for engineering/safety documents in Building 9201-5, where the explosion occurred.

The existing safety documents Building 9201-5 focus exclusively on NaK reactions with water and do not address other important reactions. For example, the NaK/water reaction was believed to be the dominant hazard, and it was the only hazard analyzed and discussed in the Building 9201-5 authorization basis. However, the sequence of events, beginning with the spraying of NaK into the furnace, created conditions favorable for the formation of potassium superoxide, and the subsequent addition of mineral oil created a shock-sensitive explosive mixture. Because this hazard was not recognized by the facility work planners, the subsequent disturbance of the mixture through prodding and poking led to an explosion and multiple injuries.

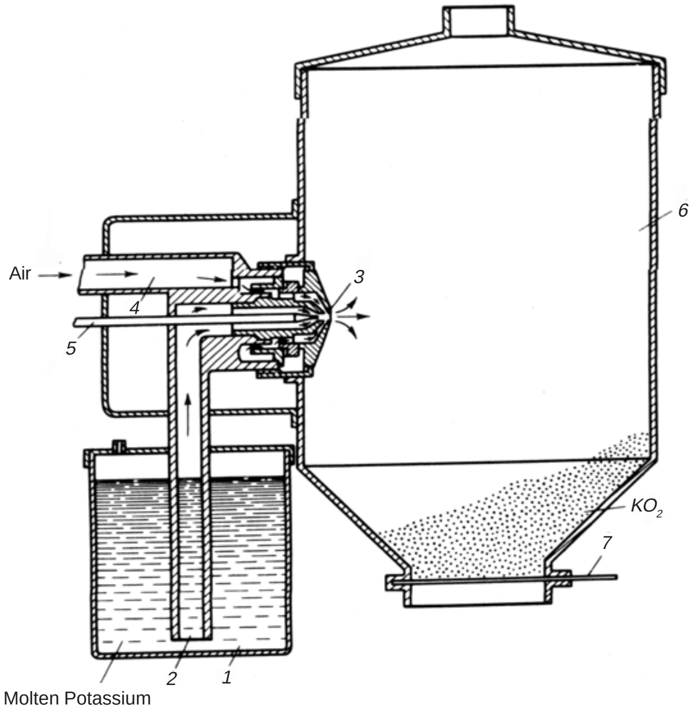
Chemical Analysis of the Spill/Spray and Explosion

The initial spill on December 1, 1999, involved a failure to close a valve, resulting in NaK spraying into the crucible while under pressure and at elevated temperatures. These conditions—forced exposure to air at elevated temperature—were favorable for the formation of potassium superoxide. Spraying NaK into the air in this manner is similar to the process used for commercial production of potassium superoxide, although commercial processes would use a higher temperature and a controlled fine spray (see Figure 6 on page 19).

Table 1. Information About NaK and Superoxide Explosion Hazards

Over the last 45 years, the formation of potassium superoxides from NaK and the explosive reaction between superoxides and organics or hydrocarbons has been documented in a wide variety of publications, including textbooks, safety manuals, MSDSs studies, and accident reports. Examples include:

- "The reaction between alkali metal peroxides or superoxides and hydrocarbons is explosive under certain conditions and many instances have been cited where violent explosions have resulted from mixing these materials." Liquid Metals Handbook-Sodium NaK Supplement-Atomic Energy Commission, 1955 (this supplement referenced for safety in 1969 purchase order for the Building 9201-5 vacuum arc skull casting furnace).
- "Potassium readily forms a superoxide, (KO_2), which may undergo vigorous reactions – with oil for example." Industrial Engineering and Chemistry, Volume 48, Marshall Sittig, 1956.
- "Superoxide may be present on the walls of tanks where it is not in direct contact with the bulk of the liquid metal. The superoxide can also exist on the surface of the pool of NaK where an oxide layer is formed. Immediate cleanup is recommended to avoid formation of superoxides… in several instances explosions have occurred in NaK systems, and in all cases there was a possibility that superoxides and hydrocarbons were present." Sodium-NaK Engineering Handbook, 1978.
- "Over the last few years there have been reports of many incidents in which personnel have been injured by explosions during the handling of potassium or sodium potassium alloys. It is concluded that the explosions were caused by the formation of potassium superoxide due to long exposure of the NaK or potassium to air and that the potassium superoxide reacted explosively with liquid metal and/or organic material." AEC Health and Safety Bulletin, 1967 (Documented eight UK explosions including NaK stored under mineral oil and subjected to disturbance or shock).
- Potassium reacts to form peroxide – "This peroxide, under certain circumstances, can react explosively with organic material. As a general safety precaution, thus, it is a good practice to keep alkali metals away from organic materials." A Primer for the Safe Use of Liquid Alkali Metals, 1967.
- "It is concluded that explosions involving NaK and superoxide KO_2 were caused by the introduction of a third or fourth component in the form of organic or moisture contamination. The impact sensitivity of dry KO_2 mixed with fuel oil is comparable to that of PETN, one of the most sensitive secondary explosives. An Explosives Hazards Analysis of the Eutectic Solution of NaK and KO_2 Aerojet Nuclear Company, Idaho National Engineering Laboratory, 1975.
- "Metallic potassium on prolonged exposure to air forms a coating of yellowish potassium superoxide (KO_2) under which is a layer of potassium oxide in contact with the metal. The previous statements that normal contact of potassium with superoxide causes ignition to occur, and that if the layer of superoxide is impacted into underlying metal by dry cutting operations or a hammer blow occurs are known to be incorrect. The explosions are caused by interaction of residual traces of mineral oil or other organic contaminants, rather than potassium metal, with the surface layer of superoxide, initiated by blade pressure on impact." Brethericks Handbook of Reactive Chemical Hazards, 1975-1990.
- "Stainless steel pots containing traces of sodium potassium alloy were immersed in oil to await cleaning. During the removal of the lid from one pot, an explosion occurred that was attributed to long-term formation of potassium superoxide, which reacted with oil when it was disturbed." Hazardous Materials – National Fire Protection Association, 1991.
- "The potassium present in NaK can react with atmospheric oxygen to form oxides (K_2O), peroxides (K_2O_2), and superoxides (KO_2) that form a crust over the NaK surface. Those oxides can be shock sensitive and can react violently (even explosively) upon contact with acids, halogens, organics, and metallic potassium in the NaK." Hazard Screening Evaluation for Reactive Metals Storage Building 9720-27, Lockheed Martin Energy Systems, 1997-1999.
- "Do not store metal under hydrocarbons. If yellow potassium superoxide contamination is suspected, do not add organics. If not handled properly, even small quantities (less than one gram) of NaK can be a significant fire and explosion hazard." Material Data Safety Sheet for Potassium – Sodium Alloy (NaK) Callery Chemical Company, 1999 (Supplier of NaK for this facility).
- "If superoxide is suspected, do not add organics. Do not store metal under oil or hydrocarbons use proper spill cleanup procedures… cover with dry soda ash, dry sodium chloride, or Ansuls MET-L-X scoop into dry metal container with additional extinguisher powder." MSDS for NaK-Division of Mine Safety Appliances, 1999.



Industrial unit for KO_2 production (1) Container with molten metallic potassium; (2) pipe for supplying molten potassium to the sprayer; (3) sprayer; (4) pipe for supplying air to the nozzle; (5) needle for controlling the supply of air and molten potassium mixture to the nozzle; (6) cylindrical KO_2 container; (7) KO_2 outlet.

Figure 6. Commercial Production of Potassium Superoxide

The important chemical reactions that are likely to have occurred at the time of the accident include:

- Reaction of NaK with air to produce oxides of potassium and sodium
- Reaction of NaK with the small amount of water vapor in air to produce hydroxides of potassium and sodium and hydrogen
- Oxidation of potassium oxide to potassium peroxide and potassium superoxide.

In a potassium fire, the dense white smoke formed is the potassium oxide (K_2O). Because of the limited quantity of water vapor present in the air at the time of the spill, a relatively small amount of the NaK would react with water vapor to produce hydroxides. As shown in the box, the reactions of potassium and oxygen in the air can produce three different oxides, depending on the conditions.

$4K$ potassium	+	O_2 oxygen	$\rightarrow$	$2K_2O$ potassium oxide
$2K_2O$ potassium oxide	+	O_2 oxygen	$\rightarrow$	$2K_2O_2$ potassium peroxide
$2K_2O$ potassium oxide	+	$3O_2$ oxygen	$\rightarrow$	$4KO_2$ potassium superoxide

If potassium oxide is subjected to an oxygen environment at an elevated temperature, the oxide will form potassium superoxide. At the time of the spill, the NaK had been heated to about 80 C. After the NaK spill, the material that sprayed into the furnace would be at a higher temperature because of the heat of the reaction. The residue noted after the spill was a combination of NaK, the oxides of potassium and sodium, potassium superoxide, and a small amount of sodium and potassium hydroxides.

The operators closed the furnace and purged it with argon to minimize further oxidation. However, the argon purge may not have been complete because the furnace is not airtight; between December 1 and 7, argon might have leaked away, and air might have diffused in. During this period, the mixture of NaK, the oxides and hydroxides of potassium and sodium, and potassium superoxide continued to react with any oxygen or water vapor in the furnace. Any oxygen present would be available to convert additional potassium oxide to superoxide.

The addition of oil to the potassium produced a shock-sensitive explosive mixture. Without the mineral oil, an explosion would not have occurred. The technical literature indicates that for an explosion to occur, a boundary layer with an organic or other material (halogen, acid) is needed.

When the operators sprayed mineral oil into the furnace on December 3, 1999, they noted "flashes and pops." These could have resulted from the reaction between moist air and NaK, and from subsequent ignition of the hydrogen and mineral oil from the heat of the reaction. Also, the oil spray flushed the oxides and superoxides off the wall of the furnace, thereby concentrating the superoxides at the bottom of the furnace where the operator was probing at the time of the explosion.

The Board believes that a significant amount of superoxide was formed during the initial spill and the ensuing rapid oxidation while conditions were favorable for superoxide formation. The explosion occurred on December 8 just after the NaK recovery team sprayed additional mineral oil in a fine mist and were using a metal rod in an effort to break up the crust. The prodding with the metal rod is the likely initiator of the explosion of the shock-sensitive mixture. It is possible that the potassium oxide/oil explosion also detonated the mineral oil mist. It is also possible that hydrogen generated by contact between moist air and NaK may have contributed to the explosion.

Some Y-12 Plant personnel speculate that the explosion might not have occurred if the spill had been cleaned up immediately. However, the contributors to the explosion were the addition of mineral oil and the disturbance of the shock-sensitive material with a tool. If the operators had promptly cleaned up the spill on December 1 using similar methods, the conditions for an explosion (superoxide, mineral oil, and a disturbance) would still have been present.

The Board estimated the magnitude of the explosion. The explosion did not rupture the eardrums of any of the individuals nearby, and the threshold for eardrum rupture is an overpressure of 5 psig. Based on the location of the individuals and the characteristics of the explosion, a few hundred grams of superoxide may have been involved in the explosion. This is a small fraction of the amount of superoxide that could have formed in the furnace.

The events that led to the explosion created all of the conditions necessary for an explosion:

- Quantities of potassium superoxide were produced during the spill and subsequent oxidation.

- An organic material (mineral oil) was added to a superoxide, creating a shock-sensitive mixture. It was also used to flush the material off the sides of the vessel, possibly concentrating superoxides at the bottom.

- A shock-sensitive explosive mixture was subjected to impact from steel tools.

The Board believes that there is still a potential for explosive mixtures in the furnace and in surrounding areas (see Exhibit #7). Analysis of one of the residue samples taken from the floor on December 17, 1999, showed that 25 percent of the potassium was in the form of a superoxide. The furnace seals were damaged in the explosion, so an argon purge might not be effective in precluding oxygen from reacting with residual NaK (see Exhibit #8). The small amount of uncharacterized material that remains immersed in mineral oil on the platform will have to be handled with extreme care. Since the superoxide hazard is not currently addressed by the authorization basis for this facility, an unreviewed safety question determination is needed.

Contributing Cause

An incompatible chemical (mineral oil) was added to a material that was not fully characterized but that was suspected to include superoxides, creating an explosive mixture.

Hazard Identification

The major contributor to the accident was the fundamental failure to identify the hazards associated with the use of mineral oil on NaK. Although this hazard is well recognized in the technical and safety literature, including the NaK MSDS, the personnel involved in planning for crucible changeout and NaK recovery did not have a full understanding of NaK hazards.

Exhibit #7. Residual NaK from Explosion Near Furnace

Exhibit #8. Furnace Showing Explosion Damage

Specifically, these personnel, including operations personnel, industrial hygiene specialists, and engineers, did not recognize the hazards associated with using mineral oil on NaK and developed a recovery plan that created an impact-sensitive explosive mixture of potassium superoxide and mineral oil.

Hazard identification is an essential element of integrated safety management: if a hazard is not identified, it cannot be analyzed and controlled. Multiple processes and controls failed to identify the hazard, including multi-disciplinary hazard identification teams, training programs, hazard identification planning, job hazard analysis, hazard screening, authorization basis documents, unreviewed safety question processes, and lessons-learned programs. Specific deficiencies in these programs are discussed throughout this report and are shown in Tables 2, 5, 6, 7, and 8.

The Y-12 Plant had 30 years of NaK experience without a serious injury, which may have resulted in complacency and a false sense of security. However, some of the events involving NaK should have prompted DUO and safety personnel to recognize the hazards associated with NaK, including its explosive characteristics. For example, when referring to the 85-gallon NaK spill in the 1980s, one interviewee stated that "there were a couple of fireballs you could have sold tickets to – real bangs." In this event, the NaK came out as a spray and a large fraction of it was immediately oxidized, with some probably becoming superoxide immediately. The potential for superoxide and the presence of yellow material that looked like superoxide were recognized. Despite the fact that different circumstances were apparent, none of the facility personnel, work planners, or managers in the DUO organization took the initiative to fully understand and analyze the conditions. Even if the hazard was recognized after superoxide was suspected and oil had been applied, the potential for explosions could have been considered and controls (e.g., engineering controls such as blast shields, or other chemical treatments for the material) could have been developed.

Mineral oil had historically been used as a "bath"—that is, NaK or NaK oxides were placed in a bucket of mineral oil. Spraying mineral oil was apparently a practice that was used by DUO in the past. This approach was made without any analysis of the potential hazards.

DUO line management, DUO facility management, and work planners believed that they had sufficient knowledge and expertise, and did not challenge the technical basis for the use of mineral oil. Given the long history of the use of mineral oil and the level of confidence in its use, it is not clear what would have prompted the DUO workers to stop work and obtain additional technical guidance, or whether additional guidance would have resulted in different actions.

Contributing Cause

DUO management at every level, facility management, and technical support (e.g., industrial hygiene and engineering) personnel did not demonstrate the technical competence or initiative to challenge unsupported assumptions about work practices (e.g., the use of oil), to seek information about hazardous materials, or to seek additional information and/or specialized assistance when unusual conditions were encountered.

Authorization Basis

Consistent with DOE Order 5480.23, *Nuclear Safety Analysis Reports*, and DOE-STD-1027-92, *Hazard Categorization and Accident Analysis Techniques for Compliance with DOE Order 5480.23*, Building 9201-5 is a Category 3 (low hazard) nuclear facility requiring a formal authorization basis.

The authorization basis is the safety envelope established by the facility operator and accepted by DOE as providing reasonable assurance of a safe level of operation. The authorization basis document for the Arc Melter Area in 9201-5 is the "Phase I Hazard Screening Analysis for the 9201-5 Arc Melt Operations," (HS/12/F/5/Jan. 25, 1991).

The Y-12 Plant's justification for relying on this 1991 hazard screening as the authorization basis document is the safety analysis upgrade program planning documents. During Phase I of the upgrade program, all the facilities were screened. If the results of the facility screening showed that all the identified accident scenarios were classified as "low hazard – low consequence," the upgrade of the safety analysis report (SAR) was delayed until Phase III. For such facilities, the hazard screening document became the authorization basis document.

The current authorization basis focuses exclusively on the hazards associated with the NaK-water reaction and does not explicitly address superoxide/oil hazards. The authorization basis was developed before many of the current formal hazard assessment procedures were developed and has deficiencies when measured against current expectations:

- Quantities of chemicals are not provided as part of the inventory.
- Chemical interactions are not addressed.
- Past accidents are not discussed.
- Reference sources are not listed.
- There is insufficient detail to identify all accident scenarios.
- Protective features are not identified.

A draft basis for interim operation (BIO) for Building 9201-5 is in review. The development, DOE comments, and revisions of the BIO have taken over four years and have resulted in four submissions of Revision 0 of the BIO to DOE. Since the BIO was drafted in 1995, essentially all the procedures for developing authorization basis and job hazard analysis documents have undergone significant revision in an effort to develop them into the LMES integrated safety management program. Many of these revisions impose new requirements on how hazard assessment documents are developed. The BIO would need extensive revision to incorporate the new requirements.

Neither the hazard screening nor the draft BIO addresses the superoxide/oil hazard. These documents were not effective in establishing controls that would have prevented this accident. However, the superoxide/oil hazard was addressed by Y-12 Plant site safety engineering in a 1997 hazard screening evaluation for reactive metal storage in Building 9720-27 and in a 1999 revision to this document. The Building 9201-5 hazard screening was referenced in performing the Building 9720-27 analysis for NaK. The relevant hazard information was not, however, incorporated into the draft BIO for Building 9201-5.

Unreviewed Safety Question Determination (USQD) Process

The USQD process provided one opportunity to discover the NaK superoxide/oil hazard. However, the Y-12 Plant did not apply this process rigorously in cleaning up the NaK spill. The USQD process is required by DOE Order 5480.22, *Technical Safety Requirements*, and is implemented locally by site procedure Y74-809. The process requires an unreviewed safety question (USQ) screen to be conducted if a proposed activity (such as spill cleanup) reduces the safety margin of the facility. If the screen concludes that the safety margin is reduced (that is if the screen is "positive"), further management review is required.

The USQ screen for the spill event was not conducted. NaK was viewed as an existing hazard, and it was informally concluded that there was no reduction in the safety margin. Because the screen was not conducted, opportunities were missed to review the MSDS, USQDs, and reference material that was available regarding the hazard.

Contributing Cause

The authorization basis and USQD processes were not sufficiently rigorous to identify hazardous conditions.

In summary, the fundamental failure to identify the hazard was the major factor in the accident. Since the hazard was not identified, it was not analyzed and controls were not in place to prevent the accident or protect the workers. The actions that were taken after the spill as directed by the recovery plan (adding oil and then impacting with a steel probe) escalated a manageable spill event into an accident with multiple injuries. Opportunities to identify the hazard were missed, including the authorization basis and USQD processes and the hazard identification and job hazard analysis (see Section 3.3).

3.2 Conduct of Operations

Deficiencies in conduct of operations contributed to this accident. Failures in procedure development and use, as well as aspects of communications, notifications, and investigation of abnormal events, led directly to the NaK spill and subsequent explosion. Table 2 identifies various failures in conduct of operations evident in this accident.

Procedure Development, Verification, and Validation

Procedures are an essential element affecting operator performance. DOE Order 5480.19, *Conduct of Operations*, requires that appropriate attention be given to writing, reviewing, and monitoring procedures to ensure the content is technically correct and specifies that procedure preparation, verification, and validation should receive high-level attention.

The development processes for the crucible changeout procedure and NaK recovery plan were flawed. Both the procedure and the NaK recovery plan required the addition of mineral oil to the NaK, even though technical literature (including MSDSs) specifically warn against use of organics with NaK. In addition, the fire protection engineering and quality assurance and personnel who were assigned review and approval authority did not adequately review technical safety documentation. Further, when developing the procedure, the reviewers did not challenge the technical basis for the use of mineral oil with NaK.

