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The Pepcon Plant Fire/Explosion: A Rare Opportunity in Fire/Explosion Investigation *

by K. R. Mniszewski**

Abstract

On May 4, 1988, a fire occurred in a large ammonium perchlorate (AP) plant located in Henderson, Nevada. The fire quickly spread through most of the facility by means of thermal radiation, fire brands, a continuous (linear) source of fuel and some natural self-propelled missiles. Two large explosions occurred during the fire, each on the order of a few hundred tons energy equivalent of TNT, claiming two lives, injuring 372 people, and damaging plant buildings as well as buildings in nearby residential areas.

During the early stages of the plant fire, a television tower maintenance crew atop a nearby mountain noticed the event and recorded most of it on videotape. The video record is unusual, spectacular, and a rare opportunity in fire/explosion investigation. It shows details of the rapid plant fire spread sequence, much of which occurred too quickly to be accurately recorded by any other means.

The videotape permitted advanced investigative fire reconstruction techniques, such as super imposing CAD outlines of the plant on the video records, using the same perspective. Various other engineering analyses were conducted for the effort as well. Timeline analyses (from witness and other accounts) aided in determining the complex sequence of events leading up to ignition, as well as the sequence of flame spread. Thermal radiation heat transfer calculations aided in determination and confirmation of flame spread theories. Explosion dynamics estimates aided in determining the locations of the initial small explosions and estimating the amount of product involved in the large explosions.

Possible causes of the accident are listed, though the official cause is still undetermined. Conclusions are listed regarding major factors involved in the ignition and extreme rate of fire spread.

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DESCRIPTION OF PEPCON PLANT AND PROCESS

The Pepcon plant was an ammonium perchlorate manufacturing facility located about 10 miles southeast of Las Vegas within the town of Henderson. The product is produced primarily for government contracts for solid propellant fuels for military missile uses, as well as for the NASA Space Shuttle boosters.

A plan view of the plant is shown in Figure 1. The manufacturing process was composed of a four-step batch process. These steps included: (1) the electrolytic oxidation of sodium chloride to sodium chlorate, in the chlorate building, (2) the electrolytic oxidation of sodium chlorate to sodium perchlorate, also in the chlorate building, (3) reaction between the sodium perchlorate and ammonium chloride to produce ammonium perchlorate, in agitator tanks within the process building, and (4) AP crystallization, filtration, drying, screening and blending to client specifications in several buildings, including the crystallizer room, the large dryer building, the small dryer building (batch house) and the blender building.

The quantity of AP within the plant grounds was estimated at 8.5 million pounds. The

bulk of this was stored in large aluminum tote bins, each holding a few thousand pounds, as well as 55 gallon plastic drums, each holding about 550 pounds. Product storage was throughout the plant, though the main bulk product stored in tote bins were in storage fields located east of the process buildings.

Product particle size ranged from a nominal 90 to 400 microns, depending on the batch made to order, though the bulk stored was of a nominal 200 micron size.

Other hazardous materials utilized in the process included nitric acid, hydrochloric acid, and anhydrous ammonia in bulk quantities.

The plant occupied about 8 acres. Most process buildings were steel frame with light fiberglass corrugated siding. Nearby occupancies included an adjacent marshmallow factory, and residential and commercial buildings within 1.5 miles.

FIRE/EXPLOSION RECONSTRUCTION ANALYSIS

Fire/explosion reconstruction analyses were undertaken utilizing photographs, video tapes, statements, and depositions. A most useful technique was the videotape analysis, using superimposed CAD imag-

ing of the plant layout to determine the location of buildings and other items. To accomplish this, a CAD model of plant structure "skeletons" was first developed from drawings of the plant. Secondly, photographs were taken from the same mountaintop where the videotape was taken, utilizing the same angle lens. This confirmed estimates of the exact field of view from the mountaintop. Thus, CAD-created slide outline overlays of structure skeletons were developed for each general videotape viewing angle. Using this technique, the location of fire spread and explosion events could be estimated at any point in time on the original video, even when the scene was obscured by smoke and flames.

Figure 2 illustrates the method utilized for overlaying CAD images on a video screen using a conventional slide projector. Of course, with the proper computer equipment, CAD images could be digitally superimposed upon a video image.

