Sierra Chemical Company
Mustang, Nevada

Investigation Report into an incident on 7th January 1998 on the cast booster plant by The US Chemical Safety and Hazard Investigation Board (CSB)

The full report can be downloaded from the CSB website

www.csb.gov/assets/document/Final_Sierra.pdf Report No. 98-001-1-NV

1 Introduction

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. 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.

2 Investigative 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. 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.

3 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 1. 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 1

3.1 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 2 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 2, perpendicular to the back wall of the production buildings. True north is 44 degrees clockwise.

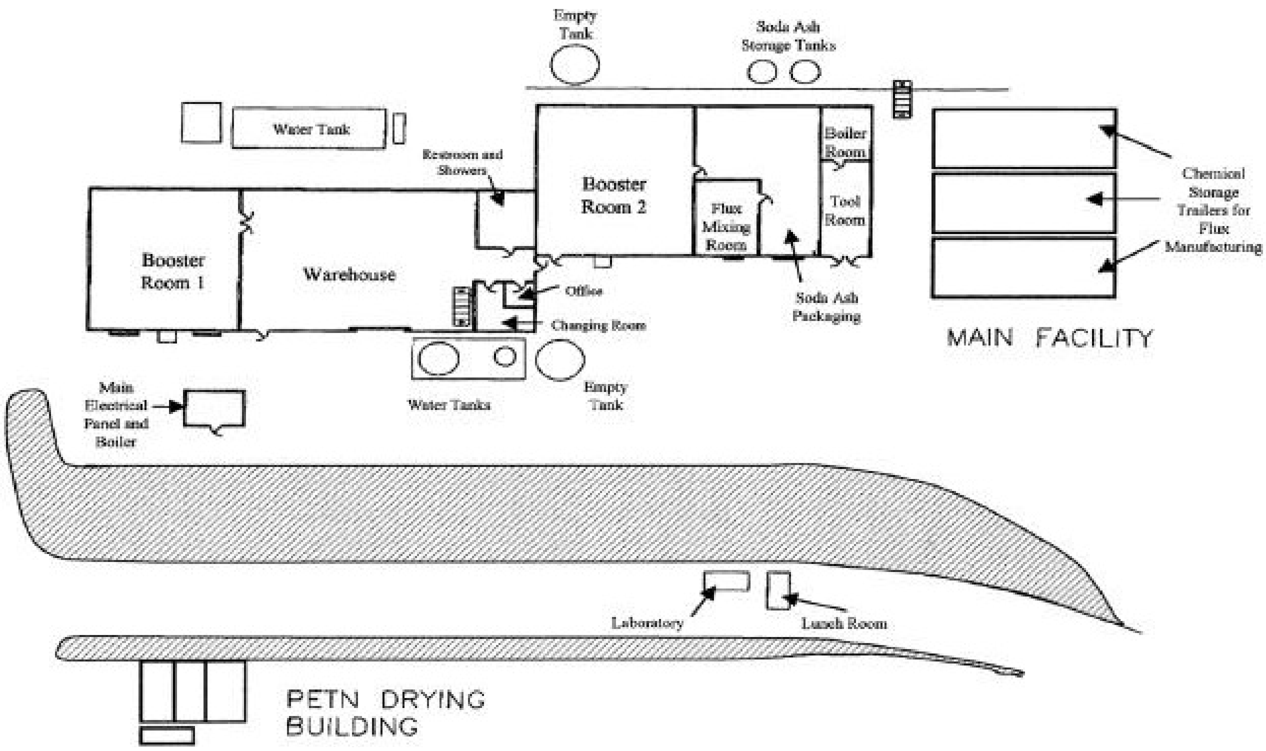


Figure 2

3.1.1 <u>Booster Room 2</u>

Booster Room 2, shown in Figure 3, 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-beam. Workers placed materials in the center of the platform between two independent melt/pour production lines.

Figure 3

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 are shown in Figure 4.