Y-12 Plant personnel prepared a detailed procedure for the skull caster crucible changeout activity, which had previously been addressed in the furnace operation procedure. The skull caster changeout procedure was incorrectly designated as a Category 3 procedure, which does not require in-hand use or verbatim compliance with the steps and sequence. The Y-12 Technical Procedure Process Control procedure and the Y-12 Conduct of Operations Manual require a procedure to be designated as Category 1 if failure to comply in a step-by-step manner could result in a significant health, safety, or environmental risk to the employee or the public. According to these requirements, a Category 1 procedure must be near at hand to the operation, open to the page for the step being performed, performed in a step-by-step manner, and signed off for designated steps. The skull caster crucible changeout procedure contains more than 400 steps and significant hazard to workers, and the activity had not been performed for over six years.

Work planning for the crucible change started in 1998, and a draft procedure was completed in early May 1999. The draft procedure underwent several stages of review, verification, and validation by Y-12 Plant personnel, including a factual verification of the procedure, a procedural walkdown, two tabletop validations, and a separate walkdown by the maintenance manager.

Despite these efforts, the verification and validation process for the crucible changeout procedure did not identify numerous errors and omissions. For example, the omission of the step to open the sump dump valve necessary to establish the correct flow path was not identified in the verification and validation process. A version of the procedure used in the verification process had the sump dump valve opened twice but never closed. The steps associated with the sump dump valve were not changed during the verification process, and most of the verification comments were editorial.

The individual performing the verification had not been formally trained on the verification process and only checked for proper format and correct equipment designators, not for technical accuracy. In addition, some of the technically oriented checklist items were checked off based on the opinions of others, not on a technical review of the procedure.

The validation process resulted in major changes to the procedure, including adding a step to close the sump dump valve after the step that opened it. However, the step reopening the dump valve was removed. The procedure was revalidated twice using tabletop validations rather than in-plant walkdowns. These revalidations did not find the error of the missing step to reopen the sump dump valve, and the procedure was never reverified following the extensive changes by the validation team. The Technical Procedure Process Control procedure that governs the verification and validation process does not require the verification to be repeated when the validation process finds major errors.

The skull caster furnace operating procedure and the crucible changeout procedure did not contain adequate provisions for abnormal conditions. The

Table 2. Conduct of Operations Deficiencies

The December 1 spill and December 8 cleaning operation with subsequent explosion demonstrated deficiencies in implementation of DOE conduct of operations requirements. The numerous deficiencies across many chapters of DOE Order 5480.19 indicate a programmatic breakdown in conduct of operations requiring prompt senior management attention to prevent future injury or loss.

DOE Order 5480.19	Observed Deficiencies
Chapter 1, Operations Organization and Administration	• Senior facility and division management have not encouraged or enforced DOE and LMES conduct of operations requirements in 9201-5. • Managers are not consistently and thoroughly monitoring the performance of the activities under their cognizance to assess performance and reinforce safety standards via tours, audits, reviews, and self-assessments. • Operators did not understand nor apply applicable facility safety planning requirements during development of the spill recovery plan. • Authority to manipulate valves and equipment is not well defined (pipefitter).
Chapter 2, Shift Routines and Operating Practices	• Operators did not adhere to the crucible changeout procedure. • Proper PPE was not worn during argon hose removal, purging the furnace, or during spill cleanup. • When the crucible drain-down activity did not produce the expected change in NaK sump tank level, the activity was discontinued, but the cause of the condition was not correctly determined. The failure of the drain down was attributed to the low temperature of the NaK rather than an improper valve lineup. (Sump dump valve was closed.)
Chapter 4, Communications	• Repeat-backs were not utilized to ensure the accurate transmission and receipt of verbal instructions.
Chapter 5, Control of On-Shift Training	• On-shift training was not performed on the NaK training manual. • On-shift training for hazards associated with NaK was not established.
Chapter 6, Abnormal Events Investigation	• The cause of the spill on December 1 was not thoroughly investigated, and root causes were not determined prior to developing a recovery plan. • The unusual and unexpected conditions on December 3, including the suspicion of superoxide formation, were not adequately investigated prior to adding mineral oil.
Chapter 7, Notifications	• The December 1 spill was not reported to DOE as required by site procedures. • The unusual and unexpected conditions on December 3 were not reported to management or the site safety engineering.
Chapter 8, Control of Equipment and System Status	• System configuration control was not maintained during the development and performance of the crucible changeout procedure. • The NaK oxide control and indicating system was abandoned without appropriate technical basis or compensatory actions. • Accurate piping and instrument drawings depicting facility-specific valve and equipment numbering were not available to the procedure writers and operators.
Chapter 10, Independent Verification	• Although the NaK system has the potential for significant personnel injury if components are mispositioned, independent verification was not designated for any system operations, including key valves such as the NaK dump valve.
Chapter 13, Operations Aspects of Facility Chemistry and Unique Processes	• Although the NaK oxide control and indicating system was abandoned, the chemical status of the NaK and associated oxide buildup in the NaK inventory was not analyzed or trended. • Warnings in the NaK MSDS on superoxide-organic interaction were not identified and considered.

Table 2. Conduct of Operations Deficiencies (Continued)

DOE Order 5480.19	Observed Deficiencies
Chapter 14, Required Reading	• The facility did not implement a required reading program that incorporated lessons learned from other NaK events or changes to the NaK MSDS.
Chapter 16, Operations Procedures	**Crucible Changeout Procedure** • The procedure development, review, verification, validation, and approval process did not produce a quality crucible changeout procedure. • The procedure was classified as Category 3, not Category 1 as required by site procedures and the circumstances. • Industrial safety and hygiene reviews did not comment on the use of mineral oil in the presence of superoxide. • The verification only checked for editorial correctness and matching labels; technical accuracy was not verified. • The individuals performing the verification and validation were not trained or qualified to perform those functions. • The procedure underwent major changes during validation with the operators, however there was no requirement to reverify the procedure. • The procedure was approved with numerous technical errors, some of which directly led to the spill on December 1. (See Table 3) • Operators did not follow the crucible changeout procedure as required by site procedures • The evolution was not stopped when errors were found in the procedure. • The procedure was not followed as written. • Procedure changes were made "on the fly" without any review and approval process as the evolution was performed. • Operational activities not addressed by the procedure were performed. • Equipment for performing the procedure, including equipment for emergency response (e.g., NaK suits, safety shower berms), was not adequately staged. **Plan for Skull Caster Furnace Recovery** • The Spill Recovery Plan directed operations, but was not an Operations Procedure or authorized LMES mechanism. • The Technical Procedure Process Control requirements were not followed. • Formal verification and validation required of a technical procedure was not performed. • The plan, which served as a safety significant technical procedure, did not have a hazard category rating for procedure use as required. • The plan was not a mandatory sequential step-by-step procedure and allowed/ required excessive "skill of the craft" interpretations. • Requirements of the Writer's Guide for Y-12 Plant Technical Procedures were not followed. • Critical MSDS information was not referenced or included. Plan actions were contrary MSDS guidance. • The plan was not reviewed outside the recovery team for technical accuracy. • A JHA was not performed in accordance with LMES requirements. • Response actions were contained in two documents, some in the plan and some in a reference procedure contrary to the technical writing guide. • PPE listed in the plan was not appropriate for the potential hazards involved as identified in lessons learned, the MSDS, and the OSHA standard. • Hazard Identification Planning Procedure (Y15-012) was not used for development of the plan. • Hazards associated with the presence of superoxide were not identified.

documents did not define the response required for an NaK spill in the furnace, even though this guidance is available in the NaK Training Manual. The emergency response to a rupture of NaK piping is to shut down the pump and open the NaK sump dump valve to drain the NaK in the system to the sump tank. The training manual states that Met-L-X should be used to cover the NaK completely, with special care being taken to add the powder carefully to prevent splashing or splattering the NaK. As soon as possible, the residual NaK should be shoveled into a steel container equipped with a lid and containing some Met-L-X powder. The NaK spill section of the crucible changeout procedure does not address the operation of the dump valve or the use of Met-L-X, but rather permits the placement of spilled NaK into stainless steel drums of mineral oil. If the emergency response for the NaK spill on December 1, 1999, had included opening the dump valve, less NaK would have spilled. The lack of an adequate spill procedure resulted in delays in the recovery, hardening of the crust, and possible additional oxidation, and the need to develop a "plan" to clean up the spill. The use of Met-L-X rather than mineral oil would have eliminated the potential for explosion.

The NaK spill cleanup on December 8, 1999, further illustrated deficiencies in the procedure development process. The cleanup was to be performed using a recovery "plan," rather than a formal procedure. The plan was not developed using the Technical Procedure Process Control procedure. Applying a "plan" to the work activity involved the violation of numerous work control requirements specified in the (work) Planners Guide, the Technical Procedure Process Control procedure, the Writer's Guide for Y-12 Technical Plant Procedures, and the Hazard Identification and Job Hazard Analysis procedures. The failure to develop a procedure (rather than a plan) to recover the spill resulted in missed opportunities to identify and correct the explosion hazard associated with superoxides and the spraying of NaK with mineral oil.

Since the plan development did not follow the formal process for a procedure, the plan was not subjected to the technical procedure development and approval process or the work package process required for maintenance work activities. There was no formal hazard identification planning or job hazard analysis, subject matter expert and discipline review was limited to informal reviews within the recovery team, and there was no formal verification and validation of the plan. In order to deviate from the procedure development requirements, the Procedure Configuration Control Board (PCCB) would have to approve a waiver/exemption. The PCCB did not approve any exemptions to site requirements and in fact were unaware of the plan. While the plan was reviewed and approved by individuals involved in its development, it was not subjected to an independent management or technical review and did not receive the required independent verification for a hazardous technical maintenance operation.

Contributing Cause

Processes for developing, reviewing, verifying, and validating procedures were not adequate to detect significant procedural errors and identify and control hazards.

Procedure Use and Compliance

Procedures provide instructions for how work should be conducted. Procedures are the key mechanism by which management establishes control over activities and the associated hazards and ensures consistency in the organization and administration of programs and activities. Procedures provide direction to ensure that facilities are operated within their design bases and are used to support safe operation. Quality procedures that are used effectively by management and the workers ensure adherence to and implementation of management policies, DOE requirements, safety and health regulations, and commitments. Procedures are the vehicle through which DOE and its contractors can institutionalize integrated safety management and quality assurance requirements to assure understanding, acceptance, and implementation at every level of the organization, and application to every activity and hazard.

While workers were draining NaK from the skull caster furnace crucible on December 1, 1999, errors in procedure use led directly to the spill in the furnace. Since the procedure was designated Category 3 (not requiring step-by-step completion), the operating crew believed that it was not necessary to stop the process when they encountered errors in the procedure. Instead, they marked up a copy of the procedure for future reference, improvised the next activity, and continued performing the evolution. This is in direct conflict with 10 CFR 830.120, Quality Assurance Requirements, and the Y-12 Conduct of Operations

Manual chapter on procedural use. 10 CFR 830.120(c)(i) states: "work shall be performed to established standards and administrative controls using approved instructions, procedures, or other appropriate means." The Y-12 Plant Conduct of Operations Manual states: "During use, procedures shall not be altered, changed, or revised without a proper review and approval." In addition, the 1988 final safety analysis report (which was never formally approved by DOE) for the 9201-5 skull caster furnace assumed rigorous procedure compliance as part of the analysis, stating: "Operating procedures shall be current and shall be followed by operating personnel." Although the workers discovered many procedural errors from the start of the evolution, they did not stop working until the NaK spilled in the furnace. Exhibit #9 shows a page from the procedure that was being used at the time of the crucible changeout, including markups. As shown in that exhibit, significant changes in important steps (such as step 29, which requires measurement of the sump level) were made during the work activity. Table 3 identifies errors in the crucible changeout procedure.

Other Conduct of Operations Deficiencies

Other deficiencies in conduct of operations also contributed to the accident. For example, the operation that directly caused the spill was the removal of the argon hose without closing drain valve NAK/S-HV-0120 at the crucible. The verbal instructions from the operations supervisor were miscommunicated to the pipefitter responsible for removing the argon hose. DOE Order 5480.19 states: "Instructions involving the operation of equipment should be repeated by the receiver to the extent necessary for the sender to ensure the instructions are correctly understood." In accordance with the Y-12 Site Verbal Communication procedure (Y10-145), this process of repeating back instructions should be used for important operational steps to ensure that the message is understood. During crucible draining, this process was not used effectively. Consequently, verbal directions to close the isolation valve before removing the argon hose were not effectively communicated.

Table 3. Crucible Changeout Procedure Errors

Procedural Errors

1. The procedure did not require opening the dump valve (NAK/S-PCV-0110).*
2. The procedure did not require closing the vent valve (NAK/S-HV-0120) prior to removing the argon hose.*
3. The procedure isolated the crucible supply and return valves inside and outside the furnace (NAK/S-HV-0103, 105, 117, and 118) prior to skull removal (step 3.4.1.5[2]), but did not re-open them prior to pump start for NaK heatup (section 4.1.2.1.2).
4. The procedure required a 15 minute purge on the hose prior to connection to clear the air out of the hose (step 4.1.2.2.[15]); however, only 3 – 5 minutes was actually performed.
5. Step 4.1.2.2.[25] required opening the crucible supply valve NAK/S-HV-0117, but the step was deleted because the valve was already opened prior to the NaK heatup in section 4.1.2.1.2.
6. Step 4.1.2.2.[26] required checking stability of (sump) probe continuity, but was deleted because the return valve had not yet been isolated.
7. Step 4.1.2.2.[27] erroneously identified the crucible supply valve NAK/S-HV-0117 to be closed. The correct valve was the return valve NAK/S-HV-0118.
8. Step 4.1.2.2.[28] required opening the crucible return valve NAK/S-HV-0118, but the step was deleted because the valve had already been opened prior to the NaK heatup in section 4.1.2.1.2.
9. The procedure did not provide instruction to tilt the crucible to facilitate draining as it should have following the closure of the return valve NAK/S-HV-0118.

*Note: These errors were not detected during the performance of the procedure on December 1, 1999.

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4.1.2.2 Draining NaK (cont.)

[24] Open AR/S-HV-0300, CRUCIBLE PURGE MANIFOLD SUPPLY VALVE, and use regulator to apply approximately 3 to 5 psi argon pressure.

Operator

[25] Open NAK/S-HV-0117, PRIMARY CRUCIBLE SUPPLY VALVE.

[26] Verify complete NaK transfer by observing stability of probe continuity.

[27] Close NAK/S-HV-0~~117~~ 118, PRIMARY CRUCIBLE ~~SUPPLY~~ RETURN VALVE.

[28] Open NAK/S-HV-0118, PRIMARY CRUCIBLE RETURN VALVE.

[29] ~~Purge line and~~ check for complete NaK transfer.

Tilt crucible to facilitate draining NaK. Compare level to previous levels

[30] Close the following valves:

- NAK/S-HV-0103, CRUCIBLE SUPPLY VALVE
- NAK/S-HV-0105, CRUCIBLE RETURN VALVE
- NAK/S-HV-0118, PRIMARY CRUCIBLE RETURN VALVE

Maintenance

[31] Purge the ½-in x 20-ft copper tubing NaK transfer line with argon to displace the air.

Operator

[32] Place a 5-gallon bucket containing approximately 3 inches of mineral oil under NAK/S-HV-0121, NAK CRUCIBLE DRAIN VALVE.

Maintenance

[33] Remove the plug on NAK/S-HV-0121, NAK CRUCIBLE DRAIN VALVE, on the bottom of the Skull Caster crucible.

[34] Remove the pipe plug from the Sump Tank fill pipe at NAK/S-HV-0116, SUMP TANK FILL VALVE.

Exhibit #9. Crucible Changeout Procedure Page Showing Markups

The December 1, 1999, NaK spill was not reported to the Y-12 Plant PSS or reported as an occurrence to DOE as required by procedure (Occurrence Notification and Reporting, Y14-192). In the Occurrence Reporting procedure, the incident would fall under the category of Violation/Inadequate Procedure, which states specifically that the "Use of inadequate procedures or deviations from written procedures that result in adverse effects on performance, safety, or reliability" should be reported as an off-normal occurrence report. The NaK spill also generated a significant amount of smoke and caused a building evacuation. If the spill and its immediate consequences had been reported to DOE and LMES management, there might have been more resources available for planning the recovery.

DOE Order 5480.19, Chapter 6, Abnormal Events Investigation, requires that facility events be thoroughly investigated to assess the impact of the event, determine the root cause of the event, ascertain whether the event is reportable to DOE, and identify corrective actions to prevent recurrence of the event. Since facility management decided that the December 1, 1999, spill was not reportable to DOE, a management review was conducted in accordance with the Y-12 Conduct of Operations Manual chapter on investigation of abnormal operational events and deficiencies. Although not as formal as the critique process, the Y-12 Conduct of Operations Manual still requires management reviews to describe the incident, perform an analysis of actual versus expected responses of personnel and equipment, and determine root causes and corrective actions. However, the management review of the spill event was deficient in several areas, including:

- It did not identify and provide corrective actions for any of the key problems that led to the spill. For example, the management review did not identify that the crucible changeout procedure had numerous errors, including valve lineup problems.

- It did not identify any concerns with the mechanic's potential exposure to NaK or to an NaK fire when he removed the argon hose without wearing protective equipment.

- It identified the event as a small NaK spill—inconsistent with information shortly after the event that estimated the spill to be about three gallons.

- It lacks the detail that was necessary for effective operations improvement and that might have prevented the accident.

- It did not involve senior management.

Operations personnel were responsible for crucible changeout and NaK recovery, but maintenance personnel were responsible for such activities as physically connecting and disconnecting purge hoses, unbolting flanges, and removing and replacing the crucible. Weaknesses in conduct of operations were evident in the planning and conduct of work performed by the maintenance organization:

- Miscommunication between the operations manager and the maintenance pipefitter was an important factor in the argon hose being removed before the isolation valve was closed, which led to the spill.

- Maintenance supervision was minimal because management assumed that the maintenance personnel were under the direction of operations.

- The maintenance department prepared a work package for crucible changeout that duplicated and paralleled the crucible changeout procedure, including the serious omissions and errors in the procedure.

- Maintenance personnel stated in interviews that they were following parts of the operational procedure, not the prepared work package.

- Maintenance supervision did not ensure that the maintenance work package prepared for the activity was "in hand" and being used effectively.

- Additionally, the step-by-step maintenance work package with a sign-off for each step was not appropriately used during the work. Though numerous steps had been completed before the accident, no steps were signed off on the job-site copy.

- The planning for the maintenance work package did not include adequate walkdowns to identify errors in the work package.

If maintenance workers had followed the work package as required, they might have stopped work when the steps could not be implemented as written.

Contributing Cause

Conduct of operations, including procedure adherence, procedure change control, stop work, system configuration control, investigation, and reporting, was not implemented as required and was not adequate to control hazards.

Overall, in the area of conduct of operations, the Y-12 Plant has not successfully transitioned from an expert-based approach to an institutionalized and rigorous process for identifying, analyzing, and controlling hazards. Unless the process focuses the participant to base decisions on technical basis documents rather than solely on individual expertise, the current approach will continue to impede implementation of integrated safety management, limit management control, and contribute to events and accidents.

3.3 Worker Safety and Health

Deficiencies in worker safety and health programs either contributed to the NaK spill on December 1, 1999, and the subsequent accident on December 8, 1999, or exacerbated the consequences of these events. Areas of concern are hazard communication, job hazard analysis, safety and health procedures and permits, and PPE.

Hazard Communication

The Occupational Safety and Health Administration (OSHA) Hazard Communications Standard, 29 CFR 1910.1200, requires employers to establish and follow a written hazard communication program, ensure that MSDSs are available in the workplace, train workers on chemical hazards in the workplace, and label hazardous chemicals appropriately. Deficiencies in several of these areas were identified in work activities associated with the crucible changeout on December 1, 1999, and the NaK recovery plan on December 8, 1999.