Probable Origin

The fire reportedly originated in or around the southeast corner of the small dryer building batch house.

The origin of the fire was most likely in a layer or drum of contaminated AP located

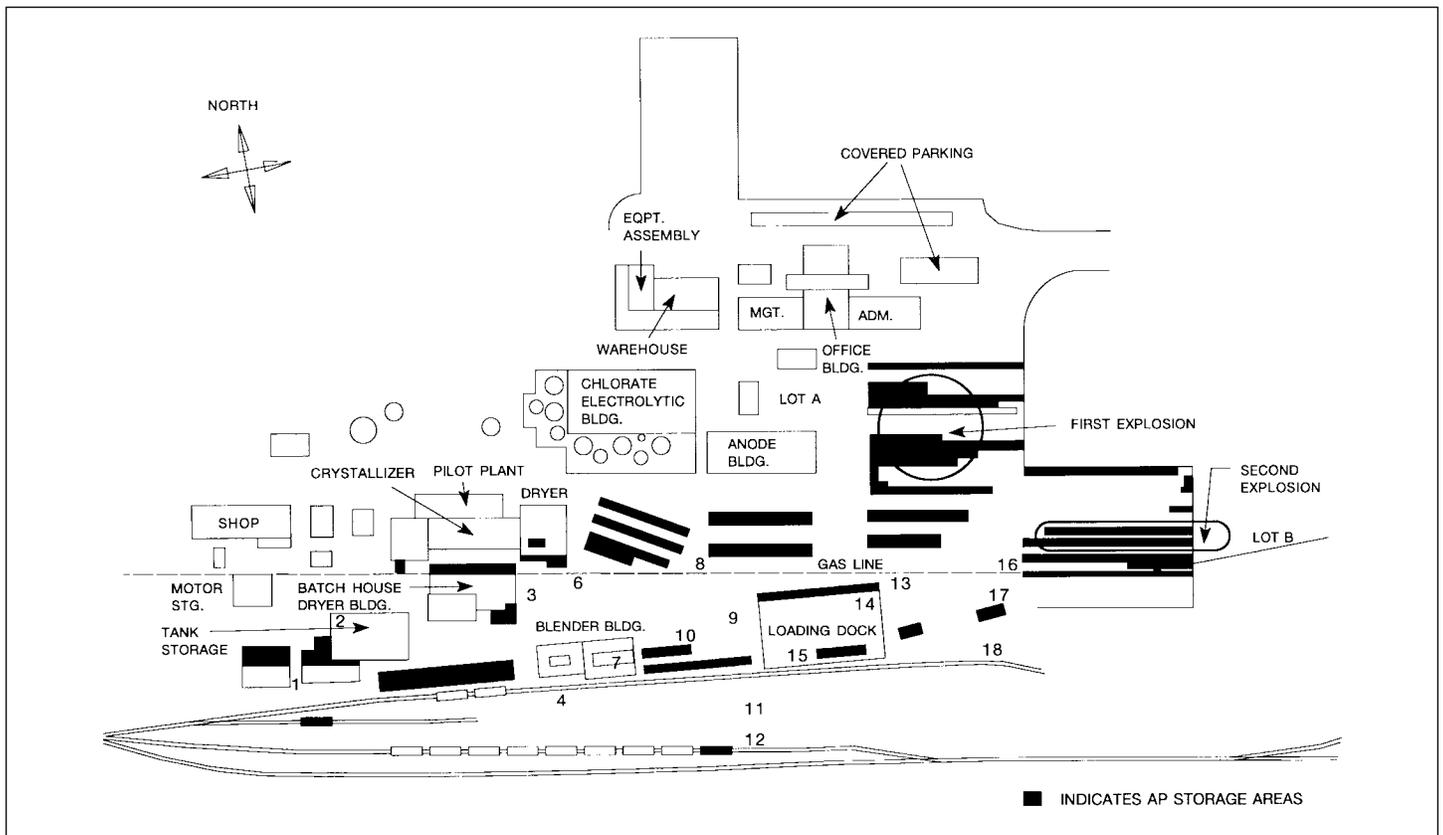


Figure 1. Pepcon Facilities and Features Map

in the batch house (southeast corner) or adjacent to the batch dryer in the batch dryer building. Early sightings of burning drums in such areas gives credence to that theory of origin. Also, a worker noted a fire on top of a tank in the batch house, while noting the fire in the northeast corner of the batch dryer building. Early sighting of smoke from process batch eaves supports this. Given the wind conditions through this wide open building, the most likely origin is on the tank in the batch house.

