U.S. CHEMICAL SAFETY AND HAZARD INVESTIGATION BOARD

INVESTIGATION REPORT

EXPLOSIVES MANUFACTURING INCIDENT

(4 DEATHS, 6 INJURIES)

SIERRA CHEMICAL COMPANY

MUSTANG, NEVADA
JANUARY 7, 1998

- **KEY ISSUES:**

- PROCESS SAFETY MANAGEMENT
- WORKER TRAINING
- PROCESS HAZARD ANALYSIS
- LANGUAGE BARRIERS

REPORT NO. 98-001-I-NV

Abstract: This report explains two explosions that took place on January 7, 1998, at an explosives manufacturing facility owned by Sierra Chemical Company, located in Mustang, Nevada. Four workers were killed and six were injured. Safety issues covered in the report include process safety management, process hazard analysis, training, language barriers, operating procedures, building siting, and employee participation. Recommendations concerning these issues were made to Sierra Chemical Company and other companies manufacturing explosives, the Institute of Makers of Explosives, the Nevada Occupational Safety and Health Enforcement Section, and the Department of Defense.

The Chemical Safety and Hazard Investigation Board (CSB) is an independent federal agency with the mission of ensuring the safety of workers and the public by preventing or minimizing the effects of chemical incidents at industrial facilities and in transport. The CSB is a scientific investigatory organization; it is not an enforcement or regulatory body. Established by the Clean Air Act Amendments of 1990, the CSB is responsible for determining the probable causes of incidents, issuing safety recommendations, studying chemical safety issues, and evaluating the effectiveness of other government agencies involved with industrial chemical safety. Section 112 (r) (6) (G) of the Clean Air Act prohibits the use of any conclusions, findings, or recommendations of the CSB relating to any chemical incident from being admitted as evidence or used in any lawsuit arising out of any matter mentioned in an investigation report. Congress modeled the CSB after the National Transportation Safety Board (NTSB), which investigates aircraft and other transportation accidents for the purpose of improving safety. Like the NTSB, the CSB makes public its actions and decisions through investigation reports, safety studies, safety recommendations, special technical publications, and statistical reviews. More information about the CSB may be found on the World Wide Web at http://www.chemsafety.gov

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EXECUTIVE SUMMARY

ES.1 Introduction

The United States Chemical Safety and Hazard Investigation Board (CSB) is a congressionally mandated, independent federal agency. Its mission is to improve the safety of workers and the public by preventing chemical incidents. One of the CSB's duties is to conduct field investigations of serious incidents to identify the causes and recommend changes to prevent recurrence.

On January 7, 1998, two explosions in rapid succession destroyed the Sierra Chemical Company (Sierra) Kean Canyon plant near Mustang, Nevada, killing four workers and injuring six others. Because of the loss of life and extensive damage, the CSB sent a team to investigate the explosion in an attempt to understand the causes of this incident. The investigation focused on identifying the most probable initiating event of the incident and the equipment, management systems, manufacturing process, and human-performance failures that led to the incident.

The Kean Canyon plant manufactured explosive boosters for the mining industry. When initiated by a blasting cap or detonation cord, boosters provide the added energy necessary to detonate less sensitive blasting agents or other high explosives. The boosters manufactured at the Kean Canyon plant consisted of a base mix and a second explosive mix, called Pentolite, both of which were poured into cardboard cylinders. The primary explosives used in the base mix were TNT (2,4,6-trinitrotoluene), PETN (pentaerythritol tetranitrate), and Comp-B, a mixture of TNT and RDX (hexahydro-1,3,5-trinitro-1,3,5-triazine). The Pentolite is a mix of TNT and PETN.

ES.2 Initiating Event

The investigation team determined that the first explosion occurred in the plant's Booster Room 2 and was followed seconds later by an explosion in the PETN building. There was no physical evidence or eyewitness that could conclusively pinpoint the cause of the explosion in Booster Room 2; however, the team identified four credible scenarios. Based on seismic data, interviews of workers, and the physical evidence observed during the investigation, the team believes the following explanation to be the most probable scenario.

The day before the incident, one melt/pour operator working in Booster Room 2 needed to leave work early. When he left, there were between 50 and 100 pounds of base mix left in his large mixing pot. The mixing pot's blade extended about two inches into the mix. The following morning, the same operator turned on the motor to the mixing pot in which the mix had stratified and solidified overnight. The bottom of the mixer blade, which was embedded in the solidified explosives in the pot, detonated the explosives by impact, shearing, or friction of the explosive material with the pot wall. Another possibility is that chunks of explosive material were pinched between the mixer blade and the pot wall, causing the detonation.

The explosive shock wave detonated several thousand pounds of explosives in the room that then destroyed the building. A heavy piece of equipment or burning debris from this first blast most likely fell through the reinforced-concrete roof or the skylight of the PETN building, initiating the second explosion 3.5 seconds later.

ES.3 KEY FINDINGS

Analysis of seismic data recorded by the Seismological Laboratory at the University of Nevada, Reno, on January 7, pinpointed the time between the explosions and their sequence. This analysis determined that "air waves unambiguously demonstrate that the northern of the two explosions occurred first." Because Booster Room 2 was located north of the PETN building, these findings confirmed the investigation team's determination that the first explosion took place in Booster Room 2.

The Kean Canyon Plant is covered under the Occupational Safety and Health Administration's (OSHA) Process Safety Management (PSM) Standard (29 CFR 1910.119). The PSM standard requires that companies using highly hazardous materials have in place an integrated safety management system. The investigation of this incident revealed that many essential elements of process safety management were missing or deficient.

The investigation also determined that reclaimed, demilitarized explosive materials purchased by Sierra from the Department of Defense (DoD) sometimes contained foreign objects. The risk of using contaminated explosive materials was not adequately examined by the company or by the DoD.

ROOT CAUSES OF INCIDENT	KEY FINDINGS
Process hazard analysis (PHA) conducted by the facility was inadequate.	Supervisors and workers from the Kean Canyon plant were not involved in the process hazard analysis of the operation. The PHA for Booster Room 1 was conducted by company personnel from other locations and did not consider safe siting of buildings or human factors issues. These deficiencies in the PHA program allowed unsafe conditions and practices in the facility to go unrecognized and uncorrected. No PHA was conducted for Booster Room 2.
Training programs for facility personnel were inadequate.	Managers believed that, short of using a blasting cap, it was almost impossible to detonate the explosive materials they used or produced. Worker training was conducted primarily in an ineffective, informal manner that over-relied on use of on-the-job training. Poor management and worker training led to a lack of knowledge of the hazards involved in manufacturing explosives.
Written ***operating procedures*** were inadequate or not available to workers.	Personnel primarily relied on experience to perform their jobs. Procedures and other safety information were not available in the language spoken by most workers. Operators routinely made changes in the steps they took in manufacturing explosives. This resulted in the use of inconsistent and hazardous work practices. There were no written procedures for Booster Room 2.
The facility was built with insufficient ***separation distances*** between different operations and the design and construction of buildings was inadequate.	Because unrelated chemical operations were located in the same building as Booster Room 2, an additional fatality and extensive property damage resulted. Close proximity of structures allowed the explosion to spread to a second building.
There was no systematic ***safety inspection or auditing program***.	Safety walkthrough inspections were unfocused and did not examine PSM program effectiveness, resulting in management being generally unaware of unsafe practices and conditions.

The ***employee participation program*** was inadequate.	Employees had not been involved in developing or conducting process safety activities. This resulted in a lack of understanding of process hazards and controls by workers. It also resulted in management not benefiting from the experience and insights of workers.

CONTRIBUTING CAUSE OF INCIDENT	KEY FINDINGS
Oversight by regulatory organizations was inadequate.	Safety inspections were conducted infrequently and inspectors generally did not have expertise in explosives manufacturing safety. This allowed unsafe conditions at Sierra to go uncorrected.

Figure 1. Causes of Incident

ES.4 RECOMMENDATIONS

Sierra Chemical Company and other explosives manufacturers

Process Safety Management (PSM) requires both careful planning and implementation. Prevention of explosions, as well as preventing propagation of explosions, requires a clear understanding of explosives safety principles and safe practices. The recommendations in this section have been prepared based on the conditions found at Sierra's Kean Canyon plant. Explosives manufacturers should evaluate the effectiveness of their explosives safety programs using the following recommendations to ensure that:

1. Process hazard analyses include examination of quantity-distance requirements, building design, human factors, incident reports, and lessons learned from explosives manufacturers.

2. Written operating procedures are specific to the process being controlled and address all phases of the operation.

3. Procedures, chemical hazards, and process safety information are communicated in the language(s) understood by personnel involved in manufacturing or handling of explosives.

4. Explosives training and certification programs for workers and line managers provide and require demonstration of a basic understanding of explosives safety principles and job-specific knowledge.

5. Process changes, such as the construction or modification of buildings, or changes in explosive ingredients, equipment, or procedures are analyzed and PSM elements are updated to address these changes.

6. Pre-startup safety reviews are performed to verify operational readiness when changes are made.

7. All elements of OSHA's Process Safety Management Standard are verified by performing periodic assessments and audits of safety programs.

8. The employee participation program effectively includes workers and resolves their safety issues.

9. Explosives safety programs provide an understanding of the hazards and control of detonation sources. These include:
   - foreign objects in raw materials;
   - use of substitute raw materials;
   - specific handling requirements for raw materials;
   - impact by tools or equipment;
   - impingement;
   - friction;
   - sparking; and
   - static discharge.

10. The following issues are addressed in plant design or modification:
    - Operations in explosives manufacturing plants are separated by adequate intraplant distances to reduce the risk of propagation.

    - Unrelated chemical or industrial operations or facilities are separated from explosives facilities using quantity-distance guidelines.

- Facilities are designed to reduce secondary fragmentation that could result in the propagation of explosions.

Institute of Makers of Explosives (IME)

1. Develop and disseminate process and safety training guidelines for personnel involved in the manufacture of explosives that include methods for the demonstration and maintenance of proficiency.

2. Distribute the CSB report on the incident at Sierra to IME member companies.

3. Develop safety guidelines for the screening of reclaimed explosive materials.

Nevada Occupational Safety and Health Enforcement Section

Increase the frequency of safety inspections of explosives manufacturing facilities due to their potential for catastrophic incidents. (Note: Nevada Governor Bob Miller signed an Executive Order on June 10, 1998, that will require inspections at least twice a year.)

Department of Defense

1. Develop a program to ensure that reclaimed, demilitarized explosives sold by the Department of Defense are free of foreign materials that can present hazards during subsequent manufacturing of explosives.

2. Provide access to explosives incident reports and lessons learned information to managers and workers involved in explosives manufacturing, associations such as IME, government agencies, and safety researchers.

1.0 INTRODUCTION

1.1 BACKGROUND

Sierra Chemical Company (Sierra) is a privately held, diversified chemical manufacturing company whose products primarily support the mining, municipal, and wastewater industries. The Kean Canyon facility manufactured explosive boosters, mixed custom flux for gold-smelting operations, and repackaged bulk soda ash for sale to the mining industry.

On January 7, 1998, at 7:54 a.m., two explosions killed four workers, injured six others, and destroyed Sierra's Kean Canyon plant, 12 miles east of Reno near Mustang, Nevada. Because of the loss of life and extensive damage, the CSB sent a team to investigate the causes of this incident.

1.2 INVESTIGATION PROCESS

The CSB investigation team conducted an on-site investigation from January 10, 1998, to February 6, 1998. The scope of the investigation team's responsibility was to examine and analyze the circumstances of the explosion, to learn what happened, and to attempt to determine the cause of the explosion. The team evaluated the process design and safety management systems to determine their adequacy in controlling the cause of this explosion. The ultimate objective of this investigation was to develop recommendations to help prevent similar incidents.

The team used the following investigation methodology, adapted to address overlapping roles and responsibilities of other agencies investigating this incident. Facts were compiled by examining evidence at the incident site, conducting interviews, and reviewing documentation. To minimize duplication of effort, the team used the information collected by other agencies to the maximum extent practical.

Events and causal-factors charting were used to establish the sequence of events chronologically and show the related conditions. Because there were no survivors from Booster Room 2, the building where the four workers were killed, hypothetical event sequences were developed to test the feasibility of specific initiating events.

An analysis of initiating events was used to evaluate their likelihood. This analysis is provided in Appendix A. Change analysis was used to identify changes in operations on the day of the incident and differences between operations in Booster Room 1 and Booster Room 2 that could provide an explanation as to why an explosion might occur in Booster Room 2. Barrier analysis was used to identify those missing physical, administrative, and management controls that contributed to the explosion.

2.0 FACILITY AND PERSONNEL DESCRIPTIONS

2.1 PLANT FACILITIES

Sierra's explosives facilities are located approximately seven miles east of the company headquarters in Sparks, Nevada. The plant is located in Kean Canyon, north of Interstate 80. Sierra also leases land in Kean Canyon to the Frehner Construction Company, which operates an adjacent gravel pit south of the plant. There was one primary access road to the explosives facility, which was controlled by a locked gate. All of the magazines and buildings at the Sierra facility had either key or combination locks. These buildings typically were locked, except when workers required access during the workday.

The Kean Canyon plant produced a variety of materials for the mining industry. The melt/pour manufacturing operation produced explosive boosters, which are used with blasting caps to initiate detonations of blasting agents or other less sensitive high explosives. Explosive raw materials and finished boosters were stored in magazines built into a hillside in the western side of the canyon.

The plant's facilities were built on a series of terraces as shown in Figure 2. The highest terrace was a storage yard for equipment and materials. The next terrace contained storage tanks for process water and soda ash. Booster production, flux mixing, and soda ash repackaging operations were located in the production building on the third terrace down, approximately ten feet below the previous terrace. A chemistry lab, an employee break room, and a parking area were located on the fourth terrace, which was 18 feet lower than the previous terrace. The PETN building and magazine were located on the fifth terrace, approximately five feet below the previous one, or about 23 feet below Booster Room 2.

Figure 2. Kean Canyon Facility

2.2 The Production Buildings

The production buildings housing the booster manufacturing, flux, and soda ash operations were constructed over several years as add-ons to an expanding operation. The explosives-manufacturing buildings were constructed of fully grouted, reinforced, 8-inch concrete block. They had asphalt and tar roofs supported by wooden trusses. A pre-fabricated metal building warehoused paper products and finished flux.

Figure 3 shows the various buildings and rooms used in the melt/pour, flux, and soda ash operations. Booster Room 2 was built before 1974 and was refurbished for the melt/pour operation in 1996. For convenience, north is shown to be at the top of Figure 3, perpendicular to the back wall of the production buildings. True north is 44 degrees clockwise.

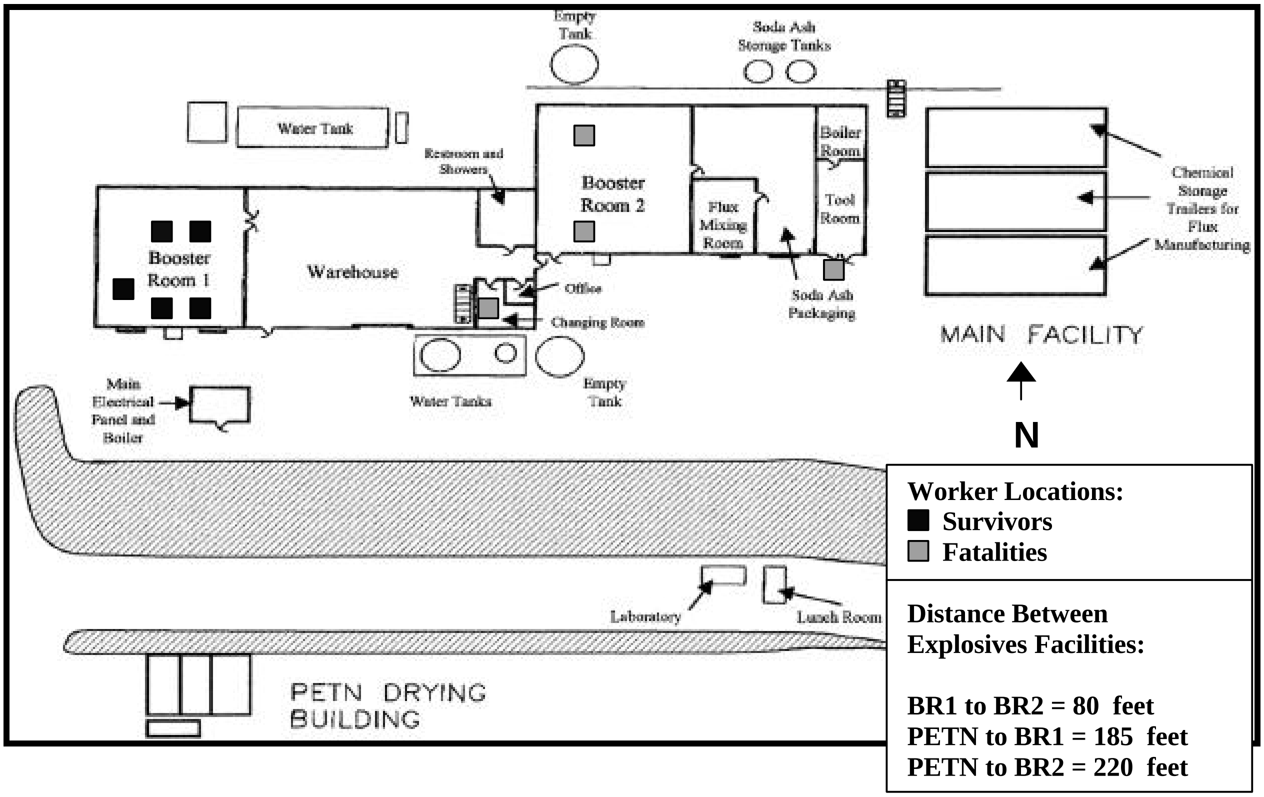


Figure 3. Layout of Production Facilities (not to scale)

2.2.1 Booster Room 2

Booster Room 2, shown in Figure 4, was approximately 40 feet wide by 40 feet long and had been put into operation about four months prior to the explosions. A platform along the north wall of Booster Room 2 had an 8-inch, reinforced, poured-concrete floor supported by steel I-beams. Workers placed materials in the center of the platform between two independent melt/pour production lines.

Figure 4. Booster Room 2

Booster Room 2 contained six mixing pots on or beside the four-foot high platform along the north wall. These pots were numbered 1 to 6 from east to west. Pots 1, 2, and 3 were placed in a mirror image of pots 6, 5, and 4, respectively. Pots 1 and 6 had not yet been placed in service. Pots 2 and 5 were used to make the base mix consisting of TNT, Comp-B, and PETN. Pots 3 and 4 were smaller, were used to make Pentolite from PETN and TNT, and were mounted in an I-beam support structure located directly in front of the raised platform. All mixing pots were equipped with gauges that indicated steam jacket temperatures and explosive mixture temperatures to aid operators in controlling the process. Each pot had an exhaust line to carry any dust or vapor from the pots outside through a series of particulate filters. The mixing pots in Booster Room 2 and the location of explosives between the pots is shown in Figure 5.

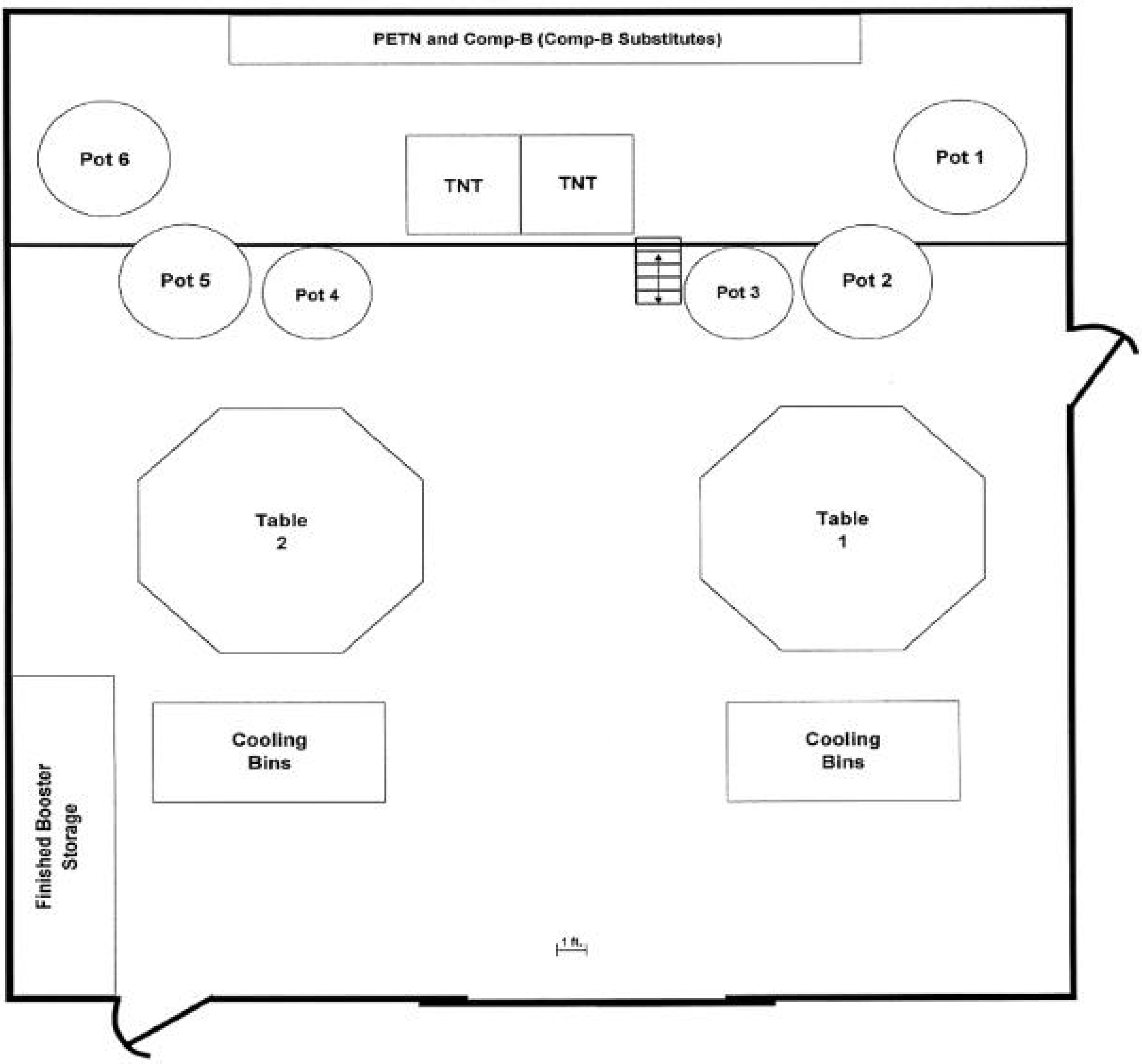


Figure 5. Booster Room 2 Layout

Pots 1, 2, 5, and 6 were acquired as excess equipment from the Department of Defense. A two-horsepower motor, coupled through a 38:1 gear reducer, drove stainless-steel mechanical mixing blades. The blades on the large pots were attached to a central shaft and curved upward along the inside surface of the pot in an elliptical fashion. The pots were stainless steel with a carbon-steel steam jacket. Two “breaker bars” extended down into the mixing pot to help agitate and break up chunks of material that might be present. Steam provided heat to the pots through the steam jacket and the two breaker bars, and through a jacket on the explosives draw-off line on the bottom of the vessel.

Pots 3 and 4 were purchased from an industrial food-processing supplier. The pots were similar to the other four pots, except they were smaller and constructed of lighter-gauge stainless steel. Stainless-steel stirrers provided agitation. The stirrers had two mixing blades extending parallel to the pot wall from the bottom of a central shaft in the shape of an anchor. Steam heated the water jackets and draw-off lines.

Two pouring tables were used to hold the booster cylinders during the pouring and cooling process. The tables had a fresh-air-supply hood that provided initial cooling for the poured boosters. Finished boosters cooled in bins located south of the pouring tables. Workers boxed the finished boosters and placed them on pallets or finished-product shelves before moving the boxed boosters to outside storage magazines. Paper products were stored on shelves on the south wall.

2.2.2 Booster Room 1

Booster Rooms 1 and 2 were similar in design and size. Booster Room 1 contained three melting and four mixing pots. Three of the mixing pots were used in the melt/pour operation. Workers used the fourth pot to maintain a liquid supply of Comp-B, one of the ingredients in the melt/pour operation. The three melting pots were used to maintain a supply of liquid TNT. The room also contained a small portable magazine in the northwest corner of the room that was used for PETN storage.

2.2.3 PETN Building and Magazine

PETN is shipped wet to reduce its sensitivity. The PETN building, where the water was removed from the PETN, was constructed of fully grouted, reinforced, 8-inch concrete block. The reinforced-concrete roof had a skylight over the drying room. The building consisted of three rooms (see Figure 3). One room was a weather room to permit the offloading of material during inclement weather. The second room, called the drip room, was where wet PETN was transferred to canvas bags and spun in a centrifuge to remove water. The last room, called the drying room, was where workers placed de-watered bags of PETN on racks to dry. Adjacent to the PETN building, and connected to it via heating ductwork, was the PETN magazine. The magazine was a skid-mounted steel structure also used for storing the PETN while it was drying. The PETN building and magazine were normally locked.

2.3 PLANT PERSONNEL

There were four classifications of personnel who worked in the melt/pour operation at Sierra's Kean Canyon facility: outside workers, melt/pour operators (operators), boxers, and supervisors. The outside workers were paid an hourly rate and worked normal shift hours. Operators and boxers were paid on production, based on the number and type of boosters produced or boxed. Although operators worked nominal shift hours, operators could, and often did, extend their hours by coming in early and/or leaving late to increase their production. The supervisor was salaried.