The Y-12 Plant hazard communication program is documented in LMES Procedure Y73-208INS "Hazard Communication Program Instruction." In the preparation for the work on December 1 and 8, several violations of this procedure were evident. Some workers did not have Hazard Communication Level I training (or equivalent) or the appropriate work area (job-specific) hazard communication training as required by the procedure. Some workers who were interviewed were not aware of how to obtain an MSDS as required by Section D of the procedure. For the Recovery Plan, the hazard identification process as described in the Hazard Identification Planning procedure Y15-012 was not implemented as required by Section B of the procedure.

MSDSs were not sufficiently analyzed or integrated into work activities as required by 29 CFR 1910.1200 and LMES Procedure Y73-208INS. MSDSs were not used effectively in preparing the recovery plan (including the three recovery plan developmental meetings) or the pre-job briefing for the recovery plan, nor were they included or referenced in the recovery plan. Before 1990, the skull caster furnace crucible changeout procedure required operators to be familiar with MSDSs (as well as the hazards in the NaK Training Manual). These requirements were dropped in subsequent revisions of the procedure. Section D.2 of Y73-208INS, and Paragraph g (8) of the OSHA Standard require that workers know how to obtain an MSDS. However, several workers who were interviewed indicated that they did not have knowledge of or instruction in how to obtain an MSDS. Workers also indicated that in preparing for the crucible changeout and NaK recovery, they had not read or been briefed on the MSDS for NaK. Although Y-12 Plant Industrial Hygiene had used the NaK MSDS in preparing for the crucible changeout procedure, their review focused on evaluating an NaK reaction with water, in order to determine appropriate respiratory protection requirements. The explosion and fire hazards of NaK, as described in the MSDS, were not adequately assessed because the MSDS was not thoroughly evaluated.

Hazard communication training on NaK was not provided for some workers in accordance with the requirements of 29 CFR 1910.1200 (h) and LMES Procedure Y73-208INS. For example, at a minimum, the OSHA Standard requires employee training on hazardous chemicals in the work area to include methods for chemical detection, physical and health hazards, and measures to be taken to protect workers from these hazards. Due to the NaK hazards, work activities on or near the skull caster furnace require both Hazard Communication Level I training and the appropriate work area (job-specific) hazard communication training for employees who could be exposed. Some of the safety staff (RCTs and Industrial Safety) involved with the December 1 crucible changeout or the December 8 recovery plan had not received Hazard Communication Level I training.

The "Strategy" section of the hazard communications procedure also requires that "work area (job-specific) hazard communication training be provided by the responsible supervisor upon entry into the work area, and whenever a new chemical is introduced into the work area." The procedure also requires that documentation for such training be "maintained in a readily retrievable format." Work area hazard communication training as described in Y73-208INS has not been developed for DUO Plant workers, although such training has been developed and implemented at Oak Ridge National Laboratory. Therefore, there are no records of DUO Plant workers having received work area (job-specific) hazard communication training. Further, DUO Plant supervisors for these events have not received hazard communication training for supervisors.

The pre-job briefing that was conducted before the crucible changeout work did not adequately inform the participants of the hazards associated with NaK and superoxides. Many of the workers did not understand key information included in the NaK Training Manual and the NaK MSDS, including what to do in case of a spill or how to respond to an NaK fire. Other than for the radiological hazard, there is no procedure or checklist that defines the content of a pre-job briefing to ensure that it is thorough and is properly conducted and documented. Interviews with personnel involved in the work indicated that some were unaware of the full range of hazards associated with NaK, including the possible production of hydrogen, formation of oxides and hydroxides, and formation of potassium superoxides in the event of a spill. There was also no recognition of the need to exclude organic material, such as oil, if the superoxide is suspected.

The pre-job briefing for the recovery activities was conducted informally before the work began and consisted primarily of assigning tasks to the operators. Because the recovery team met several times before then, the workers thought they understood the hazards and believed that a detailed pre-job briefing was not necessary. Many of the participants might therefore not have fully understand the hazards associated with NaK, including the basic information from the NaK Training Manual and the NaK MSDS.

Job Hazard Analysis

The hazards associated with NaK and mineral oil were not sufficiently identified, analyzed, or understood in accordance with OSHA requirements or Y-12 Plant procedures. Appendix B of 29 CFR 1910.1200 requires that employers "conduct a thorough evaluation (of hazardous chemicals), examining all relevant data and produce a scientifically defensible evaluation." The fire and explosion hazards of NaK and prohibitions against adding organics (e.g., mineral oil) if yellow potassium superoxide contamination is suspected are detailed in several NaK MSDSs. This MSDS data and other relevant technical data and technical reports on NaK were not thoroughly evaluated and used in preparing work documents and job hazard analyses (JHAs). The NaK MSDS, for example, states that "very small quantities of NaK (less than one gram) can be a significant fire and explosion hazard." Neither the fire nor the explosion hazard for work activities inside the skull caster furnace chamber was identified or evaluated. As discussed previously, a hazard screening evaluation for another Y-12 Plant facility discusses the superoxide/oil hazard, but this information was not reviewed or utilized as part of the JHA for the work in the skull caster furnace.

An initial job screening and a JHA were conducted in preparation for the crucible changeout on December 1, 1999. However, the JHA did not provide enough detail to adequately correlate job steps with hazards and controls. For example, many steps and a variety of hazards and controls are involved in "performing work inside skull caster furnace chamber," although the JHA addresses these activities in one job step. LMES Procedure Y73-043 cautions JHA preparers to avoid such generalities. Some stated job steps, such as "exposure to NaK," are not job steps; they are hazards associated with specific, but undefined, work steps. Since the job steps are not clearly delineated in the JHA, the hazards and controls for those steps are not defined. Some hazards that are identified in other technical references are not identified in the JHA, such as the potential for fire, explosions, and formation of NaK superoxides. Further, the JHA process did not include fire protection engineering, even though the dominant hazard was a pyrophoric material. The Board believes that including Y-12 Plant fire protection engineering in the planning process could have alerted the JHA team to the fire and explosion hazards of NaK, and the need for flame-retardant clothing and other controls.

For the recovery plan on December 8, 1999, the facility work planners did not perform an initial job screening and hazard identification screening as required by LMES Procedure Y15-012, nor did they perform a JHA as required by LMES Procedures Y15-012 and Y73-043.

Safety and Health Procedures and Permits

No Y-12 Plant safety and health procedures identify or address the hazards of working with liquid metals, such as NaK. For example, the Hazard Identification Planning procedure Y15-012 does not include liquid metals in the hazard identification checklist, even though the checklist addresses other hazardous materials, such as mercury, lead, and beryllium. Although the crucible changeout procedure references LMES Procedure Y79-11 on welding, burning, and hot work (W/B/H) as "an other needed document," the reference is only to welding activities when the crucible is reinstalled in the furnace. This permit does not apply to work with NaK.

Appendix F of LMES Procedure SH-116PD addresses "Evaluating W/B/H for Clothing Ignition Factors" and requires the evaluation of clothing ignition factors for some non-welding activities, such as molten salt bath operations. However, this procedure was not used in preparing for the crucible changeout on December 1, 1999, or the recovery plan on December 8, 1999. The Board believes that an evaluation of clothing ignition factors for NaK work activities is relevant. The Board believes that the application of this procedure would have resulted in an evaluation of clothing, and possibly additional requirements for the use of fire retardant clothing during NaK work activities.

Several safety permits were identified for the December 1 and 8 work activities to address radiological hazards, asbestos, and energized equipment. However, no permits were issued for the dominant hazard, which was the NaK. LMES Procedure 70-525 requires an Operations Safety Work Permit (OSWP) if the work presents "a condition of extraordinary or unusual liability to accident occurrence, which could result in serious injury, illness or property damage." According to the procedure, "work with toxic or corrosive materials" is an example of when an OSWP should be used. In fact, since working with NaK should require a Type I OSWP, an additional, formal health and safety evaluation would have been required for both crucible changeout and NaK recovery. This type of formal recognition and review of the NaK hazards might have alerted work planners to the full range of hazards.

Contributing Cause

OSHA, DOE, and site requirements related to worker safety were not effectively implemented in the areas of hazard communication, hazard identification, job hazard analysis, and industrial safety and health procedures/permits.

Personal Protective Equipment

Designation of PPE for both crucible changeout and NaK recovery was not in full compliance with OSHA or Y-12 Plant requirements. Work activity planning did not address the PPE recommendations from the NaK manufacturer, nor did it consider similar PPE requirements described in the final safety analysis report, the NaK Training Manual, a 1992 NaK occurrence at Y-12, or previous versions of the crucible changeout procedure. In addition, NaK suits were not ready to use in support of NaK spill recovery. NaK suits have been demonstrated to be effective in protecting workers against serious thermal or chemical burns.

The work documents that prescribe PPE for crucible changeout and spill recovery are confusing and in some cases were not followed. For example, several RWPs stated, "Respiratory Protection Not required by RADCON – See applicable procedure or permit (OSWP, BWP, Asbestos, Etc.) for Respiratory Protection required by Industrial Hygiene." Step 2[1] of the crucible changeout procedure states that the type of respirator is included on the applicable RWP, but no respirator type is identified in the applicable RWPs since such information was not provided by Industrial Hygiene. Documenting the respiratory protection requirements in this manner is inconsistent with Section B.9.f of the Radiological Work Permit procedure Y75-56-FO-122, which requires the permit number or procedure requiring respiratory protection to be entered on the RWP if respiratory protection is required only by Industrial Hygiene. The RWP procedure, in section B.11.f(3), also requires that safety clothing required by Industrial Hygiene/Occupational Safety be referenced in the RWP. The RWPs did not reference any additional PPE requirements because Industrial Hygiene had not referenced additional PPE.

In another example, the crucible changeout procedure requires NaK protective equipment for any operation "when the potential to come into contact with NaK is possible." This crucible changeout procedure was used in preparing the recovery plan. However, neither the crucible changeout procedure nor the JHA clearly identifies which operations have the potential for contact with NaK. Some PPE requirements were conflicting between the procedure and the plan. For example, Step 2 [8] of the crucible changeout procedure states that "personnel required to be in the vicinity of the operation, and who wear chrome leather secondary NaK protection shall wear fireproof clothing as issued to welders" (i.e., coveralls treated with flame-retardant chemicals). However, some steps of the recovery plan also require operators to wear chrome leather gloves, but there is no requirement for flame retardant clothing. One worker stated that "there was quite a bit of division whether there was a need to put on a flame-retardant suit" (see Exhibit #10).

Some PPE requirements in the RWPs were also in conflict with the PPE requirements in the recovery plan. For example, the recovery plan requires personnel on the platform to wear a cloth hood, while the RWP for this task indicated "cloth with no hood." Some PPE was not sufficient for the application. As an example, long-sleeved chrome leather gloves were required only for two of the steps in the recovery plan; most steps required standard work gloves. Burned gloves with the seams blown out found at the accident scene were standard-issue, short gloves made of leather, cloth, and latex. The failure to prescribe flame-retardant clothing or ensure the use of chrome leather work gloves for all work activities contributed to the magnitude of the injuries incurred (see Exhibit #11).

PPE selection was based on a hazard analysis that was incomplete (for the crucible changeout) or not documented (for the recovery plan). Both 29 CFR 1910.132 and SH 116PD, "Personal Protective Equipment Program," require a documented and certified hazard assessment, such as a JHA or an operating procedure that identifies the hazards and incorporates the applicable PPE. The recovery plan was not accompanied by a written hazard assessment and does not fully satisfy these requirements. The JHA for crucible changeout does not address either a fire or explosion hazard for work activities inside the skull caster furnace chamber. Therefore, hazard controls, such as PPE, were not identified or evaluated for these events.

The potential interaction of NaK with water, and resultant formation of a sodium hydroxide and potassium hydroxide smoke cloud, was evaluated for PPE considerations. However, the evaluation is incomplete because it did not estimate the sodium hydroxide and potassium hydroxide concentrations and did not provide a technical basis for the use of either a full-face respirator with a P-100 cartridge or an NaK hood with supplied air.

The respiratory protection requirements for operators were inadequate for the concentrations of sodium and/or potassium hydroxides that could have been expected in an accident. Similarly, the failure to define respiratory protection requirements for observers in the vicinity of the furnace was inconsistent with concentrations that could be expected. Information in the facility authorization basis documents could have been used to estimate concentrations in the event of a spill and thus to define PPE requirements for workers and observers. However, the facility authorization basis document was not adequately used in the preparation of the JHA or in the specification of PPE. For example, the authorization basis document for the Arc Melt Facility, the "Phase I Hazard Screening Analysis for the 9201-5 Arc Melt Operations," estimates concentrations of sodium hydroxide resulting from a spill of 30 gallons of NaK. An extrapolation from this analysis indicates that a spill of three gallons (comparable to the spill on December 1) would have resulted in sodium hydroxide concentrations in excess of Immediately Dangerous to Life or Health (IDLH) values, and in excess of American Conference of Governmental Industrial Hygienists (ACGIH) ceiling concentrations for sodium hydroxide within 15 feet of the furnace. If the airborne release fraction of sodium or potassium was greater than one percent, as assumed in the hazard screening analysis, then the sodium hydroxide and potassium hydroxide concentrations would have been greater. The Sodium-NaK Engineering Handbook indicates that the release fractions could be as high as 20 to 60 percent.

The respirator protection in use at the time of the spill and the explosion did not comply with site procedures or MSDS recommendations. Procedure Y73-050PD states that an air-purifying respirator cannot be used if IDLH conditions are likely to exist. Further, the NaK MSDS recommends a National Institute for Occupational Safety and Health (NIOSH)-approved self-contained breathing apparatus (SCBA), and not an air purifying respirator "when inhalation of fumes or smoke is possible."

PPE for Workers Contacting NaK

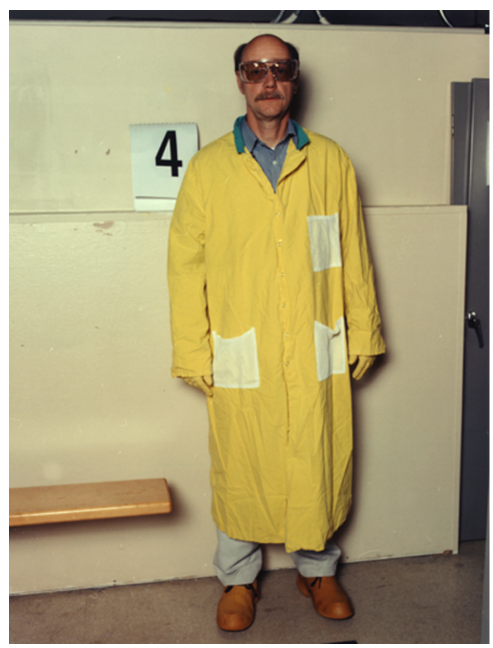
- Impervious NaK suit including respiratory protection and chrome gloves
- Full protection against thermal and chemical burns
- Not worn and not staged

PPE for Support Personnel

- Derived from site requirements
- Includes full face respiratory protection and flame-retardant materials
- Not worn

PPE Worn by Three Workers

- Standard coveralls (not flame-resistant)
- Leather gloves (not flame-resistant)
- Cartridge-type respirator (not supplied air)



PPE Typical of That Worn by Other Workers

- Standard lab coats (not flame-resistant)
- Standard shoe covers and gloves (not flame-resistant)
- No respirator

Exhibit #10. Comparison of Personal Protective Equipment

NaK Resistant Chrome Leather Glove

Standard Work Glove Burned from Explosion/Fire

Exhibit #11. Comparison of Recommended Chrome Gloves to Regular Gloves Worn During the Accident

PPE requirements for the December 8, 1999, spill recovery did not adequately incorporate the lessons learned from previous occurrences and accidents. For example, corrective actions from the 1992 occurrence required "non-participatory and inspection" personnel to wear chemical goggles, safety shoes, company-supplied clothing, and half-face respirators and to maintain a safe distance (i.e., 15 feet). However, industrial hygiene and line management did not specify requirements for observers and supervisors other than standard PPE (i.e., lab coat, shoe covers, and gloves). In addition, some corrective actions from the 1997 welding fatality at K-25, such as the evaluation of anti-contamination clothing for flame-retardant requirements, were too narrowly applied to only welding activities. As a result, other activities at the Y-12 Plant that could also result in clothing fires (e.g. liquid metal, metal grinding and glass blowing operations) were not addressed by the 1997 corrective actions.

The PPE requirements for personnel involved with systems containing NaK were also inconsistent with the NaK manufacturer's recommendations, the 1988 final safety analysis report for the skull caster furnace, and earlier versions of the crucible changeout procedure. The NaK manufacturer, Callery Chemicals, requires goggles or a face shield, dry leather gloves, and fire-retardant protective clothing with no cuffs or pockets. Where smoke is possible, SCBA is required. Contrary to the manufacturer's recommendations, some crucible changeout activities specified leather gloves dipped in mineral oil (not dry), and failed to specify flame retardant clothing, clothing without cuffs or pockets, or an SCBA. The 1988 final safety analysis report required PPE consisting of a "face shield, flame proof coveralls, hard hat and shoes when [operators] are working with NaK." The current crucible changeout procedure (and recovery plan) also omitted some PPE requirements that were in older versions of the procedure. For example, earlier procedures required Nomex® (flame-retardant) coveralls for crucible removal, repair, cleaning, and installation. The Nomex® requirement was included in procedures until November 1989.

NaK suits were not staged at the furnace for the spill recovery on December 8 for either planned work evolutions or response to abnormal events (see Table 4 and Exhibit #12). Section 9 of the recovery plan requires an NaK suit for cleaning the furnace walls and floor. For abnormal response actions, Section 2 of the recovery plan refers to the abnormal response action of the crucible changeout procedure (Section 4.8), which requires the use of an NaK suit for both NaK spills and external NaK oxidation events, either of which could have occurred in removing the spilled NaK from the furnace.

Exhibit #12. NaK Locker Showing the Lack of NaK Suits

Radiological Control personnel informed the team that on November 12, 1999, they had performed radiological contamination surveys on the NaK suits located in the skull caster area safety equipment locker. Fixed contamination was identified on the interior of the NaK suits but no removable contamination was found, as documented on the survey. Radiological Control personnel moved the suits to the Boundary Control Station where they were at the time of the accident.

Contributing Cause

Y-12 Plant management systems and processes were not effective in ensuring the availability and use of PPE that was appropriate for work activities involving pyrophoric reactive liquid metals and for protection against thermal burns, caustic chemical burns, and inhalation of toxic and radioactive smoke.

Workplace Radiological Controls

Work at the time of the explosion was conducted under RWP 1999-D2-00057-O-U. PPE consisted of cotton coveralls, surgeon's gloves, work gloves, booties, and rubber shoe covers. NaK suits, flame retardant clothing, or chrome-lined gloves were not specified because the planners determined that they were not required. Respiratory protection was not required for radiological protection purposes; however, it was required for industrial hygiene purposes. RWP 1999-D2-00057-O-U also required intermittent radiological control coverage. Some of the individuals in the area at the time of the accident were working under another RWP that covered individuals conducting tours and inspections. PPE specified on that RWP consisted of lab coats, surgeon's gloves, and rubber shoe covers, as a minimum.

In general, PPE for radiological protection was appropriate and was worn as prescribed on the RWPs

Table 4. NaK Suits Unavailable for the Recovery Plan on December 8th

NaK suits were not readily available or staged to support the Recovery Plan either for planned evolutions or for abnormal response.