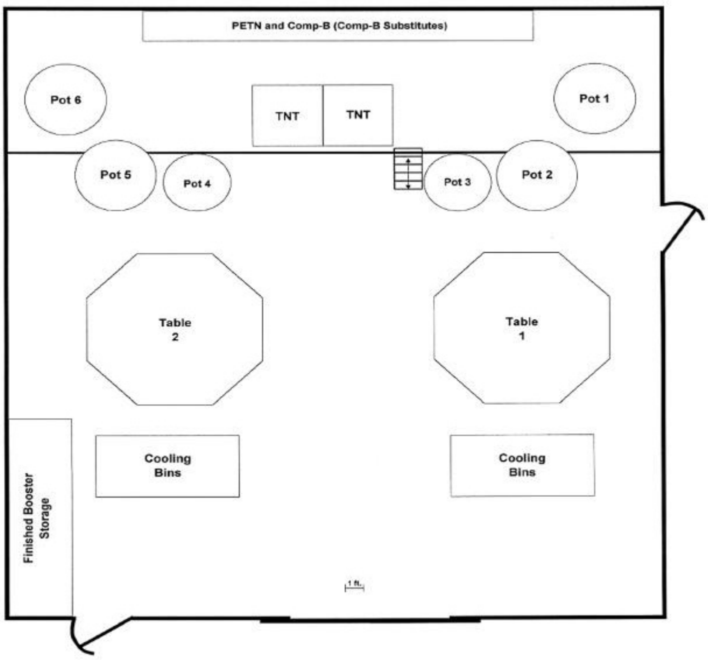


Figure 4

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.

3.1.2 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.

3.1.3 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 2). 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.

4 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.

5 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 below. 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.

5.1 Sequence of events

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. 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. 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 5.

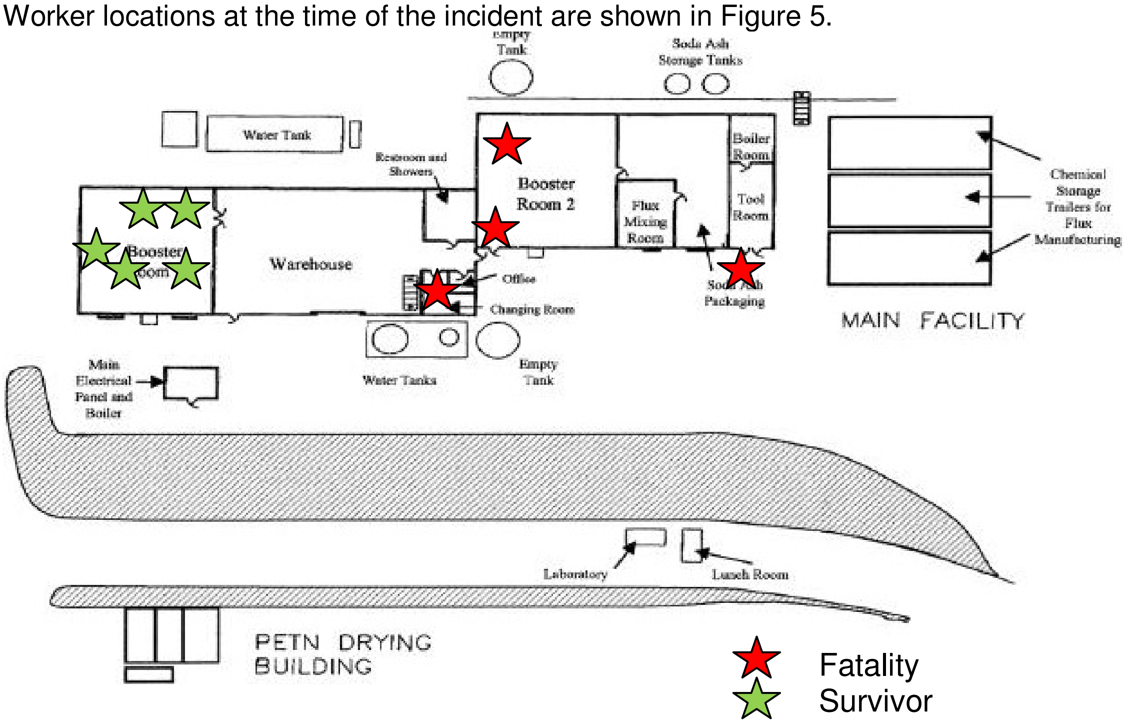


Figure 5

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,

5.2 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.

5.3 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.