Outside workers were responsible for the PETN drying process and for handling raw materials and finished goods. They would stock the booster rooms once each day to ensure that the rooms had enough raw materials for all shifts of the next day's operation. They added TNT to the melting pots in Booster Room 1 to maintain a constant supply of liquid TNT. They were also responsible for loading and unloading shipments of materials to and from the explosives magazine. When sufficient rejected (unusable) boosters accumulated, the outside workers would break up the rejected boosters to recover the explosives for reprocessing.

Boxers packed finished boosters into boxes for storage. They assisted outside workers in moving materials into and out of the booster rooms.

The duties of the operators varied, depending on the room, the shift, and the experience of the individual. Nominally, an operator was responsible for start up of the mixing pots, preparing two mixes, pouring the mixes into the booster cylinders, and placing finished boosters into the cooling bins. Operators on the day shift in Booster Room 1 worked in teams of two. The first operator would prepare the mixes and pour the base mix. The second operator would set up the table to prepare for the pour and then pour the Pentolite. The more senior operator generally was responsible for preparing the mixes. In Booster Room 2 and during the Booster Room 1 second shift, the operator worked by himself on one line. In Booster Room 2, the lines were totally independent. In Booster Room 1, the lines shared certain pots.

The supervisor spoke Spanish and English and had over 20 years' experience with the company. He oversaw production and was responsible for establishing production runs, monitoring work practices, safety and quality, shipping and receiving materials, and cleanup. The supervisor conducted safety meetings with an emphasis on housekeeping, washing before eating, and never taking contaminated clothing home. Because most workers spoke only Spanish, the supervisor was the principal translator and communications link between management and employees at the plant.

3.0 ANALYSIS OF THE INCIDENT

On January 7, 1998, two explosions occurred at the Sierra Kean Canyon facility and resulted in four fatalities, six injuries, and catastrophic damage to the site. The first explosion occurred at 7:54:03 a.m., and was followed by a second, larger explosion 3.5 seconds later, as recorded by the Seismology Laboratory at the University of Nevada, Reno. The interval between explosions was estimated by the laboratory to be accurate to ± 0.2 seconds. The CSB investigation team determined that the first explosion occurred in Booster Room 2, the second in the PETN building.

The explosions involved a number of explosive materials, including PETN, Comp-B, TNT, and other explosives purchased through the Department of Defense demilitarization program, such as A-3 and LX-14, used in place of Comp-B. Management estimates of the explosive materials present in the operating facilities at the time of the incident are presented in Figure 6. The total quantities of each explosive ingredient are based on management's estimate of inventory differences following the explosion, compared to the December 31, 1997, inventory, and reconciled to account for shipments made and received. There were 47,000 pounds of unaccounted-for explosives estimated to have been destroyed by the explosions and subsequent fire.

Location	TNT (lbs.)	Comp-B (lbs.)	PETN (lbs.)	Total (lbs.)*
Booster Room 1**	14,000	2,000	4,000	20,000
Booster Room 2	9,000	2,000	1,000	12,000
PETN Building and Magazine			15,000	15,000

*Based on company's estimate and includes the explosive quantities in finished boosters.
**No detonation occurred in this room.

Figure 6. Estimate of Explosive Materials in Operating Buildings at Time of Incident

The quantities of explosives reported for each booster room in Figure 6 are management's estimates. Workers estimated that Booster Room 2 contained 7,000 to 8,000 pounds of explosives, rather than the 12,000 pounds estimated by management. Regardless of which estimate of explosives in Booster Room 2 is most accurate, the PETN Building by all accounts contained a greater quantity of explosives: about 15,000 pounds.

3.1 SEQUENCE OF EVENTS

Operators were responsible for the preparation of explosive mixes, the operation of the mixing pots, and pouring mixes into booster cylinders. (See Figure 5 for layout of Booster Room 2.) At 3:00 p.m. on January 6, an operator for the west side of Booster Room 2 left work early, leaving 50 to 100 pounds of melted explosive base mix in pot 5. He mentioned this to the other operator in the room, who later checked and saw the explosives in pot 5.

Explosives manufacturing operations began the next morning, January 7, shortly after 6:00 a.m. in Booster Room 1. Both Booster Rooms 1 and 2 were scheduled to make 227-gram boosters that day. Two teams of two workers each had finished mixing operations for the first batch of the day and were beginning to pour. A fifth worker was also working in Booster Room 1, packing the finished boosters from the previous day.

The operator for the west side of Booster Room 2 arrived at work, and at about 7:30 a.m. visited Booster Room 1 to greet his fellow workers who were pouring boosters. He talked briefly with a Booster Room 1 operator about a pouring pitcher he had returned to that worker's locker in the change room, and then left at about 7:35 a.m. The supervisor arrived at approximately 7:40 to 7:45 a.m., stopped in Booster Room 1 for about 5 minutes, then rode to the nearby gravel pit in a backhoe with another worker.

Besides the operator assigned to the west side of Booster Room 2, there were three other workers in or near Booster Room 2. One of these three, an outside worker, was in the changing room waiting to clock-in at 8:00 a.m. A boxer was packing finished boosters in Booster Room 2, and the last worker was moving materials from storage trailers to the flux room. The suspected locations of the four workers are consistent with the locations of human remains found during the investigation. Worker locations at the time of the incident are shown in Figure 3.

When the first explosion occurred, a worker in Booster Room 1 saw a huge fireball engulf a truck, which was parked immediately outside the building. The Booster Room 1 worker was thrown against the west wall, as the ceiling and east wall of the room collapsed on top of him and four other workers. Seconds later, a second, louder explosion occurred. After the explosions, the north, west, and south walls of Booster Room 1 were still standing; however, the rest of the site, including Booster Room 2, was essentially leveled. The site of the PETN building and adjacent magazine was now a 40- by 60-foot crater, which had a depth of as much as six feet. The explosions were felt as far as 20 miles away.

3.2 POST-EXPLOSION EVENTS

A total of 11 Sierra employees were at the site at the time of the incident. Following the explosions, five workers in Booster Room 1 were trapped temporarily under the collapsed building, but were able to crawl out within a few minutes; three were seriously injured and two received minor injuries.

Concerned about possible additional explosions, the workers from Booster Room 1, after calling for other possible survivors, went to the entrance to the facility. There they met two other workers who had been in the gravel pit below the site, approximately 350 feet southwest of the PETN building. The other four workers who were believed to have been in or near Booster Room 2 had been killed by the explosions.

The blast effects of the explosions leveled the site and threw structural materials, manufacturing equipment, raw materials from the booster and flux operations, and other fragmentation up to 1,000 yards away. Figure 7 shows Booster Room 1 and Figure 8 shows Booster Room 2 following the explosions. The legs and cross bracing from an empty tank, which previously stood at the corner of the change room, were imbedded in a motor home located 900 feet from the production building. The doors of one of the large magazines and a portable magazine located west of the production facility were sprung open by the negative pressure pulse; however, large quantities of explosive materials that were stored inside did not detonate. Many undetonated boosters had been scattered throughout the site by the explosion. Other hazards at this time included fires, toxic chemicals, and potential detonation of the explosives in Booster Room 1 as the fire progressed.

Figure 7. Booster Room 1 After Explosion

Figure 8. Booster Room 2 After Explosion

3.3 Initial Response

At approximately 7:58 a.m., the Washoe County Sheriff's Office and the Truckee Meadows Fire District received a report of an explosion approximately ten miles east of Reno and responded. The Sparks and Reno Fire Departments also responded. Initial emergency responders arrived at the blast site at approximately 8:10 a.m., but did not attempt to extinguish the fires because of the potential for further explosions and fragmentation hazards from burning explosives. Instead, workers were evacuated immediately to an emergency shelter. Within about an hour of the explosion, the south wall of Booster Room 1 collapsed due to the heat of the fire. By approximately 11:00 a.m. the following day, the major fires were out.

The initial scene was evaluated by the Operations Chief and the owner of Sierra. They determined that the area in which the blast had occurred was unsafe because of fires that were still burning and the possibility of secondary explosions involving large quantities of explosives in storage magazines. Emergency crews and equipment were relocated, and firefighters allowed the fires to burn out. A command post was established at a safe distance from the site.

An Incident Command System (ICS) with a unified command structure was established immediately. It was directed by the Truckee Meadows Fire District and the Washoe County Sheriff's Office. The ICS consisted of a multiple-branch organization divided into rescue, fire suppression, hazardous materials, law enforcement, and environmental jurisdictions. A secure perimeter was set up around the site 24 hours a day. This secure perimeter continued until January 13th.

A second scene evaluation was conducted with representatives from the Fire District, Sheriff's Office, Consolidated Bomb Squad, and Sierra's chemist and owner. This team first entered the site and created a safe path of entry, preserved evidence, determined the safety of the site, and looked for survivors. Once the team finished, the site was declared to be relatively safe, and the recovery of human remains and investigative phases began.

The ICS used a modified grid search, combining teams from the specific branches of the ICS structure. The search for survivors was enhanced by the team's efforts to identify and mitigate hazards, which included unexploded devices and leaking propane and diesel fuel. There was also chemical contamination from destruction of the flux mixing room, the soda ash packaging room, and the laboratory; and damage to bulk chemical storage tanks and trailers. The Washoe County Health District performed air sampling and determined that no significant health risk existed from the plume of smoke.

The Washoe County Sheriff and the U.S. Treasury Department's Bureau of Alcohol, Tobacco and Firearms (BATF) treated the blast site as a possible crime scene. Law enforcement personnel controlled entry into the site. On Thursday, January 8th, the BATF National Response Team arrived to assist in the investigation. Teams located and collected evidence, took photographs and videotape, surveyed and diagrammed the scene, and rendered explosive items safe.

The CSB investigation team arrived Friday, January 9, and began its investigation the next day. By late Monday afternoon, January 12, the Washoe County Sheriff and BATF search teams announced that all remains of victims had been recovered from the site. On Tuesday, January 13th, the site was released to the CSB and the Nevada Department of Business and Industry for further investigation, and to the Washoe County Health District to continue mitigation of spills of environmentally sensitive chemicals. The Sheriff's Office and the BATF concluded that there was no evidence of a criminal act.

3.4 SEQUENCE OF EXPLOSIONS

Before the investigation team could determine the cause of the explosions, it was necessary to first determine which building exploded first. The Seismological Laboratory at the University of Nevada, Reno, reported that their network of sensors recorded two explosions on January 7. Analysis of this seismic data pinpointed the time between the explosions (3.5 seconds) and the sequence of explosions. The seismologists reported that "air waves unambiguously demonstrate that the northern of the two explosions occurred first." Because Booster Room 2 was located north of the PETN building, these findings confirmed the investigation team's determination that the first explosion took place in Booster Room 2. Moreover, seismic data indicated that the second explosion was stronger than the first. Because PETN has a higher energy content per pound than the explosives that were stored in Booster Room 2, and the PETN building contained more explosives than did Booster Room 2, these findings were also consistent with the investigation team's conclusion that Booster Room 2 exploded first, followed by the PETN building. The seismology report is provided in Appendix B.

In addition to the seismic data and physical evidence, interviews of workers provided further bases for the determination of the sequence of explosions.

Some of the physical evidence concerning the sequence of explosions was noted by BATF prior to the CSB investigation team's assessment. The BATF report is provided in Appendix C. The BATF observed that the blast crater from the PETN building explosion was essentially free of building debris from the booster-production level of the plant. This indicated that the PETN building exploded second. The CSB investigation team subsequently noted that a piece of roofing from the production building was in the PETN crater. The CSB team concluded that this piece of the roof could have remained airborne for several seconds longer than the 3.5 seconds between explosions. This would explain why the piece of the production room roof landed in the PETN crater.

The plant was located in a bowl in hilly terrain. The position of the grass on the hillsides east of the buildings provided evidence of blast effects. When first examined by BATF, the grass pointed radially outward from the PETN building, not from Booster Room 2. This also indicated that the second blast came from the PETN building.

Layering of debris further demonstrated the sequence of the explosions. The concrete roof of the Boiler Building fell on top of pieces of its walls. (The Boiler Building is labeled "Main Electrical Panel and Boiler" in Figure 3.) These were in turn located on top of a corner and pinned down a seven- by ten-foot sheet-metal sliding door from the east side of Booster Room 1. A small tank, previously located outside the Boiler Building, also came to rest on this door. When the sliding door was finally lifted (see Figure 9), no debris was under it, even though it was surrounded by debris from the concrete Boiler Building. This layering, like archeological strata, indicated that the blast from Booster Room 2, which knocked down the wall between the warehouse and Booster Room 1, blew out the sliding door to the raised platform in Mixing Room 1. The second blast from the PETN building destroyed the Boiler Building and its concrete roof fell down on top of pieces of the wall.

Figure 9. Lifting the Sliding Door

The main body of a 12-foot-diameter tank with a conical lower portion, that was previously located near the southeast corner of the change room south of Booster Room 2, was blown directly south approximately 850 feet. It landed on the north entrance road to the Frehner Construction Company truck parking lot. The steel-pipe stand on which this vertical tank had been elevated was found along the east side of the entrance road to the plant, where two of its large legs and cross bracing struck the mobile home (Figure 10) which housed the guard for the Frehner Construction Company. The top of the tank landed across the road northwest of the PETN building. Because this tank had been elevated, it was fully exposed to blast effects from the PETN building. Had the PETN building exploded first, this tank would have toppled toward Booster Room 2 and the adjacent flux mixing room. The tank and its support legs, however, were found on the side of the PETN building furthest from Booster Room 2. This indicated that Booster Room 2 exploded before the PETN building exploded.

Figure 10. Mobile Home Hit by Legs of Tank and Cross Bracing

A flatbed truck, which had been parked facing east on the terrace, south of the tanks outside of the change room/office, came to rest after the explosions facing southeast, with the cab diagonally hanging over the edge of the riprapped slope between terraces. The driver side of the engine and cab of the truck showed multiple fragment penetrations. A mixing pot fragment was found lodged on the driver's side of the truck. The passenger side of the truck showed blast damage that lifted the front of the cab off of the chassis. A pile of riprap was found on the uphill side of the driver-side front tire, with a path cleared in the riprap on the other side of the tire (see Figure 11). There was less riprap material on the uphill side of the passenger-side front tire. A steel cargo rack, which had been welded to the front of the truck bed behind the driver, was found hanging from the bed on the driver side on top of other blast debris from the vicinity of Booster Room 2.

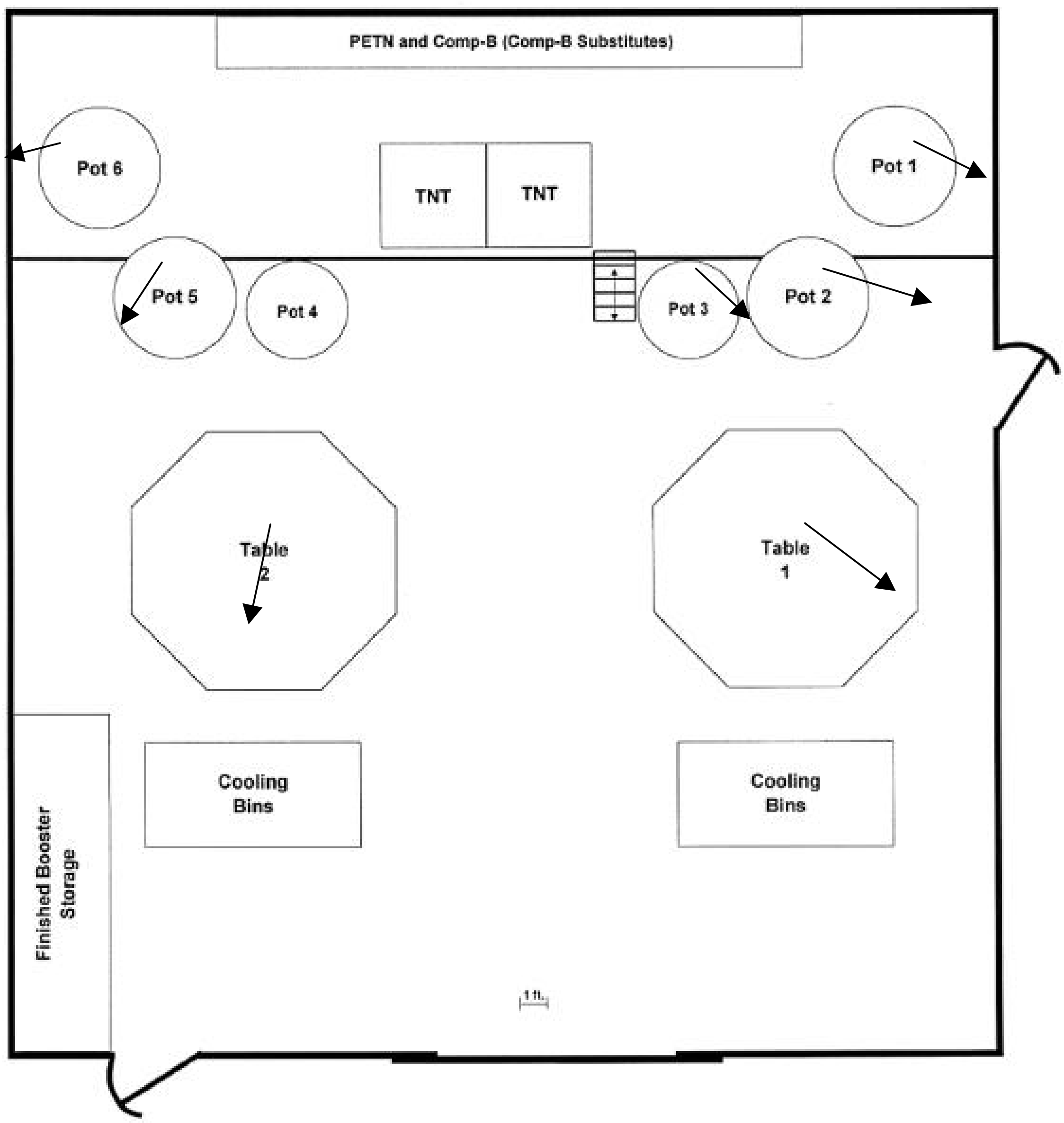
Figure 11. Flatbed Truck Showing Riprap Against Tire

The investigation team determined that the front of the truck was struck by the blast from Booster Room 2, and the blast propelled the truck partially over the slope, with the undercarriage resting on the brow of the slope. The axis of the truck was nearly perpendicular to the brow of the slope. The blast from the PETN building then struck the passenger side of the truck, which rotated the front of the truck back uphill about six feet, with upward damage to the cab. The second blast also tore the cargo rack from the front of the truck bed and deposited it on the uphill side of the truck on top of debris from Booster Room 2, including part of the stand from pot 4. This second blast lifted the passenger side of the vehicle, which resulted in more riprap being pushed uphill by the driver-side tire. Because the last movement of the truck was uphill, away from the PETN building, observations of the final truck position and condition supports the conclusion that the first explosion occurred in Booster Room 2.

Another truck, a pickup, that had been parked outside Booster Room 1 facing east, was found rolled over on the driver-side door following the incident. Both sides of the vehicle showed evidence of blast effects, with the passenger side having the greatest damage. The driver-side door showed characteristic concave dishing, which could not have been caused by rollover on the level ground. This indicates that the first blast came from Booster Room 2. The second blast, from the PETN building, struck the passenger side of the pickup truck and overturned the vehicle.

The physical evidence indicated that the first explosion originated in Booster Room 2. The time delay between explosions showed that the PETN explosion was not initiated by ballistic overpressure from the explosion in Booster Room 2. The investigation team concluded that in the rain of debris, a heavy metal component or piece of debris from the initial blast went through the skylight or the roof of the PETN building and initiated the second explosion.

The investigation team found a number of identifiable components from Booster Room 2, including table bases and several mixing-pot shafts. Figure 12 shows the original location of these items in the room and the direction (indicated by an arrow) that each traveled following the explosion. The presence of pot fragments and components in virtually all directions indicates that mixing pot 5 exploded before the staged explosives on the platform did. Figure 12 also shows that the blast was concentrated in the areas where these explosives were staged.



ILLUSTRATED ITEM	DISTANCE TRAVELED
Pot 1 with shaft intact	240 feet
Full shaft assembly, less mixing blades, and lid from pot 2	675 feet
Shaft from small mixing pot, less mixing blades, believed to be from pot 3	1250 feet
Approximately 18" piece of shaft from pot 5	450 feet
Pot 6 lid with shaft assembly, less mixing blades	480 feet
Table 1 base	455 feet
Table 2 base	380 feet

Figure 12. Details Regarding Trajectories of Booster Room 2 Equipment

Two witnesses provided information relevant to the sequence of the explosions. A worker boxing explosives in Booster Room 1 saw, out of the corner of his eye, a fireball come over a pickup truck parked outside a sliding door to the building. The blast from the first explosion threw the worker back into a pile of empty boxes stacked along the west wall, and the roof collapsed. He then heard a louder explosion. The investigation team believes that the fireball the worker saw was from the explosion in Booster Room 2 and that the blast from that explosion blew down the east wall of the room and threw the worker into boxes on the west wall. If the PETN building had exploded first, the blast, if not deflected by the terracing and pickup truck, would have thrown the worker toward the north wall. This is corroborated by the interview of an operator who was working in Booster Room 1. When the first explosion occurred, he was blown about 14 feet east across the room.

At the time of the incident, a Sierra employee was loading gravel in the gravel pit and was facing in the general direction of the plant. He heard the first explosion and saw dark smoke from the blast coming from the general vicinity of the change room. The second, brighter explosion was to the right of the first. From his vantage point, the PETN building was to the right of Booster Room 2. A bright flash is characteristic of a PETN explosion. Thus, his account corroborated the investigation team's conclusion that Booster Room 2 exploded first and the PETN building exploded second.

3.5 Background on Plant Operations

3.5.1 High-Explosive Raw Materials

The manufacture of the high-explosive boosters at Sierra's Kean Canyon facility involved melting, mixing, blending, and pouring three energetic raw materials. Two of the raw materials are single compounds; the third raw material is a blend of two energetic compounds and a binder. The materials were TNT (2,4,6-trinitrotoluene), PETN (pentaerythritol tetranitrate), and Comp-B, a mixture of TNT and RDX (hexahydro-1,3,5-trinitro-1,3,5-triazine) with wax added as a desensitizing agent. The nominal composition of Comp-B is 63 percent RDX, 36 percent TNT, and one percent wax.

At Sierra, Comp-B was purchased as surplus material through the Department of Defense (DoD) demilitarization program. In addition to Comp-B, the lots of surplus material purchased were known to include other reclaimed explosive substances. These explosive materials included Comp A-3, Comp H-6, LX-14, and Octol. Boxes of material labeled as PBX4 and believed to be

PBX-9404 were also stored in the main magazine, alongside and intermixed with boxes of the other explosive compositions. Boxes labeled as HMX were also seen in the magazine and identified by workers as a substitute raw material.

These explosive compositions are all made of combinations of four basic explosive compounds, TNT, RDX, HMX, and PETN. The chemical names and some properties of the four compounds are listed in Appendix D. Of these four compounds, TNT generally is recognized as the most stable and least sensitive. The explosives RDX and HMX are both heterocyclic nitramine compounds that are very stable chemically, but more sensitive to initiation than TNT. The fourth compound, PETN, is considerably more sensitive to initiation than the other three compounds, especially when dry. In general, the sensitivity of explosives is enhanced by increases in temperature.

3.5.2 Melt/Pour Operations in Booster Room 2

Two separate production lines were located in Booster Room 2. There were no TNT-melting pots. All of the TNT used in the process was added to the mixing pots in a flake form. Since beginning operation on September 18, 1997, only four of the six pots in Booster Room 2 had been used. Each production line used one large base-mix pot and one smaller Pentolite-mix pot. A new steam system put into service in Booster Room 2 provided high-capacity, low-pressure (less than 15 psig) steam heat to the mixing pots. The system was capable of quickly heating and melting the materials.

Only a day shift schedule was worked in Booster Room 2. At the beginning of the day, all of the PETN, flake TNT, and Comp-B-type materials needed for making boosters were already on the platform near the mixing pots, having been staged during the previous afternoon. The shift in Booster Room 2 normally started between 7:00 and 7:30 a.m. Unlike Booster Room 1, where there were two operators per process line, Booster Room 2 had only one operator per process line. Based on a composite of interviews with operators, the normal initial steps for starting up melt/pour operations in Booster Room 2 included:

1. Check the pots for material.

2. Open the steam supply and condensate return valves to the base-mix and Pentolite pots.

3. Turn on the mixing motors.

4. Break up chunks of Comp-B, if necessary.

The investigation team noted that some of the operators interviewed said that they did not check for material left in the pots. Operators reported that at the end of the shift, the base-mix and Pentolite mixing pots were normally left empty.

3.5.3 Melt/Pour Operations in Booster Room 1

Booster Room 1 had been in operation for over twenty years. It contained three TNT-melting pots and four mixing pots. Two of the mixing pots were used for base mix. One of the mixing pots was used for Pentolite, which was used to finish the boosters. The last mixing pot was called the “Comp-B pot” because it was used to melt the materials that were commonly referred to as Comp-B. This additional pot was used because of the slow heat-up rate of the hot-water system in Booster Room 1.

Unlike Booster Room 2, in which employees worked only one shift, Booster Room 1 had a second shift that started at about 3:00 p.m. Working the second shift in Booster Room 1 resulted in operators using different steps to begin melt/pour operations. For example, since operations were already in progress from the day shift, there was no need to inspect the contents of mixers prior to beginning production. In Booster Room 1, the base-mix and Pentolite-mixing pots were normally left empty at the end of the second shift.

The investigation team determined that the use of different operating steps in Booster Room 1 and Booster Room 2 was significant. Operators trained during the second shift in Booster Room 1, but who were later assigned to work in Booster Room 2, probably did not use a work routine that included looking into mixing pots prior to beginning melt/pour operations.