- NaK suits were not staged at the furnace on December 8th to support the recovery operations. The recovery plan required NaK suits for both the performance of the plan and for responding to abnormal operations.
- Some components of the NaK suit (e.g., vests) were not moved by DUO Maintenance after the spill event on December 1st and could not be located.
- The NaK suit undergarment (fram suit) required modification (i.e., cutting off the feet of the suit) before it could be worn.
- The NaK hood with breathing air modification is not a NIOSH approved respirator as required by the Y-12 Respiratory Protection Program (Y3-050PD), OSHA 29 CFR 1910.133 and DOE Order 440.1A.
- Analysis has not been performed to demonstrate that the NaK hood with breathing air is suitable for expected concentrations of NaOH or KOH or potassium oxides.
- The recovery plan did not include a prerequisite to verify that the breathing air supply had been tested and certified prior to use.

at the time of the accident and during recovery activities following the accident.

Neither RWP specified the appropriate PPE for work with NaK. Both RWPs failed to identify, require, and provide the appropriate PPE to protect workers from chemical and thermal burns and irritation from caustic smoke resulting from the accident. As a result, the severity of the injuries incurred was exacerbated.

A much more structured and effective process is needed to ensure that the appropriate PPE for all potential hazards related to work activities is identified, provided, and properly used to protect worker safety and health.

3.4 Training

The OSHA Hazard Communications Standard, 29 CFR 1910.1200, requires employers to train workers on chemical hazards in the workplace. LMES has established sitewide requirements specifying that training related to hazardous materials be provided to the workforce. For example, LMES General Employee Training (Module 50018507,Section II. E. Safety and Health) establishes training requirements related to potentially hazardous chemicals in the workplace.

Weaknesses exist in many of the important Y-12 Plant training documents as they relate to the use of NaK. Some training documents do not specifically address NaK. Where NaK is addressed, information about superoxides is absent or inadequate to ensure that personnel can recognize the presence of superoxides or how to control their hazards. The following training documents do not provide adequate information to ensure that Y-12 Plant personnel fully understand the potential hazards associated with NaK:

- The NaK Training Manual for Personnel Operating the NaK System for the 9201-5 Skull Caster (1988) does not discuss the formation of superoxides, the characteristics/appearance of superoxides, the potential for unstable conditions associated with shock-sensitive superoxides, or the hazards associated with chemical incompatibilities with acids, halogens, and hydrocarbons (including mineral oil). The manual does not provide information to aid operating personnel in recognizing superoxides.

- Section IV. C., First Aid, of the NaK Training Manual indicates that if NaK contacts skin, "All visible NaK should be brushed from the skin with a dry cloth and the skin should be washed thoroughly with water, followed by a sponging with 3% acetic acid to neutralize any residual caustic." Current first-aid standards no longer recommend acid washes for treatment of caustic exposures, and the 3% acetic acid has been removed from the safety equipment lockers.

- The lesson plan for pyrophoric metals and pyrophoric non-metallic solids (approved 7/15/97), which is used to train fire fighters, discusses the fire hazards associated with NaK alloys and specifically recognizes that "potassium in NaK will react with atmospheric oxygen to form three different oxides. These oxides form a crust over the NaK surface. If the crust is permeated and the superoxide is allowed to mix with the potassium in the NaK then a very high temperature thermite reaction can occur." Although this document specifically mentions superoxides, it does not address explosion hazards associated with superoxides in contact with acids, halogens, or organics, such as mineral oil.

- Work area (job-specific) hazard communication training has not been developed or provided to DUO workers.

In addition to weaknesses in the training materials, there has been little formal training on NaK systems. Operators, chemical processors, industrial hygienists, quality assurance personnel, RCTs, work planners, and operations management personnel have not received formal training on NaK. The NaK Training Manual states that all NaK system operating personnel should be thoroughly trained in NaK safety procedures and fire-fighting methods. Personnel (other than fire department personnel) have not received training on NaK safety procedures or NaK fire-fighting methods.

Weaknesses were also evident in other aspects of training. As discussed previously in Section 3.3, the Y-12 Plant does not meet certain OSHA, DOE, and site-specific training requirements in the areas of hazard communication and PPE. In addition, the General Hazard Communication Training Program Instructor's Manual (SAP module 50061690 Hazard Communication Level I) states that training should include the location and use of MSDS. However, some personnel involved in the accident were not familiar with the location and use of MSDSs.

The Y-12 Plant relies on on-the-job training (OJT) for some aspects of training, in accordance with Y-12 procedures (Y90-027, Conduct of Training procedure). Training records confirm that OJT is provided to chemical operators on some subjects, but none of the recent OJT addressed NaK. Some Y-12 Plant personnel indicated that DUO supervisors use the NaK Training Manual to conduct OJT for chemical operators and other facility personnel. However, personnel involved with the accident and a review of training records did not indicate that training was provided on this manual. Several of the personnel involved in the accident stated that they never were given a copy of the manual. Even if provided, OJT based on this manual would not adequately address the superoxide/oil hazards, since the manual has not been updated for more than ten years and does not adequately address these hazards.

Neither formal training nor OJT addressed responding to emergency conditions involving NaK. The emergency procedures in effect in August 1997 were superseded by a September 1998 Facility Emergency Plan. The hazards summary sheet in this document indicates that the building does not contain NaK.

Overall, the formal training and OJT provided to the facility personnel are not adequate to ensure that personnel who operate NaK systems are aware of safe handling practices and NaK hazards. DUO facility personnel are given little or no specific training on the hazards associated with the combination of superoxides and mineral oil. In the absence of training, facility personnel have relied on information passed on from other workers or supervisors without an adequate basis. For example, the personnel who were interviewed stated that it was common knowledge that mineral oil was the first thing to put on NaK to stabilize it or to make it safe, including extinguishing NaK fires. This erroneous information has been passed down from operator to operator since the installation of the NaK systems and has never been corrected by training or lessons-learned programs.

Contributing Cause

Training programs, including training documents, formal training, and OJT, have not been effective in ensuring that personnel with safety-related responsibilities have current training on NaK systems and that they understand the hazards associated with incompatible chemicals, such as superoxides and mineral oil.

To be effective in protecting worker safety and health, information related to significant hazards and their controls must be institutionalized into training materials, including tests and lesson plans. Y-12 Plant processes have not been effective in ensuring that readily available information on the superoxide hazard was captured, incorporated, or taught in a timely manner. Effective training could have helped to identify the hazard and prevent the accident.

3.5 Emergency Response

In general, the Board concluded that the emergency response to this accident was adequate to ensure that the injured personnel were given appropriate medical treatment. A review of logs, interviews, and Y-12 Plant critiques indicates that the fire department arrived within a few minutes of the 911 call. There were no delays in attending to the victims, and ambulances were available for transport to medical facilities. Mutual aid was exercised when an ambulance from the East Tennessee Technology Park responded to the Y-12 Plant to be on standby while the Y-12 Plant ambulances were off site. The PSS promptly categorized the event as an "operational emergency not requiring classification" and activated the Y-12 TSC, as required. For the seriously injured personnel, medical treatment took priority over radiological concerns; however, all personnel involved were surveyed in a timely manner. Injured personnel were surveyed by REAC/TS at the hospital, and other personnel evacuated from the building were surveyed at the 9201-5 Boundary Control Station or at the assembly area.

Workers in the area of the accident scene displayed courage in mitigating the emergency and attending injured co-workers during the initial chaotic minutes of the accident. The furnace cover was closed, small fires were extinguished, injured personnel were stripped of burning clothing, showers were administered, and personnel were promptly evacuated to the Boundary Control Station for transport to the hospital. The workers performed these actions despite the risk of further injury to themselves immediately following an explosion that temporarily caused shock, anguish, loss of hearing, and burns.

Although the individual response actions were commendable, deficiencies in emergency planning and facility design could have aggravated conditions and increased the severity of the accident and injuries. For example:

- Workers did not have recent fire fighting or refresher training with special training on liquid metal reactions and fires.

- An operator stated that because they could not find temporary berming for the safety shower, one operator was diverted from responding to the accident, and the lack of berming created a slip hazard for other workers involved (see Exhibit #13). Preplanning for emergencies should utilize engineered controls such as permanent berming rather than administrative controls. Pooling of water caused a worker to slip and fall twice while carrying the most seriously injured person.

- Emergency equipment, such as NaK suits, had been moved from a normal storage location prior to the work.

- Fire detection alarms for the high bay had been deactivated; therefore, no alarms were received during the explosion, although significant smoke was generated. The 911 call was the only notification of the accident. Although the 911 call was timely in this accident, the lack of fire alarms could have delayed the response and treatment in other circumstances (e.g., if all personnel were incapacitated by the blast or fumes).

Radiological response at the accident scene and at the hospital was timely and effective. The accident area was promptly controlled and treated as an exclusion area, and samples were taken to verify boundaries and determine accident conditions. Because roof vents opened during the accident, roof samples were taken after the accident. Sample results indicated no contamination or potential release from the building. Nasal smears were promptly taken as an initial indicator of possible uptakes. Although all nasal smears were negative, arrangements were made to obtain urine and fecal samples. Decontamination of personnel and control of material on site and at the hospital were sufficient to prevent the spread of contamination.

The emergency management critique conducted by facility personnel solicited and collected feedback from field responders, participants, fire department, TSC staff, and other critique attendees. Logs and documentation were also reviewed as part of the Y-12 Plant critique. The critique identified the following concerns for further review and evaluation:

- Three initial emergency responders did not use SCBAs during the initial entry into Building 9201-5 based on a report of no fire and information that building personnel were seriously injured, requiring time-urgent response. The expected response is to initially respond in SCBAs, and there was concern about using the protocol for this and other emergencies.

Exhibit #13. Safety Shower Showing Lack of Berms and Burned Clothing

- Access controls were not adequate to prevent unauthorized personnel from re-entering 9201-5 West, an area designated as part of the accident scene that had been evacuated.

- Although the Emergency Operations Center (EOC) was not required to be activated for this emergency, activating the EOC would have facilitated interface with state and local governments and DOE. Systems and staffing in theY-12 TSC were not available to accomplish all required offsite interfaces.

- Incident command strategic goals and tactical objectives were not clear, given the lack of use of procedures, checklists, drawings, and other resources at the command post.

- The Y-12 TSC was overstaffed, creating a crowded work environment, because most of the TSC staff did not interact properly with the automated paging system.

- Although the automated paging system had no failures, the Y-12 Site Office indicated that several of their staff should have been paged. However, the emergency response duty roster provided by the Oak Ridge Operations Center did not identify these additional notifications.

- Internal and external organization relationships for emergency public information were not clearly understood.
- There were minor telephone problems in the Y-12 TSC.
- Logistical problems were encountered with video camera support of reentry operations.
- Not all TSC staff used the TSC checklists.
- Internal communications within Y-12 were not timely.

In general, these concerns did not impact the highest priority emergency response objective of this accident —namely, providing timely medical treatment to injured workers. However, the number and nature of these concerns indicate that additional attention is needed to ensure that emergency response, including internal and external communications, will be effectively coordinated.

The Radiological Control department conducted an additional critique specifically for its personnel on December 14, 1999, to determine how to improve emergency response. The critique, attended by about 25 personnel, included all key responders to the accident. It was detailed, introspective, and focused on identifying areas for improvement. While radiological response to the accident was timely and appropriate, the critique identified needed improvements in several areas, including pre-staging of equipment, transport of equipment to the hospital, availability of equipment at the assembly areas, radio discipline, support to the incident commander, and shift turnover. Because of the number of personnel involved in the emergency, responding RCTs had to gather equipment from a variety of sources. The critique noted that pre-staging equipment in a few central locations would further facilitate emergency response.

Contributing Cause

Deficiencies in emergency planning and facility fire systems, including training on fire fighting and staging of safety equipment (safety shower berms and NaK suits), could have aggravated conditions and injuries.

3.6 Facility Design and Configuration

Several aspects of the accident and emergency response were directly or indirectly affected by deficiencies in facility design. In addition, configuration control of some facility systems was not sufficient to ensure consistency with design specifications.

The skull caster furnace was installed with an oxide control and indication system (OCI) to provide monitoring and removal capability. The skull melt furnace technical manual discusses the system and does not include provisions for operating the furnace without it. However, the OCI system was abandoned some years ago, creating the opportunity for oxide buildup since then. Operators needed to heat the NaK to higher temperatures during draining to improve flow, indicating that oxide had built up. (Oxide formation inhibits the ability of NaK to flow freely at room temperature.) The continued operation of the furnace without the OCI system has not been justified technically, thus violating numerous site requirements (e.g., configuration control, modifications, conduct of operations). Y-12 Plant personnel indicated that the OCI system could not be made to function properly after it was installed in 1969.

System operators believed they had taken some compensatory actions, such as maintaining the NaK sump tank level high enough that any oxide floating on the top of the NaK would not be added to the loop and circulated through the system. However, these actions were never included in the furnace operating procedure. Additionally, the fact that oxides are heavier than NaK and sink instead of float in an argon environment may have negated the effect of the assumed compensatory actions.

Other facility design deficiencies could have increased the severity of the accident. Because of the significant reaction of NaK with water, postings on the skull melt furnace required the exclusion of water from the furnace area. For some equipment, such as the cooling water system adjacent to the furnace, raised berms prevented water migration toward the furnace area. However, other potential entry points for water were not considered:

- The safety shower near the furnace does not have permanent berming. Consequently, during the accident, water from the shower pooled and ran under the furnace, where it interacted with NaK from the explosion. Pooling of water on the floor also caused the person carrying the most severely injured person to fall twice while assisting him. An operator stated that at one time there were temporary berms for the safety shower; however, they could not be located and were not put in place during the accident.

- Part of the room adjacent to the high bay containing the furnace has fire protection sprinklers, and there are no berms to prevent water from the sprinklers from migrating south toward the furnace.

- Roof vents located directly above the furnace could activate, allowing rainwater to fall directly on the furnace. These vents activated during the accident (see Exhibit #14). Rainwater could therefore have entered the furnace during the time it took to close the furnace.

The fire protection system for the high bay was modified from its original design and was not adequate to cause a fire alarm during the accident, although the accident involved an explosion, heat, and large amounts of smoke. The lack of adequate fire alarms for an area containing equipment with potential for heat, fire, and severe chemical reactions could have increased the severity of the accident by delaying emergency response. The four roof vents in the high bay opened during the explosion, possibly due to the blast pressure (since they did not open during the spill, which generated a significant amount of smoke). However, the system configuration for the roof vents is indeterminate. Engineering does not have confidence in the electrical design drawings, and the system has been modified several times without adequate control of the drawings. Operations personnel stated that there was no switch for activating the roof vents, as shown on the design drawings.

As originally designed, the high bay area above the skull caster furnace had seven smoke detectors that would cause a fire alarm and would open the roof vents to vent smoke. Modifications in the late 1960s removed these detectors from service. The accident investigation team found no justifications or fire hazards analysis for their removal. However, fire protection and engineering staff stated that they may have been removed due to nuisance alarms caused by heat and smoke from operation of the furnace. Those modifications left the high bay without adequate fire alarm protection. Additional modifications shown on

Exhibit #14. Open Roof Vents

design drawings connected the two roof vents over the skull melt furnace to a push button switch located in an office; however, as noted above, building personnel were unaware of the switch, and no switch was located. During a fire protection system upgrade, the other two roof vents were connected to smoke detectors for a large industrial saw and an oven in the general area, but away from the skull caster furnace. During testing of the new system before the spill and accident, the roof vents did not function, so they were presumably electrically inoperable at the time of the spill and accident. A work request was initiated to correct the deficiency, but the work had not been completed before the NaK spill and accident.

The roof vents did not open during the spill, which produced a significant amount of smoke. Therefore, Operations contacted the fire department to investigate the vents. The investigation revealed that the smoke detectors were about 10 feet over the floor by the saw and oven, and were too low to detect smoke from or over the skull caster furnace. Operations personnel stated that during the accident, a large amount of smoke was in the area of the industrial saw, yet the detectors did not cause an alarm. Fire protection engineering indicated that the detector for the saw was not installed with a collector (an umbrella-type plate) above the detector to concentrate the smoke to improve detection capability. The fire alarm operated satisfactorily during testing after the accident. Fire protection engineering and the fire department have implemented compensatory measures in the form of a fire watch at four-hour intervals, and they are evaluating options for permanent action.

Contributing Cause

Deficiencies in the facility design and configuration control of systems and equipment, including fire protection systems and berms, caused additional difficulty in responding to the accident and could have made the accident worse.

3.7 Integrated Safety Management Systems

To ensure that management systems were examined as potential contributing and root causes of the accident, the Board reviewed the role of LMES management in promoting and implementing integrated safety management (ISM). The Board also reviewed management's role in the Y-12 Plant ISM program in selected areas, including the role of the DUO Operational Safety Board (OSB) in preparing for the work activities, quality assurance, lessons learned, communication of hazards, and management involvement in safety.

The ISM system provides a formal, organized process for planning, performing, assessing, and improving the safe conduct of work. Properly implemented, ISM is a "standards-based approach to safety" requiring rigor and formality in the identification, analysis, and control of hazards. Safety management requirements are institutionalized through DOE directives and contracts to establish a safe work environment. The system establishes a hierarchy of components to facilitate the orderly development and implementation of safety management throughout the DOE complex. The guiding principles and core functions of ISM are the primary focus for contractors in conducting work efficiently and in a manner that ensures the protection of workers, the public, and the environment. The accident investigation program requires that accidents be evaluated in terms of ISM to foster continued improvement in safety and to prevent additional accidents.

The ISM program at the Y-12 Plant has been contractually required since 1998. LMES's ISM system requirements were established through procedures in 1997 and 1998. The procedures establish a protocol for implementing ISM at the facility and activity level. At the facility level, implementation of ISM is intended to provide the operations line managers with the technical resources and processes necessary to fulfill their ISM responsibilities for managing their safety envelope. The facility relies on establishing OSBs and assigning key technical resources to these boards for ensuring that work is safely planned. Work planning is conducted using a multi-disciplined team that forms the OSB so that potential hazards are identified and analyzed and controls are integrated and put in place to protect the worker, the public, and the environment.

To determine where improvements were needed, LMES management conducted a self-assessment in 1997 to evaluate the programs that implement ISM functions at each level. The self-assessment incorporated the results of the 1997 Type A accident investigation of a welder fatality at K-25; Defense Nuclear Facilities Safety Board technical reports; and other information related to ISM. Opportunities for improvement from this LMES self-assessment included:

- The need to formalize requirements for job walk-downs to ensure appropriate line, technical, and environment, safety, and health (ES&H) support involvement in hazard identification

- The need to consistently apply one job hazard analysis process across the site

- The need to formally include non-nuclear hazard identification and analysis in planning for operational work

- The need to improve the control of routine work and the processes for determining the grade of the task being evaluated

- The need to provide line managers with the tools and ES&H support resources to execute their safety responsibilities.

DUO is attempting to implement ISM. The charter for the DUO OSB defines the roles and responsibilities of OSB members, and the use of multi-disciplinary teams is encouraged. An OSB was used for developing both the changeout procedure and the NaK recovery plan. Time was taken to plan for recovery of the spilled NaK using multi-disciplined teams. At the request of DUO management, an experienced industrial hygienist and a safety specialist participated on these teams.

Notwithstanding these DUO efforts, this accident highlighted deficiencies in work planning and control that contributed to both the NaK spill and the subsequent explosion. The deficiencies were evident in work definition, planning, hazard identification, hazard analysis, developing adequate controls, and work performance—both leading up to the NaK spill on December 1, 1999, and in the work activities associated with NaK recovery that resulted in the accident. A number of controls for ensuring safe work conduct were bypassed, and numerous procedure violations occurred at all levels of the Y-12 organization. The weaknesses spanned multiple organizations and demonstrated inadequate management commitment and implementation of ISM. Table 5 summarizes deficiencies in the application of the five core functions of ISM as they relate to this accident.