5.4 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.

6 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 to be found in the full report.)

6.1 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 mixer motor. The investigation team concluded that and, thus, he failed to look in the pot the next morning before turning on the steam 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.

6.2 Other credible scenarios

6.2.1 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.

6.2.2 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 basemix 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.

6.2.3 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 basemix 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 aluminium 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.

7 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.

7.1 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.
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.
BR 2 had a different design of valve that did not require use of the metal tools so this was not considered to be the cause of the explosion.

7.2 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.
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.

7.3 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.

8 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, 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.

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.

9 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 BR1. 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.

10 Training

10.1 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.
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.

10.2 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.

11 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.

12 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.

13 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.

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.

14 Incident investigation programme

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.

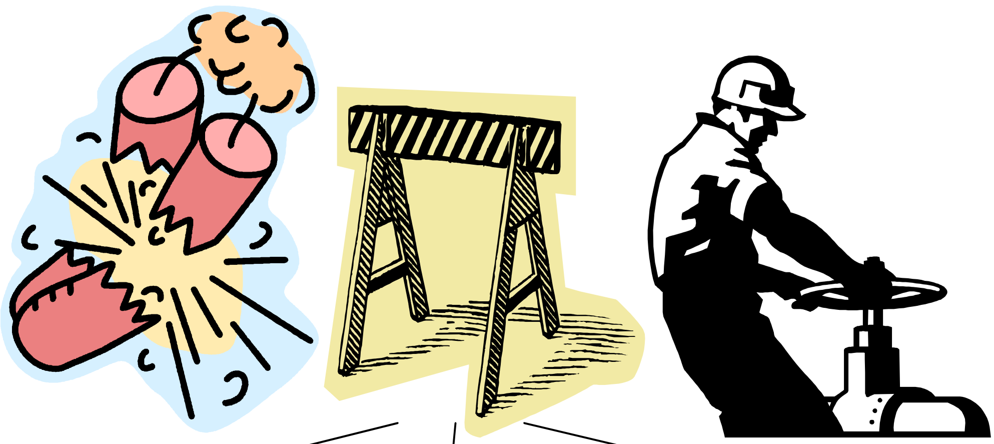
15 Safety audits

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.

16 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.

Hazard **Barriers** **Target**



<u>Physical</u>

- Use of Q/D
- Siting requirement
- Facility design to prevent secondary explosion

<u>Administration</u>

- Process Hazard Analysis
- Procedures
- Management of change
- Training

<u>Management</u>

- Direct Supervision
- Management oversight
- Industry and Regulatory oversight

16.1 <u>Administrative Barriers</u>

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 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.

16.2 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.

16.3 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.

17 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?

Change Analysis

- 13 changes identified
- Each considered for relevance in the credible scenarios
- Used to support the probable scenario

18 Root and Contributing causes analysis

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**
  - Hazard study was inadequate
  - Training programmes inadequate

- OI’s inadequate or not available
- Insufficient safety distances
- No systematic auditing/inspection programme
- Employee participation programme inadequate

- **Contributing cause**
  - Oversight by regulatory organisations inadequate

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

19 Recommendations

19.1 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.
  - 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:
    a. foreign objects in raw materials;
    b. use of substitute raw materials;
    c. specific handling requirements for raw materials;
    d. impact by tools or equipment;
    e. impingement;
    f. friction;
    g. sparking; and
    h. static discharge.
– 10. The following issues are addressed in plant design or modification:
    a. Operations in explosives manufacturing plants are separated by adequate intraplant distances to reduce the risk of propagation
    b. Unrelated chemical or industrial operations or facilities are separated from explosives facilities using quantity-distance guidelines.
    c. Facilities are designed to reduce secondary fragmentation that could result in the propagation of explosions.

19.2 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.

19.3 Nevada Occupational Safety and Health Enforcement Section

Increase the frequency of safety inspections of explosives manufacturing facilities due to their potential for catastrophic incidents.

19.4 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.

20 Melt/pour incidents elsewhere.

The following explosions 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.

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 exhaustventilation 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

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 nonsparking screwdriver with a rawhide mallet 2 Fatalities Joplin, Missouri

By the Chemical Safety and Hazard Investigation Board**.**

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