4.0 ANALYSIS OF CREDIBLE INITIATING SCENARIOS AND PROCESS SAFETY MANAGEMENT

Several credible incident scenarios were identified and considered by the investigation team. While the investigation of this incident determined one of these scenarios to be the most probable, an absolute determination of which scenario actually caused the incident is not the most important issue. Each of the credible scenarios demonstrated the existence of serious safety system failures at the Kean Canyon plant. While one of these scenarios was found to be the most probable by the investigation team, the other scenarios could have easily resulted in a disaster on another occasion. Examination of each credible scenario provides a more complete understanding of the safety problems at the Kean Canyon plant. (An alternative scenario that attributes the initial explosion to an act of sabotage was presented to the CSB for its consideration. The CSB's analysis of and response to this alternative scenario is found in Appendix E.)

4.1 MOST PROBABLE SCENARIO

Solidified Material in Pots at Start of Day Shift

The night before the explosion, an operator in Booster Room 2 left 50 to 100 pounds of explosives in base-mix pot 5. This was verified by another operator on the parallel production line who looked into pot 5. This other operator indicated that the depth of explosive material left in pot 5 was about four inches, which matched the weight of explosives that he estimated.

At the end of each day, operators were instructed to leave a steam line valve to each pot partially opened to keep the boiler cycling, to prevent freezing of condensate in the lines. This amount of steam would be insufficient, however, to maintain any quantity of explosive mix above its melting point if outside temperatures were below freezing. OSHA investigators reported that the temperature during the night before the explosion dropped to between 20 and 25 degrees Fahrenheit.

Without agitation, the different explosives and binders of the mix tend to stratify due to their different densities. This stratification would increase the sensitivity of portions of the explosive material left in the pot. Turning on an agitator immersed two inches into a solidified mass of stratified explosives presents a high risk of explosion from the impact. An overcurrent protection device on the electrical mix motors in Booster Room 2 would stop the motor if the blade was unable to break up the explosives, but not before the startup torque was applied to the explosives. Due to the solidified material in the explosives draw-off line on the bottom of the pot, it would be impossible for the explosives to simply break free of the pot without causing friction with the interior of the pot and shearing a portion of the explosives in the draw-off line.

The day before the explosion, the operator who had left explosives in his pot offered the remaining material to the operator on the other production line in Booster Room 2. Because the operator who was leaving did not reach a firm agreement on whether the second operator would use the residual explosives, it is possible that no steam valves were left open that afternoon because leaving the valves open would make the remaining base mix too runny to pour. The operator who left early may have mistakenly thought that his remaining base mix would be used that afternoon and, thus, he failed to look in the pot the next morning before turning on the steam and mixer motor. The investigation team concluded that this was the most likely scenario.

The worker mixing in Booster Room 2 on the day of the explosion had learned to perform the basic melt/pour operation in Booster Room 1 while working on the second shift. The second-shift workers in Booster Room 1 had a different starting process than the day-shift workers. Because mixing pots would already be in operation when they came to work, they did not need to turn on the mixing pot motors. This fact affected operator training. The on-the-job training was based on what operators needed to know to perform their work. Even if a trainer explained the need to check a pot before turning the mixing motor on, there was seldom an operational need to turn the mixing motor on. It is doubtful that workers who learned the melt/pour operation on the second shift would have developed a work habit of checking a mixing pot before turning on the mixer motor.

The operator who left the material in his pot had been working in Booster Room 2 for eight weeks prior to the incident. His normal practice was to leave both of his mixing pots empty. Because he was the only person working his production line, he would normally know whether his pot was empty when he started work the next day. Some of the operators who worked in Booster Room 2 indicated that they did not need to look into the mixing pots in the morning because the pots were left empty at night.

Leaving material in the mixing pot overnight was a change to normal operation, but it was an acceptable practice at the Kean Canyon facility to alter the usual process without discussion or management approval. Several months before the incident, when material had been left overnight in the Comp-B mixing pot in Booster Room 1, management made it clear that this was an unacceptable practice because it delayed the operation of the day-shift workers. Facility management did not consider this to be a safety issue. Since the pots in Booster Room 2 heated material much faster than the pots in Booster Room 1 did, it is possible that the operator on the day of the incident thought that leaving material in the pot would not be hazardous.

Metallurgical analysis of mixer parts found after the incident provided further evidence supporting the CSB's conclusion that explosive material was left in pot 5. This analysis showed that damage to the hub of the mixing blade was consistent with it having been in contact with explosives at the time of detonation. This metallurgical analysis is contained in Appendix F.

4.2 OTHER CREDIBLE SCENARIOS

4.2.1 Dry Mixing of PETN in the Pentolite Mixing Pot

One significant difference in the operations of the two booster rooms was that in Booster Room 2, PETN was added to the Pentolite pot without first adding TNT. This was done to reduce residual moisture from the PETN. The supervisor indicated that Booster Room 2 was given the PETN with the higher moisture content because the mixers in that room had a higher heating capacity.

The practice of adding the PETN to the heated pot, without TNT as a solvent and lubricant, created conditions that were ideal for generating static electricity or high friction in the pot. Operators did not know that of the four explosives used in the process, PETN was most susceptible to electrostatic discharge, impact, and friction. Because supervisors at the facility did not observe the start-up processes in Booster Room 2, and because there was no written procedure for operations in this room, there was no way for supervisors to be aware that operators were mixing PETN without first adding TNT.

4.2.2 Chunks of Explosive Material

Operators routinely broke up chunks of explosive raw material by using a hammer. Use of any type of hammer to break chunks of explosives could cause a detonation. Workers described sometimes using a plastic mallet or a bronze hammer to break up the chunks of explosive raw material in a box, which was placed on other boxes or on the floor. Several workers indicated that they had used a steel, or carpenter's hammer to break up the material. Another practice was to knock the pieces together over the pot-feed opening. Workers described pouring some of the contents into a second empty box and then breaking up the contents with a hammer.

Use of a carpenter's hammer or a bronze mallet to break apart large chunks created a serious potential for detonation due to impact or impingement of the material. It was also possible that there were foreign objects in the raw material that could have sparked or resulted in impingement of the explosives when struck with a steel carpenter's hammer.

Even if a bronze, non-sparking hammer was used, an explosion could still be generated due to the impact of the tool. Moreover, LX-14 had recently been introduced into the booster-making process, and it had larger and harder chunks that required greater force to break apart.

An additional problem faced by the workers in Booster Room 1 was the slow heat-up rate of the hot water system, which delayed the pouring operation. In the initial steps of filling the base-mix pot, some liquid TNT was added, followed by Comp-B. To compensate for the slow heat rate, the operators broke up any large chunks in the Comp-B, LX-14, or other materials before they added the material to the base-mix and the Comp-B pots. The workers indicated that there had been a recent increase in the size and hardness of the chunks of the Comp-B or LX-14 materials they were receiving. Even though the mixers heated faster in Booster Room 2, the operators there would still break the larger chunks of Comp-B materials before they added it to the base-mix pots.

Another detonation hazard involved the possibility of large chunks of explosive material being impacted between the mixing blade and the pot walls or breaker bars. The inner wall of the large base-mix pots in Booster Room 2 were made of 3/8-inch stainless steel. As a result, these mixing pots were more rigid than the approximately 1/8-inch mixer wall thickness of stainless steel pots used in Booster Room 1. This structural rigidity increased the potential for friction, shearing, and impact.

4.2.3 Foreign Objects in Mixers

Workers reported hearing scraping noises in the mixers in Booster Room 1 caused by foreign objects. Adding reclaimed explosives containing metal foreign objects created a high potential for detonation due to friction or sparking of the foreign objects. If the material left in the base-mix pot in Booster Room 2 had partially melted before adding more Comp-B materials to the pot, it is possible that foreign objects in the material may have scraped along the inside of the pot, causing friction, which ignited the mix.

Operators in Booster Room 1 indicated that it was common to find foreign objects in the Comp-B pot and the base-mix pots. Most of the foreign material originated in the Comp-B. The operators used the metal handle of a plastic bucket to help retrieve the foreign objects. Included in the operators' descriptions of foreign material found in the pots were nuts, bolts, screws, a conical-shaped piece of copper, and aluminum posts from booster-mold trays. These foreign objects were responsible on earlier occasions for causing damage to the inner shell of the large Comp-B pot in Booster Room 1.

Operators in Booster Room 2 also found foreign materials in the base mix, but these items tended to end up in the boosters rather than remaining in the pots. This was because the draw-off lines and valves were larger in the new Booster Room 2 facility.

4.3 UNSAFE WORK PRACTICES AND USE OF SUBSTITUTE MATERIALS

Interviews with workers revealed the use of many unsafe work practices involving explosive materials. The investigation team also found problems with the substitution of different raw materials in the manufacturing process.

4.3.1 Unplugging Draw-off Lines with Metal Tools

The investigation team found that operators regularly used metal tools to unplug mixing pot draw-off lines in Booster Room 1. Several explosives manufacturing incidents during melt/pour operations at other companies have been caused by using metal tools to chip or forcefully break

apart clogs in draw-off valves (see Appendix G). In Booster Room 1, draw-off lines and valves, especially on the Comp-B pot and the large base-mix mixing pot, clogged frequently.
Two tools generally were used to clean out the clogged valves. The first tool was the wire handle of a plastic bucket. The loop in the end of the handle was used to help augur the material from the valve. The second tool was a 0.5-inch-diameter steel rod, with a looped handle. The working end of the rod was honed to a sharp point, which helped to break up the clogged material. The plant manager found this tool in Booster Room 1 on more than one occasion. When the manager found the rod in the booster room, he stated that he told operators not to use the tool, and the rod was taken to the tool room. Operators reported, however, that this tool was routinely kept in Booster Room 1 and was also used to push unmelted TNT on the surface down into the liquefied TNT in the melting pots.

Operators indicated that it was sometimes very difficult to clear valves, so they had to use more force. The metal rod would be jammed into the valve repeatedly until the mass of material was broken free. The tool would have to be extracted quickly when the clog was freed because the hot, melted explosive mixture would flow from the open valve stem and would burn the worker clearing the valve if the worker was not fast enough. Being burned by the molten liquid was considered to be the primary hazard associated with this activity.

Although use of the metal rod was common in Booster Room 1, it was not generally used in Booster Room 2 because of an improvement in the design to the draw-off valve and because of the higher heat capacity of the steam system. When clogs formed, the operators could increase steam to the draw-off line and melt clogged material within a few minutes. It is therefore unlikely that the operator in Booster Room 2 would have had a reason to use the rod on the morning of the incident. The investigation team concluded that this was not the cause of the incident.

4.3.2 Breaking Down Rejected Boosters

Metal hammers were sometimes used to break apart rejected boosters. The outside workers broke down the boosters in the northwest corner of Booster Room 1, by the PETN magazine. Use of hammers created a serious potential for an impact or impingement ignition. Use of a steel hammer added the potential for sparking. Workers broke down rejected boosters when approximately 300 had accumulated. This occurred about every two or three months. The breakdown process involved placing the rejected booster on a block of wood on the floor and striking the booster with a hammer. A plastic hammer, a bronze hammer, and a steel carpenter hammer were all reported to have been used, depending on what was available. The chunks of the booster were poured out of the booster cylinder into a pile on the floor.

Another hazard involved cleaning up the scrap pieces of the boosters using synthetic bristle brooms, plastic dustpans, and plastic buckets. This created electrostatic charges in the waste material. An electrostatic discharge potentially could detonate the material.

4.3.3 Using Different Explosive Materials

The potential safety hazards of using LX-14 or other substitute Comp-B materials was not subjected to a management of change review before it was introduced into the pots. The problem with LX-14 came to the attention of operators and management only when the material did not melt. Management was not informed that any problems existed with the size and consistency of the chunks. The operators considered these properties to be within the normal range of variability for Comp-B.

Workers reported that recently, the operators had added three and one-half cases of LX-14 to the Comp-B- melting pot. The LX-14 material did not melt for more than three hours. The LX-14 had been purchased as part of a lot with other materials at a government auction. The surplus explosive materials received from auctions were receipt-inspected to ensure that the number of boxes corresponded to the lot description. The boxes were not opened and inspected, however, because this caused material to spill from the boxes during later handling or storage. The lots were stored in magazines away from the processing buildings.

The outside workers considered everything in these lots to be Comp-B. When they staged several boxes of the LX-14, they did not realize that it would not melt. On this occasion, when the LX-14 did not melt, the operators were paid at the outside worker hourly rate for part of their shift that day because management recognized that the problem was caused by the LX-14 and not by operator mistakes. As a result of this incident, the operators were told they should not add more than one box of the LX-14 to a batch of base mix.

The LX-14 incident was addressed by management as a production problem. Management's solution was to use less of it in the mix. Workers did not have an adequate understanding of the chemical and physical properties of the material, and the effects of this material change on the melt/pour operation were not analyzed. There was no management of change review of the material in the surplus lots to determine suitability. The decision of what material should be used was left to the outside workers, who brought the material to the booster rooms. There was so much variation in the physical characteristics, packaging, and consistency of what was added to the mixing pots as “Comp-B,” that the workers did not differentiate or recognize that adding an unknown explosive material to the pots was potentially dangerous. The compositions and properties of the high explosives used as Comp-B substitutes vary widely. These differences had previously caused operational problems at Sierra.

4.4 BUILDING SPACING AND CONSTRUCTION

Buildings at Sierra were not located at safe distances from each other in order to prevent the propagation of an explosion from one building to another. Based on the explosive quantities contained in the buildings (itemized in Figure 6), the lack of effective barricading, and published safe intraplant distances (IME, 1996), Booster Room 2 should have been located at least 490 feet from Booster Room 1, rather than the actual separation distance of about 80 feet.

Additionally, Booster Room 2 and Booster Room 1 should have been located at least 245 feet from the PETN building, rather than the actual separation distances of about 220 feet and 185 feet, respectively. Moreover, if Sierra considered both booster rooms to be a single explosive facility for hazard analysis purposes, the recommended separation distance from the PETN building should have been increased to at least 295 feet.

The flux operation and other chemical activities that were unrelated to the manufacture of explosives were located in rooms adjacent to the Booster Rooms. This resulted in one additional fatality and destruction of the chemical facilities from the explosion in Booster Room 2. The OSHA PSM standard requires explosives manufacturers to analyze the siting of their facilities.

DoD safe siting standards do not directly apply to commercial operations; however, the “DoD Ammunition and Explosives Safety Standard” provides useful guidelines for performing OSHA-required siting analysis. According to the DoD, buildings used for administration or unrelated industrial activity should be separated from explosives operations by at least 1,250 feet.

A skylight had been installed over the drying room at the east side of the PETN building. The skylight could be breached by overpressure from an explosion in Booster Room 2. The skylight also made it easier for falling, hot debris from Booster Room 2 to penetrate the PETN building and detonate the explosive material. This could happen even if recommended barricaded intraplant distances had been used. The probability of hot debris falling through the roof of the PETN building would decrease, however, if the buildings were separated by the recommended distances. Terracing, which acted as a barricade, could protect only against high-velocity ballistic fragments that were projected horizontally. Terraces could not protect against falling debris.

Building construction was also inadequate. Booster Room 2, like Booster Room 1 and the PETN building, had walls constructed of fully grouted, reinforced, 8-inch by 8-inch by 16-inch concrete blocks. The PETN building had a concrete roof that provided a degree of protection from external events.

Concrete-block construction is a poor choice for explosive operations because of the many secondary fragments it produces in an explosion. Better alternatives are identified in "Structures to Resist the Effects of Accidental Explosions" (DoD 1990).

4.5 Process Hazard Analysis

The OSHA PSM standard requires that explosives manufacturers perform a process hazard analysis (PHA) of their operations. Conducting an effective PHA requires that the PHA team includes personnel who have experience with the process and equipment that is being analyzed. No one from the Kean Canyon plant was involved in conducting the PHA of this facility. The PHA team included Sierra's president, the vice-president for explosives, a process safety management specialist, and the compliance/engineering manager. This team performed PHA's of the booster-manufacturing process in Booster Room 1, and of the on-site transportation and storage facilities, completed on December 20, 1993, and May 17, 1994, respectively. A PHA was not performed on Booster Room 2. Management believed that a PHA for Booster Room 2 was not necessary because of the similarity of the operation with that in Booster Room 1.

Operators were not aware of the existence of any PHA's. When interviewed, some of the participants in the PHA did not recognize hazards listed in the study. For example, even though the PHA states that static electricity can potentially cause a detonation, one participant interviewed said that static electricity was not a hazard.

Sierra managers were aware of some recent safety-related incidents in the explosives manufacturing industry. They had not systematically incorporated lessons learned from incidents at other companies into the PHA program, however.

For example, clogged draw-off valves were routinely cleared at the Kean Canyon plant by using a half-inch-diameter metal rod. Management understood the hazards associated with this activity and had copies of a report describing how this practice had caused a detonation at another site. All of the operators interviewed by the investigation team, however, considered the practice of using a metal rod to clear clogged valves a normal, routine operating practice.

The human factors analysis portion of the PHA did not include specific analysis of the effect of performance errors by booster room operators. The explosives and chemicals in co-located operations, hazards of those materials, process-safety information, and facility siting also were not covered.

The PHA of Booster Room 1 stated that workers should perform a visual inspection of raw materials to prevent placing scrap metal into the mixing pots. Operators and the plant supervisor reported that, in practice, raw materials were rarely inspected before pouring the material into the pot. The only documented inspection was a visual inspection of the contents of one box, done without removing the contents, which occurred occasionally when a new shipment arrived. Operators normally did not find scrap metal until it came out of the draw-off valve into their pouring pitcher, or it was found in the bottom of the pot after the pot was empty.

The PHA also did not consider safe distance requirements in the siting of buildings and explosive materials. Lack of safe distance allowed the explosion in Booster Room 2 to destroy the flux room. As a result, a flux room worker died and unrelated chemical facilities were destroyed.

4.6 Operating Procedures

Written operating procedures were not used or available to workers at the Kean Canyon plant to ensure consistent and safe melt/pour operations. Written procedures were not used to train the operators who provided the on-the-job training. Consequently, procedures used in the melt/pour operations were largely left up to the individual operator, who was production-oriented due to

Sierra's use of a piece-work-based pay system. The lack of formal operating procedures for Booster Room 2 was a major contributor to the incident.

None of the operators had seen any written procedures at the Kean Canyon plant, and there was significant variation in the actual procedures used by different operators. Management had developed a generic operating procedure for the melt/pour process in Booster Room 1; however, it was not specific to the pouring line or operating shift, and did not address all phases of the operation or emergency procedures.

None of the managers recalled observing the startup process in Booster Room 2 since it had been activated four months before the explosion. Managers could not describe what the specific steps were, or should be, to start up the line in Booster Room 2.

4.7 TRAINING

4.7.1 Worker Training

Sierra's almost total reliance on the use of on-the-job training created a situation in which hazards were poorly understood and controlled. The melt/pour-training program relied on oral communication and physical demonstration to communicate the senior operator's expectations for job performance. Training effectiveness was dependent on the work habits, skills, experience, and memory of the operator doing the training. There were incentives to complete the training quickly. The trainer could lose salary if conducting training reduced the number of boosters the trainer produced. Moreover, without management-provided written procedures, checklists, standards, or performance criteria, the content of the training and the determination of what constituted acceptable performance was left to the discretion of the trainer.

Unless properly structured, implemented, and evaluated, on-the-job training can result in important information being omitted. Failure to communicate important information can result in the use of inconsistent work practices among employees. The on-the-job training program at the Kean Canyon plant made no provision for introducing new information from industry-wide experience.

The first step in the melt/pour operation training process was for the trainee to watch the experienced person perform each of the steps. After watching for varying periods of time, the trainee was allowed to perform the operation under the supervision of the experienced person. The qualification process took between one and two months to complete, depending on the progress of the trainee. When the trainee demonstrated an understanding of a task and the ability to perform it to the satisfaction of the trainer, the trainee was considered to be qualified. The information provided during the training period was at the discretion of the trainer. There was no written checklist or documented performance criteria for the training.

The worker performing the melt/pour task in Booster Room 2 on the day of the incident initially had been trained to perform melt/pour operations in Booster Room 1. He had been performing melt/pour operations for about one year before he began working in Booster Room 2. He had qualified to operate in Booster Room 2 in November 1997. An operator who had six years experience and who developed the melt/pour procedure used in Booster Room 2 did the qualification training. The trainer had received his training from an employee in Booster Room 1 but had adapted his routine to address the differences between the two booster rooms.

Workers generally understood the need to work safely with explosive materials; however, they lacked the detailed information needed to do that. Workers in both booster rooms used work practices long recognized to cause detonations in melt/pour operations in military facilities. The workers were not aware of the hazards of these unsafe practices.

The production supervisor often demonstrated the explosive capability of boosters by having workers witness the use of boosters during quality testing. Explosives safety may have been discussed during these demonstrations and during meetings that were held periodically. There was no documentation, however, of the content provided to workers on the specific hazards of working with explosives. After the explosion on January 7, some workers interviewed indicated they had not recognized the potential for such a serious incident.

4.7.2 Manager and Supervisor Training

The investigation team found serious deficiencies in line managers' and the supervisor's technical understanding of the reasons why work precautions were necessary when working with explosive materials. Managers primarily relied on their personal work experience in addressing plant safety.

Management believed that, short of using a blasting cap, it was almost impossible to detonate the explosive materials used or produced at the Kean Canyon plant. This was the case even though the PHA of Booster Room 1 and Sierra's own product literature identified numerous potential hazards that could lead to explosions.

Managers emphasized housekeeping as their primary safety concern. They did not adequately implement control measures identified in the PHA of Booster Room 1 into work practices. Management did not prepare a PHA for Booster Room 2.

4.7.3 Language Barriers

Spanish was the only language understood by the majority of the operating staff at the Kean Canyon plant. The generic OSHA training program used at the facility included a few Spanish-language videotapes, but Material Safety Data Sheets (MSDS's) for the chemicals used on-site were not written in Spanish. The production supervisor and three of the production workers spoke and read both English and Spanish. When safety training was provided for the workers, it was conducted in English and translated into Spanish by one of the employees who spoke both languages. This was normally the production supervisor. Tests were written in English, and the supervisor translated the questions and the workers' answers. The translation process allowed opportunities for changes in meaning based upon the quality of the translation. There were no policies or procedures at the facility written in Spanish that could be referenced during training or during subsequent operation.

4.8 EMPLOYEE PARTICIPATION IN PROCESS SAFETY MANAGEMENT

Absence of employee participation in process safety activities was a major cause of the lack of understanding of hazards by the workers. The employee participation program at the Kean Canyon plant made no provision for employees to be involved in the development of safety programs and policies. According to the workers, no operators helped develop any of the programs. Workers were not aware that an employee participation program existed. Based on interviews with workers, their safety activities were generally limited to preventing fires, using dust masks, and clothing control. While employees were told to report problems, the issues they raised were considered by the supervisor to be production issues even though they could also have safety hazard implications.

4.9 MANAGEMENT OF CHANGE

There was no evidence that process changes were systematically evaluated using a management of change procedure. Many changes in the design, staffing, and the operation of Booster Room 2 had taken place since it was constructed. Some of these changes were implicated in the credible scenarios determined by the investigation team (see section 4.2). Process changes included:

- leaving explosive material in pots;
- the varying composition of the Comp-B and substitute materials;
- single-operator versus two-operator operation;
- changes in heat transfer rates;
- changes in pot size and rigidity; and
- use of damp PETN.

Appendix H, Change Analysis, contains an analysis of the issues cited above.

4.10 INCIDENT INVESTIGATION PROGRAM

Sierra had an incident investigation program, but workers were unaware of it, and no investigations had been conducted. The program did not have criteria for identifying and investigating near-misses.

In addition, lessons learned from incident investigations conducted at other explosives plants had not been communicated to Sierra personnel. This allowed unsafe practices to go uncorrected. The failure to systematically incorporate lessons learned from incidents at other sites and to conduct investigations of internal incidents and near-misses, perpetuated a lack of understanding of the hazards of the explosives manufacturing.

Sierra is a member of the Institute of Makers of Explosives (IME) and, as such, management had knowledge of serious incidents at other member companies. Appendix G contains brief summaries of explosions in similar operations that are of value in understanding the importance of safety recommendations and standards established by the explosives industry, regulatory agencies, and the DoD.

4.11 SAFETY AUDITS

Management had no planned program of oversight to determine that safety management programs were effectively implemented or that safe work practices were followed. When supervisors and managers performed walkthrough inspections, they did not verify the knowledge and performance of the workers against documented standards.

Managers and workers indicated that managers visited the facility often. During these visits, if managers saw something that appeared to be unsafe, they brought it to the attention of the worker or the supervisor. These management walkthroughs, however, were not intended to verify specific elements of safety programs or the effectiveness of PSM activities.

4.12 THE PIECEWORK-BASED PAY SYSTEM

The pay of some of the employees at the Kean Canyon Plant was based on piecework. In this pay system, wages were pegged to an individual worker's rate of production. This created a potential to minimize time spent on activities such as on-the-job training that could reduce production.

Three basic pay policies were used for workers involved in Sierra's explosives manufacturing operation. The pay policies included salary for professionals, supervisors, and managers, hourly rates for outside workers, and piece rates for workers involved in the melt/pour operation and boxing of the finished product. Sierra had used this pay policy for nearly 30 years.

The pay and productivity of operators at the Kean Canyon facility was found by the investigation team to be comparable to two other booster manufacturers. While there was a potential for the piecework pay policy to affect the safety of operations, there was insufficient evidence to conclude that it contributed to the explosion at the Kean Canyon plant.

4.13 PROCESS SAFETY INFORMATION

Workers at the site did not use and were not aware of most written safety programs and documentation. They were aware of Material Safety Data Sheets (MSDS's) and the information they contain; however, they were not aware of any specific hazards associated with the materials except that they were explosives and required workers to wear a dust mask. Information had been communicated orally because MSDS's were not available in Spanish, the primary language understood by most of the Kean Canyon workforce. Sierra maintained information on the manufacturing process, such as process and instrument diagrams, design codes and standards, a simplified process-flow diagram for Booster Rooms 1 and 2, and MSDS's for most of the explosives it used.