Workers, supervisors, and managers at the facility level abandoned the ISM approach and reverted to an "expert-based approach," relying on individual expertise and informal practices in implementing the changeout procedure on December 1. Further, there was a tendency to assume that the group had adequate knowledge of NaK and not to seek outside information or expertise (e.g., from MSDSs, NaK manuals, and vendors), even when unusual and unexpected conditions were encountered. This complacency about the adequacy of knowledge within the group led to a false sense of security regarding the hazards. The facility personnel then proceeded to develop the recovery plan without due consideration of the Y-12 Plant requirements for rigorous planning, thorough hazard identification, documented hazard analysis, and formal procedural controls for hazardous work. The reliance on an expert-based approach indicates that the work planning processes envisioned by ISM are not yet fully understood and accepted by the workforce and are not being promoted and enforced by senior management.

Contributing Cause

Work planning processes at the facility level are not being implemented with the rigor, detail, and formality required by the core functions of ISM.

Although some positive steps have been taken, LMES management has not effectively implemented ISM or effectively carried out its guiding principles. Table 6 presents significant weaknesses and failures in the implementation of each of the seven guiding principles of ISM. In addition, the accident investigation board determined that the improvement areas identified in the LMES self-assessment have not been adequately addressed, as evidenced by the fact that the weaknesses highlighted in this accident are similar to those that LMES identified in 1997.

LMES had opportunities to apply the principles of ISM in every phase of the activity, from crucible changeout through spill cleanup. These opportunities, presented in Table 7 on page 48, further demonstrate how this accident could have been prevented if ISM had been properly applied.

DUO Operational Safety Board

The DUO organization convened the OSB for the crucible changeout procedure. The roles and responsibilities of OSB members for this activity are defined in "Operational Safety Board Charter, Depleted Uranium Operations," dated March 1998. Members are responsible for ensuring that work and safety planning are integral functions and activities are properly scoped; hazards are identified and analyzed; hazard controls are properly developed, integrated, and implemented; and work is performed as required by controls.

More specific member responsibilities are detailed in the Charter for the DUO Organization Manager and Operations Manager, as well as for technical support members. These responsibilities include authorizing activities based on screenings and reviews; ensuring that personnel are trained to perform their assigned work; ensuring that hazards are identified and adequate controls are in place during the execution of work; verifying and validating technical procedures for operational activities; and incorporating controls into the work steps of these procedures. However, there were significant deficiencies in implementing these roles and responsibilities for the crucible changeout procedure and the NaK recovery plan. For example:

- The OSB did not effectively implement the roles and responsibilities defined by their organizational charter.

- Members of the OSB did not seek additional technical advice or information on these hazards from readily available sources or lessons learned from other NaK-related accidents, but relied on past practice and group knowledge.

Table 5. Deficiencies in the Application of the Core Functions of Integrated Safety Management

There are significant weaknesses in integrated safety management and the implementation of the five core functions that caused the NaK spill and the accident. Many of the weaknesses resulting in the spill also existed in the processes that resulted in the accident. Weaknesses existed in all core functions and at several levels within the Y-12 organization including upper management. These weaknesses included:

Define the Work

- Special training requirements to work with NaK were not defined.
- The recovery plan did not contain a section that defined the purpose or scope of work as required by both the technical procedure and the work planning guide processes.
- The scope or extent of work with NaK superoxides was not defined.
- The work was defined as a less formal maintenance/operations bypassing formal requirements.

Analyze the Hazards

- NaK (and oxides) Material Safety Data Sheets (MSDSs) were not analyzed to understand the explosive hazards.
- Technical basis and understanding of mineral oil use with NaK, oxides, and superoxides were lacking.
- An adequate technical basis to prescribe appropriate PPE was not developed for both activities.
- Workers were unaware of the extent of hazards associated with superoxides (readily available from Bldg. 9720-27 event and multiple other sources).
- There was a failure to complete the hazard checklist and develop a job hazard analysis for a hazardous spill recovery.

Develop and Implement Controls

- DOE and DUO management were not adequately involved in the review of the activity and procedures.
- Significant deficiencies existed in the crucible changeout procedure after verification and validation.
- Lack of QA involvement and independent review existed during procedure development and hazard analysis.
- The crucible changeout procedure was developed as a Category 3 versus Category 1 procedure for a hazardous task with over 400 steps that had not been performed in over four years.
- A recovery plan was used, rather than a technical procedure, for the spill recovery operation.
- Critical MSDS information related to superoxide/organic hazards was not integrated into work activities.
- Hazard identification/analysis was not developed for recovery as required by OSHA and site procedures.
- Most workers involved had no NaK training, had not read the NaK training manual, and had little understanding of the NaK MSDSs and explosive hazard of NaK and mineral oil when combined.
- Roles and responsibilities between maintenance and operations were not clearly specified for crucible changeout.
- There was a failure to wear appropriate PPE on December 1, 3, and 8.

Perform Work Safely

- Pre-job briefings other than radiological were informal, not well documented, and not effective in conveying the extent of hazards.
- The crucible maintenance work package was not used and step-by-step signoffs were not completed as required.
- Operations and Maintenance failed to stop work and obtain technical assistance or management approval when work package or procedure errors were detected during crucible changeout.
- There was inadequate investigation of system configuration for abnormal sump levels (valve lineup).
- There was inadequate operations and maintenance supervision oversight and control of system configuration.
- There was a failure of the worker close to the furnace to use appropriate PPE during spill recovery.
- The recovery plan improperly directed spraying mineral oil onto the NaK, a cause of the accident.

Feedback and Improvement

- Supervisors and workers had little knowledge of past NaK events.
- Lessons learned from a 1992 NaK event were not considered in reviewing the NaK hazards for the recovery plan.
- Corrective action and responses to management directed by a 1994 yellow alert were not adequate.
- Comprehensive lessons learned from a 1997 NaK event in Bldg. 9720-27 were not effectively applied sitewide.
- PSS and DOE were not informed of the spill, and no event report was written for the occurrence.

Table 6. Weaknesses in Implementing the Guiding Principles of Integrated Safety Management

Guiding Principle	Observed Weaknesses
Line Management Responsibility for Safety Guiding Principle #1: *"Line Management Is Directly Responsible for the Protection of the Public, Workers, and the Environment."*	• LMES management has not effectively implemented ISM or an equivalent worker safety program ensuring the identification, control, and mitigation of significant hazards to workers. • Management was not adequately involved in the Operational Safety Board (OSB) in development, verification, validation, quality, and change control for the crucible changeout procedure and NaK spill recovery plan. This contributed to a loss of configuration control for the NaK cooling system, an NaK spill, and directing workers to take an unsafe action in spraying mineral oil in violation of the MSDS and applicable publications. • LMES management has failed to effectively apply the known lessons learned from previous NaK events as well as other accidents in order to prevent this accident and to mitigate the impact on worker health and safety. • LMES management has not established effective mechanisms for communicating information on the hazards of NaK. • LMES management has not assured a safety culture where workers are willing to stop work and to re-enter the hazard identification and analysis phases of ISM or to seek management and technical assistance when procedures do not work or unusual or unexpected conditions are encountered.
Clear Roles and Responsibilities Guiding Principle #2: *"Clear and Unambiguous Lines of Authority and Responsibility for Ensuring Safety Shall Be Established and Maintained at All Organizational Levels Within the Department and Its Contractors."*	• LMES facility management roles and responsibilities associated with the OSB were not understood or implemented to ensure the adequacy of procedures and plans to protect the health and safety of workers. • The "as requested" service role of the LMES quality assurance organization is not effective in fulfilling defined QA objectives including assuring the adequacy of work and hazard control processes, the conduct of independent and management assessments to assure the adequacy of programs and processes and continuous improvements. • The defined roles and responsibilities for determining the events requiring reporting were not effective in assuring that the December 1 NaK spill was reported to DOE. • LMES management has failed to establish effective accountability for adherence to institutional controls including procedures, work and hazard control processes, and to prevent over-reliance on informal work controls and skill-of-the-craft.
Competence Commensurate with Responsibilities Guiding Principle #3: *"Personnel Shall Possess the Experience, Knowledge, Skills, and Abilities That Are Necessary To Discharge Their Responsibilities."*	• LMES failed to establish and maintain competencies on the hazards associated with NaK and the explosive interaction between potassium superoxide and mineral oil for personnel responsible for hazard identification and analyses and the safety of workers. • Workers involved in the crucible changeout on the NaK spill cleanup were not adequately trained on the NaK hazards including superoxide-organic interactions, the use of NaK suits and PPE or emergency response including liquid metal fire fighting as required by OSHA. • LMES managers and workers failed to seek adequate technical expertise or to consult readily available literature when unusual or unexpected conditions were encountered including a suspicion of the presence of potassium superoxide.

Table 6. Weaknesses in Implementing the Guiding Principles of Integrated Safety Management (Continued)

Guiding Principle	Observed Weaknesses
Define the Scope of Work; Balanced Priorities Guiding Principle #4: *"Resources Shall be Effectively Allocated To Address Safety, Programmatic, and Operational Considerations. Protecting the Public, the Workers, and the Environment Shall Be a Priority Whenever Activities Are Planned and Performed."*	• DOE and LMES failed to prioritize the resources necessary to complete a replacement melting system that does not employ NaK that was a lesson learned from a 1992 NaK release. • LMES failed to assure the availability and use of appropriate personnel safety equipment for personnel working with NaK as identified following a 1992 NaK release including NaK suits, flame resistance coveralls, chrome leather gloves, spats, and appropriate respirators.
Identification of Safety Standards and Requirements: Analyze the Hazards Guiding Principle #5: *"Before Work Is Performed, the Associated Hazards Shall Be Evaluated and an Agreed Upon Set of Safety Standards Shall Be Established That, if Properly Implemented, Will Provide Adequate Assurance That the Public, the Workers, and the Environment Are Protected from Adverse Consequences."*	• The implementation of the LMES hazards identification and analysis process was inadequate in identifying and mitigating the potassium superoxide/mineral oil hazard including failure to carry out their Hazard Identification Planning process and JHA or to consider information in the NaK MSDSs or a hazard screening for NaK in another Y-12 facility. • The authorization basis for this facility and the melter operation failed to address, analyze, and provide controls that would mitigate and control the potassium superoxide/mineral oil hazard. • The USQ screening performed for the NaK spill cleanup did not follow procedures, did not consider available information in the MSDS or hazard screen for another facility, and failed to determine that the potassium superoxide/mineral oil combination was an explosive hazard not enveloped by the existing authorization bases. • The explosive superoxide-organic interaction, including the sensitivity to shock, was identified in a hazard screening evaluation for NaK stored in another Y-12 facility by LMES facility safety engineering but not communicated, incorporated into the 9201-5 authorization basis, or utilized in the hazards analysis factors that could have prevented this accident. • The MSDS for NaK on the LMES network states that if superoxide contamination is suspected, do not add organics. This statement was not effectively employed in the hazard analysis or development of the spill recovery plan and hazard controls. • Deficiencies are evident in implementation of OSHA, DOE, and Y-12 Plant site requirements in the areas of conduct of operations, hazard communications, occurrence reporting, quality assurance, and USQD.
Hazard Controls Tailored to Work Being Performed: Develop and Implement Hazard Controls Guiding Principle #6: *"Administrative and Engineering Controls To Prevent and Mitigate Hazards Shall Be Tailored to the Work Being Performed and Associated Hazards."*	• The procedure developed for the crucible changeout was not adequately verified, validated, properly categorized, technically accurate, or of a quality adequate to conduct the activity, control the system configuration, and prevent the NaK spill that led to the accident. • The "Plan" developed to conduct the NaK spill cleanup was not an authorized LMES mechanism for controlling hazardous activities and was inadequate to control or mitigate the hazards involved. • Neither the crucible changeout procedure nor the NaK spill cleanup plan was effective in identifying the potassium superoxide hazard or preventing the addition of mineral oil and the accident.

Table 6. Weaknesses in Implementing the Guiding Principles of Integrated Safety Management (Continued)

Guiding Principle	Observed Weaknesses
Operations Authorization: Perform Work Within Controls **Guiding Principle #7: *"The Conditions and Requirements to be Satisfied for Operations to be Initiated and Conducted Shall Be Clearly Established and Agreed-Upon."***	• Because of the failure to identify the hazard present, the hazard analysis, hazard controls, and recovery plan were not effective in identifying and assuring the provision of the personnel protective equipment necessary to protect the workers from injury and exposure. • Changes were made to the crucible changeout procedure and implemented without "stopping work" to obtain management review and approval in accordance with LMES requirements. • The authorization basis for Building 9201-5 is the 1991 hazard screening, which did not accurately reflect the hazards associated with NaK. • The draft BIO for Building 9201-5 has not been approved after four years of comments and revisions. • Senior facility management did not review and approve or ensure that adequate procedures, plans, and controls associated with the crucible changeover or NaK spill cleanup activities were in place or authorize the activities. • Line management did not assure that personnel involved in the crucible changeout or NaK spill recovery were trained and cognizant of the hazards associated with the work that required precautions and protective equipment. • The pre-job briefings were not sufficient to assure an adequate understanding by all personnel involved in the work of the hazards involved and the necessary controls including the information contained in the NaK MSDS, and that all personnel were aware of those controls.

Table 7. Opportunities Existed to Apply ISM Principles

Crucible Changeout Activity - December 1, 1999

Actions	ISM
Changed procedure with pen and ink changes numerous times and kept working.	By ISM and LMES process, should have stopped and obtained review and approval for changes **before** proceeding.
Failed to open NaK dump valve resulting in NaK trapped in crucible cooling piping at 10 psi argon pressure.	Valve should have been in procedure with a step signoff — this was a loss of system configuration control.
Workers observed a 4-inch lower NaK sump level than expected and hoped for — elected to work back through procedure, once again failing to open the NaK dump valve.	An unusual or unexpected condition should result in stopping work to analyze the problem and system configuration, to resolve discrepancies and obtain management permission prior to proceeding — backing out and working back through a procedure shouldn't be done without analysis and approval. Could have prevented the NaK spill and the accident.
Pipefitter sent into furnace to disconnect argon hose without appropriate PPE.	Hazard analysis should have identified potential for NaK release and fire in enclosed area and need for PPE.
Verbal direction to close isolation valve not completed, resulting in spraying of NaK into furnace under pressure.	Isolation valve closure should have been in procedure — verbal directions should be repeated back — system valving operations should be done by personnel knowledgeable of system and hazard (another loss of system configuration control and a personnel near-miss).
Potassium superoxide probably formed during spraying NaK into air.	Hazard should have been recognized and controlled.

NaK Spill Recovery Planning and Interim Actions - December 1-7, 1999

On Friday, December 3 an inspection of the furnace and NaK spill revealed unusual and unexpected conditions: • Configuration of NaK • Reactions/smoke • Yellow color "suspected superoxide."	**Stop** and re-enter hazard analysis phase, conduct additional research or consult additional expertise.
Mineral oil sprayed on NaK spill, furnace walls, and suspected superoxide.	Additional hazards analysis, research, consultation of experts, or review of MSDS would have identified incompatibility of superoxide and mineral oil and potential for explosion. Proper cleanup is to cover with Met-L-X and remove promptly.
The spraying of mineral oil resulted in reactions and smoke and since superoxides were already apparently present, could have resulted in the explosion and accident on December 3 (lacking only the impact/shock).	There should have been a hazard analysis or documented safety bases for spraying oil — the workers wore no NaK PPE or respirators and an explosion on December 3 could have had worse consequences.
Monday – December 6, additional mineral oil sprayed into furnace and on spill.	Would not have added mineral oil in presence of superoxide and would have worn protective clothing if hazard analysis was performed.

Table 7. Opportunities Existed to Apply ISM Principles (Continued)

NaK Spill Recovery "Plan"

The "Plan" is not an authorized LMES document for controlling hazardous work.	Use approved procedure—section of crucible change-out procedure if adequate.
A JHA was not conducted for NaK spill cleanup — since considered "routine" maintenance activity.	Conduct JHI/JHA for LMES process and initial hazards and controls—task was not routine but hazardous and had not been conducted recently.
USQD screen on NaK spill cleanup informal (e-mail); and inadequate to identify superoxide-mineral oil-impact hazard.	Should have involved knowledgeable experts, use of MSDS, research, understanding of NaK, and review of plan and use of mineral oil—site safety engineering involvement should have linked superoxide warning in 9720-27 hazard evaluation.
MSDS not used in developing plan and analyzing hazards.	MSDS warned not to use organics if superoxide is suspected—OSHA requirement.
Plan did not identify superoxide hazard, and actually directed workers to perform unsafe act to spray mineral oil on NaK spill with "suspected superoxide present" and then to prod the NaK to break it up—the very conditions that caused the explosion.	An adequate hazard analysis, USQ, use of the MSDS, and an approved and adequate procedure would not have directed an unsafe action.
The plan did not specify appropriate PPE for workers directly involved in handling NaK or support personnel and NaK suits and other PPE not provided or worn.	Lessons learned from the 1992 NaK release, the MSDS, and other reference materials specify appropriate PPE and respirators—equipment that would have prevented or significantly reduced the injuries.

NaK Spill Cleanup - December 8, 1999

The hazard analysis and pre-job brief did not identify superoxide hazard or prescribe appropriate PPE.	The hazard should have been identified and prevented or mitigated through adequate competencies and involvement of safety personnel including formal PPE evaluation and involvement of fire protection engineering and site safety engineering.
The MSDS was not present at the job site or reviewed during the hazard analysis or pre-job briefing (OSHA requirement).	Review of the MSDS would have identified the hazard of spraying mineral oil and poking NaK if superoxide was present and assisted in selecting PPE.
Workers were not in appropriate PPE for NaK hazard including potential for fire, explosion, and inhalation of caustic smoke.	Appropriate PPE would have prevented or substantially reduced injuries.
Workers poked and probed NaK with metal tools to break up while spraying additional mineral oil establishing the conditions necessary for an explosion in the presence of potassium superoxide.	Accident would have been prevented by adequate hazards analysis, use of available reference materials, competencies and understanding of the hazard, hazard controls, and use of lessons learned. It could have been mitigated by appropriate use of PPE.
Workers, or the individuals responsible for their safety, were not trained on NaK or superoxide-organic hazard.	Training and competency—a principle of ISM and hazard training is an OSHA requirement.
The plan did not specify appropriate PPE for workers directly involved in handling NaK or support personnel and NaK suits and other PPE not provided or worn.	Lessons learned from the 1992 NaK release, the MSDS, and other reference materials specify appropriate PPE and respirators—equipment that would have prevented or significantly reduced the injuries.

- The OSB failed to ensure that operating personnel who perform work at the arc melter were adequately trained on NaK safety procedures; the hazards of NaK, superoxides, and mineral oil; MSDSs; and NaK fire fighting methods.

- Effective hazard controls were not established for the work involved. Personnel were not provided the proper PPE. Proper safe distances from the NaK recovery operation were not determined, and proper fire extinguishing material (Met-L-X) was not used.

- The OSB permitted hazardous work (NaK spill recovery) to be conducted utilizing a plan, which was an unauthorized mechanism. The plan was deficient and directed workers to perform operations (i.e., spraying mineral oil) that were unsafe and contrary to MSDS provisions.

The OSB was not effective in implementing many of its roles and responsibilities for crucible changeout and spill recovery, and therefore failed to implement many of the elements of ISM. The OSB did not recognize or take action to correct serious flaws in work planning, hazard identification and control, and work authorization. Overreliance on past practices; failure to seek a technical understanding of the hazards associated with NaK, superoxides, and mineral oil; and lack of rigor by the OSB in discharging its responsibilities resulted in ISM not being adequately applied to the work activities involved in this accident.