Maintenance records were kept solely at the site and were lost in the explosion. Safety training records and MSDS's were kept at both the Kean Canyon facility and the main office in Sparks. All of the other documents were maintained solely in the Sparks office. With the exception of a few training materials that were in Spanish, all of the documentation was written in English. None of the program documents were dated.

4.14 REGULATORY OVERSIGHT

The principal agencies responsible for the safety of explosives manufacturing operations at the Kean Canyon plant were the Nevada Occupational Safety and Health Enforcement Section (OSHES) and the Truckee Meadows Fire Protection District (TMFPD). The experience and training of the staffs of these agencies that was needed to conduct comprehensive inspections of explosives manufacturing facilities was limited.

The Nevada OSHES had responsibility for ensuring compliance with general industry safety and health standards adopted from the federal Occupational Safety and Health Administration (see 29 CFR 1910). These standards include requirements for safe storage of explosives and process safety management of explosives manufacturing operations. The most recent OSHES inspection of the Kean Canyon plant was conducted in 1996. It was an industrial hygiene evaluation of practices used to control lead exposures in the flux-mixing operation. Booster Room 1 was not in operation during this inspection, but explosives storage was evaluated. The melt/pour equipment in Booster Room 2 had not yet been installed. The Reno OSHES office had some familiarity with explosives operations, but the staff had little formal training in explosives safety. OSHES could request the assistance of federal OSHA inspectors with explosives expertise, but such expertise might not be readily available for routine inspections.

The TMFPD inspects facilities for compliance with the Nevada State Fire Marshal Regulations (Nevada Administrative Code Chapter 477). Those regulations establish the Uniform Fire Code (IFCI 1997) as a minimum standard statewide. The Uniform Fire Code (UFC) contains explosive safety requirements in Article 77, "Explosives." The CSB investigation team determined that TMFPD inspectors were not trained or qualified to do an explosives safety evaluation; their inspections, therefore, tended to focus on fire prevention.

The BATF licensed the Kean Canyon plant to manufacture and import explosives. The BATF inspects licensed facilities to ensure the safe and secure storage of explosives, that explosives are properly inventoried and controlled, and that all records are kept accurately. The last BATF inspection of the Kean Canyon plant was conducted in 1995. Although the BATF licenses manufacturers of explosives, it does not inspect the manufacturing process.

On May 4, 1988, a large explosion took place at a PEPCON plant near Henderson, Nevada. A Governor's Blue Ribbon Commission was established and it examined the adequacy of regulations pertaining to the manufacture and storage of highly combustible materials. The Commission's report stated in part, "all hazardous industries require at least one rigorous annual inspection." The identification and prioritization of inspections for businesses that had the potential for catastrophic incidents had not been done at the time of the Sierra explosion.

After the explosion at Kean Canyon, Nevada Governor Bob Miller established the Commission on Workplace Safety and Community Protection to again analyze Nevada's laws and policies pertaining to the manufacture of explosives. This Commission was chaired by Major General Drennan Clark. The Clark Commission issued numerous recommendations for improving safety (Clark, 1998). On June 10, 1998, Governor Miller signed Executive Orders implementing some of the recommendations of the Clark Commission. One of these Executive Orders requires safety inspections of explosives manufacturing facilities at least twice per year.

The Clark Commission also examined environmental and community protection laws. The U.S. EPA has enacted the Risk Management Program standard (40 CFR Part 68) which requires employers to develop a Risk Management Plan for certain hazardous operations. The Nevada Division of Environmental Protection is expected to adopt the EPA program.

5.0 METHODOLOGIES USED TO DETERMINE CAUSES OF THE INCIDENT

5.1 CHANGE ANALYSIS

Change analysis is one of the tools used to help identify the cause of incidents. In change analysis, one question is considered: What was different about the operation on the day of the incident? If Sierra manufactured boosters for more than 20 years without serious incident, what changed to permit this explosion to occur?

In the initial steps of change analysis, all possible changes are considered. The potential effects of the changes on the incident are then analyzed. Appendix H provides a summary of the changes that were considered to have the most direct impact on the detonation of the explosives in Booster Room 2.

5.2 BARRIER ANALYSIS

Barrier analysis is used to identify administrative, management, and physical barriers that could prevent, control, or reduce energy flows such as explosions to targets such as people or objects. This barrier analysis was concerned with those barriers that could have prevented or mitigated the impact of explosions but that either failed or were missing. The summary of this analysis, in Figure 13, shows barriers associated with all four credible initiating events.

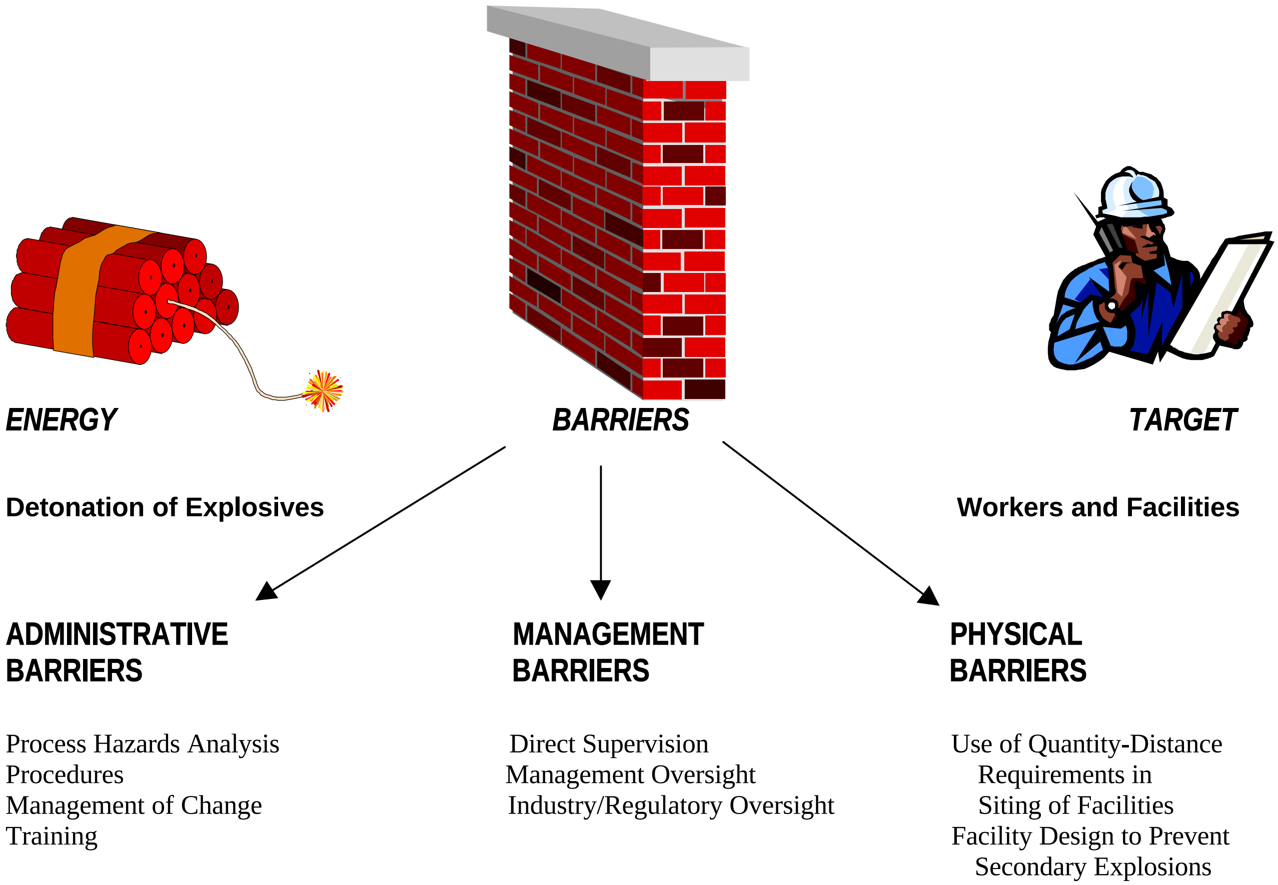


Figure 13. Barrier Failure Analysis

5.2.1 Administrative Barriers

One principle for administratively dealing with explosives hazards is to minimize risk by exposing the minimum number of people to the least quantity of hazardous material for as short a time as feasible. No personnel or explosives limits were established for production areas at the Kean Canyon plant. Thus, the storing of large quantities of explosives (shown in Figure 6) in the production areas was common practice. Because workers were not taking finished boosters to storage magazines as they were produced, there was more explosive material in the booster rooms than necessary.

Safety systems under the PSM program were not effectively implemented. Although a PHA had been developed, it did not address operation of a mixer with solid materials, hammering chunks of explosive materials or boosters, or addition of PETN to the mixing pot without TNT to dissolve it. The PHA's recommended actions for controlling static electricity, hot pot, scrap metal, and pour valve problems were not implemented. No Kean Canyon plant personnel were involved in conducting the PHA. Other than informal safety reminders and observing the testing of boosters, workers had no formal training regarding explosives safety. There were no written procedures provided to the workers.

5.2.2 Management Barriers

The supervisor who was primarily responsible for worker safety had no formal explosives safety training. There was no supervision of operations when the plant manager was not at work. There was no systematic verification that safety management systems were implemented and that safe work practices were being followed.

Neither industry nor regulatory agencies have established training guidelines to ensure that owners and explosives workers understand fundamental explosives safety and manufacturing principles and practices.

5.2.3 Physical Barriers

The skylight in the roof of the PETN building may have permitted falling debris to more easily penetrate the building and cause the second explosion. Thus, the design of the PETN building did not prevent propagation from the explosion in Booster Room 2.

5.3 EVENTS AND CAUSAL FACTORS ANALYSIS

Why did this incident occur? Events and causal factors analysis seeks to answer this question by determining all relevant factors that allowed events leading to an incident to occur. There are several levels of incident causes that were examined in this effort. The first level looked at the sequence of events that led to the incident. In this level, the direct or proximate cause of the incident is determined. To focus solely on the direct cause of an incident without dealing with the underlying root causes would be like treating symptoms rather than the disease. Therefore, the investigation team examined the factors that caused or allowed the sequence of events (direct causes) to take place.

The subsequent levels of investigation examine management safety systems. This includes examination of the implementation of the various elements of PSM. In this level of investigation, the underlying root and contributing causes of the incident are determined. Root causes normally involve failures in multiple safety management systems. Contributing causes are those factors that increase the probability or severity of an incident.

5.4 ROOT AND CONTRIBUTING CAUSES

Underlying root causes found at various management levels permitted the explosion at Sierra to occur. Addressing root causes has a greater effect on improving safety. The root causes as well as contributing cause of this incident are shown below.

ROOT CAUSES OF INCIDENT	KEY FINDINGS
Process hazard analysis (PHA) conducted by the facility was inadequate.	Supervisors and workers from the Kean Canyon plant were not involved in the process hazard analysis of the operation. The PHA for Booster Room 1 was conducted by company personnel from other locations and did not consider safe siting of buildings or human factors issues. These deficiencies in the PHA program allowed unsafe conditions and practices to go unrecognized and uncorrected. No PHA was conducted for Booster Room 2.
Training programs for facility personnel were inadequate.	Managers believed that, short of using a blasting cap, it was almost impossible to detonate the explosive materials they used or produced. Worker training was conducted primarily in an ineffective, informal manner that over-relied on the use of on-the-job training. Poor management and worker training led to a lack of knowledge of the hazards involved in manufacturing explosives.
Written ***operating procedures*** were inadequate or not available to workers.	Personnel primarily relied on experience to perform their jobs. Procedures and other safety information were not available in the language spoken by most workers. Operators routinely made changes in the steps they took in manufacturing explosives. This resulted in the use of inconsistent and hazardous work practices. There were no written procedures for Booster Room 2.

Figure 14. Causes of Incident

ROOT CAUSES OF INCIDENT	KEY FINDINGS
The facility was built with insufficient ***separation distances*** between different operations and the design and construction of buildings was inadequate.	Because unrelated chemical operations were located in the same building as Booster Room 2, an additional fatality and extensive property damage resulted. Close proximity of structures allowed the explosion to spread to a second building
There was no systematic ***safety inspection or auditing program***.	Safety walkthrough inspections were unfocused and did not examine PSM program effectiveness, resulting in management being generally unaware of unsafe practices and conditions.
The ***employee participation program*** was inadequate.	Employees had not been involved in developing or conducting process safety activities. This resulted in a lack of understanding of process hazards and controls by workers. It also resulted in management not benefiting from the experience and insights of workers.
CONTRIBUTING CAUSE OF INCIDENT	**KEY FINDINGS**
Oversight by regulatory organizations was inadequate.	Safety inspections were conducted infrequently and inspectors generally did not have expertise in explosives manufacturing safety. This allowed unsafe conditions at Sierra to go uncorrected.

Figure 14. Causes of Incident (continued)

6.0 RECOMMENDATIONS

The goal of the CSB recommendations is to communicate and institutionalize lessons learned. Accordingly, the recommendations are organized by responsible agencies, organizations, or groups.

Sierra and other explosives manufacturers

Process Safety Management (PSM) requires both careful planning and implementation. Prevention of explosions, as well as prevention of propagation of explosions, requires a clear understanding of explosives safety principles and safe practices. Recommendations in this section have been prepared based on the conditions found at Sierra's Kean Canyon plant. Explosives manufacturers should evaluate the effectiveness of their explosives safety programs using the following recommendations (numbered for identification) to ensure that:

1. Process hazard analyses include examination of quantity-distance requirements, building design, human factors, incident reports, and lessons learned from explosives manufacturers. (98-001-I-NV-R1)

2. Written operating procedures are specific to the process being controlled and address all phases of the operation. (98-001-I-NV-R2)

3. Procedures, chemical hazards, and process safety information are communicated in the language(s) understood by personnel involved in manufacturing or handling of explosives. (98-001-I-NV-R3)

4. Explosives training and certification programs for workers and line managers provide and require demonstration of a basic understanding of explosives safety principles and job-specific knowledge. (98-001-I-NV-R4)

5. Process changes, such as the construction or modification of buildings, or changes in explosive ingredients, equipment, or procedures are analyzed and PSM elements are updated to address these changes. (98-001-I-NV-R5)

6. Pre-startup safety reviews are performed to verify operational readiness when changes are made. (98-001-I-NV-R6)

7. All elements of OSHA's Process Safety Management Standard are verified by performing periodic assessments and audits of safety programs. (98-001-I-NV-R7)

8. The employee participation program effectively includes workers and resolves their safety issues. (98-001-I-NV-R8)

9. Explosives safety programs provide an understanding of the hazards and control of detonation sources. These include:
   - foreign objects in raw materials;
   - use of substitute raw materials;
   - specific handling requirements for raw materials;
   - impact by tools or equipment;
   - impingement;
   - friction;
   - sparking; and
   - static discharge. (98-001-I-NV-R9)

10. The following issues are addressed in plant design or modification:
    - Operations in explosives manufacturing plants are separated by adequate intraplant distances to reduce the risk of propagation.

    - Unrelated chemical or industrial operations or facilities are separated from explosives facilities using quantity-distance guidelines.

    - Facilities are designed to reduce secondary fragmentation that could result in the propagation of explosions. (98-001-I-NV-R10)

Institute of Makers of Explosives (IME)

1. Develop and disseminate process and safety training guidelines for personnel involved in the manufacture of explosives that include methods for the demonstration and maintenance of proficiency. (98-001-I-NV-R11)

2. Distribute the CSB report on the incident at Sierra to IME member companies. (98-001-I-NV-R12)

3. Develop safety guidelines for the screening of reclaimed explosive materials. (98-001-I-NV-R13)

Nevada Occupational Safety and Health Enforcement Section

Increase the frequency of safety inspections of explosives manufacturing facilities due to their potential for catastrophic incidents. (Note: Nevada Governor Bob Miller signed an Executive Order on June 10, 1998, that will require inspections at least twice a year.) (98-001-I-NV-R14)

Department of Defense

1. Develop a program to ensure that reclaimed, demilitarized explosives sold by the Department of Defense are free of foreign materials that can present hazards during subsequent manufacturing of explosives. (98-001-I-NV-R15)

2. Provide access to explosives incident reports and lessons learned information to managers and workers involved in explosives manufacturing, associations such as IME, government agencies, and safety researchers. (98-001-I-NV-R16)

BY THE CHEMICAL SAFETY AND HAZARD INVESTIGATION BOARD

Paul L. Hill, Jr.
Chairman

Gerald V. Poje
Member

September 23, 1998

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APPENDIX A: Analysis of Ignition Sources

Potential ignition sources were evaluated based on physical evidence, analysis of changes, worker interviews, and historical information. The relative likelihood of each ignition source was judged on a qualitative scale based on factors that either supported or reduced the likelihood. The table below contains the results of the team's analysis.

POTENTIAL IGNITION SOURCE	RELATIVE LIKELIHOOD	SUPPORTING FACTORS	FACTORS THAT REDUCE LIKELIHOOD
Electrical Equipment Arc/Sparking	Low	Booster Room 2 differed from Booster Room 1 in that electrical motors instead of hydraulic systems were used to drive the mixing blades. If the electric systems were not installed properly, grounded, and maintained, then an electrical arc, spark, or fire could supply the stimulus to ignite or detonate the raw materials and the boosters that were present in Booster Room 2. Forklift operations in the booster room could also supply electrical sparks.	Explosion-proof motors, wiring, and lighting had been installed in Booster Room 2. The electrical panels and most of the wiring were located outside of the booster room. The electric motors for the mixing pots were supplied with a positive airflow around the motor housings which reduced the risk of dust and explosive material buildup near the motor windings.
Static Electricity	Low	The booster room floor had been painted with a non-conductive epoxy paint that would prevent the dissipation of static-charge buildup. The bristles of the brooms, used to sweep the floor area, were made of synthetic fibers that through friction with the floor could generate a static charge. The booster room also contained plastic buckets and dust pans that could form a static charge through friction with worker clothing and other materials. The workers frequently wore their own personal clothing under the company-supplied cotton coveralls. Friction between personal clothing with a high synthetic fiber content and the	Cleaning operations, which could be a source of static charge, would not be expected in Booster Room 2 at the time (7:54 AM) of the incident. *DoD Contractors' Safety Manual for Ammunition and Explosives* states "Humidification for preventing static electricity accumulations and subsequent discharges is usually effective if the relative humidity is above 60 percent." The relative humidity, reported by the weather service that morning, was over 80 percent in Reno. It was reported that PETN with a higher moisture content was brought to

POTENTIAL IGNITION SOURCE	RELATIVE LIKELIHOOD	SUPPORTING FACTORS	FACTORS THAT REDUCE LIKELIHOOD
Static Electricity (continued)		cotton overalls could supply an ideal condition for formation of a static charge. Because of the cold outdoor temperature on the day of the incident, the workers wore their regular clothing under their coveralls. The pouring of dry explosives, especially PETN, and airflow friction from the ventilation system could generate hazardous levels of static electricity. During the interviews of Sierra employees, operators reported that static-charge buildup occurred during raw-material handling in the booster room. The problem appears to have been particularly severe while pouring dried PETN. At the time of the explosions, the pots could be at their operating temperature of 85°C, and although the relative humidity reported by the weather service was over 80 percent, the relative humidity near the operating areas of the pots could be well below 60 percent.	Booster Room 2 due to the higher heat capacity of the steam-heated mixing pots. The electric discharge energy required to detonate PETN increases with increasing water content. Cold ambient temperatures also increase the ignition energy required.
Mechanical Spark Caused by Nails When Pallet is Dragged Across Concrete	Low	Mechanically generated sparks could ignite dust and explosive raw material on the booster-room floor.	The raw explosive materials already had been staged in Booster Room 2 the previous day. The forklift was not in use. Ignition of dust on the booster-room floor is not likely to transition from deflagration to detonation.
Ferrous Metal Objects Impact, Generating a Spark	Moderate	The Comp-B that was used as a raw material sometimes contained foreign material. If the foreign object was composed of a ferrous material and was impacted by a hammer blow or mixer-blade, then a spark could have resulted and ignited the raw material.	Some employees visually inspect the Comp-B as it is opened.
Friction and Static when Dry PETN is Mixed	Moderate	PETN was sometimes added to the Pentolite mixing pot before molten TNT was present to remove any residual moisture. The presence of dry PETN increased the ignition sensitivity.	

POTENTIAL IGNITION SOURCE	RELATIVE LIKELIHOOD	SUPPORTING FACTORS	FACTORS THAT REDUCE LIKELIHOOD
Friction when Pallet Slides Over Explosives on Floor	Improbable	Such mechanical action could supply sufficient energy for ignition.	The interviewed workers were aware of the potential dangers of bulk explosives or excessive manufacturing residue and waste on the pour-room floor. Good housekeeping practices were emphasized. Raw materials already had been staged in the booster rooms so no movement of pallets would be expected.
Forklift Strikes Explosives	Improbable	A forklift impact on containers of the raw material or the finished product could supply enough energy by spark, friction, or impact to trigger an ignition and/or detonation of the contacted material.	The forklift was located in the warehouse, and workers who might use it had not started work.
Striking Explosives with Metal Tools	Moderate	It was common practice to break up rejected boosters of Comp-B with both plastic and steel hammers. A review of U.S. Army incident summaries indicates that numerous past incidents were caused by the impact of hand tools on explosives containing TNT and RDX.	Only two boxes of rejected boosters had accumulated in Booster Room 2 since it went into operation. Rejected boosters were to be taken from Booster Room 2 to Booster Room 1 to be broken up and recycled. The explosion occurred in Booster Room 2.
Mixing Blade Impacts Hardened Explosives	High	If residual solid-base mix or Pentolite remained in the pot and the melt-pot mixing blade was engaged, impact forces on the explosives could ignite a large quantity (~50lbs.) of the base mix or Pentolite. Reportedly, about 50-100 lbs. of base mix had been left in pot 5 the preceding night. The crossover of personnel and melting techniques from the evening shift to the day shift increased the chance of operators not taking the proper sequence of steps to ensure a melt had formed before engaging the mixing blades. Because the operator in Booster Room 2 had previously worked on the second shift in Booster Room 1, he never had to inspect the pot in Booster Room 1 before turning on the mixer. An inspection of the pot was not needed in Booster Room 1	When asked, operators recognized that the pots should be inspected at the beginning of a shift to ensure that no solid material was present in the pot. Most operators, however, did not include this step in describing the melt/pour process. No startup checklist existed and a record to ensure that the inspection occurred was not maintained.

Potential Ignition Source	Relative Likelihood	Supporting Factors	Factors that Reduce Likelihood
Mixing Blade Impacts Hardened Explosives (continued)		because the heat would have been left on and the material still would have been melted from the previous shift. Because the two operators in Booster Room 2 had talked about the leftover base mix, the operator who left it may have assumed the other operator had used it.	
Tool or Pot Component Drops into the Pot	Low	Workers indicated that at times large pieces of Comp-B were broken up with hammers on top of, or even on the edge of, the opening into which the raw explosive materials were poured into the pot.	A component entering one of the large mixing pots is unlikely. The large mixing pots have no internal removable parts, and the penetrations through the lid around the shaft and breaker bars do not permit materials to enter the pot. Because of the heating capacity of the pots in Booster Room 2, there was less need to break down Comp-B clumps.
Foreign Object in the Explosives Struck by Mixing Blade	Low	Foreign materials were frequently found in the Comp-B. Comp-B and substitute materials were recovered from DoD munitions and would be expected to have foreign materials present from the demilitarization operations. Only cursory visual inspections of the Comp-B were used to eliminate foreign materials. The Comp-B was never screened on site to remove foreign objects. If a foreign object were to jam between the mixing blade and the pot wall, drag friction and pinching could readily provide the energy necessary to ignite or detonate the base mix.	There was an approximately one-inch clearance between the mixing blade and the tank wall. Any foreign objects that might strike the mixing blade and pot wall would need a size greater than about one inch. The tanks in Booster Room 2 were designed with a drain line that provided additional clearance below the mixing blade in the base of the pot. The mixing blade turned at a relatively low rotation rate, so the impact velocity on a foreign object present in the mix would be minimal.
Open Flame due to Lighters/Smoking	Low	Workers were not prohibited from bringing smoking materials into the change room in their regular clothes. Cigarettes and a lighter were found in a coat located in the debris near the change room.	The operator who was working in Booster Room 2 smoked little, if at all, and workers knew that they were only to smoke in the break room and could be fired if they were caught smoking anywhere else.
Chemical Reaction Between Explosive Types	Improbable	The Comp-B used to produce the boosters is demilitarized material. The explosive is purchased through a bid process delivered in bulk quantity “as is.”	Explosives, including HMX, LX-14, Comp A-3, and Comp-H-6, had been melted and blended before without evidence of chemical reaction. An immediate

POTENTIAL IGNITION SOURCE	RELATIVE LIKELIHOOD	SUPPORTING FACTORS	FACTORS THAT REDUCE LIKELIHOOD
		Examination of the Comp-B currently in Sierra's inventory showed that, besides the material labeled as Comp-B, other military explosive compositions were included. Other demilitarized explosives present in the storage magazine included HMX, LX-14, Comp A-3, and Comp H-6. These explosive formulations were found in the same storage area of the magazine and often were observed on the same pallets as the Comp-B. All explosives were packaged in similar brown cardboard boxes that differed only in the attachment of a small label identifying the contents. The operators were not trained to recognize the difference in properties of the non-Comp-B explosives. Instead, they treated the non-Comp B explosives like Comp-B and added the other explosive formulations to the base mix as if the other compositions were actually Comp-B. Operators relied on process experience to limit the amount of some material, like HMX, that they would add to the mix because they observed that the material would not melt. Sierra did not test the explosives for chemical purity, nor was the material subjected to physical sensitivity tests, such as differential thermal analysis. The actual chemical purity and the behavior of different batches of raw material when heated was therefore unknown. Chemical incompatibility and the possibility of violent chemical reaction among the different explosive compositions cannot be ruled out, especially given the manufacturing process of heating, melting, and blending.	and violent chemical reaction without some early indication of reaction, like the emission of NOx vapors, is not considered a credible failure mode.

POTENTIAL IGNITION SOURCE	RELATIVE LIKELIHOOD	SUPPORTING FACTORS	FACTORS THAT REDUCE LIKELIHOOD
Cross-Contamination Between Processes	Improbable	Other chemicals, incompatible with explosives, were handled in a room adjacent to Booster Room 2. The chemicals were used to manufacture flux. Explosive materials on the pouring tables and surrounding floor were swept up and added to a subsequent batch of base mix in a mixing pot. One forklift serviced both booster-production and flux-manufacturing areas.	The floor of the adjacent building in which the flux operations were conducted was about six inches below the level of the floor in Booster Room 2. Any contamination from floor sweepings would need to be elevated to the booster room. The raw materials for the flux operations were stored separately from the raw materials for the booster fabrication. Workers trained in booster fabrication and flux-composition manufacture did not enter each other's work areas. The operations of melting and pouring the explosive compositions would have the effect of self-cleaning the pots, which would minimize the effects of cross-contamination even if present. Periodic steam cleaning of the booster rooms would remove chemical contamination.
Mechanical Failure of Bearings	Improbable	Enough energy could be generated by a bearing failure to generate heat and sparks, thus igniting nearby combustible material.	The transmission and bearings were located inside a casing outside the pot in which the explosives were being mixed. The transmission was new, and the bearings reportedly were being greased periodically. A bearing failure would be unlikely at or shortly after startup and would not contact the explosives.
Propane Leak and Fire	Improbable	Ignition of leaking propane in the booster room could cause detonation of explosive raw materials. Propane was used to fire the steam boiler.	Leaking propane is easy to detect due to the addition of an odorizer. There were workers who walked close to the boiler room as they came to work, and there were workers working in the vicinity. Ignition of a buildup of propane in the boiler room would be unlikely to impact explosives in the booster room, which was separated by distance and two concrete-filled block walls. A propane fire by itself would give nearby workers a chance to respond. There was no indication of such a response.

Potential Ignition Source	Relative Likelihood	Supporting Factors	Factors that Reduce Likelihood
Steam Boiler Explosion	Improbable	The steam boiler had not received a final inspection.	The boiler was a low-pressure boiler with pressure relief at 15psi. Inspection of the boiler following the explosion showed no signs of an internal explosion.
Sabotage	Improbable	A variety of means could be used intentionally to detonate explosives.	The Sheriff and BATF investigation found no evidence of a criminal nature or of an intentional act.

APPENDIX B: Seismology Report

Seismic Analysis of the Kean Canyon Explosion

JOHN G. ANDERSON, KENNETH D. SMITH, GENE A. ICHINOSE

University Nevada Reno Seismological Laboratory
Mackay School of Mines

Mail Stop-174
Reno, NV, 89557-0141
phone (702) 784-4265
fax (702) 784-1833
email ichinose@seismo.unr.edu
url http://enigma.seismo.unr.edu

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Abstract

An unfortunate industrial accident at a the Sierra Chemical Company plant east of Reno, Nevada, consisted of two explosions that occurred within about 3.5 *seconds* and were separated by ≈ 75 meters along a direction of S33°E (US Chemical Safety and Hazard Investigation Board). Using an high precision cross-correlation method applied to both seismic and air-waves recorded at several seismic stations in northern Nevada, we are able to resolve the relative locations, azimuth between the sources and the chronology of two explosions. The difference in moveout of air-waves between the two explosions, measured at several stations, associates the southern site with the second explosion. The separation of explosions, based on an analysis of these air-wave arrivals, at 3 stations is about 73 meters with an uncertainties ranging from ±7 to 21 meters. We obtained only a single estimate of source separation using P-waves which is 80 meters with a larger uncertainty of ±78 meters. We did a simultaneous determination of the separation and the azimuth of the explosions which combines the moveout at different stations. The best solution occurs with a separation of 73.2 meters with the second explosion occurring at azimuth of S35E from the first. These estimates are well within uncertainties of investigation by the US Chemical Safety and Hazard Investigation Board. From the relative spectral amplitudes of P- and air-waves, we suggest that explosion B had downward directivity, while A may have been more upwards directed. The corner frequency of the P-waves is much smaller than expected for the physical dimension of the explosions, indicating that attenuation is exerting a major influence on the P-wave spectrum at high frequency. The results from this analysis suggests that relative

location of small earthquakes with nearly identical seismograms can be achieved with similar accuracy using a regional seismic network.

Introduction

Two explosions occurred ≈ 3.5 *seconds* apart at the Sierra Chemical Company facility ≈ 20 km east of Reno, Nevada, on January 7, 1998. The events were heard and felt throughout the Reno-Sparks metropolitan area. Unfortunately, four people lost their lives and six more individuals were injured in the explosions. The recently organized United States Chemical Safety and Hazard Investigation Board (CSB), with the cooperation of several state agencies, initiated an investigation into the accident with the long range goal of improving the safety at explosive manufacturing facilities. An important aspect of the investigation was determining the chronology of events.

View of booster room 1 following the explosion, with west wall still standing. The five workers in this room survived.

For More on CSB investigation see http://www.chemsafety.gov

The two explosions were recorded on several stations of the western Great Basin seismic network (Figure 1). From these records, the estimated origin time of the first explosion was 15:54:03.300. ±30*sec* GMT (7:54 AM PDT), with approximate location 39°North 31.8 minutes, 119°West 38.0 minutes. However, based on information provided by the CSB *(John Piatt, personal communication)* the location is 39°North 32.5 minutes, 119° West 38.1 minutes. We used the CSB's location in our subsequent analysis based on seismograms; it is well within normal uncertainties for earthquake locations. Treated as an earthquake, the magnitude of the event is estimated to be M ≈ 2.0. Four of the stations that recorded the explosion were recently installed digital broadband seismographs that were acquired through a grant to the University Nevada Reno from the Keck Foundation. Several of the seismograms are shown in Figure 2. The seismograms include two conspicuous P-wave arrivals, followed by an "N-wave" *(Kanamori et al., 1991)* that is created by the shock wave traveling in air. An examination of the seismograms (Figure 2) shows that there are two explosions separated in time by about 3.5 seconds. The phase that appears to be an S-wave in Figure 2 is the P-wave arrival from the second explosion, although there may be some amplitude contribution from an Lg phase. The station geometry relative to the source area is such that the P-wave arrival from the second source is nearly coincident with the expected Lg arrival from the initial event at both PAH and WCN. Evidence for the interpretation of these phase arrivals is based on the nearly same time separation observed in the air-wave arrivals at several stations. The larger amplitude of the P-wave and air-wave phases for the second event suggests that this was the larger of the two explosions, although the coupling of the explosion must also be taken into account in this interpretation.

Figure 1. Westert Nevada digital seismic stations, location of the chemical explosions and the Reno Sparks, and Carson City urban areas.

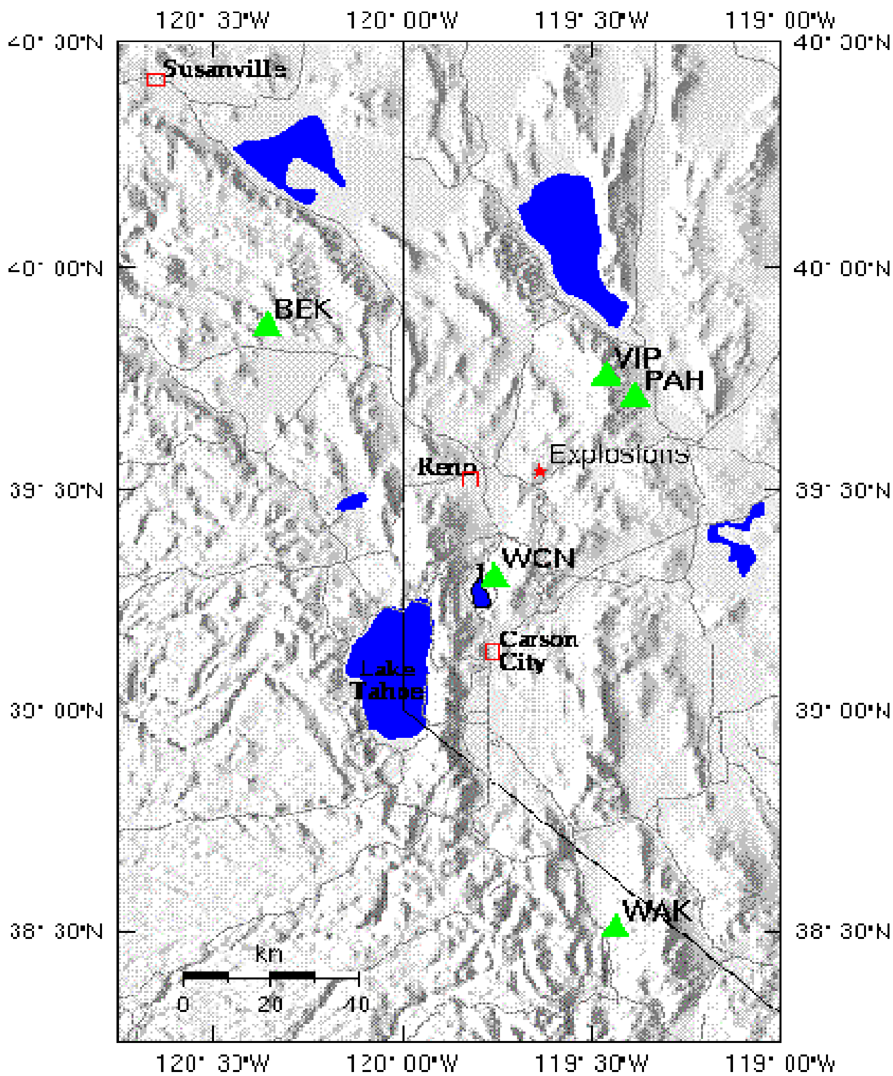


Table 1. Station locations, and their distances and azimuths to the estimated explosion site.

Code	Name	Latitude°N minutes	Longitude°W minutes	Elevation (km)	Distance (km)	Azimuth (°)
WCN	Washoe City, NV	39 18.10N	119 45.38W	1.50	28.6	201.5
VIP	Virginia Pk., NV	39 45.24N	119 27.65W	2.49	27.9	32.2
PAH	Pah Rah Range,NV	39 42.39N	119 23.05W	1.50	28.3	49.4
BEK	Bekwourth, CA	39 52.00N	120 21.52W	1.74	71.8	300.4
WAK	Walker, CA	38 30.26N	119 26.23W	1.89	116.3	171.5

Figure 2a.

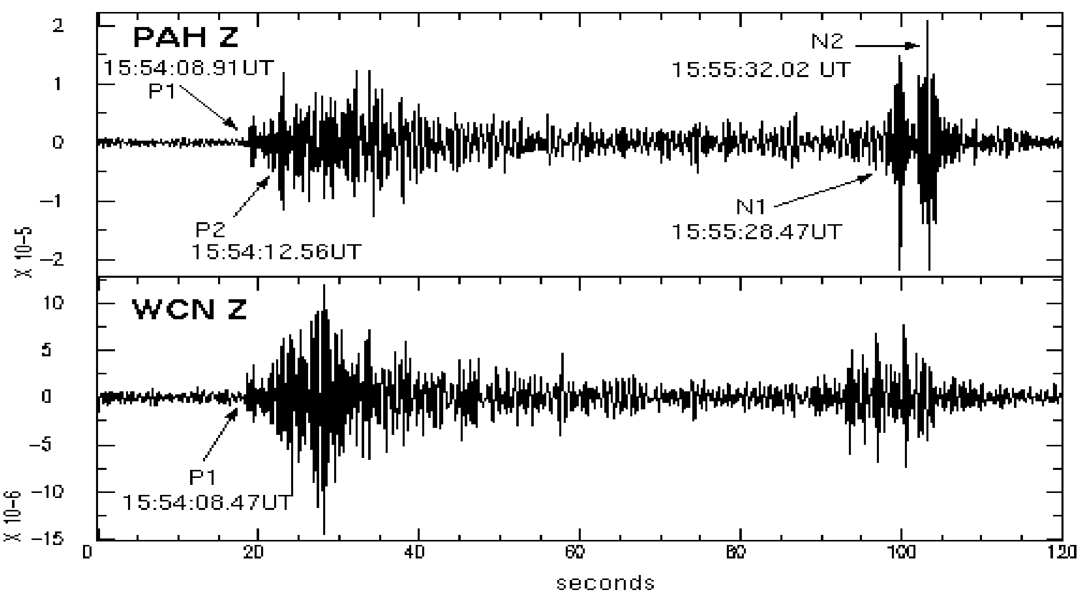
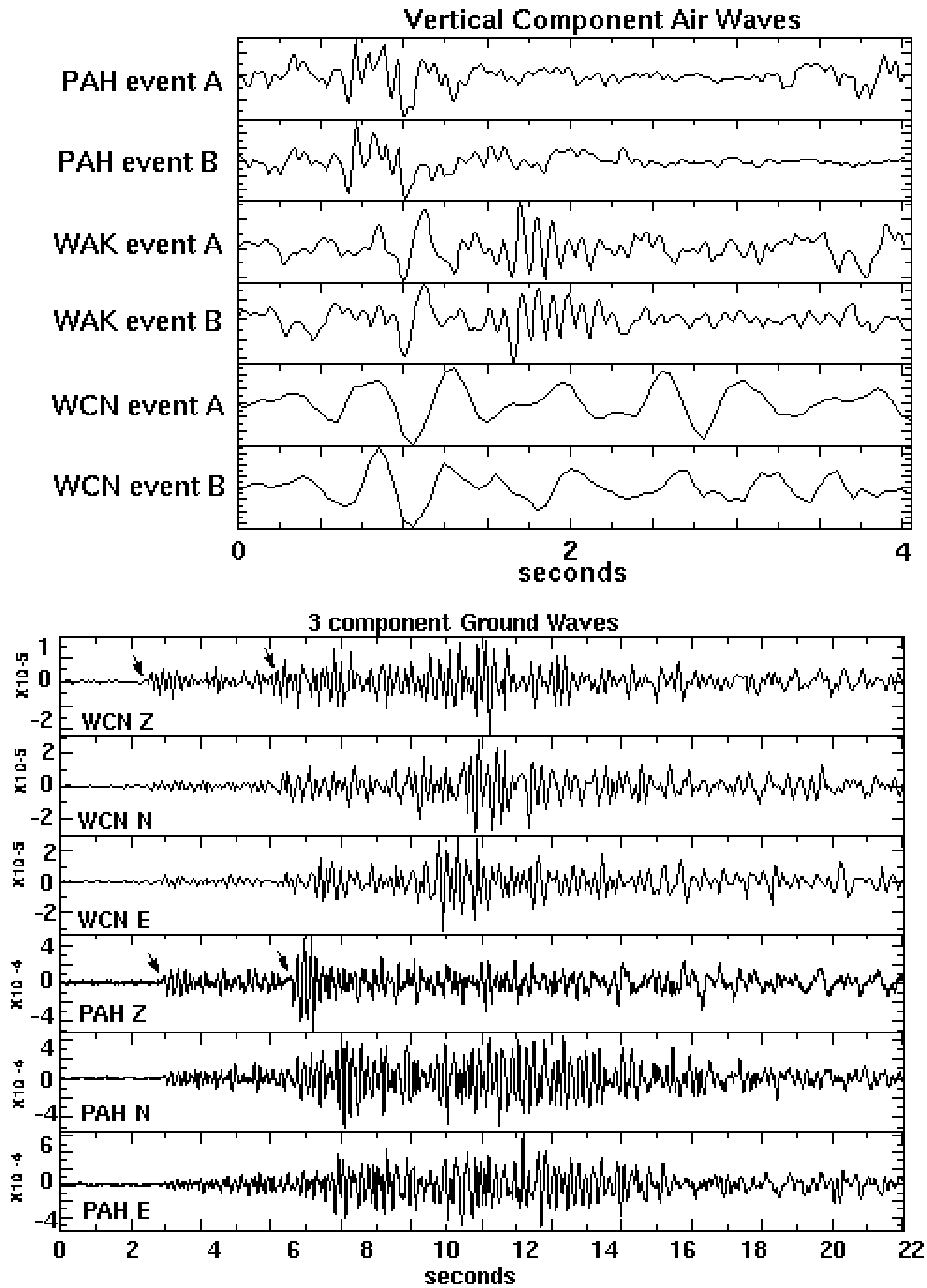


Figure 2a. Vertical component seismograms from station PAH and WCN. The P1 and P2 labels indicate P-wave arrivals for explosion A and B. N1 and N2 labels indicate the N-wave (air wave) arrivals for explosion A and B.

Figure 2b. Seismograms of low-passed filtered vertical component air waves and 3 component seismic waves used in this analysis. The arrows point to the arrival of P-wave of explosion A and B.

Figure 2b.



In their request to the Seismological Laboratory *(John Piatt, personal communication)*, the CSB reported that two explosions were separated by a horizontal distance of approximately 250 feet (76.2 meters), along a strike of 147° . Uncertainties in these measurements are due to uncertainty on where the "centers" of the explosions were located. The northern explosion occurred in a building that was formerly about 40 feet by 40 feet in dimension *(CSB, 1998)*, and the southern explosion left a kidney-shaped crater that was about 30 feet across and 50 feet long (John Piatt, personal communication). A circular approximation would have a radius of 40 feet. Based on these dimensions, the separations between the centers of the explosions could be uncertain by as much as several meters, and the azimuth could be uncertain by a few degrees. According to testimony to the CSB (John Piatt, personal communication), there were about 7500 to 8000 pounds of explosives (TNT or COMP-B) at the northern site, and about 15000 pounds of explosives (PETN) at the southern site. Based on several independent lines of evidence, the CSB has come to the conclusion that the northern explosion occurred first.

We are interested in these events because they provide the opportunity to test a cross-correlation method to estimate relative source locations. We have observed numerous cases of nearly identical seismograms called multiplets in routine monitoring activities, and have experimented with the cross-correlation of digital seismograms to estimate the spatial separation of seismic sources. By being able to actually measure the source locations on the ground, the resolving power and the errors associated with this methodology can be directly evaluated.

Analysis and Results

We located the initial explosion (explosion A) from the P-wave arrivals recorded at the UNR Keck digital stations and one helicorder record from an analog station (Table 1). The existing regional network of analog stations did not trigger on the explosion. We used the 1-D velocity model (Table 2) to estimate of the absolute location of the first explosion. Since the location determined from the P-wave arrivals of the first event is only 1.2 km from the known mapped location of the explosions, our confidence in the velocity model in Table 2 is increased.

Table 2. Velocity model used in location of explosion.

P-wave Velocity (km/s)	Depth to top of Layer (km)
3.0	0.0
4.5	1.0
5.5	2.0
6.0	4.0
6.1	7.0
6.2	12.0
6.4	18.0
6.8	28.0
7.8	38.0

To find the relative locations of explosions A and B, one requires knowing the precise time difference between the explosions, $t_b - t_a$, that can be measured from the records of P- and air-waves. We performed cross-correlations on windows of the P- and air-wave arrivals in the frequency domain *(Fremont and Malone, 1987)*. The frequency domain technique can establish finer relative time estimates that are below the limit imposed by the sampling interval. This is required for relative locations with a precision on the order of several meters. The time difference between the two explosions is proportional to the slope of the phase of the cross spectrum,

$$t_b - t_a = \frac{\phi(\delta f)}{2\pi\delta f} \tag{1}$$

where $\phi(\delta f)$ is the phase of the cross spectrum over a frequency range delta f. The intercept is fixed at 0 Hz and a line is fit to $\phi(\delta f)$ by simple least squares. The seismogram with both explosions are windowed by 2 seconds around each of the P-wave and air-wave arrivals and then cosine tapered. The windowed seismogram of explosion A is then initially aligned by routine picking relative to the seismogram of explosion B, and the time shift from the slope of the phase of the cross spectrum is finally used to correct this initial alignment.

A measure of the coherency of the phase arrivals is used to determine the frequency range over which the slope of the cross-spectrum phase is analyzed. The normalized coherency between two time series measures the similarity of their shapes, ranging between 0, when they are completely dissimilar, to 1 when they are identical. The coherency in the frequency domain, C(f), between the Fourier transform of seismograms $s_1(f)$ and $s_2(f)$ is defined here following Menke et al. (1990),

$$C(t_b - t_a, \Delta f, f) = \frac{|< s_1^*(f) s_2(f) >|^2}{< s_1^*(f) s_1(f) >< s_2^*(f) s_2(f) >} \tag{2}$$

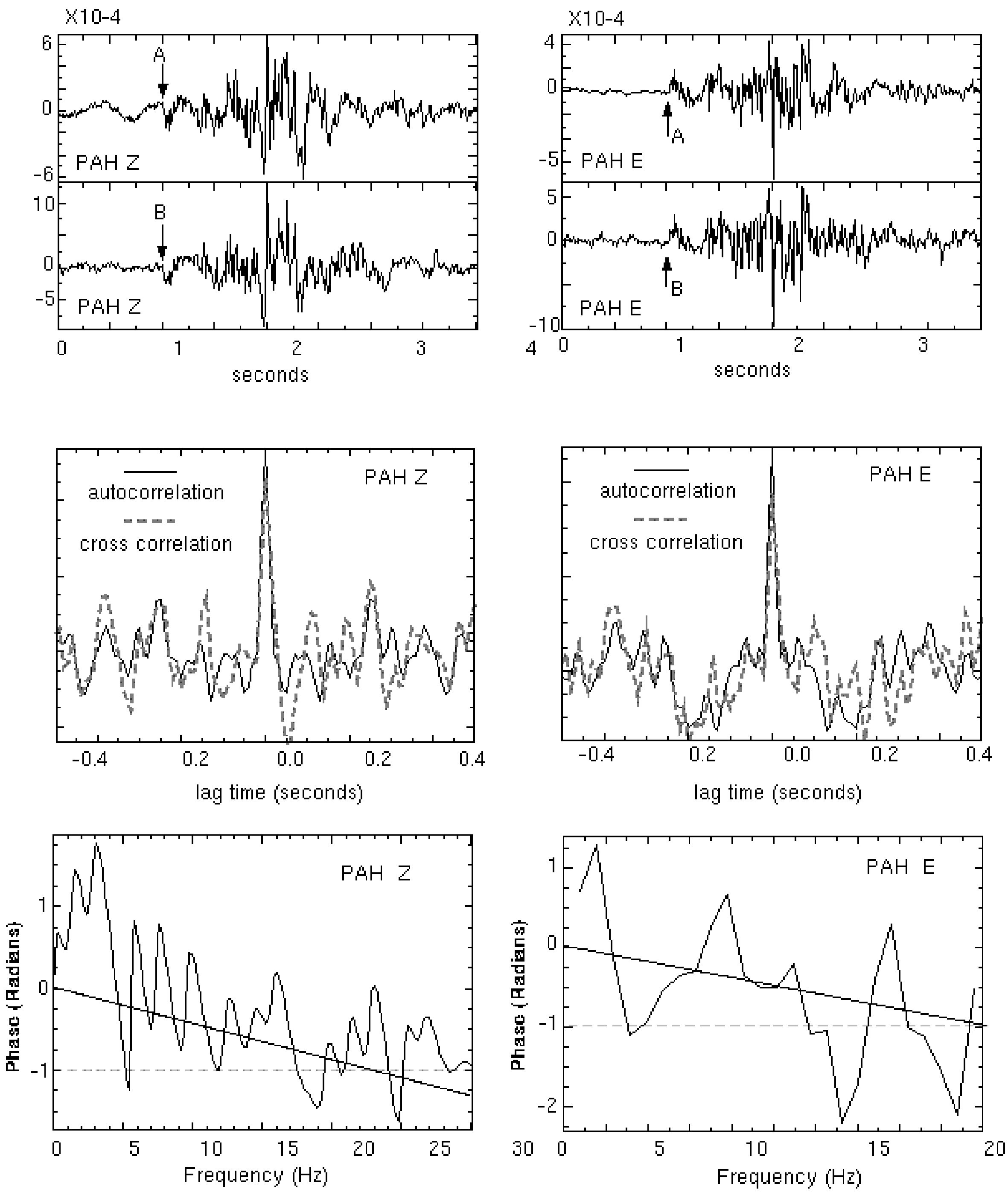
where f is frequency, < > denotes boxcar averaging over frequency interval Δf centered on f, and s* denotes complex conjugation. The windowed seismograms are shifted by $t_b - t_a$ as estimated from equation (1). We find that the coherency between phase arrivals falls-off at high frequencies, and therefore we only fit $\phi(\delta f)$ for f above 80% coherency. This fall-off is probably due to the slight difference in the travel paths from the source separation, later arrivals from the first explosion superimposed upon the record of the second, and possible differences in the details of the two source time functions. An example of the cross-correlation is shown in Figure 3, and the apparent time lags with uncertainties derived from these cross spectra are given in Table 3.

Table 3. Time after the first explosion until the maximum of the cross correlation of the first and second explosion.

Station	Component	P-wave $t_b - t_a$ (sec)	Uncertainty (ms) *	Air-Wave $t_b - t_a$ (sec)	Uncertainty (ms) *
WCN	Z	3.599	11	-	-
WCN	E	-	-	3.403	10
PAH	Z	3.582	6	3.582	9
PAH	N	-	-	3.542	-
WAK	Z	-	-	3.330	11
WAK	N	-	-	3.330	-

*** Standard Deviation of phase spectra converted to apparent time separation between explosions.**

Figure 3.



The vertical and east-west component of air-waves recorded from PAH with the cross- and auto-correlation functions. The bottom panels show the slope of the phase of the cross spectrum are fit over the frequency range of > 80% coherency.