Contributing Cause

The OSB was not effective in implementing its roles and responsibilities for crucible changeout and spill recovery.

Quality Assurance

10 CFR 830.120, "Quality Assurance Requirements," establishes the basic quality assurance requirements for a DOE nuclear facility. DOE Order 414.1A, *Quality Assurance*, further delineates and invokes those requirements for implementation by DOE contractors. Included in those requirements are training and qualification of personnel to ensure that they can perform their assigned work; performing work in accordance with established technical standards and administrative controls, using approved instructions and procedures; designing items and processes on the basis of sound engineering/scientific principles and standards; managers' assessing their management processes and identifying and correcting problems; and planning and conducting independent assessments to measure the adequacy of work performance and promote improvement. Deficiencies in each of these areas were found during the course of this Type A accident investigation.

The Y-12 Plant Quality Assurance (QA) organization does not perform activities within DUO on a regular basis, and there are few criteria that would trigger involvement by the QA organization. The QA program relies on each line organization to integrate quality into its activities and processes. The Y-12 QA organization provides services to other Y-12 organizations "as requested," and QA services must be funded by the requesting line organization. This approach to funding can be a disincentive to using the quality organization for an independent review, particularly when funding is limited or reduced.

The level of QA involvement within DUO was limited over the past few years and did not identify numerous weaknesses in the areas that QA is required to address:

- In the area of personnel training and qualification, numerous deficiencies were found with respect to NaK and hazard communication training, including lack of training on NaK safety procedures and fire fighting methods (see Sections 3.3 and 3.4).

- The Y-12 QA organization and the DUO QA point of contact were not asked to review or be involved in the development of the crucible changeout procedure or the NaK recovery plan, nor were they involved in any of the related planning or walkdown activities.

- Neither the QA organization nor any other independent review organization identified the design and configuration control deficiencies (e.g., fire protection, points of water entry) or questioned the technical basis for operations in the absence of the OCI system.

- DUO line management self-assessments did not effectively identify and correct conduct of operations deficiencies in the Arc Melt organization, as evidenced by the large number of weaknesses identified in conduct of operations (see Section 3.2).

- In the past year, the only independent assessments of the DUO organization by the Y-12 QA organization examined conduct of operations. The QA assessment did not ensure that weaknesses were identified and corrected.

- Although the Facility Evaluation Board's annual independent assessments of ISM include DUO, the QA organization is not used effectively to accomplish the objectives in the QA rule, including the conduct of independent assessments to ensure the effectiveness of work and hazard control processes and to achieve continuous improvement in processes and the infrastructure essential to ES&H and ISM.

- At the Y-12 Plant, the line organization has primary responsibility for QA, with assistance as requested and occasional independent assessments by the QA organization. Although institutional procedures are in place, there has not been sufficient internal or independent QA involvement in Building 9201-5, as evidenced by deficiencies in design, training and qualification, and conduct of operations.

Lessons Learned, Communication of Hazards, and Corrective Actions

There have been opportunities for LMES and the Y-12 Site Office (YSO) to investigate, communicate, and apply information on the hazards associated with NaK. The failure to follow up and apply such information indicates the lack of effective communication mechanisms and the ineffective application of lessons learned to ensure that important hazards information, such as the potential for a NaK superoxide explosion, is effectively communicated and followed up by LMES management.

LMES has an established lessons-learned program at Y-12. An August 1999 ISM independent assessment noted that the lessons-learned program was not effectively capturing lessons learned from all sources and transmitting them down to the working level. An LMES corrective action plan, OR-Y12-SME-98-7, identified corrective actions that were implemented and validated. An assessment, IA-Y-89-LL-0014, conducted in October 1999, concluded that the lessons-learned program was adequate.

An effective lessons-learned program is an essential management tool for identifying and communicating important safety information that can be used to prevent accidents and protect workers, the public, and the environment. However, if line management does not review and apply the lessons learned, as necessary, opportunities for improving safety and preventing accidents are lost. Table 8 provides examples in which the Y-12 Plant has not effectively incorporated lessons learned from previous events and accidents. Of particular concern is the failure to apply information from two 1997 events involving the discovery of NaK containers and the subsequent identification, though a hazard screening, of the hazards associated with NaK, superoxides, and organics (e.g., mineral oil). As a result of this screening, the facility safety engineering organization had definitive knowledge of the potential explosion hazard involving superoxides and mineral oil. Although the information was known within the facility safety engineering organization (which also performed the safety analysis for Building 9201-5) since at least 1997, it did not get communicated and applied at Building 9201-5.

Y-12 Plant management failed to effectively implement corrective actions for previous incidents, events, and accidents that involved selection and use of PPE. The occurrence report an a 1992 incident involving removal of residual NaK from a skull melt crucible and exposure of workers to a vapor cloud noted the need to revise procedures to reflect proper PPE requirements. The applicable operating procedure was revised, yet problems with use of PPE were evident during this accident. Several accidents at other LMES sites in the past few years, including the welder fatality in 1997, involved improper selection and use of PPE. As evidenced by the weaknesses detailed in Section 3.3, there continue to be significant problems in the use of PPE at Building 9201-5.

DUO personnel did not report the December 1, 1999, spill to the PSS as required and did not inform YSO, thereby missing additional opportunities for higher-level management involvement as part of a formal critique. Thresholds for reporting occurrences have not been carried out within DUO in accordance with the LMES Conduct of Operations Manual, Y14-001-INS. Facility personnel indicated that they did not believe the spill to be reportable. However, notification in this case would be required by Y14-192, "Occurrence Notification and Reporting," under four possible categorization criteria: Violation/Inadequate Procedures, 1F-ON(2); Operations, 1H-ON(1); Near Miss Occurrences, 10B-ON(2); and Potential Concerns/Issues, 10C-ON(2). YSO only became aware of the spill as a result of the December 8, 1999, accident even though the YSO Facility Representative had met with the DUO Manager on December 3, 1999, two days after the spill. In addition, the Facility Representative's review of the PSS daily log indicated that the PSS had not been notified of the spill.

The Y-12 Plant has not adequately addressed many of the deficiencies identified during the 1998 Office of Oversight integrated safety management evaluation of the Y-12 Plant. This evaluation did not address Building 9201-5 but reviewed selected non-nuclear facilities. Deficiencies in the DUO organization are similar to those identified by the Office of Oversight, indicating that LMES management's corrective actions to date have not been effective. The 1998 Oversight evaluation concluded that:

- There was no structured process for hazard identification, analysis, and development of controls for non-routine work activities within non-nuclear facilities.

- Training for supervisors and ES&H staff, including industrial hygiene, had not been kept current.

- OSBs had not been effectively implemented, and management needed to apply sufficient attention to ensure that the technical competence needed to safely manage and operate the Y-12 plant is maintained.

- Corrective actions were not consistently identified and implemented, and ES&H reviews identified repeat findings that line organizations had not adequately corrected.

Contributing Cause

LMES management did not effectively utilize the lessons-learned program to apply information on the hazards related to work activities and operations and to ensure that deficiencies were corrected.

Management Involvement

The involvement of senior LMES management, DUO management, and YSO in safety at Building 9201-5 has been limited. Thus management missed opportunities to prevent the accident by participating in safety-related decisions and questioning the technical basis for lower-tier management decisions. Examples include:

- In accordance with the "Operational Safety Board Charter, Depleted Uranium Operations," the DUO Organization Manager can serve as the OSB Chairman and conduct "expanded/more extensive OSB reviews as required." However, the DUO Manager was not involved with the OSB for the crucible changeout procedure or the NaK recovery plan. Even after the spill, DUO management did not take a more active role. This lack of DUO upper management involvement in the OSB process resulted in a missed opportunity to challenge the conclusions and approach being taken by the OSB.

- On the day of the spill, the DUO assessment coordinator conducted a management review, rather than a formal critique (which would have been required if the spill was reported to DOE), of the NaK spill. One of the actions agreed upon at the review was to develop a plan rather than a Category 1 procedure for the recovery operation. This decision represents another missed opportunity for upper management to challenge the OSB's underlying assumptions: the use of a plan for the spill recovery operation; a more fundamental technical understanding of the behavior of NaK, superoxide formation, and mineral oil; and the continuing reliance on past practices. In agreeing to produce a plan, the OSB violated numerous site requirements associated with the development of technical procedures.

- The DUO organization used an informal USQD process that was not carried out in accordance with Y74-809, "Unreviewed Safety Question Determinations." The decision that a USQD was not required for the NaK spill was made without reference to the USQD Screening Worksheet, which requires approval by the Operations Manager and the USQD Manager. Instead, the decision was made informally and communicated to the individual heading up the NaK recovery team via e-mail. This is yet another missed opportunity for the management review and approval required when the Worksheet is used.

The YSO Facility Representative (FR) conducts walk-throughs and assessments in DUO areas. However, the number of assessments and walk-

Table 8. Lessons Learned

Information on the hazards associated with NaK was available to LMES management that could have been incorporated and applied at Building 9201-5. However, that information was not effectively communicated and or used for the crucible changeout or spill recovery activities.

- In 1992, an incident occurred at 9201-5 involving the removal of residual NaK from an arc melt crucible and overexposure of workers downwind to potassium and sodium hydroxides. The event resulted in an Occurrence Reporting and Processing System report being generated with two corrective actions dealing with the need for proper PPE and NaK training. Similar deficiencies were evident during the crucible change out and spill recovery activities at Building 9201-5.
- In1994, a lessons learned document was received from an external source concerning a sodium accident that occurred at a French facility, killing one worker and injuring four others. The lessons learned were disseminated to LMES facilities on May 5, 1994 with a request to respond with specific information. The response from the organization where the skull caster furnace resided lacked evidence of any in-depth review, but was accepted by site management without challenging the technical basis. However, there is no evidence this information was used to evaluate the hazards of NaK at the skull caster furnace.
- In 1997, a storage container in Building 9720-5 that contained an estimated 2.5 gallons of NaK was discovered that had not been analyzed as part of the existing authorization basis for the facility. This resulted in an occurrence report and lessons learned issued to the site to address issues associated with this discovery. There was no evidence that this information was analyzed and applied at Building 9201-5.
- In 1997, containers were discovered residing in Building 9720-27 and holding solid sodium and NaK alloy that had not been considered in a previous preliminary hazard screening. The USQD that resulted from this as-found condition provided LMES yet another opportunity to communicate, evaluate, and analyze the hazards associated with NaK at Building 9201-5.
- A draft hazards screening evaluation document for Building 9720-27, dated April 17, 1997 and the final approved version of that document, Y/EN-5621R2, dated July 1999, more accurately addressed the hazards involved with NaK and superoxides. The 1999 screening document referenced the Phase I Hazards Screening Analysis for Building 9201-5, but no action was taken to communicate that information to the Building 9201-5 personnel.
- The Facility Safety engineering organization that prepared these documents was also involved in the preparation of the draft BIO for 9201-5, yet the information describing these hazards with NaK, which was known at the Y-12 site for at least two years, did not get communicated and used in the development of the draft BIO for 9201-5 or in the spill recovery plan.
- It was only after the December 8, 1999, explosion that current information on the hazards of NaK, superoxides, and organics was disseminated and incorporated into the draft BIO that has now been submitted for DOE approval.
- The Acting Assistant Manager for Defense Programs (Y-12 Site Office) approved the screening document, Y/EN-5621R2, in July 1999, yet the hazards information did not get communicated and used in the crucible changeout or spill recovery activities.

throughs has been limited due to the large number of facilities covered by the FR, who only spends a few hours a month in Building 9201-5. As a result, the FR relies on informal agreements with the Arc Melt Unit Manager to keep informed of important ongoing activities. The FR was aware of the plans to change out the crucible and knew that a procedure was being developed for that purpose; the Arc Melt Unit Manager was to tell the FR when crucible changeout was to take place. However, the FR was not informed, and yet another opportunity was missed for review of the procedure, this time by the FR.

An alternative arc melt process that does not require the use of NaK has been under way at Y-12 since 1992. This initiative was driven by the Y-12 Site objective to reduce the weapons program footprint and associated costs rather than the elimination of hazards associated with the use of NaK. In the 1992 occurrence report, the lessons learned/corrective actions noted that DUO intended to replace the NaK system with the alternative process, referred to as Vacuum Induction Melt/Vacuum Arc Melt (VIM/VAR). This system was acquired and installed but required significant development effort before it could be used. During the mid-1990s, DUO experienced budget cuts, and the development activity received low priority and made limited progress. The recent restart of a weapons program that required the use of the arc melter made it necessary to use one of the systems. DOE and LMES management decided that the alternative system would take too long to bring to full operation and therefore decided to use the skull caster furnace with the NaK system to meet production requirements. If sufficient funding had been sustained immediately after 1992 incident, the new process could have replaced the process that uses NaK and thus could have served as an organizational control to prevent the accident.

Overall, the results of this accident investigation indicate that management at OR and YSO, senior LMES management, and DUO management above the operation management level did not maintain an adequate awareness of the activities and safety-related incidents under their areas of responsibility. In addition, management at these organizations did not take sufficient action to ensure that effective QA programs were in place, that lessons learned were adequately addressed, and that ISM was effectively implemented at the facility level.

Contributing Cause

Management at all levels (OR, YSO, senior LMES management, and DUO management above the operation management level) did not maintain an adequate awareness of the activities and safety-related incidents under their areas of responsibility and did not ensure that adequate feedback mechanisms were in place.

4.0 Conclusions and Judgments of Need

The accident investigation board determined that the direct cause of the explosion and resulting injuries was a disturbance (impact with a steel probe) of an unrecognized and unanalyzed shock-sensitive explosive compound (consisting of potassium superoxide and mineral oil) that was formed when mineral oil was inappropriately sprayed on a previous NaK spill.

As discussed throughout this report, there were 14 causal factors that contributed to the accident. The accident investigation board assessed the circumstances of the accident and the contributing causal factors and identified six root causes, which are included in Table 9. The Board's determination of the root causes used formal analytical techniques, including change analysis, barrier analysis, and events and causal factors analysis. The results of these analytical techniques are summarized in Appendix B.

The overall conclusion of the accident investigation board is that the explosion and subsequent injuries could have been prevented. Although some progress has been made in implementing ISM within the DUO organization, there were failures in management systems and ISM processes within OR and within every level of the LMES management chain. Because of these failures in the management system and ISM processes, there were numerous missed opportunities to prevent the December 1, 1999, spraying of NaK into the furnace and the December 8, 1999, explosion.

The accident investigation board also concluded that significant and prompt senior DOE and LMES management attention is needed to enhance worker protection by improving implementation of ISM and management systems. The Board has identified a set of judgments of need, which are included in Table 9.

Table 9. Root Causes and Judgments of Need

Judgments of Need	Root Causes
#1: Strengthen the training and competence for workers and for managers, engineers, and safety professionals responsible for worker safety. A. Strengthen training for workers, including sitewide workers, on specific hazards such as NaK through such means as hazard communication training and General Employee Training. B. Institutionalize unique hazards such as NaK, liquid metals, and superoxide into training programs and procedures, including tests and lesson plans. C. Conduct immediate training on NaK/superoxide for anyone entering the arc melt area, including hazard concerns, the incompatibility of mineral oil, emergency response, and fire fighting. D. Require managers, engineers, and safety professionals responsible for worker safety to obtain, maintain, and demonstrate competence in work-related hazards, material incompatibilities, and concerns. E. Incorporate hazardous material MSDSs, safety manuals, and other relevant information on lessons learned into training. F. Establish processes to assure that hazard training is in compliance with applicable OSHA and DOE requirements. G. Develop and implement a work area (job-specific) hazard communication training program at Y-12, and require supervisors to receive hazard communication training for supervisors.	LMES failed to establish, seek, or maintain an adequate level of knowledge and competence on the hazards associated with NaK, including the formation of superoxide, the incompatibility of superoxide and organics, and the explosive sensitivity of the mixture to impact or shock.
#2: Strengthen the implementation of the ISM core functions and existing LMES processes to assure that all potentially hazardous work and activities are subjected to effective, formal, and documented hazards analysis. A. Strengthen the process to assure that all potentially hazardous activities are subjected to formal and effective hazard analyses, including job hazard identification and JHAs. B. Eliminate any loopholes that would bypass formal hazard analyses, including classifying a job as "routine" maintenance. C. Revise the authorization basis for the potassium superoxide hazard and expedite review and approval of the BIO by DOE. D. Conduct a USQD on current conditions in the arc melt area to assure adequate compensatory safety measures and control of recovery. E. Require MSDSs and other relevant hazards information to be incorporated into hazard analysis and control processes. F. Significantly strengthen the USQD process to include formal analysis and documentation; involvement of appropriate technical expertise; assessment of activity, controls, and safety information and MSDS; and management review and approval. G. Establish a process to assure that when a unique hazard such as superoxide is identified in the safety analysis for one facility, it is appropriately considered and incorporated into the authorization basis and hazard analyses for other facilities with the same hazard. H. Strengthen the management and independent QA oversight of hazard analysis and control processes. I. Ensure that fire protection engineering is involved in hazard analyses for work with the potential for a fire or explosion. J. Incorporate "welding-like" hazards (e.g., molten metals) into hazard identification and analysis.	LMES's implementation of the hazard analysis and control processes failed to identify, prevent, or mitigate the explosive interaction of potassium superoxide, mineral oil, and impact. The NaK Material Safety Data Sheet was not used.

Table 9. Root Causes and Judgments of Need (Continued)

Judgments of Need	Root Causes
#3: Strengthen the identification and implementation of engineering, administrative, and worker protection controls for potentially hazardous work and activities. A. Strengthen the implementation of the OSB process by involving senior management and applying the process to all hazardous activities and procedures. B. Strengthen the procedure development, verification, and validation processes to assure technically accurate and useable procedures. C. Strengthen engineering resources for maintaining and documenting facility configuration, including accurate as-built piping and instrument drawings. D. Strengthen implementation of ISM to assure that only approved mechanisms or procedures are used to control potentially hazardous work and activities. E. Strengthen the control over the categorization of procedures by involving the OSB and senior management to assure that the categorization is appropriate to work complexity, hazards, and frequency of performance. F. Strengthen the management and independent QA oversight of the hazard control process to assure continuous adherence to established processes and improvement. G. Review and analyze the basis and priorities associated with the failure to maintain funding for the completion and startup of a safer melting system as a lessons-learned commitment from the 1992 NaK release. H. Utilize the DOE hazard control prioritization hierarchy with engineering controls as a first priority, administrative controls as a second priority, and PPE as the priority of last resort. I. Evaluate and correct any fire protection detection deficiencies that prevented a fire or smoke alarm following the NaK explosion. J. Improve pre-job briefings to assure that hazards, hazard controls, and PPE are adequately addressed and understood.	LMES management systems and processes did not assure adequate procedures or controls to prevent the loss of system configuration control resulting in an NaK spill or to preclude the addition of mineral oil and impact in the presence of potassium superoxide during NaK spill recovery.

Table 9. Root Causes and Judgments of Need (Continued)

Judgments of Need	Root Causes
#4: Strengthen the implementation of the ISM feedback process through the improved sharing of technical expertise and information and through use and appropriate application of lessons learned from events, accidents, and near misses. A. Ensure adequate research or communication with experts when conducting hazards assessments, developing or revising authorization basis, or conducting unique or hazardous operations, or when unusual or unexpected conditions are encountered. B. Significantly improve LMES corporate and site response to lessons learned from Y-12 and other sites by including broader application, tracking and implementation, and upgrading of management systems, processes, programs, and ISM core functions as warranted. C. Significantly improve the incorporation of lessons learned, corrective actions, and commitments into programs, policies, procedures, and training materials. D. Establish a process to assure that commitments or corrective actions resulting from events and accidents are not deleted from programs, processes, or procedures during subsequent revisions. E. Establish an independent corporate LMES panel to review and evaluate common causal factors between the last six Type A accident investigations at Lockheed Martin sites and the implications for ISM and key processes such as procedure quality and use, hazard analysis and controls, application of skill of the craft, system configuration control, control of routine work, training, management involvement, and QA.	LMES management failed to effectively communicate or utilize information from the hazard screening evaluation, lessons learned, previous events and accidents, studies, analyses, and publications in planning and controlling this work and the associated hazards to worker health and safety. Knowledge of this hazard and expertise to address it were readily available at the Oak Ridge Reservation and other DOE sites.