Based on the time separations from the cross-correlations method, we estimate L, the distance separation of the second event relative to the first as a function of β, the hypothetical direction from the first source to the second, using:

$$L_{ij}(\beta) = \frac{c\,\Delta t_{ij}}{\cos(\beta - \theta_i) - \cos(\beta - \theta_j)} \qquad (3)$$

where c is either the air velocity of 343 m/s or P-wave velocity of 3000 m/s, Δt_{ij} is the difference in the times between the explosions at stations i and j, and β is the azimuth from the first explosion to the i th station. The better resolution results from an analysis of the air-wave arrivals because of the substantially slower air velocity. L_{ij} is computed from values of ranging from 0 to 180° for the 3 station pairs to find a simultaneous best solution at $\beta \approx 145.1°$ (S35°E) and L $\approx$ 73.2 meters (Figure 4). The relative location estimates based on the P- and air-waves are shown in Figure 5 along with the error estimates. The results for the air-wave unambiguously indicate that the second explosion B was southeast of the first explosion A. This result leads to the conclusion that the initial explosion was at the northern site, which is consistent with the analysis of the CSB.

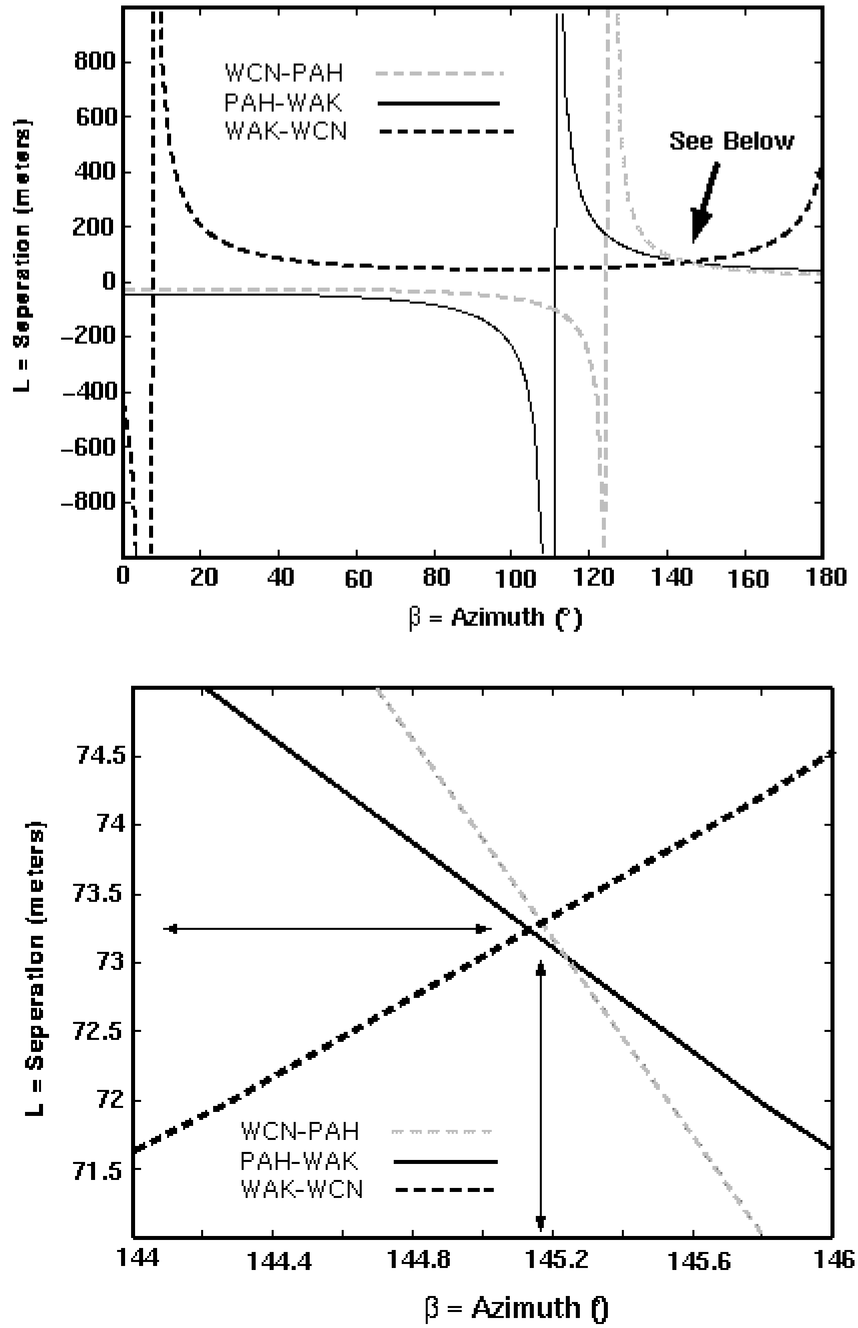


Figure 4. A plot of L, the source seperation versusβ, the azimuth between sources. The arrows point to the best solution for L and β.

The relative locations based on the moveouts of these phases are, within error bars, consistent with the location of the second event based on the CSB investigation. The differences in separation between our estimate (73.2 meters) and the CSB estimate (76.2 meters) is small compared to the source dimensions, and the difference in azimuth between our estimate of S35°

E (145.1°) and the CSB estimate of S33°E (147°) is also within the range of angles that is allowed by the source sizes. The uncertainties in measuring $t_b - t_a$, shown in Table 3, corresponds to the standard deviation of $\phi(\delta f)$. This standard deviation is considered as the maximum uncertainty of determining the slope using equation (1). There is always a $2\pi n$ uncertainty in unwrapping the phase spectra but since an initial shift was performed, we expect n to equal around 1 and the maximum uncertainty in n to be less than 2π. The uncertainties in determining the slope of the cross phase spectra are then propagated through equation (3) by fixing β and using the correct polarities of the $t_b - t_a$ uncertainties. This gives the maximum uncertainty in source separation given only a pair of stations and their geometry. The importance in receiver geometry on uncertainty is shown by the difference in separation uncertainties, with ± 7 meters between PAH and WAK, which are almost along strike of the explosions, and ±21 meters between WCN and WAK, which are relatively more perpendicular to the strike. The $t_b - t_a$ uncertainties are not propagated through the simultaneous determination in L as a function of β because it is used to show the best combined estimates of these parameters.

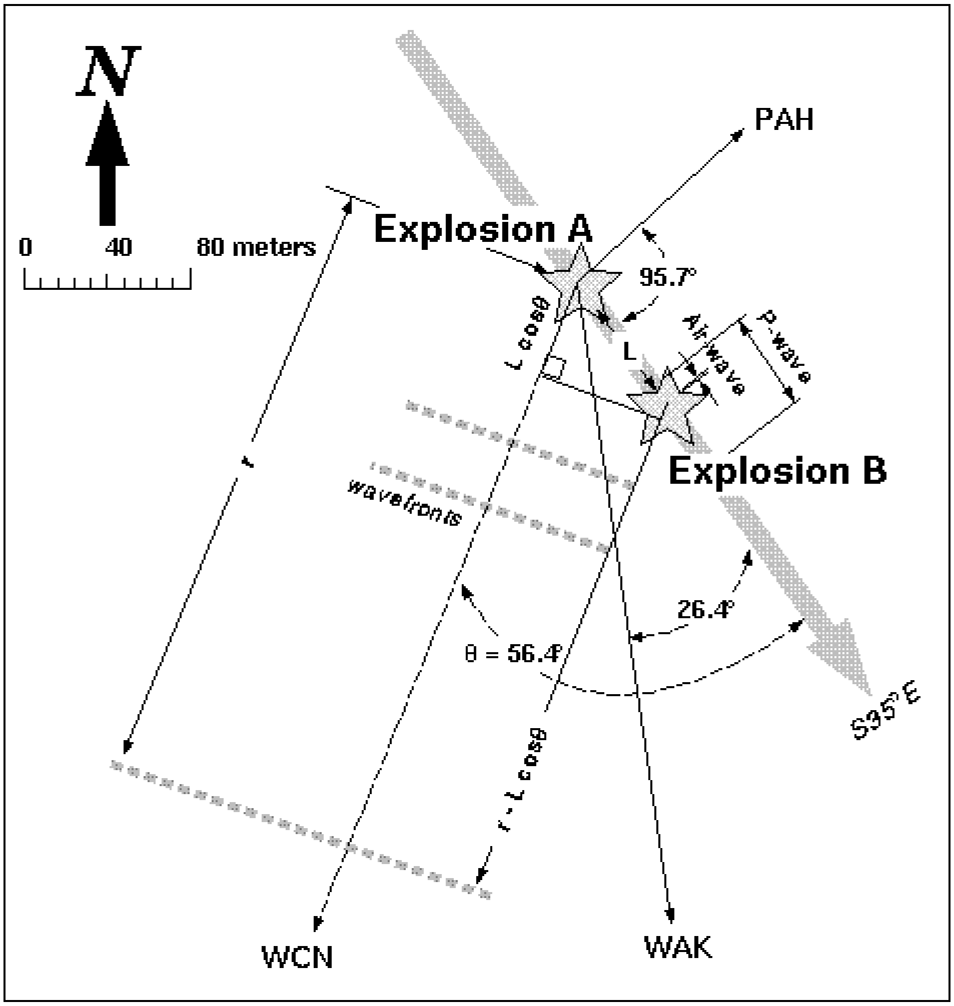


Figure 5. A Schematic map of the explosion site with likely geometry of explosions marked as "stars" and the estimated relative seperations shown as uncertainties along azmuith of S35°E. See equation (3) in text for variable definitions. The

There is no significant source of error associated with timing in the recorder itself. The digital stations maintain absolute timing by synchronizing with a GPS time signal that is broadcast from the Seismological Laboratory. The GPS signal is broadcast every second and a high precision oscillator in the seismograph unit is phase-locked to UTC by this pulse. A radio frequency delay of 44 ms, which occurs in the electronics and telemetry systems, is accounted for in establishing absolute time of the recorded waveforms. A timing mismatch of 1 msec between the GPS time and the internal clock time results in a clock correction that is reported by the instrument. Timing errors during regular operation rarely exceed several msec. Because the two explosions occurred within 3.5 sec, the absolute timing of the instrumentation is not critical, and only the error in the digitization rate is relevant. The manufacturer reports that errors in the digitization rate for the internal oscillator do not exceed 1 msec for any one sample and are expected to be on the order of 50 microsec. If the oscillator would drift more than 1 msec over any recording period, then a timing correction would be initiated by the instrument and its results would be recorded in the instrument log. For the air-wave, 1 *msec* would introduce an error of about 0.3 meters in the source location.

Atmospheric conditions that affect the speed of sound can shift the estimated separations slightly. We used an air velocity of 343 m/s *(Kinsler et al., 1982)*. For a 10% uncertainty in the assumed air velocity of 343 m/s, which is greater than expected, the relative source separation error would be ±7.0 meters, which does not impact our conclusion as to the relative source locations or chronology. A consistent wind velocity across the array on the morning of the blasts would not be significant; a 10 MPH wind is only 1.3% of the speed of the air-wave.

One of our objectives was to see if it is feasible to measure the separation between the events using the P- and S- waves. From Table 4, we see that the best estimate of the separation using the P-waves is 79.9 m, which is consistent with the estimates using the air-waves. However, the uncertainty in the time separation for the P-waves from WCN and PAH leads to a large uncertainty on the separation. The P-wave at WAK, 116 km epicentral distance, was too weak to provide a reliable separation. We consider these results to be very encouraging. With an adequate signal-to-noise ratio, the locations of closely spaced multiple events recorded at three or more stations should be resolvable.

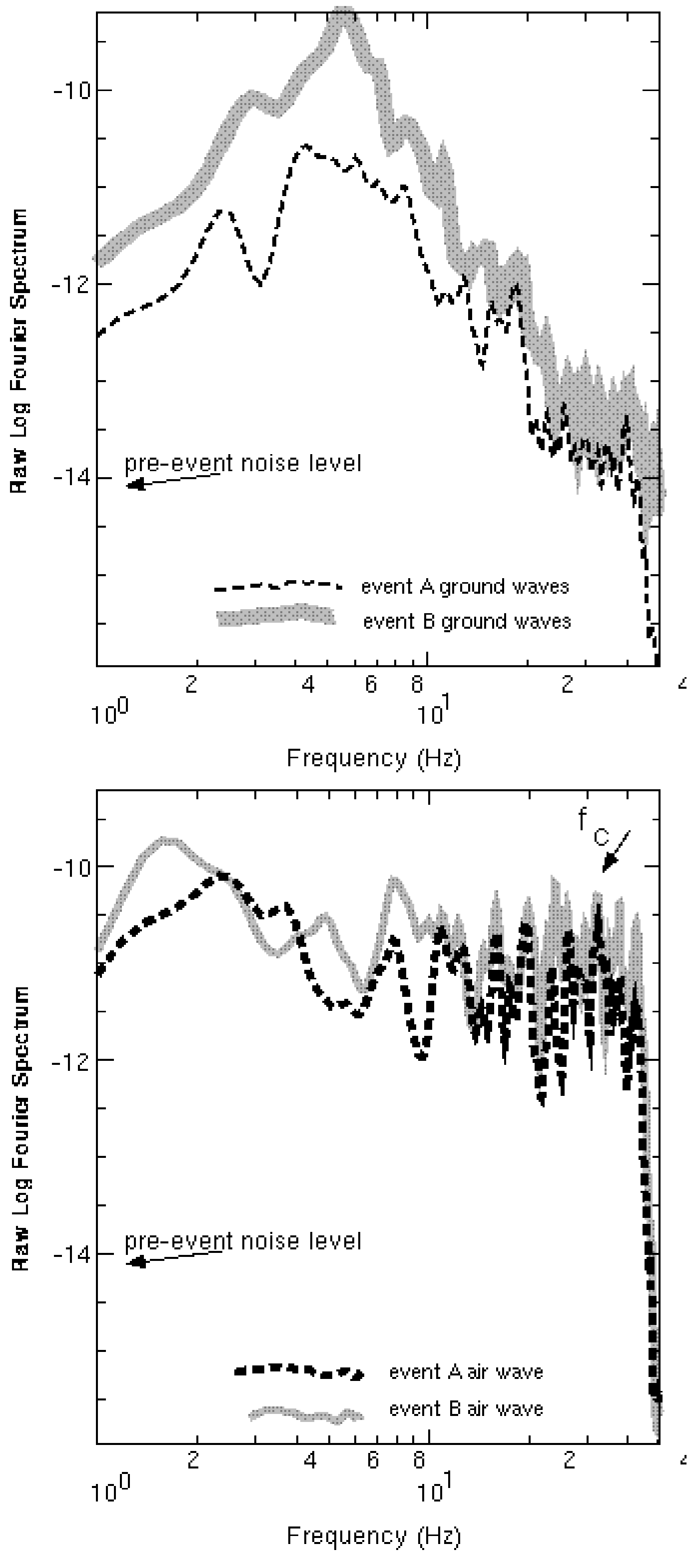
Table 4. Geometry and results of source separation estimation.

Path	P-wave (sec) *	Air-wave (sec) *	θ_i°	θ_j°	Separation (m)	Uncertainty (m)
WAK-PAH	-	**0.2126**	**-26.4**	**95.7**	**72.3**	**66.36-80.14**
WAK-WCN	-	**0.0752**	**-26.4**	**-56.4**	**73.3**	**52.12-94.20**
WCN-PAH	-	**0.1374**	**-56.4**	**95.7**	**73.2**	**63.30-83.20**
WCN-PAH	**0.0144**	-	**-56.4**	**95.7**	**79.9**	**1.8-158.0**

*** Δt_{ij} is the difference in $t_b - t_a$ between station pairs along path.**

Figure 6 shows the uncorrected spectra of the P-wave and the air-wave from the two explosions at PAH (Guralp CMG-40 velocity sensor). The three components are log averaged and then smoothed. Based on the P-wave at PAH, explosion B was 3 to 4 times larger than explosion A, consistent with reports that the second site "B" contained more explosives. The spectrum of air-waves of explosion B is only a little larger than explosion A. This may suggest that explosion B was more coupled to the ground, allowing more energy to be partitioned into the ground than into the air. The CSB hypothesized that the second explosion was triggered when debris from the first explosion crashed through the ceiling or skylight at the second site. If so, we speculate that the second explosion may have been triggered at the top of the stockpile, resulting in downward directivity and a different partitioning of energy between the ground and the air.

Figure 6. Uncorrected P-wave and air-wave



The spectral curves are the smoothed log average of the three components of motion. The arrow points to peak spectral value of a noise window before explosion A.

The physical dimensions of the explosions, like the dimensions of earthquakes, should be related to the corner frequency, fc, measured from the Fourier spectrum. To test this, we used an equation for the earthquake source radius r from Brune (1970),

$$r = \frac{2.34\,c}{2\pi f_c}, \tag{4}$$

where c is either the P-wave velocity or the speed of sound in air. The measured crater of the second explosion B was about 12 meters across and 1.8 meters deep, suggesting that = 6 meters is the expected source radius. The northern explosion A did not leave a crater, consistent with upwards rather than downwards directivity. The building was formerly 40 feet by 40 feet (CSB), giving an upper limit to the source radius of about 6 meters.

The Fourier spectra from the air-waves, in Figure 6b, are relatively flat from 1 Hz to above 30 Hz. The high frequencies of the air-waves are limited by the anti-aliasing filters in the recorder ($\approx$ 40 Hz). The spectrum from explosion A might suggest the presence of a corner at about 30 Hz, which from equation (4) would give a source radius of 4 meters. Such a result is reasonable considering the independent information about the size of the building.

The P-wave spectra fall off rapidly above 6 Hz, so we take 6 Hz to represent the corner frequency of these spectra. In equation (4) we do not have the P-wave velocity, so arbitrarily assume it to be 1000 m/sec, which we consider reasonable for weathered bedrock. With this combination of parameters, equation (4) gives $r \approx 60$ m, which is about a factor ten larger than the estimate from the air-wave and from ground observations. We therefore suggest that attenuation along the path has played a major role in decreasing the amplitude of high frequency P-waves. The P-waves spectra have decreased to amplitudes comparable to the pre-event noise above 20 Hz, implying that the attenuation eliminates the chance to use P-waves to estimate the source dimension for such small events whether earthquakes or explosions. For earthquakes, the P-waves would only need to pass through the near surface zone of severe attenuation once, so resolution of a high corner frequency should be somewhat better than in this case.

Conclusions

We have analyzed the relative arrivals of both seismic P- and air-waves at a number of seismic stations to estimate the spatial separation and orientation of two closely-spaced explosion sources that occurred within approximately 3.5 seconds. By using precise timing from the cross-correlations of the air-waves from multiple stations, and assuming an air velocity of 343 m/s, we estimate that the separation is about 73.2 meters. This accuracy results from the relatively slow velocity of the air phases. We also estimate that the two sources align along an azimuth of S35° E. The separation and orientation of the two explosions were well within uncertainties of the data provided by the CSB. The separation determined from the relative P-wave arrivals is similar, 80 meters. From the relative spectral amplitudes of P- and air-waves, we speculate that explosion B may have had a downward directivity, whereas explosion A may have been more upwardly directed. From the viewpoint of forensic seismology, this experiment was successful, in that the air-waves unambiguously demonstrate that the northern of the two explosions occurred first. We confirm that the relative separation of sources can be determined precisely using only a pair of regional seismic stations. We are encouraged that this approach can also be applied to earthquakes.

Acknowledgments

We acknowledge the Sierra Chemical Company, and everyone else who was so adversely affected by this unfortunate event. David vonSeggern and Diane dePolo estimated the magnitude of the event. We thank the Keck Foundation for their generous gift that allowed installation of the digital stations used in this research. This work was also made possible through financial support provided by U.S. Geological Survey NEHRP grant 1434-94-G-2479.

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APPENDIX C: Bureau of Alcohol, Tobacco and Firearms Report

DEPARTMENT OF THE TREASURY
BUREAU OF ALCOHOL, TOBACCO AND FIREARMS

OFFICE OF LAW ENFORCEMENT

Statement of Explosives Technology Branch

To: RAC Robert Stewart
Bureau of Alcohol, Tobacco and Firearms
350 South Center Street, Room 380
Reno, NV 89501

I/N: 745904-98-0009

ETB: W-98-027

Date: January 20, 1998

On January 8, 1998, the Midwest Region Response Team was directed to respond to the Sierra Chemical Plant near Mustang, Nevada. An explosion in their booster plant on January 7, 1998 resulted in the death of four employees and the destruction of the plant.

The booster plant was comprised of two large offset buildings, a break room, a laboratory, and a PETN drying room. The areas of concern are the two large offset buildings, containing booster rooms one and two, and the PETN drying room. Both of these areas were of industrial type construction consisting of a concrete foundation, cinder block walls, and a plywood roof with a composite of fiber insulation and an external rubberized material. These areas were bordered by a rear dirt berm and an approximate 30 degree downslope towards the front, on the south side.

The two large offset buildings comprised, from left to right, booster room one, a storage area, locker room, booster room two, flux room, and tool room. This combination of buildings sat at the top of a hill at the base of a mountain.

Located approximately 50 yards downhill from booster room one was the PETN drying room. This building was comprised of three areas. The first room was empty and allowed workers to shield themselves from the weather while they downloaded PETN. The second room contained a centrifuge and an area where the PETN would be hanged to drip dry. The third and final room contained racks where the PETN was laid down to complete the drying process. This structure was located north, on an uphill grade approximately 100 yards from the entrance of the plant.

Primary areas of interest were booster room two, and the PETN drying room. Booster room two included six mixing kettles aligned in a U shape toward the rear wall, two circular pouring tables centered in front of the kettles, and a cooling bin toward the left front wall. The mixing kettles were numbered one through six from right to left. Mixers 1, 2, 5, and 6 were large kettles, and could contain approximately 100 pounds of Composition B explosives. Mixers 3 and 4 were small kettles, and could contain approximately 80 pounds of Pentalite explosives. Mixers 1 and 6 were never used. Booster room two used steam to mix the explosives verses heated water used in room one, and all mixers were hydraulically controlled. In addition, booster room two was new and had only been operational for a couple of months.

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Reportedly, a crystaline coating adhered to the ceiling of booster room one. Interviews revealed the origin of the crystals. The crystals resulted from emitting vapors in the mixing process. These supposed explosive vapors would rise to the ceiling and resolidify in the form of crystals.

A question was also raised as to whether or not the mixing kettle motors in booster room two were in fact explosion proof. These types of motors prevent the introduction of inadvertent sparks from electrical current into the mixing kettles. At the time of this report, this could not be verified.

On the morning of the accident, approximately 3,000 pounds of explosives were contained in booster room two. Conversely, the PETN drying room, as outlined above, contained approximately 11,000 pounds of wet PETN that morning. And according to an employee, the centrifuge was turned off and no one had yet gained entrance to the drying room prior to the explosion.

On this day, two people were assigned to work in booster room two. One was late for work and the other was seen in booster room one at approximately 7:30 a.m. At that time, booster room one, according to interviews, had been operational for a couple of hours and contained more explosives than booster room two, but no specifics could be given. All that could be ascertained was that each booster room could contain approximately 5000 pounds of explosives.

After being seen in booster room one, the employee scheduled to work in booster room two had to proceed to the employee locker room. According to interviews, it was customary for an employee to take up to 10 minutes to change clothes in the locker room prior to beginning their shift. This puts the employee entering booster room two at approximately 7:40 a.m. (the blast occurred at 7:54 a.m., leaving about 14 minutes of operational time for the employee). Using 7:40 a.m. as the time of entry, the employee would enter booster room two, ensure that the appropriate amount of explosives were present to start the mixing process , inspect the mixing kettles (through interviews, it was determined that the kettles were not always cleaned but procedure is to leave the pots empty), and start the mixing process in the large, Composition B pot, which could take up to an hour. Since one employee was late, the only kettle that should have been started the morning of the accident was kettle number 5. Procedure states that this kettle would be started, and at the latest possible moment, the smaller, Pentalite kettle would be started. The pouring process would then begin with an 80/20 Composition B and Pentalite mixture, respectively.

Post blast investigation revealed that structural and kettle fragmentation had been thrown to the northeast and northwest side of the mountain, which buttressed the structure containing both booster rooms. Lighter fragmentation had been propelled eastward into an adjoining canyon. Small pieces of what should be mixing kettle 5, to include the drive shaft, were found on the hill to the east and more, small kettle pieces were found to the west. These pieces of fragmentation displayed detonation effects. The fact that these

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pieces were found at far distances established not only a blast pattern, but also the presence of immense force. These factors indicate that high explosives were present in what procedure states should be mixing kettle 5.

Further investigation of the PETN drying room blast crater indicated the absence of fragmentation from booster room two in or around the area. Additionally, a blast pattern was outlined on the grass on the east hill with dust that can be followed directly back to the PETN drying room crater. This blast pattern is indicated by the grass on the hill being blown down in a northeast direction. In addition, fragmentation from the trailers that were staged next to the tool room, hence booster room two, was found on the east hill covered with dust from the PETN drying room crater. Also, the right wall of booster room one was sandwiched between the concrete floor and its front wall. Finally, a seismographic report states that the second detonation was of greater magnitude than the first.

All of these indicators state that booster room two detonated first, followed by the PETN drying room. If the PETN drying room had exploded first, fragmentation from booster room two would have been present in and around the PETN crater. Scene processing indicates that this is not the case. The detonation of booster room two created fragmentation that dispersed and hit the PETN drying room, causing the PETN drying room to detonate. This secondary detonation created a detonation wave and fragmentation that formed a blast pattern originating from the PETN drying room.

The grass on the east hill was blown down in a northeast direction, displaying a blast pattern, and again indicating that the PETN drying room detonated second. If the PETN drying room had detonated first, the grass would have blown the grass in a northeasterly direction, and then the blast from booster room two would have blown the grass in a easterly direction. This is not the case.

Trailer fragmentation on the east hill is covered with dust from the PETN crater, which outlines the blast pattern mentioned above. This indicates that booster room two detonated and threw trailer fragmentation to the east. Then the PETN drying room detonated and covered the trailer fragmentation with its dust. Had the opposite occurred, the trailer fragmentation would not have been covered by dust from the PETN crater, it would have been laying on top of it and the blast pattern would, again, lead back to booster room two.

When looking up the hill, the right wall of booster room one was blown down, followed by its front wall, which landed on top of it. This indicates that booster room two exploded, and its pressure wave knocked down the right wall of booster room one. Then the PETN drying room exploded and its pressure wave knocked down the front wall of booster room one.

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Finally, a seismographic report states that the second blast was greater than the first blast. This correlates to the fact that there were more explosives in the PETN drying room than in booster room two. Hence, booster room two detonated, followed by the PETN drying room.

In conclusion, it is the opinion of the undersigned that booster room two detonated and then the PETN drying room detonated. Exactly what caused the booster room to explode is unknown. However, there is no evidence of any criminal act and, thus, the explosion was accidental.

Lori L. Stark
Explosives Enforcement Officer

Jerry A. Taylor
Explosives Enforcement Officer

EXPLOSIVE	CHEMICAL NAME	PROPERTIES	INITIATION SENSITIVITY			
			IMPACT		FRICTION (NEWTON)[1]	ELECTROSTATIC (JOULES)[2,3]
			(Newton-meters)[1]	LASL[2] (cm)		
TNT	2,4,6-trinitrotoluene	Pale yellow crystals if granulated, or flakes. Density of crystals: 1.65 g-cm^{-3} MP = 80.2°C (176.4°F)	15	157	>353	0.46-2.75
RDX	hexahydro-1,3,5-trinitro-1,3,5-triazocine	Colorless crystals Density: 1.82g-cm^{-3} MP = 204°C (399°F)	7.5	23.3	120	0.22-0.55
HMX	octahydro-1,3,5,7-tetranitro-1,3,5,7-tetraazocine	Colorless crystals Density: 1.96g-cm^{-3} (β modification) MP = 275°C (527°F)	7.4	26.1	120	0.20-1.03
PETN	Pentaerythritol tetranitrate	Colorless crystals Density: 1.76g-cm^{-3} MP = 141.3°C (286.3°F)	3	12.5	60	0.19-0.36

NOTES:
1 (Kohler and Meyer 1993)
2 (Gibbs and Popolato 1980)
3 Results for a brass electrode.

APPENDIX E: Response To Alternative Scenario

Comments were submitted to CSB for its consideration of an alternative scenario to the one presented by CSB investigators at the Board of Inquiry in Reno, Nevada, on April 16, 1998. The alternative scenario contends that the PETN Building exploded first, followed by a blast seconds later in Booster Room 2, and that the initial blast was caused by possible sabotage to cover the theft of a large quantity of PETN or some other unknown reason.

This appendix contains the CSB investigators' response to this alternative scenario. It also contains a summary of the arguments opposing the CSB scenario, and the CSB investigators' response.

The comments did not provide any conclusive evidence or analysis causing the CSB investigation team to alter its conclusions regarding the sequence and cause of the explosion at the Kean Canyon plant. Subsequent examination of the evidence has actually strengthened the CSB's conclusions related to the sequence of the explosions, which refutes the claims made in the comments.

- The University of Nevada, Reno, provided an analysis of seismic data that their seismologists believe demonstrates conclusively, based on the relative locations of the blasts, that the first explosion occurred in Booster Room 2 and was followed by the explosion in the PETN Building.

- In addition, explosives modeling experts at the Department of Energy's Oak Ridge National Laboratory compared the quantities of explosives present in the two locations to the seismic data showing that the second blast was stronger than the first. They found the quantities of explosives correlated well with the first explosion occurring in Booster Room 2, followed by the explosion in the PETN Building.

- This information, coupled with the observation that the last movement of the flatbed truck located over the edge of the slope south of Booster Room 2 was uphill, away from the PETN crater, all prove that the sequence of explosions as described in this report is correct.

EVIDENCE RELATED TO THE SEQUENCE OF EXPLOSIONS

The comments regarding the sequence of explosions and the CSB investigators' response are summarized below.

1. **Comment:** The pattern in the grass on the hillside east of the plant cited by the BATF investigators on initial entry is not meaningful because of the distance from the grass to the buildings of about 200 feet.

CSB: The grass patterns observed by the BATF support the contention that the PETN Building explosion occurred second because the grass pointed away from that location.

2. **Comment:** A blast from the PETN explosion caused all the damage that resulted in the layering near the Hot Water Boiler Building. [This is the building CSB refers to as the "Boiler Building" and which is labeled "Main Electrical Panel and Boiler" in Figure 3.] The blast wave from the explosion in the PETN Building pressurized Booster Room 1, which blew out the seven- by ten-foot sliding door which provided access to the platform on the east side of Booster Room 1. The same blast wave destroyed the walls of the Hot Water Boiler Building and blew the west half of the roof north, where it came to rest leaning against the south wall of Booster Room 1 near the loading dock. The second half of the roof landed upside down on the sliding door.

CSB: Layering of material is considered by the investigation team to be a helpful indicator of sequence. The layering observations provide strong corroborating information that helped the investigators establish the sequence of events.

The first issue raised by the comment was whether there were three layers or two layers of material on top of the Booster Room 1 sliding panel door. There were three layers of material. The Boiler Building roof slab and concrete cap were clearly evident. Below the Boiler Building roof slab was another piece of concrete that was part of a wall of the Boiler Building. The chunk of concrete underneath the Boiler Building roof slab was sandwiched between the Boiler Building roof slab and the Booster Room 1 sliding panel door. This chunk of concrete from the Boiler Building wall was moved by the incident investigation team just prior to lifting the Booster Room 1 sliding panel door to inspect under it. The Boiler Building wall material was on the Booster Room 1 sliding panel door and was clearly not part of the Boiler Building roof slab. Rather, it was located between the two pieces. The ground under the Booster Room 1 sliding panel door was free of debris from the Boiler Building or the PETN Building. This fact establishes that the Booster Room 1 sliding panel door reached the ground before debris from either of these sources.

The second issued was whether the south wall of the Boiler Building moved through the Boiler Building. The comment quotes a statement made by a CSB investigator: "The south wall of the Boiler Building was essentially blown through the building and landed on top of that door, and then the roof came down on top of that, giving us three layers of material." This response indicates the writer of the comment misconstrued this statement. From all of the comments, it is clear that the writer assumed the statement meant that the entire wall went through the building intact and landed on the sliding door. What was actually meant by the statement was that the south wall of the Boiler Building collapsed into the Boiler Building. The collapse of the south wall allowed the Boiler Building to be pressurized, causing the walls to move outward. Chunks of the Boiler Building's concrete walls landed on top of the Booster Room 1 sliding door that was on the ground at the north-east corner of the Boiler Building. Only a small section of the Booster Room 1 sliding panel door had wall material on it.

The comment also questioned the movement of the Booster Room 1 sliding panel door. It concludes that it would be "very improbable that a blast effect from the PETN Building traveling south to north demolishing a massive concrete building in its path would not entrain the light-weight door panel." This conclusion is not justified by the physical conditions present during the blast. There would be very turbulent conditions due to the effects of the topography of the site and the Boiler Building. It is more reasonable to conclude that the Booster Room 1 sliding panel door would remain on the ground, for two reasons: 1) the door panel was laying flat on the ground after the Booster Room 2 blast, and therefore had a low profile to the PETN blast effects, and 2) the Boiler Building shielded the ground behind it from the blast effects and therefore the Booster Room 1 sliding panel door remained in its final location.

The scenario proposed by the comment is not probable for an additional reason. The concept of the PETN Building blast causing the Booster Room 1 sliding panel door to be propelled to its final location so that the Boiler Building could fall on top of it is not credible. There were delays between the time the blast effects reached the Boiler Building and the same effects reached Booster Room 1. There were additional time delays needed to create the differential pressure to propel the Booster Room 1 sliding panel door from the building. There were still more delays needed for the door to travel from Booster Room 1 to the boiler room and land on the ground. Meanwhile, the Boiler Building walls, the tank, and the roof had only to fall to the ground with the aid of the blast. The scenario presented by the comment is highly unlikely given the photographic evidence of the undisturbed incident scene. Based on the physical evidence, the investigation team maintains that the source of differential pressure that led to the panel door movement was the explosion in Booster Room 2 and that the Booster Room 2 explosion occurred before the PETN Building explosion.

3. **Comment:** The configuration and construction of Booster Room 2 resulted in a highly directional blast which would have left the PETN crater free of debris if the second explosion had occurred in Booster Room 2. Further, the one piece of roof debris in the crater was cited as evidence that the first explosion occurred in the PETN Building.

   CSB: (See response to comment 7.)

4. **Comment:** The PETN explosion propelled the empty pneumatic tank originally located at the corner of the change room to an intermediate position leaning against Booster Room 2. The second explosion in Booster Room 2 then blew the tank and components to their final locations. This is proposed as the explanation for the upper lid being found southwest and pneumatic piping that fed into the lid to the southeast. Splattering noted on the top of the pneumatic tank was the result of the Booster Room 2 explosion melting and dispersing roofing material onto the lid of the tank.

   CSB: The sequence of events and explanation of the damage in this comment is not consistent with the actual damage sustained by the tank. The most significant contradiction in the comment's description is that the conical section at the base of the tank was pushed into the cylindrical portion of the tank, turning that part of the tank inside out. If the tank was leaning up against the building as described by the comment after the PETN explosion, the base of the tank would be pointing away from Booster Room 2 at the time of the Booster Room 2 explosion. This position would have resulted in greater damage to the sides and top of the tank and does not account for the base of the tank being turned inside out.

The sudden pressurization of the tank when the conical section was forced up through the base of the tank and violent acceleration due to the blast in Booster Room 2 explains the damage and eventual position of the various components of the tank.

The comment noted black spattering on the top of the tank lid, which they believe came from the asphalt roof material. There are many ways this material could have been deposited on the top of the tank. One of these is from the plume of the fire from the warehouse. Trucks in the lower Frehner Construction Company truck lot approximately 1200 feet from Booster Room 2 showed similar black spattering on the hoods.

Based on the physical evidence, the investigation team still concludes that the tank was damaged and propelled by the explosion in Booster Room 2. And that the location of the tank confirms the sequence of events to be first an explosion in Booster Room 2 followed by the PETN Building explosion.

5. **Comment:** The flatbed truck, which was facing east, and located just south of the change room, was struck by the blast from the PETN building which lifted the front of the truck and rotated it counter-clockwise 45-60 degrees to the north. The second blast from Booster Room 2 then propelled the truck south, where it came to rest on the edge of the terrace slope.

   CSB: The comment has several major deficiencies. First, it does not address the riprap evidence (discussed in Section 3.4 of the report) showing that the last movement of the truck was uphill, away from the PETN Building and toward Booster Room 2. Second, the comment does not address the cargo rack being on the Booster Room 2 side of the truck on top of building debris, including part of the stand from one of the two small mixing pots. The other observations and conclusions in the comment are inconclusive because they are sequence independent (damage to cab and grill), can have multiple explanations (small piece of wood stuck in the grill), or are unsupported conclusions (breaking of the base plate weld).

   Photographic evidence shows a piece of the sheet metal wall from the production buildings jammed up under the frame over the back side of the rear dual tires on the passenger side of the truck. The portion of this sheet metal that extended beyond the outside dual tire was wrapped up and back around the outer member of the flatbed frame. The siding was blown out by the Booster Room 2 explosion, struck and became affixed to the bottom of the truck frame. With the truck's intermediate position facing south over the brow of the slope, the PETN blast caught the exposed portion of sheet metal protruding from behind the back dual and pushed it up and around the outside member of the truck frame. This siding could not end up in this position if the truck was facing Booster Room 2 as proposed by the comment.

A piece of mixing pot fragment lodged in the driver's side of the engine block. The radiator and other engine components were displaced toward the passenger side of the vehicle. This shows that the truck was facing east when struck by the blast from Booster Room 2 and could not be facing Booster Room 2 as the comment contends.

Another inconsistency in this comment is the assumption that if the Booster Room 2 blast occurred first, the truck would have rolled over when the PETN Building blast struck it. The physical evidence does not support this assumption. The chassis of the truck was resting on the brow of the slope when the PETN Building explosion occurred. In this configuration the truck had a lower center of gravity and consequently was not overturned by the blast. However, using the comment's conclusion, if the PETN Building exploded first, then the truck should have been rolled over by that blast, which was strong enough to destroy the concrete Boiler Building and roll a pickup truck onto its side.

Because the last movement of the flatbed truck was away from the PETN Building, the CSB concludes that the first explosion occurred in Booster Room 2.

6. **Comment:** All the damage to the pickup truck located south of the west door to Booster Room 1 was caused by the blast from the PETN building.

   CSB: The dishing depression of the door sustained by the pickup truck is characteristic of blast damage and could not have been caused by the mirror mounting hardware. The damage to it was caused by an over-pressurization condition. The blast effects of the Booster Room 2 explosion blew out all the reinforced, solid-grouted concrete-block walls of Booster Room 2, turned over the forklift located in the warehouse, blew the sliding panel door off of Booster Room 1, and caused the east wall of Booster Room 1 to collapse into the Booster Room. This massive release of energy was sufficient to cause the blast damage to the pickup truck parked outside Booster Room 1. Because a day's production of boosters (3000 to 4000 pounds of explosives) were either boxed or in bins on the south side of Booster Room 2, which shared a common wall with the restroom/shower area, explosion of this material had no substantial barrier to prevent blast damage to the west.

   The comment that pallets south of Booster Room 1 were not moved to the west is incorrect. Aerial photographs taken of the site after the explosions show pallets on the roadway west of their original position in addition to those that traveled northwest.

7. **Comment:** There was no heavy high trajectory debris from Booster Room 2 found near the PETN Building of the type required to penetrate the steel reinforced roof or the skylight, which had a grill of rebar on 8-inch centers to prevent unauthorized entry. The roof of Booster Room 2, composed of plywood, 2 x4 wood trusses, and sheet metal roofing, could not produce the necessary missile. However, the roof of the PETN building could produce a missile that could penetrate the Booster Room 2 roof and strike the PETN stored there.

CSB: The comment asserts that, “It is to be noted that no heavy trajectory type material was found between the PETN Building and Booster Room 2 nor was any recognizable material fitting this description found within a 200 foot radius of the PETN Building.” That there is relatively little material from the booster manufacturing buildings found immediately near the PETN crater supports the conclusion that the PETN Building must have exploded after Booster Room 2. There were large items from the general location of Booster Room 2 found within and beyond a 200-foot radius, however.

That there is very little material inside the PETN Building crater is easily explained if the PETN Building explosion occurred second. The PETN Building explosion left a forty-foot diameter crater in its former location; it knocked over the Boiler Building; it rolled the pickup truck on its side; and deposited pieces of the PETN Building and its contents over 2000 feet away. One of the steel-plate sides of the PETN magazine, which was originally located on the south side and adjacent to the PETN Building, was thrown approximately 160 feet to the east-south-east. A single piece of metal roofing found in the crater after the PETN Building explosion must have had a high trajectory, which kept it in the air beyond the 3.5 seconds between explosions.

There were ample materials in Booster Room 2, including metal struts, pipes, I-beams, shafts, mixer components, and pieces of the concrete wall that could have had the correct trajectory and be energetic enough to penetrate the PETN Building. Booster Room 2 materials were found within the perimeter of the original Booster Room 2. Materials were also found adjacent to Booster Room 2, and in trajectories that crossed or pointed toward the PETN Building. Mixing pot 6 was located within 20 feet of Booster Room 2 to the south. The pneumatic tank had a trajectory that carried it toward the PETN Building. Also, a stand from one of the work tables in Booster Room 2 landed approximately 160 feet beyond the PETN Building on a trajectory from Booster Room 2 that passed over the PETN Building. Because of the energy released during the explosion in the PETN Building, it is reasonable to assume that any large object hitting and detonating the PETN Building would not be found near the crater. This is further supported by the finding that there were no pieces of the PETN Building or magazine near the PETN crater. The overpressure from the explosion in Booster Room 2 would have destroyed the skylight over the east end of the PETN Building. Thus, hot or burning debris falling through this opening could also have initiated detonation of the PETN.

The comment has not disproved or provided convincing evidence to alter the CSB team’s conclusion that the explosion in the PETN Building was initiated by effects from Booster Room 2.

8. **Comment:** The presence of stainless steel fragments north of Booster Room 2, which came from pot 4, shows that the initial explosion did not occur in pot 5; it exploded sympathetically with other explosives in the room.

CSB: The comment states that “If the small amount of explosives (approximately 50 lbs. in pot 5) had been the initial explosion in Booster Room 2, the thin wall stainless steel small pot situated to the east and slightly south of pot 5 would not have contributed any fragment debris to the north.” This conclusion is unsupported by the physical evidence.

Pot parts, especially large pieces, were primarily found to the East, South, and West of Booster Room 2. None of the larger pieces, such as shafts, upper assemblies, or intact mixing pots were found to the north of Booster Room 2. Mixing pot leg brackets from large mixing pots and a portion of a mixing blade from a large pot, however, were found north of Booster Room 2. The chaos in Booster Room 2 during the explosion, other explosions in the room, or explosions from the PETN Building could have propelled smaller objects to their final locations to the north. It is not possible or necessary to determine all of the forces acting upon all the material at the site. That pot parts were found in virtually all directions demonstrates the chaotic nature of the explosion. Most of the stainless steel fragments found to the north were from the inner wall of large pots, which were thicker than the walls of the smaller pots.

9. **Comment:** The PETN ground level blast was concentrated in a narrow angle facing in a northwesterly direction. This rolled over the pickup truck in this zone, was witnessed by the worker boxing boosters in Booster Room 1, and propelled the witness against the west wall. The employee then heard a second explosion and the roof collapsed.

CSB: The blast sequence has been clearly established by the flatbed truck, layering, damage patterns, and other evidence. The observations and conclusions of individuals subjected to the explosion describing the conditions in the booster room are limited by their recollection of conditions that existed for milliseconds during the blasts. Perceptions of the direction of the blast are not valid given the conditions and the time for the boxer to observe the outside events from within the building out of the corner of his eye through a partially open sliding door. Given the setback of the truck from the edge of the slope, it is much more likely that the fireball seen by this worker originated from the explosion in the Booster Room 2 on the same level, than from the PETN Building 23 feet below the elevation of the witness and farther away.

The comment states the direction of ground blast effects were “narrowly concentrated” in a north-westerly direction. The blast was not focused. The PETN Building was located immediately south of a five-foot high riprapped slope leading up to the terrace below the production level. The PETN Building blast tore away a portion of the first berm on the north and deposited a fan of dirt on the next terrace and the riprapped slope to the production level. This gave the appearance of the blast being focused. In reality, the blast was essentially hemispheric, with blast effects in all directions.

Terracing and the pickup truck parked south of the PETN building’s open sliding door would have deflected the blast substantially. The line of sight from the center of the PETN crater to the open sliding door to Booster Room 1 was less than 20 degrees from being perpendicular to the south wall. Thus, the residual force would be directed more toward the north than toward the west wall where this witness landed.

There is independent corroboration that the first blast came from the east side of the room. The operator working beside the big pot in Booster Room 1 was thrown west across the room under the cooling bins toward the open door, rather than away from it.

The comment's discussion concerning the chevron pattern of the roof trusses in the warehouse supports the intensity of the blast emanating from Booster Room 2 but does not clarify explosion sequencing.

In the interviews of Booster Room 1 workers, no one ever described the piece of the roof of the Boiler Building coming through the south wall of Booster Room 1 just west of the loading dock. If the PETN Building detonated first, this would have occurred during the initial blast and would have been a significant event that the workers would have noticed.

Statements of the boxer in Booster Room 1 indicate that the first explosion threw him against the boxes stacked against the west wall, and caused the lights to fail and the roof to collapse. This sequence is confirmed in the interview he provided to the CSB. He then heard the second explosion, which was louder than the first, which is consistent with the larger quantity of PETN exploding after Booster Room 2. In another interview, of an operator in Booster Room 1, the operator stated that the roof collapsed after he heard the second explosion. This conflicts with the statements of Booster Room 1 workers interviewed by the CSB investigators.

10. **Comment:** When the windows were blown out of the backhoe in the gravel pit, the supervisor driving was stunned for a moment and then looked over his shoulder and saw the explosion of Booster Room 2 with the building "flying apart" and a black cloud over the main operating buildings. He indicated that the PETN Building exploded first followed by that of Booster Room 2.

CSB: The comment states that "This stunned [the supervisor] and after a moment he thought the shattering of the glass had been caused by a blowout of the large pneumatic tire behind him to the right." This assertion was directly contradicted during CSB's interview with the worker's supervisor. The Sierra legal representative was present when the supervisor stated clearly and unequivocally that the supervisor was not stunned and that he turned his head immediately to see what had happened. In spite of his conclusions, his description of the physical events does not support the PETN Building explosion being first. In fact, the supervisor never saw the PETN explosion. He assumed that the flash of light in the cab, the glass breakage, and blast he felt resulted from an explosion in the PETN Building.

11. **Comment:** In accordance with provisions from the DoD proposed rule (32 CFR Part 184), *Contractors' Safety for Ammunition and Explosives*, the protective construction provided in the design of the Sierra facilities serves as an alternative to the Institute of Makers of Explosives (IME) quantity-distance requirements. There are no quantity-distance requirements between working bays located in the same operating building since explosives were not transported from bay to bay. "Inhabited Building" separation distances are designed to protect the general public. Buildings occupied in connection with the manufacture, transportation, storage, or use of explosive materials are not considered to be "inhabited buildings" requiring this separation.

CSB: In this comment, the writer takes exception to the investigation team's observation that the IME quantity-distance recommendations were not met at the Kean Canyon facility. The response contends that the interpretation made by the investigation team is in error and provided a memorandum from an industry-hired investigator that states that " 'protective construction' is allowed in order to 'suppress explosion effects' as an alternate to distances that may be listed in the q[uantity] d[istance] table." It is unclear how this information, taken from a draft DoD standard, could apply to IME's guidance.

The industry-hired investigator's memorandum concludes that "Certainly the intent of 'Section 184.44 (c)' – to provide protection of personnel against death or serious injury against explosion communication between adjacent bays – can have no finer example than the design at Kean Canyon's operating building. All the employees in the first bay, Booster Room 1, were protected when the explosion occurred in the second bay, Booster Room 2."

The fatalities of the worker in the change room and the worker outside the flux manufacturing room, and the explosion in the PETN Building demonstrate that personnel and facilities adjacent or near to the booster manufacturing rooms were not protected. It is evident that the design did not effectively suppress explosion effects, as asserted by the memorandum. None of the construction at Kean Canyon could suppress the effects of several thousand pounds of explosives. Such a claim is ludicrous.

Section 3.2.16 of IME's Publication 3*, Suggested Code of Regulations for the Manufacture, Transportation, Storage, Sale, Possession and Use of Explosive Materials*, states in part:

"High explosive manufacturing buildings located on explosive materials plant sites . . . shall be separated by minimum distances conforming to the requirements of the 'Intra Plant Distance Table For Use Only Within Confines of Explosives Manufacturing Plants'."

Using the 20,000 pounds of explosives in Booster Room 1 and assuming that the terracing served as an effective barricade between facilities, the required minimum separation distance between the PETN Building and Booster Room 1 would have been 265 feet, rather than the actual separation of 185 feet. The comment may argue that Booster Rooms 1 and 2 were bays in the same building and Intraplant Quantity-Distance requirements don't apply between these bays. But if it is assumed that Booster Room 1 and 2 are explosive bays in the same building, the total quantity of explosives in the combined production buildings according to Sierra's own estimates would have been 32,000 pounds and the minimum distance from the production building to the PETN Building would be 295 feet.

The "DoD Ammunition and Explosives Safety Standard" siting requirements state: "Administration and industrial areas shall be separated from potential explosive sites by inhabited building distances." Because the minimum inhabited building distance is controlled by the fragment hazard distance of 1250 feet, the Frehner Construction Company gravel pit operations and the Sierra chemical operations did not meet this criteria.

12. **Comment:** The only credible scenario to explain how the first explosion occurred in the PETN building is sabotage in an attempt to cover up the theft of PETN. Several individuals could easily transport a large quantity of PETN from the site by backpack.

CSB: Having set out to show that the first explosion occurred in the PETN Building, the comment concludes that the explosion was the result of sabotage to mask the theft of a large quantity of PETN explosive. This was the only initiating event possible in this locked building that was unoccupied with no equipment in operation in the cold early morning of January 7, 1998. Because the PETN Building was locked, access would require insider assistance. Otherwise the missing lock and/or damaged door would have been clearly evident the following morning. In fact, the supervisor and workers present that morning drove past the door to the PETN Building and did not detect anything unusual the day of the incident. Setting off a delayed explosion to mask a theft and yet provide time to escape would require experience in the use of explosives and a timer to delay the ignition. The National BATF team members are trained to look for evidence of such devices, but found none. There was no indication that any of the workers other than the supervisor had ever detonated any explosives, and the supervisor's experience was limited to the testing of boosters. The gate into Sierra's Kean Canyon Plant was locked during off-hours and the Frehner Construction Company guard who monitored traffic into the site was located near that gate.

13. **Comment:** The CSB either misquoted or distorted testimony [interviews]. The CSB's investigators' statements that the operation was not controlled by any management system; that individuals were encourage to create processes that were efficient; that operators changed their processes as they liked; and that they did not require other outside reviews or independent oversight of those actions and might not even communicate to others what they were doing, are all evidence of this. Management felt it had strict control, consistent and frequent overview, and repetitive training to control the operation.

CSB: Multiple witness interviews support the conclusions made by the incident investigation team.

14. **Comment:** A double-axle trash trailer parked near the edge of the terrace south of Booster Room 2 and the Flux Room, was propelled into the wall of the flux room by the PETN explosion and then southeast by the explosion in Booster Room 2.

CSB: This evidence is not useful for establishing sequence. The trailer could have first been blown down to a lower terrace by the explosion in Booster Room 2 and then blow east by the explosion in the PETN Building. Alternately, the original location could have been further east than believed, such that the Booster Room 2 explosion blew the trailer components directly to their final resting points. The CSB investigators did not examine this issue because the preponderance of other evidence supported the CSB scenario.