Table 9. Root Causes and Judgments of Need (Continued)

Judgments of Need	Root Causes
#5: Expedite the understanding, acceptance, and implementation of the ISM core functions through improved use of and adherence to work and hazard controls, including procedures. A. Require all hazardous, complex, or infrequently conducted work and activities (including maintenance) to be conducted with procedures in hand, step-by-step, and in proper sequence. B. Strengthen system configuration control through increased use of step signoffs, valve alignment checklists, or independent verification for key steps that could impact the safety of workers or the public. C. Ensure the review and adherence to all applicable procedure prerequisites, precautions, limitations, cautions, and warnings. D. Ensure that when procedures are not correct or will not work as written, or when unusual conditions are encountered, work is stopped and management and technical assistance sought for ANY procedure changes before proceeding. E. Establish and communicate a stronger LMES policy on use of and adherence to procedures and other work and hazard controls, including accountability mechanisms. F. Strengthen management and supervisory field presence and independent QA assessments to improve use of and adherence to controls, including procedures. G. Ensure that abnormal events are reported to LMES senior management and OR, and via the Occurrence Reporting and Processing System per DOE requirements. H. Ensure that abnormal conditions are fully investigated via the critique process to thoroughly determine the cause and corrective action, and ensure that corrective actions are verified to be complete and effective. I. Strengthen implementation of conduct of operations, including operating practices, communications, abnormalities, investigation, notification, configuration control, and procedures. J. OR and YSO need to strengthen line management oversight and increase field presence to ensure effective implementation of ISM.	OR, YSO, and LMES have not established or assured a safety culture that implements an ISM process in which workers are consistently held accountable for adherence to procedures and hazard controls and are willing to stop work and seek management and technical assistance when procedures do not work or abnormal conditions are encountered.

Table 9. Root Causes and Judgments of Need (Continued)

Judgments of Need	Root Causes
#6: Improve the identification, availability, and use of appropriate personal protective equipment to protect workers against work-related hazards. NOTE: This provision has been a factor in the last three Oak Ridge Type A accident investigations. A. Ensure the availability of essential PPE through effective procurement, distribution, storage, and inspections and testing. B. Strengthen the coordination between safety professionals, including industrial safety, industrial hygiene, health physics, and fire protection engineering, in identifying necessary PPE. Consider using a common form or permit to designate PPE. C. Strengthen processes to assure that lessons learned and corrective actions for PPE related to previous events or accidents are tracked and appropriately applied to similar work or hazards. D. Ensure adequate research, use, and adherence to PPE recommendations or requirements as defined by MSDSs, OSHA, LMES policies, the National Fire Protection Association, and DOE. E. Establish and implement a more formal, rigorous, and documented process for selection of PPE, including the type of respirators. The process should include full analysis of the hazards and compliance with requirements and regulations. F. Ensure that personnel are property trained and physically qualified to utilize PPE, including NaK suits and respirators, for work-related hazards and emergency response. G. Strengthen the oversight of the availability, selection, and use of PPE by management, QA, and safety professionals. H. Ensure that PPE requirements for work activities are clear, consistent, and unambiguous in work documents (RWPs, JHAs and procedures). I. Prior to performing a work activity, verify that all PPE has been assigned and is available, and that workers have been briefed on the use, precautions, limitations, and prerequisites of the prescribed PPE.	LMES management systems and processes were not effective in assuring the provisions for and use of appropriate personal protective equipment for working with a pyrophoric liquid metal and protecting against thermal and caustic chemical burns and the inhalation of toxic and radioactive smoke.

5.0 Board Signatures

Date: 2/11/2000

S. David Stadler
DOE Accident Investigation Board Chairperson
U.S. Department of Energy
Office of Environment, Safety and Health

Date: 2/11/2000

Chip Lagdon
DOE Accident Investigation Board Member
U.S. Department of Energy
Office of Environment, Safety and Health

Date: 2/11/2000

William E. Miller
DOE Accident Investigation Board Member
U.S. Department of Energy
Office of Environment, Safety and Health

Date: 2/11/2000

Bruce Breslau
DOE Accident Investigation Board Member
U.S. Department of Energy
Office of Environment, Safety and Health

Date: 2/11/2000

Pete O'Connell
DOE Accident Investigation Board Member
U.S. Department of Energy
Office of Environment, Safety and Health

6.0 Board Members, Advisors, and Staff

Chairperson	S. David Stadler, DOE, Office of Oversight
Member	Bruce Breslau, DOE, Environment, Safety and Health
Member	Chip Lagdon, DOE, Office of Oversight
Member	William E. Miller, DOE, Office of Oversight
Member	Pete O'Connell, DOE, Environment, Safety and Health
Advisors	Mohammed Mozumder, DOE, Office of Defense Programs Mark Good, Paragon Technical Services, Inc. Bernie Kokenge, Paragon Technical Services, Inc. Jim Lockridge, Paragon Technical Services, Inc. Thomas McSweeney, Battelle Columbus Ed Stafford, Paragon Technical Services, Inc.
Medical Advisor	Joseph Falco, M.D., Brookhaven National Laboratory
Analytical Support	Jeff Oakley, Battelle Columbus
Technical Writer	Thomas Davis, Paragon Technical Services, Inc.
Administrative Support	Barbie Harshman, DOE, Office of Oversight Lee Roginski, Paragon Technical Services, Inc. Marcia Taylor, Battelle Columbus Kathy Moore, Battelle Columbus Michelle Stover, Battelle Columbus

APPENDIX A
BOARD APPOINTMENT MEMORANDUM

EH2-01390

Department of Energy
Washington, DC 20585

December 10, 1999

MEMORANDUM FOR: G. LEAH DEVER, MANAGER
OAK RIDGE OPERATIONS OFFICE

FROM: DAVID MICHAELS, PhD, MPH
ASSISTANT SECRETARY
ENVIRONMENT, SAFETY AND HEALTH

SUBJECT: Investigation of the December 8, 1999, Chemical Explosion at the Y-12 Plant, Oak Ridge, Tennessee

I hereby establish a Type A Accident Investigation Board to investigate the December 8, 1999, Chemical Explosion at the Y-12 Plant. I have determined that it meets the requirements for a Type A investigation consistent with DOE Order 225.1A, *Accident Investigations*.

My office will lead the investigation, with the Board chaired by a member of my management staff. I appoint Dr. S. David Stadler, Acting Deputy Assistant Secretary for Oversight, as the Accident Investigation Board Chairperson. The Board will be composed of the following members: Chip Lagdon, ES&H Evaluations; William Miller, ES&H Evaluations; Pete O'Connell, Worker Protection Programs and Hazards Management; and Bruce Breslau, ES&H Evaluations. A representative from the Office of Defense Programs will also be designated to serve on the Accident Investigation Board. The Board will be assisted in the investigation by advisors and other personnel as deemed necessary by the Board Chairperson.

The scope of the Board's investigation will include, but not be limited to, analyzing causal factors, identifying root causes resulting in the accident, and determining Judgements of Need to prevent recurrence. The investigation will be conducted in accordance with DOE Order 225.1A. The investigation and analyses will be conducted within the framework of the Department's Integrated Safety Management Policy to assure maximum benefit to improving safety and sharing lessons learned throughout the complex.

The Board will provide my office with periodic reports on the status and progress of the investigation. These reports should not include any findings or arrive at any premature conclusions until an analysis of all the causal factors has been completed. Discussions of the investigation and copies of the draft report will be controlled until I accept and authorize release of the final report. The final report should be provided to my office by February 18, 2000.

cc: T. Gioconda, DP-1
D. Stadler, EH-2
J. Fitzgerald, EH-5
C. Huntoon, EM-1
W. Magwood, NE-1
R. Poe, OR
J. Mullins, OR AI POC

APPENDIX B
APPLICATION OF ANALYSIS METHODS AND TOOLS

B-1. Causal Factors Analysis

A complete causal factors analysis was performed to evaluate the causal factors of the accident, including the direct cause, root causes, and contributing causes. The analytical techniques that were used were events and causal factors charting and analysis, barrier analysis, and change analysis. The **direct cause** of the incident is the immediate events or conditions that caused the accident. **Root causes** are the causal factors that, if corrected, would prevent recurrence of this and similar incidents. **Contributing causes** are other events and conditions that collectively with other causes increased the likelihood of an accident but individually did not cause the accident.

The **direct cause** of the explosion and resulting injuries was the disturbance (impact with a steel probe) of an unrecognized and unanalyzed shock-sensitive explosive compound (consisting of potassium superoxide and mineral oil) that was formed when mineral oil was inappropriately sprayed on a previous NaK spill.

Section 3 of the report presents the analysis of the various safety-related processes and systems and identifies the contributing causes of the accident. Root cause analysis of these contributing causes rolls them up to higher-level root causes, which are listed, along with a short discussion of each, in Table B-1. Figure B-1 shows the contributing causes and most-directly-related root causes. Figure B-2 shows an events and causal factors chart for this accident.

B-2. Barrier Analysis

Barrier analysis identifies three types of barriers associated with the accident: (a) administrative barriers, (b) management barriers, and (c) physical barriers. A barrier is defined as anything that is used to control, prevent, or impede process or physical energy flows and that is intended to protect a person or object from hazards. Barriers that either failed or were missing led to the accident. Successful performance by any of these barriers would have prevented or mitigated the severity of the accident. The barriers that failed are summarized in Table B-2.

B-3. Change Analysis

Change analysis identifies changes or differences that might have affected the accident. These were analyzed to determine whether the change or difference might have contributed to the accident. The results of this analysis are shown in Table B-3.

Table B-1. Root Cause Analysis

Root Causes	Discussion
LMES failed to establish, seek, or maintain an adequate level of knowledge and competence on the hazards associated with NaK, including the formation of superoxide, the incompatibility of superoxide and organics, and the explosive sensitivity of the mixture to impact or shock.	There was an overall lack of technical competence and knowledge related to the interactive hazard involving NaK, superoxide, mineral oil, and shock or impact. There was also a failure to establish or maintain competence in the hazards associated with NaK through the available literature, technical expertise, or training. There was an overreliance on the skill of the craft and the knowledge of selected individuals and a reluctance to get additional expertise to help.
LMES's implementation of the hazard analysis and control processes failed to identify, prevent, or mitigate the explosive interaction of potassium superoxide, mineral oil, and impact. The NaK Material Safety Data Sheet was not used.	Many aspects of the hazard analysis and control process failed for both the December 1 spill and the December 8 explosion. No formal hazard analysis was performed for the spill recovery that led to the December 8 explosion, and MSDSs and other standard references were not utilized to identify the presence of superoxide and the importance of not adding mineral oil. There was a failure to comply with the NaK MSDS's warning on the formation of potassium superoxide and its incompatibility with organics. There was a failure to obtain the technical safety basis before spraying mineral oil onto an NaK spill containing potassium superoxide.
LMES management systems and processes did not assure adequate procedures or controls to prevent the loss of system configuration control resulting in an NaK spill or to preclude the addition of mineral oil and impact in the presence of potassium superoxide during NaK spill recovery.	Many processes and procedures were incorrectly implemented, not implemented, or incorrectly written. Procedures were not adequately categorized, verified, and validated; changes were not adequately controlled; and a "plan," which is not an authorized LMES mechanism, was used to control a hazardous work activity. Senior facility management was not adequately involved in the review and approval of procedures and revisions.
LMES management failed to effectively communicate or utilize information from the hazard screening evaluation, lessons learned, previous events and accidents, studies, analyses, and publications in planning and controlling this work and the associated hazards to worker health and safety. Knowledge of this hazard and expertise to address it were readily available at the Oak Ridge Reservation and other DOE sites.	Many textbooks, analyses, and previous accidents documented the explosive incompatibilities of potassium superoxide and organics. This information was not communicated or utilized by LMES in preparing the work activity or recovery plan. The 9720-27 hazard screening evaluation actually documented the superoxide-organic explosive interaction and shock sensitivity, but the information from Facility Safety Engineering was not communicated or effectively utilized by LMES management.
OR, YSO, and LMES have not established or assured a safety culture that implements an ISM process in which workers are consistently held accountable for adherence to procedures and hazard controls and are willing to stop work and seek management and technical assistance when procedures do not work or abnormal conditions are encountered.	The overall ISM system failed because DUO still was using expert-based systems (skill of the craft) instead of following ISM system procedures and control. Work should have been stopped, a hazard analysis performed, and management approval obtained when procedures did not work as written or when unusual conditions, such as a low NaK sump level or suspected superoxides, were encountered.

Table B-1. Root Cause Analysis (Continued)

Root Causes	Discussion
LMES's management systems and processes were not effective in assuring the provisions for and use of appropriate personal protective equipment for working with a pyrophoric liquid metal and protecting against thermal and caustic chemical burns and the inhalation of toxic and radioactive smoke.	Appropriate PPE that could have prevented or reduced the severity of the injuries, including thermal burns, chemical burns, and toxic chemical and radiological uptakes, is defined in LMES accident lessons-learned documents, OSHA requirements, and NaK MSDSs. The selection of PPE on the day of the accident or for other preliminary activities was not based on these requirements or on sound and documented analyses.