15. **Comment:** A vertical metal wall panel from the south wall of the flux room has damage to the first 18 inches of the panel consisting of indentations and sandblasting while the top of the panel is shredded outwards. The damage at the bottom was caused by crushed rock south of the concrete apron being blown by the PETN explosion against the wall. The Booster Room 2 explosion then caused the shredding damage.

CSB: The CSB investigators did not examine this wall panel, but believes that there are other explanations that could account for such damage. The shredding of the wall panel was most likely caused by the blast from Booster Room 2; however, the damage to the lower portion of the panel could have been caused on impact or by its orientation to the effects of the second blast from the PETN Building explosion.

16. Comment: The roof of Booster Room 2 consisted of plywood covered by galvanized sheet metal panels, which were later covered by plywood and a fiberglass-asphalt top layer. Some galvanized sheet metal panels were found north of Booster Room 2 that show penetrations from both sides. Falling debris from the PETN explosion caused penetrations from one side followed by fragmentation from the Booster Room 2 explosion.

CSB: The CSB investigators did not examine this evidence. It is likely that all of this damage resulted from the blast in Booster Room 2, however. Some penetrations that appear to be from the top could have resulted from the sheet metal being blown away from roof trusses. Fasteners pulling through the sheet metal could give the appearance of a penetration from above. Due to the separation of explosives within the room and the generation of primary and secondary fragments, it is possible for the fragments from Booster Room 2 to have penetrated both sides of the roofing. Other penetrations could simply be due to the exposed panel being struck by falling metal fragments after the explosions.

17. Comment: An empty tank was strapped on a low-boy trailer east north east of the PETN Building on the same terrace. The PETN explosion struck the rear of the trailer and propelled it, and pieces of the tank along a line from the PETN building through the original location of the trailer. If Booster Room 2 had exploded first, the blast would have hit the side of the tank and propelled it south.

CSB: Because of the 80-foot setback of Booster Room 2 from the edge of the terrace to the south and the difference in elevations, the tank on the lowboy would not experience the direct impact of the blast that it would have experienced if it had been located on the same level. The trailer and tank were also partially shielded by a storage unit that was visible to the investigators. The tank was well secured to the trailer so the trailer itself kept the tank from being propelled south. Thus, this evidence was not seen as useful in establishing sequence.

EVIDENCE RELATED TO THE CSB'S INCIDENT SCENARIOS

The comments in response to the scenarios presented by the CSB investigators are presented below with the CSB's responses.

18. Comment: The use of sparking steel hammers or carpenters' hammers to break up explosives does not seem probable and was most likely a mistranslation of what was actually said. The supervisor stated that the use of steel hammers was strictly forbidden due to their spark potential. It appears, however, that workers, in violation of rules, occasionally used steel hammers and such use was quickly stopped.

CSB: There are multiple references in CSB interviews of Sierra employees to the use of steel hammers to break up lumps of Comp-B or reject boosters, and one employee's statements clarified the type of steel hammer they used as a carpenter's hammer. The scenario proposed by the CSB, however, had nothing to do with sparking. The detonation was due to "impact or impingement of explosives between the hammer and either a foreign object in the material or another hard surface." This result is possible whether the hammer was made of steel or a nonsparking material like bronze.

19. Comment: Turning on the agitator to pot 5 with solidified explosives present is not credible because the pots were left steam heated at night at a temperature of 180 degrees F, the operator who saw the residual explosives in this pot stated that the level was approximately 1 1/2 inches below the mixing blades, it was standard procedure to inspect the pots prior to activating the agitator, and the overload circuit protector was set to trip if the mix became too thick.

CSB: a) Cooling/solidification

The owner of Sierra stated that he asked the operators to leave one valve on each pot cracked open to ensure that the boiler would cycle to prevent freezing. He indicated from his observations that the temperature in the steam jacket would be 90-100 degrees. He confirmed that if explosives were left in the pot overnight, they would solidify. The morning of the incident was one of the coldest days that winter, which would further increase the likelihood that the explosives had solidified. Worker statements indicated that sometimes no valves were left cracked open.

It was standard practice for operators to shut off the valves and add flake TNT to bring the temperature of the mix down to get the proper viscosity. Because the operator who left explosives in his pot in Booster Room 2 may well have thought that his co-worker was going to use the remaining base mix, he could have left the steam valves to that kettle off in order to maintain the proper consistency. The co-worker indicated that typically, the Booster Room 2 operator who left explosives in his pot would leave the steam valve opened slightly to the draw-off line. The co-worker, however, did not check or open any valves on pot 5.

b) Mix Level

The co-worker told CSB investigators that the remaining base mix left in pot 5 was three to four inches deep and half-way up the hub at the base of the stirring blade. In the alternative scenario, it appears that this worker may have been stating that the level was 1 to 1 1/2 inches below the top of the stirring blade hub, which would be consistent with his earlier statements. The entire blade was not encased in solidified explosives. The mixing blades had only about one inch of clearance between the blade and the inner pot wall, as described in management interviews. Thus, the lowest portion of the blade extended into the solidified explosives.

CSB investigators also did an independent calculation using the inside diameter from drawings provided by Sierra to estimate the level based on the worker's estimate of quantity (one bucket full, about 50 pounds). The results were as follows:

2 inches	13.1 pounds
3 inches	28.8 pounds
4 inches	**50.3 pounds**
5 inches	77.0 pounds
6 inches	108.5 pounds

Thus, the worker statements we received concerning the amount of explosives left in pot 5 was supported by the calculation.

c) Failure to Inspect Pot

One operator working in Booster Room 2 did not feel the need to look inside his mixing pots every time. Another worker who had worked a few days in Booster Room 2 stated that he didn't think that the operator who left material in pot 5 normally looked into his pots before he turned the mixer on.

d) Spark/Pressure

The mixer used with the pots are capable of delivering over 4,000 inch pounds of torque (based on a manufacture's calculation dated January 30, 1998). This is more than enough torque energy to cause a detonation. The motor overloads in the mixers do not instantaneously drop out and were set at 8.5 to 9 amps (based on photographic evidence and manufacture's interpretation of the setting). Since only the lowest portion of the blade extended into the solidified explosives near the central mixing shaft, the explosives provided much less resistance to the torque of the mixing blade.

20. Comment: A spark from the mixing pot striking metallic debris in Comp-B is improbable because: 1) the operator would not have reached the point in the process in which Comp-B is poured into pot 5; 2) metal fragments were typically too small to be caught in the one-inch clearance between the agitator and pot wall; 3) Sierra had not had such an event over the past 25-year history using manual screening; and 4) the quality of reclaimed government explosives was improving.

CSB: The CSB scenario was misquoted by the comment. The actual scenario involved detonation of explosives by impact, friction, or shearing when foreign materials or hard lumps of Comp-B or substitute materials were added to the mixing pot. A bolt could easily be of sufficient size to be caught between the blade and the inner wall of the pot. Previously, the Comp-B pot in Booster Room 1 had sustained damage from foreign materials being caught between the mixing blade and the wall. The CSB investigators' timelines for each scenario were based on operators' accounts of the startup sequence. There was enough variation in this sequence that it is impossible to know exactly how the operator in Booster Room 2 was conducting his operation the morning of the incident. Sierra's manual screening process failed to eliminate foreign materials. This is clearly evident because most foreign materials were discovered in the pot after the pour.

21. Comment: Initiation by static electricity resulting from pouring dry PETN or drying PETN in the mixing pot is improbable. PETN was not dried in Pentolite pots before adding TNT, because this would cause clumping of the mixture, which would slow production. Also, the incident occurred before the operator would have reached this point in the operation.

CSB: The statements of the senior operator in Booster Room 2 clearly described the process of dry mixing of PETN to reduce residual moisture. When questioned further, he provided several assurances about putting the PETN in the pot without TNT. He did it all the time. This was the same operator responsible for training the other operators in Booster Room 2.

An operator normally would not begin with the Pentolite Pot. If the operator working the morning of the incident checked and saw the residual solidified base mix, however, he might have gone ahead and started the Pentolite mix while the base mix melted.

APPENDIX F: Visual and Metallographic Analysis of Mixer Parts

A visual examination of three items was performed. The items included:

- the hub portion of the cast mixing blade where the hub connected to the drive shaft of pot 5;
- a piece of the mixing blade believed to be from the same hub/mixing blade casting of pot 5; and
- an approximately 18-inch top section of the pot 5 shaft.

Following the visual analysis, sectioning and metallographic examinations were performed on portions of the hub and the mixing blade fragment.

Except for pot 5, the four large mixing pot shafts from Booster Room 2 remained intact following the blast. The three intact drive shafts still had the hub portion of the cast mixing blade firmly attached to the drive shafts. Because the shafts and hubs of all but pot 5 were accounted for, the remaining hub and the fractured portion of a shaft that were recovered at the site were determined to be those from pot 5.

The analysis found that the mixing blade hub was subjected to extreme shock loading as evidenced by shear bands and internal cracks. The mixing blade metallographic specimen showed the presence of mechanical twins that are an indication that the blade sections had been cold worked. Unlike the hub section, the blade fragment did not contain localized shear bands that are indicative of intense shock loading. From the limited metallographic study, the type of cold working that resulted in the mechanical twins observed in the blade fragment could not be determined.

Based upon the visual examination of the fracture surface of the drive shaft, the primary fracture mode could not be conclusively established. Further fractographic analysis using a scanning electron microscope would be expected to aid in establishing the fracture mode(s). Similarly, the visual examination of the fracture surface on the mixing blade fragment did not permit conclusive identification of the reason(s) for failure.

Interviews of Sierra workers indicated that 50 to 100 pounds of base mix was left in pot 5 at the end of the shift the day before the explosion. The metallurgical analysis concluded that the damage to the hub is consistent with shock loading that could result from contact with high explosive material upon detonation. This evidence strongly suggests that explosives were present in pot 5 when the explosion occurred.

The absence of shock loading on the piece of the mixing blade indicates that it was not in contact with explosives when the explosion occurred. One possible reason for the lack of shock loading is that the fragment may have been from a pot other than pot 5. Alternatively, the blade fragment may have been above the level of the 50-100 pounds of explosive remaining in the pot and thus experienced a less intense shock loading.

APPENDIX G: Melt/pour Incidents Elsewhere

The following table summarizes explosions that have occurred in melt/pour operations at other sites. These accounts indicate the degree of hazard associated with melt/pour operations and the types of initiating events that must be controlled. The source of this data is the U.S. Army and the IME.

Date	Event Description	Outcome	Location
7/24/16	Clogged draw-off pipe was being cleared with brass rod, which impinged heated Amatol (60/90) against steel pipe, causing detonation.	1 Fatality 3 Injuries	Trent, Great Britain
11/04/18	Foreign material was present in the melt pot due to lack of screening of fresh TNT or reworked Amatol. Approximately 1,200 lbs. of TNT was added to the pot from boxes without screening or examination. About 200 lbs. of scrap Amatol was added directly.	64 Fatalities 100 Injuries	Perth Amboy, New Jersey
12/12/41	Sublimed TNT crystals in ventilator duct due to high TNT vapor (0.87 mg/m^3) caused the explosion. Sublimed TNT crystals are sensitive to friction, impact, or static spark.	13 Fatalities 53 Injuries	Burlington, Iowa
3/4/42	Draw-off valves slamming shut were suspected in detonation of TNT (60-40 Amatol). Also, the exhaust-ventilation system was clogged by sublimation. The TNT vapor level was 0.80 mg/m^3.	22 Fatalities 84 Injuries	Burlington, Iowa
3/24/45	A hot-water hose with brass nozzle was being forced into a clogged draw-off pipe on a TNT melt unit. Impact or friction caused the explosion.	2 Fatalities	Joliet, Illinois
5/26/45	The agitator impacted a screen in a mixing pot or the valve diaphragm failed, resulting in metal-to-metal contact in TNT melt operation.	9 Fatalities 6 Injuries	Grand Island, Nebraska

Date	Event Description	Outcome	Location
10/01/51	Excess Comp-B detonated when warheads struck each other or fell to ground. Metal-to-metal contact of items coated with Comp-B caused the detonation.	5 Fatalities	Hawthorne, Nevada
2/20/59	Friction between a steel spatula and concrete floor contaminated with DNT-sublimated crystals caused a detonation.	1 Injury	Dottikon, Switzerland
7/6/61	Prolonged heating of 60 lbs. of molten Pentolite (55% PETN/45% TNT) led to detonation after seven hours. (Rotary valve was involved in explosion.)	Property damage	Seneca, Illinois
10/8/63	Cyclotol (70% RDX/30%TNT) detonation caused by impingement of explosives with spark-proof hammer and screwdriver while cleaning draw-off lines and valves.	2 Fatalities	Milan, Tennessee
8/16/68	Detonation of cyclotol melt operation probably caused by adding “riser scrap,” which is explosive solidified in the risers used to fill projectiles and grenades, that normally is introduced into the melt pot when the molten explosive could bathe the scrap and soften it for re-melting. If riser scrap added prematurely, impact of the agitator could provide source of detonation. Evidence of detonation inside the melt pots was found.	6 Fatalities 4 Injuries	Shreveport, Louisiana
7/25/79	Decomposition of PETN during melting released oxides of nitrogen. Heat was removed but the reaction continued until detonation.	Property damage	East Camden, Arizona
8/18/89	A clogged draw-off line had been removed from a pot. Pentolite in the line detonated when struck by a non-sparking screwdriver with a rawhide mallet.	2 Fatalities	Joplin, Missouri

APPENDIX H: Change Analysis

Scenario 1. The mixer blade impacted solidified explosives that had been left in pot 5 in Booster Room 2 the previous day.

Scenario 2. Foreign materials or hard lumps of Comp-B or substitute materials that were added to the base mix in pot 5 caused a detonation due to impact, friction, or shearing.

Scenario 3. Electrostatic discharge or friction detonated PETN that had been added to the Pentolite in pot 4 and allowed to heat up without any TNT in the pot to dissolve the PETN and act as a lubricant.

Scenario 4. The breaking of lumps of Comp-B or harder or more sensitive substitute materials with a steel hammer caused a detonation outside the mixing pot due to impact or impingement of explosives between hammer and a foreign object in the material or another hard surface.

Each of the changes identified in the Change Analysis Table had some influence on the melt/pour operation in Booster Room 2. This analysis shows that specific conditions that were present in the room when the incident occurred could have caused the detonation. The investigation team concluded that Scenario 1 is the most likely cause of this incident. This conclusion is based on the analysis of the number and types of changes as well as the probable human interaction with those changes.

The investigation team believes that these change factors support the conclusion that the melt/pour operator in Booster Room 2 did not verify the contents of mixing pot 5. He turned on the mixing element of pot 5 with 50 to 100 pounds of solid explosive material in it. This action resulted in the detonation of the material in the pot, which then propagated to the rest of Booster Room 2 and then to the PETN Building and magazine. The explosion resulted in the death of four workers and the injury of six others.

There is a strong case for the conclusion that Scenario 1 caused the explosion. It assumes, however, that the operator did not look into the pot before turning on the mixer. If the operator did look into the pot and did not turn on the mixer, then Scenarios 2, 3, or 4 could explain how the detonation occurred.

Item #	Change Description	Effect on Scenario 1	Effect on Scenario 2	Effect on Scenario 3	Effect on Scenario 4
	Equipment Change				
1	Larger mixing pots were installed in Booster Room 2. The large mixing pots had an inside diameter of 46 inches. The smaller mixing pots in Booster Room 1 had diameters of less than or equal to 36 inches.	The larger pots had an inside radius of 23 inches, compared to an inside radius of 18 inches on the next-largest mixing pots used at the facility. This increased the surface area of the material left in the bottom of the larger pot. For the depth of material left in the pot, there was 27% more surface area. This would contribute to greater amounts of adhesion, crystal shearing, and rotational friction generated due to the mixing blade than from any previous configuration. This increased the likelihood of detonation due to friction, adhesion, or crystal shearing. It would also contribute to more rapid melting of material in the pot.	The larger capacity of the mixer allowed more material to be added during the initial steps of the process. Consequently, the operator could have added large amounts of the LX-14 and Comp-B to the pot. If this happened, then the material would be mixed in a dry configuration for several minutes before there was sufficient melting to reduce friction, eliminate impingement, or impact chunks of the explosive between the mixer blades and "breaker bars," or between the mixer blades and mixer walls. If foreign material was in the chunks, it could have caused additional friction or sparking until the material had melted.	Not Applicable	Not Applicable

Item #	Change Description	Effect on Scenario 1	Effect on Scenario 2	Effect on Scenario 3	Effect on Scenario 4
	Equipment Change				
2	The larger mixing pots in Booster Room 2 had “breaker bars.” These were not present in Booster Room 1.	Not Applicable	The “breaker bars” provided an additional component for the material to interact with during the mixing operation. If material were left in the bottom of mixing pot 5, then the working clearance between the “breaker bars” and the bottom of the mixer would be changed, possibly allowing impingement or impact to occur.	Not Applicable.	Not Applicable.
3	Wall thickness of larger mixing pots, including pot 5, compared to mixing pots used in Booster Room 1.	The heavier construction of the large mixing pots made them more rigid. Consequently, there would be little or no yielding when materials were forced between the mixing blades and walls of the pot. This, in combination with low-speed, high-torque mixing, could provide the motive force for a friction detonation of the material.	The heavier-walled pots were more rigid. As a result, there would be little or no yielding to materials between the mixing blades and walls. This, in combination with low-speed, high-torque mixing, could provide the motive force for a friction detonation of the material.	The heavier-walled pots were more rigid. Consequently, there would be little or no yielding to materials between the mixing blades and walls. This, in combination with low-speed, high-torque mixing, could provide the motive force for a friction detonation of the material.	Not Applicable.

Item #	Change Description	Effect on Scenario 1	Effect on Scenario 2	Effect on Scenario 3	Effect on Scenario 4
	Equipment Change				
4	The steam system's heat capacity was greater than the hot-water system used in Booster Room 1.	The steam-heat system in Booster Room 2 had a higher heat capacity than the hot water system in Booster Room 1. The operators were able to melt material faster, and the pots had less buildup of material on the internal components. The operators were used to working with "clean" pots in Booster Room 2. They were less concerned about the internal condition of the pots than when they worked in Booster Room 1.	The higher heating capacity of the steam system in Booster Room 2 allowed the operators to add larger chunks of material to the pots.	PETN with a higher moisture content was brought to Booster Room 2 because it could be dried out without causing a significant delay in production. The practice for starting the Pentolite pot in Booster Room 2 was to put the PETN in the pot and allow it to mix without other materials while it dried out. This occurred while the melt/pour operators were doing the setup, which typically would take about 20 minutes.	With the higher heat capacity of the steam system, there was less need to break up some of the chunks of material being added to the pots. Workers were used to doing this operation, however, from their experience working in Booster Room 1.

Item #	Change Description	Effect on Scenario 1	Effect on Scenario 2	Effect on Scenario 3	Effect on Scenario 4
	Process Change				
5	Normally, all material in the mixing pots was used up before the end of day shift. On this occasion, 50-100 lbs. of material was left in the pot at the end of the shift.	The material would harden overnight when the steam heat to the pot was reduced at the end of the shift. If the operator failed to look into the pot in the morning, he could have turned on the steam and then turned on the mixer with a large amount of solid explosive in the pot. This action could have resulted in a detonation due to crystal shearing, high friction in breaking the adhesion of the pot walls, or the friction of turning the material without any lubrication while the pot heated up.	The operator may have noticed that there was material in the pot. If he did, he would have waited about 10 minutes before adding the LX-14 or Comp-B to the mixer. On the surface, the pot contents may have looked liquid, but it is unlikely that the large mass of material would have been dissolved in this time frame. Adding chunks of material or material that could contain foreign objects in it could have provided a mechanism for detonation. The chunks may have been impacted or impinged during the mixing, friction in the dry mix may have been a detonation source, or metal objects in the mix could have been caught between the solid mass of residual mix and the bottom or sides of the mixing pot. All of these mechanisms may have been present.	If the operator noticed that pot 5 had a mass of material in the bottom, then he may have proceeded with the next step in his startup process, which would be to add PETN to the Pentolite pot 4.	If the operator recognized that there was material in the pot, he may then have decided to proceed with opening the LX-14 and Comp-B boxes. It was common practice at the facility to break up larger chunks of material using a steel hammer. This was done to reduce the time it takes for the material to melt. The process of breaking up the material included hitting the material in a shipping container, which could be located on the concrete floor or on another box of explosives. The operator may have been at this step of his process when the detonation occurred.

Item #	Change Description	Effect on Scenario 1	Effect on Scenario 2	Effect on Scenario 3	Effect on Scenario 4
	Process Change				
6	PETN added to the mixing pot without TNT	Not Applicable	Not Applicable	In Booster Room 1, the PETN was added after some liquid TNT was added to the Pentolite-mixing pot. The TNT acted as a lubricant, and allowed the PETN to go into solution soon after being added. The electrostatic-discharge conditions described in the Environmental Changes section of this table would not be present if this step were followed in Booster Room 2.	Not Applicable.
7	Comp-B added to base-mix pot without first adding liquid or melting solid TNT	Not Applicable	The company's written procedure describing proper operation of the melt/pour process directed that the TNT be added before the Comp-B materials. This would have ensured that the Comp-B, which often was chunky and sometimes had metal foreign materials, would have some lubrication and fluid to help protect it from friction, impingement, and impacts during its melting. Adding the Comp-B first	Not Applicable	Not Applicable

Item #	Change Description	Effect on Scenario 1	Effect on Scenario 2	Effect on Scenario 3	Effect on Scenario 4
	Process Change				
			typically allowed a brief period of time when the material was still solid and thus susceptible to friction, impingement, or impact. If solid material left over from the previous evening were still in the pot, then it would increase the time of susceptibility.		
8	Single person operating the booster line instead of two people usually operating in Booster Room 2.	In Booster Room 1, two workers worked together in each production line. In Booster Room 2, only one person was operating each production line. This increased the number of tasks that needed to be performed, which increased the time pressures on the individual. This factor has a significant effect on human error. Time constraints affect decision processes and may influence individuals to take risks or act in unusual ways.	See explanation in Scenario 1 to the left.	Working by himself would increase the time between adding PETN and subsequently adding the TNT to the Pentolite pot.	See explanation in Scenario 1 to the left. Added time constraints and increased workload would have increased the likelihood of human error during the performance of this task.

Item #	Change Description	Effect on Scenario 1	Effect on Scenario 2	Effect on Scenario 3	Effect on Scenario 4
	Process Change				
9	Hot water to the mixing pots was normally left on in Booster Room 1. In Booster Room 2, only one valve was left "cracked" open on the mixing pots overnight.	Workers in Booster Room 1 would not expect to find hard material in the bottom of a mixing pot, even if they left material in the pot overnight. This would tend to reduce the dependence on checking the pots because generally there would not be any solid material in the pots. Because the worker running the production line the morning of the incident learned his trade in Booster Room 1, the possibility that the material would be hard in the morning may not have occurred to him.	Not Applicable	Not Applicable	Not Applicable
	Material Change				
10	LX-14 material had larger and harder chunks	Not Applicable	See Scenario 2, Item 5, discussion. Increasing the size and hardness of chunks makes this situation worse.	Not Applicable	See Scenario 4, Item 5, discussion. Increasing the size and hardness of chunks makes this situation worse.

Item #	Change Description	Effect on Scenario 1	Effect on Scenario 2	Effect on Scenario 3	Effect on Scenario 4
	Operator Change				
11	The operator in Booster Room 2 had been trained and was experienced in operating in Booster Room 1 on the second shift. He had been working the day shift in Booster Room 2 for approximately 8 weeks.	The operator in Booster Room 2 had received on-the-job training for the melt/pour operation while working on the second shift in Booster Room 1. At the start of the second shift, the mixing pots would be mixing and already hot. In some instances, some material might have been left in them. Second-shift operators do not need to turn the mixer motor on; therefore, the operator in booster Room 2 may not have developed a habit of looking into the mixer before turning the mixer on. Even if the on-the-job training emphasized this precaution, the worker would not do it when working on the second shift in Booster Room 1.	Not Applicable	Not Applicable	Not Applicable

Item #	Change Description	Effect on Scenario 1	Effect on Scenario 2	Effect on Scenario 3	Effect on Scenario 4
	Operator Change				
		Also, because it was a common practice to leave the pot empty at the end of the shift, failure to perform a precautionary look into the mixing pot would not normally be dangerous.			
12	The second operator was not working the morning of the incident.	The second operator knew that there was material left in pot 5. Had he been in the room, he may have reminded his coworker about the material left in the pot the previous evening.	Not applicable. This person would follow similar work practices or would not have corrected the other individual's technique.	Not applicable. This person would follow similar work practices or would not have corrected the other individual's technique.	Not applicable. This person would follow similar work practices or would not have corrected the other individual's technique.
	Environmental Change				
13	Low temperature outside (low to mid twenties), 81% relative humidity.	Booster Room 2 did not have a heater. The practice of leaving one of the valves on the pot cracked a small amount may have been enough to keep the material semi-liquid under certain conditions. In this instance, the quantity of material left in the pot combined with the cold	The cooler the material was in pot 5, the longer it would take to heat to liquid state. Adding material before the solid mass left in the pot had turned to liquid would have increased the likelihood of friction, impingement, or impact of materials.	Humidity drops by a factor of approximately one-half for every 20°F of temperature rise. Based on this property of temperature and humidity, as the temperature inside the pot was raised toward 200°F, the relative humidity in the pot would approach 0%. Low humidity, combined with the PETN granules and the	Not Applicable.

Item #	Change Description	Effect on Scenario 1	Effect on Scenario 2	Effect on Scenario 3	Effect on Scenario 4
	Environmental Change				
		outside temperature would contribute to the material being in solid form on the morning of the incident.		mixing action, would create ideal conditions for electrostatic discharges, which could result in detonation of the PETN.	