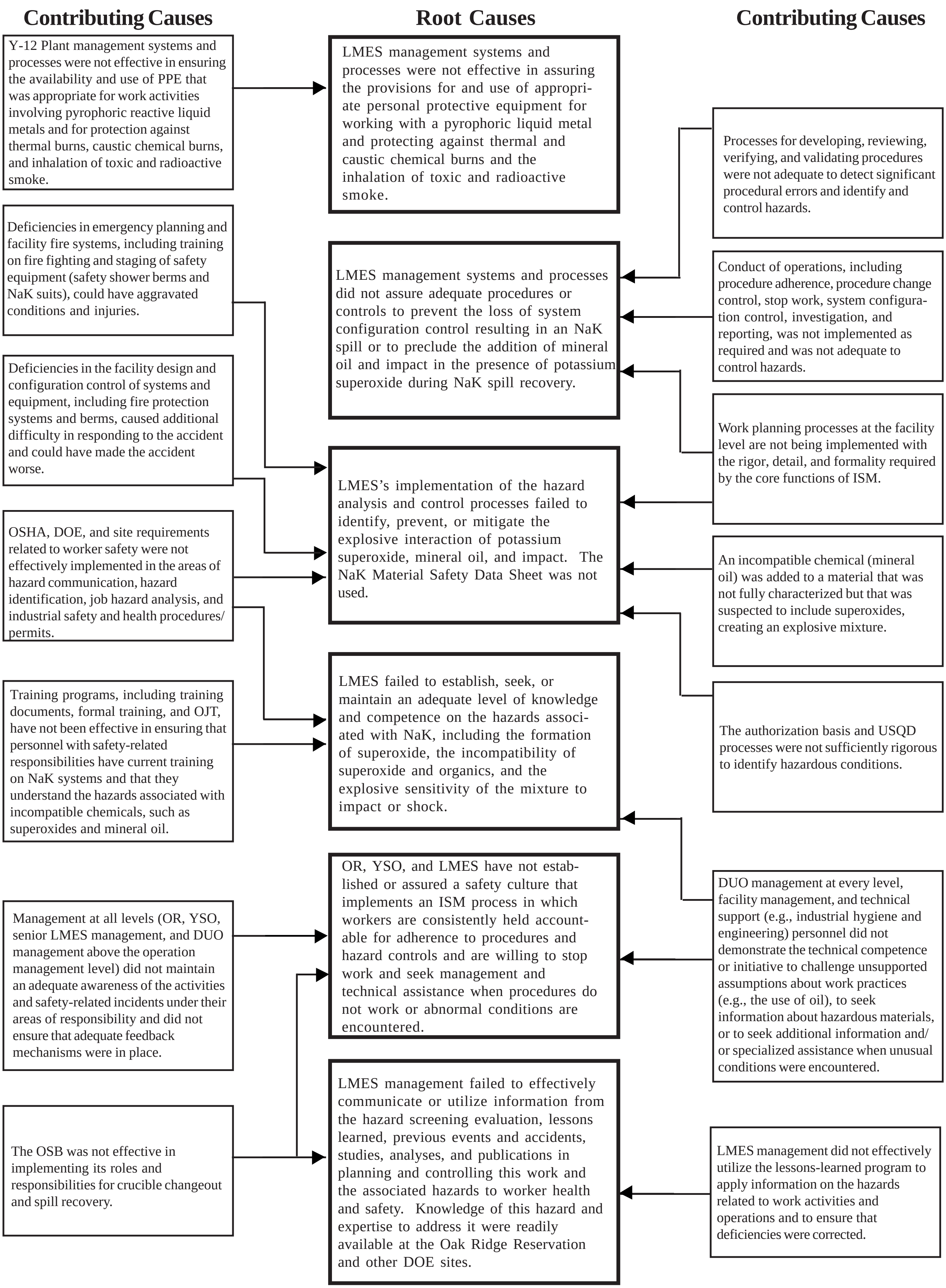


Figure B-1. Root and Contributing Causes

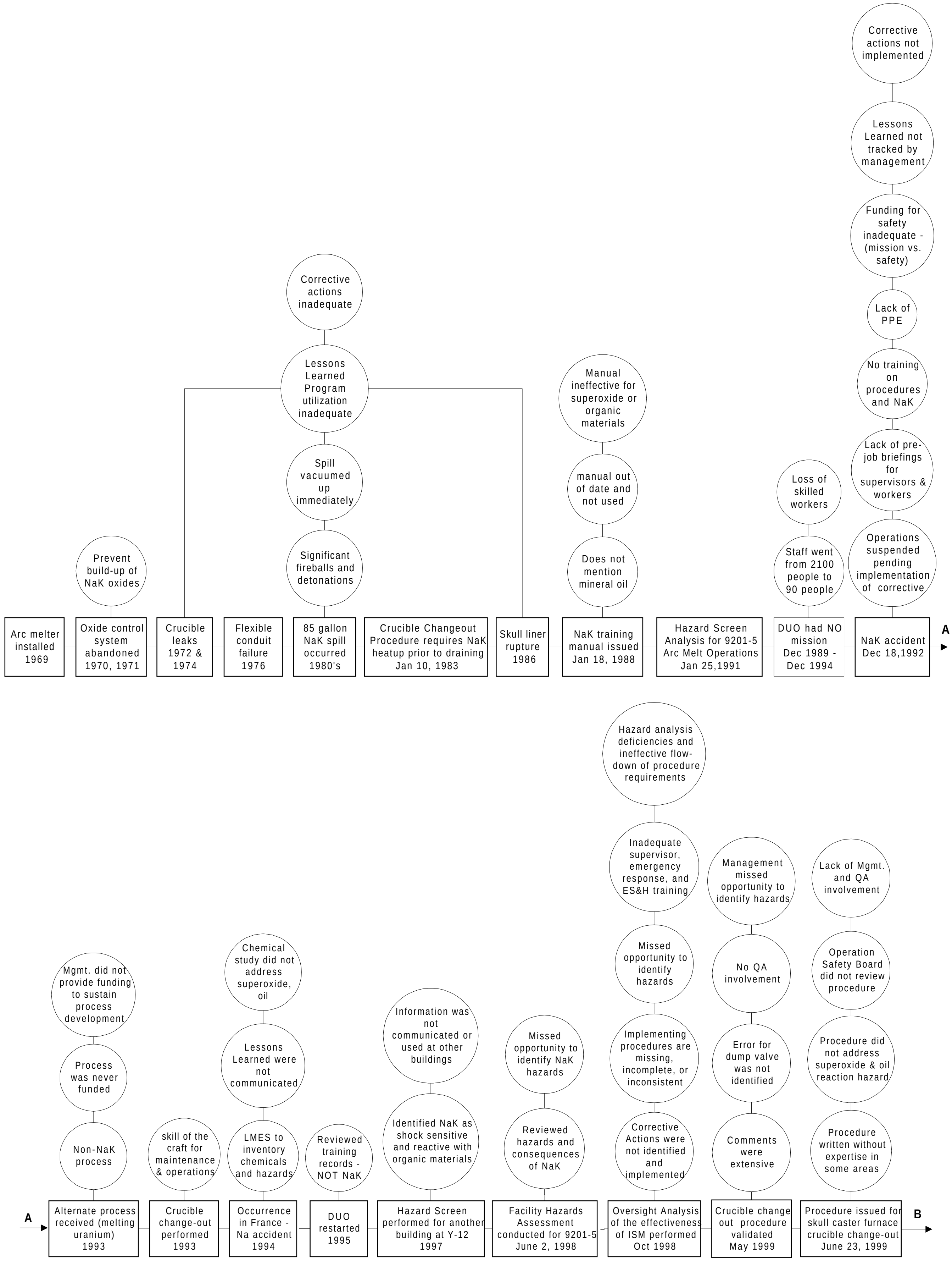
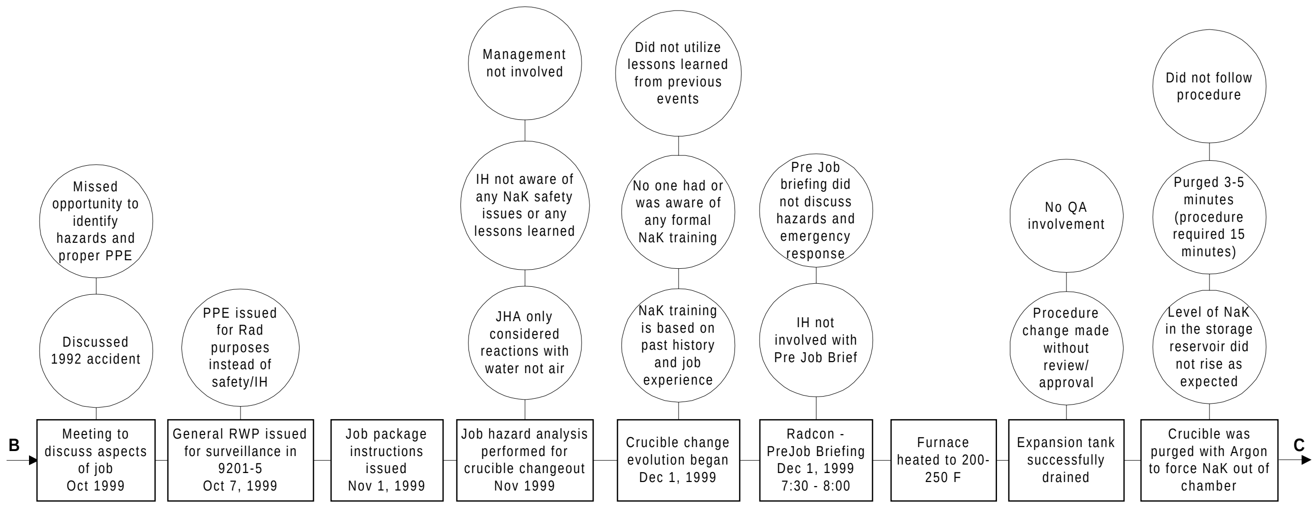


Figure B-2. Events and Causal Factors Chart



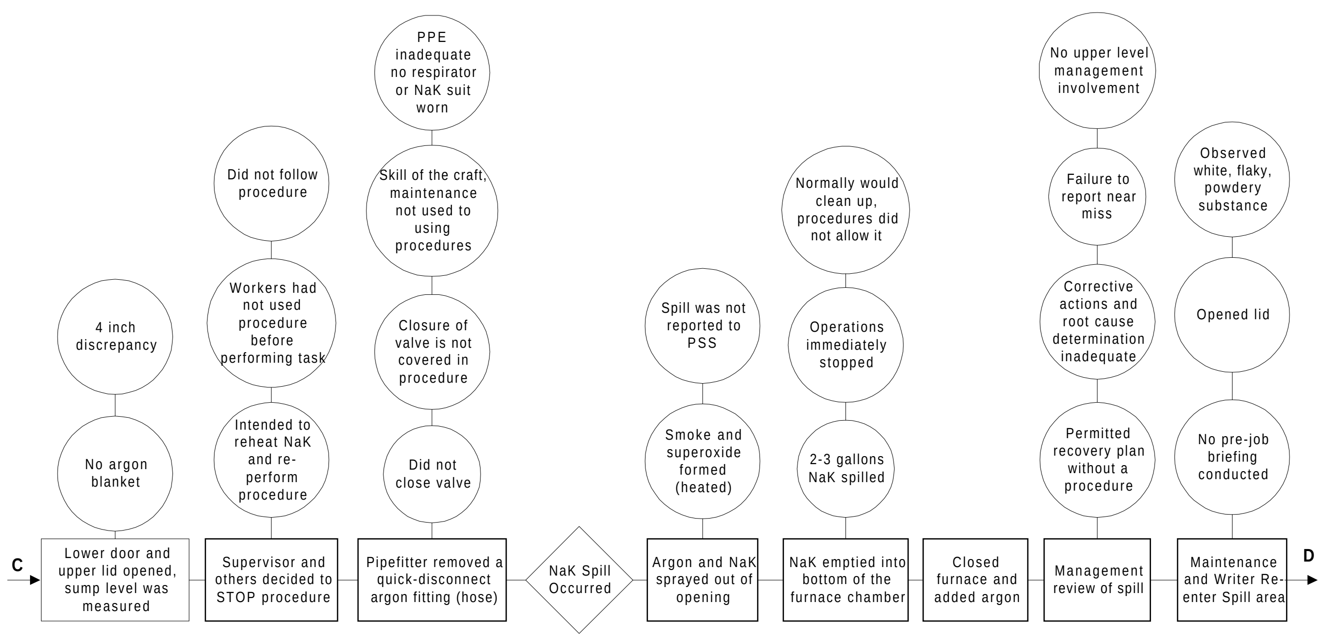


Figure B-2. Events and Causal Factors Chart (Continued)

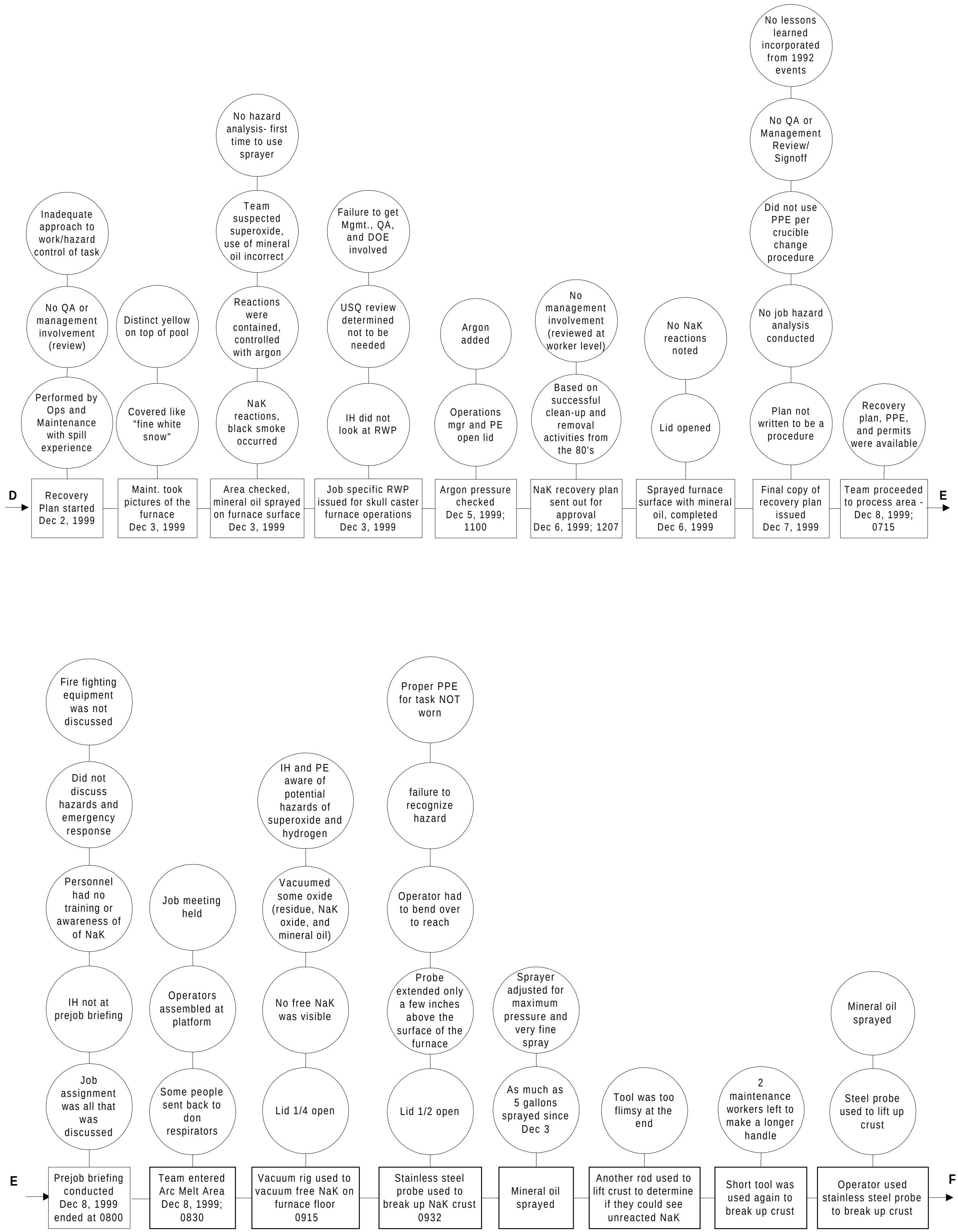


Figure B-2. Events and Causal Factors Chart (Continued)

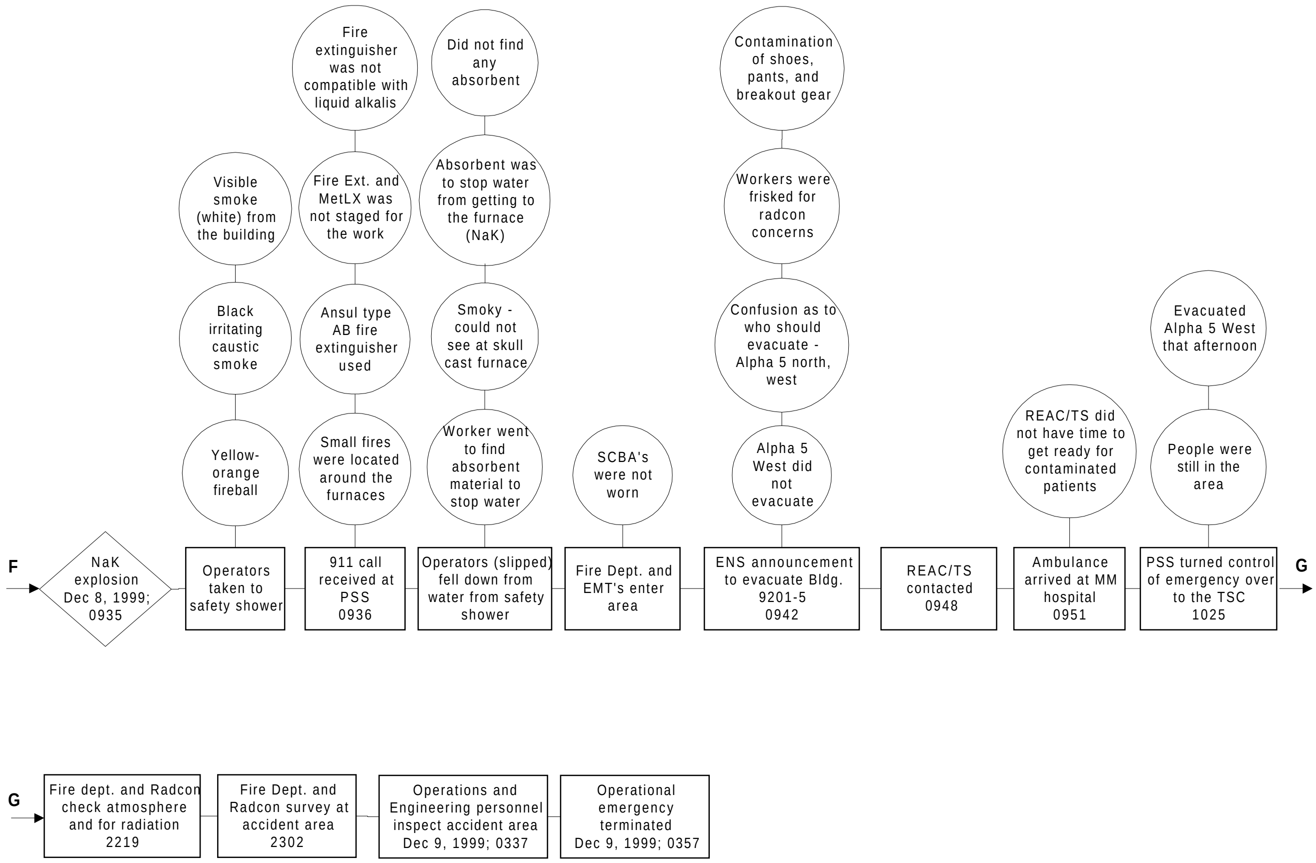


Figure B-2. Events and Causal Factors Chart (Continued)

Table B-2. Barrier Analysis Summary

Administrative	Pre-Job Briefing Procedures Procedure Verification and Validation ORPS/Accident Reporting Material Safety Data Sheets and Reference Documents Job Hazards Analysis Skill of the Craft
Management	Training Operational Safety Board Integrated Safety Management Process Lessons Learned/Corrective Actions Communication
Physical	Personal Protective Equipment Configuration Control – Oxide Control and Indication System Tools Anti-oxidation Material – Met-L-X vs. Mineral Oil NaK System Piping – Configuration Management

Table B-3. Change Analysis

Change or Difference		Analysis	
Planned/Normal	**Present**	**Difference**	**Analysis**
Maintenance workers perform maintenance activities while supervised by maintenance supervision.	Maintenance workers were performing operator functions and were supervised by operations.	Maintenance workers performed a task that was normally performed by an individual with expertise in operations. Maintenance work is not procedure driven.	Maintenance personnel are not adequately trained to be aware of the hazards of NaK or the requirements for following procedures. Maintenance personnel did not have the same level of training or experience in the identification and hazards of NaK or the equipment. Maintenance work usually involves expert-based routine work.
NaK is submerged in mineral oil. (According to reference books and the MSDS, this is for long-term storage and must not be used if superoxide is present.)	A fine spray of mineral oil was used on the NaK.	Mineral oil was sprayed on the NaK as a fine mist.	The use of mineral oil is not recommended for NaK and creates a shock-sensitive explosive when superoxides are present.
A clearly written recovery procedure is written for the cleanup work to be performed.	The activity was performed by use of an informal "recovery plan."	The level of review for the informal "recovery plan" is not as rigorous as for a procedure.	The informal "recovery plan" was not reviewed and validated, and not all hazards and emergency response actions were identified and mitigated. A formal job hazard analysis was not prepared.
PPE requirements for recovery specify an NaK suit for any work that has a potential to come in contact with NaK.	Workers wore only anti-contamination work coveralls.	Workers were not protected against the NaK.	The NaK suits could have reduced the seriousness of the burns caused by the explosion. *The procedures clearly state that an NaK suit should be worn.*
PPE requirements specify that flame-retardant cover-alls be worn in the arc melter area.	Workers wore standard coveralls or lab coats.	Following the explosion, burning clothing caused some burns.	The required use of flame-retardant coveralls was dropped in the early 1990s for unknown reasons.
The crucible changeout procedure contains a detailed contingency plan for an NaK spill.	The procedure contained inadequate contingency plans and the spill was to be cleaned up seven days later. Mineral oil used to "slow" oxidation created an impact-sensitive explosive mixture.	The contingency plan in the procedure to clean up the NaK spill was inadequate. The spill was not cleaned up using the procedures recommended in the MSDS. The MSDS recommends immediate cleanup using Met-L-X or other powdered extinguishing agents.	No adequate spill contingency plan was written into the changeout procedure. The likelihood of an NaK leak or spill is fairly high, according to past experience.
Workers are adequately trained to perform NaK work.	Workers were not trained and did not understand that mineral oil and NaK creates a shock-sensitive mixture if superoxide is present.	Workers did not fully understand the hazards and chemistry of NaK.	There was an overall lack of training in and awareness of the hazards and chemistry of NaK and superoxide.
Job hazard analysis identifies hazards, and no oil is added.	No job hazard analysis was performed for the cleanup recovery work.	Not all appropriate hazards of the job were identified.	There was no formal job hazard analysis, and the informal analyses failed to identify the hazards associated with the superoxide, resulting in hazardous work being performed without appropriate PPE.
December 1 Spill (Major Changes)			
The skull caster furnace crucible changeout procedure is performed as written.	The procedure was validated and changed while work was being performed.	The procedure was incorrect and work continued to be performed. (See Section 3.2.)	This caused the December 1 spill.
The skull caster furnace crucible changeout procedure is followed step by step as required for a Category I procedure.	The procedure was classified as a Category III procedure.	The procedure was not followed step by step, and each step was not verified.	This caused the December 1 spill.

Tables, Figures, and Exhibits

Tables

Exhibits

Figures

Abbreviations Used in This Report

ACGIH	American Conference of Governmental Industrial Hygienists
BIO	Basis for Interim Operation
CEDE	Committed Effective Dose Equivalent
CFR	Code of Federal Regulations
CO	Chemical Operator
DOE	U.S. Department of Energy
DNFSB	Defense Nuclear Facilities Safety Board
DP	Office of Defense Programs
DUO	Depleted Uranium Operations
EAP	Employee Assistance Program
EH	Office of Environment, Safety and Health
EOC	Emergency Operations Center
ES&H	Environment, Safety, and Health
FR	Facility Representative
FS	Front-line Supervisor
IDLH	Immediately Dangerous to Life or Health
IH	Industrial Hygienist
ISM	Integrated Safety Management
JHA	Job Hazard Analysis
LMES	Lockheed Martin Energy Systems
MSDS	Material Safety Data Sheet
NaK	Sodium Potassium Alloy
NIOSH	National Institute for Occupational Safety and Health
OCI	Oxide Control and Indication System
OJT	On-the-Job Training
OM	Operations Manager
OR	Oak Ridge Operations Office
ORMMC	Oak Ridge Methodist Medical Center
OSB	Operational Safety Board
OSHA	U.S. Occupational Safety and Health Administration
OSWP	Operations Safety Work Permit
PE	Process Engineer
PPE	Personal Protective Equipment
PS	Process Support Engineer
psi	Pounds per Square Inch
PSS	Plant Shift Superintendent
QA	Quality Assurance
RCT	Radiological Control Technician
REAC/TS	Radiation Emergency Assistance Center/Training Site
RWP	Radiological Work Permit
SAR	Safety Analysis Report
SCBA	Self-Contained Breathing Apparatus
TSC	Technical Support Center
USQ	Unreviewed Safety Question
USQD	Unreviewed Safety Question Determination
YSO	Y-12 Site Office