Many of the early exterior fire sightings indicated the presence of fire on the upper exterior north side of the building. The only plausible scenario to achieve this is for an AP barrel to ignite, jetting its flames upwards for some time, thus igniting the fiberglass siding and dryer insulation.

One worker made very early observations of a fire in the interior corner of the batch dryer building behind the dryer. He noted fire up against the wall burning on a purlin from inside a drum, and going up the side of the wall. At first the batch dryer was not on fire. Then the fire spread to the batch dryer insulation.

One worker observed fire in drums in front of the dryer, which another worker was trying to fill with water.

Several workers made an early fire observation of a burning poly drum in the southwest corner of the batch dryer building, in the batch house. Several noted red globs spewing from the burning drum, at the southwest corner. One noted the drum burning like a rocket engine with flames at least 15 ft. high, and perhaps up to the ceiling. It is suspected that the two burning drums were ignited by means of flaming particle transmission through a wall opening or door opening, aided by wind currents. It is assumed that the drum in the batch house ignited first, because the wind direction favors that scenario. Also, early smoke observations through the center batch house building roof favor such a scenario.

Other sensitive areas where ignition could have occurred include dust accumulations on purlins or floors, though the early sightings of the burning tank and drums favor them as the origin.

Probable Causes

The most probable cause is slag from welders' cutting torches. Witness accounts of welders' activities fit the time frame well.

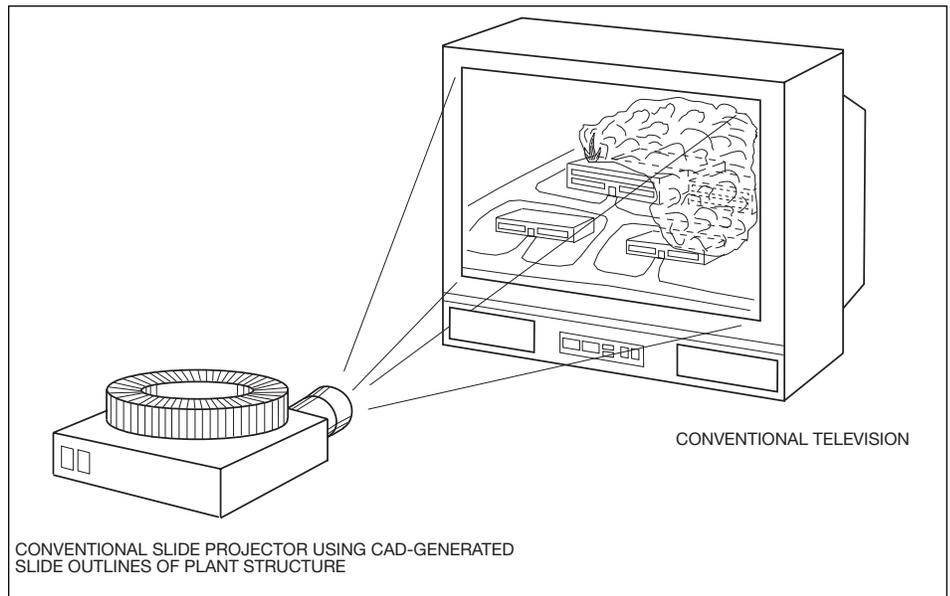


Figure 2. CAD Superimposition Process

Hot slag is a good ignition source for contaminated AP, and wind conditions were sufficient for lofting particles a distance from the cutting site. The cutting location was less than 60 ft., away from the most likely site of origin. The wind at that time was quite strong at 17 mph from the southwest, about 210 to 240 degrees. Strong wind currents are assumed to have existed within the building as well, since it was fairly wide open. A lofted particle (hot slag or burning AP) traveling at a wind speed of about 17 mph (25 ft./sec.) need only stay luminous for a few seconds to remain as a viable ignition source. A layer of contaminated barrel of AP without a lid is a perfect material for ignition (i.e., it is documented that contaminants such as rust, other metal oxides and organics render AP very sensitive).

A plant worker stated that many fires have occurred in the past due to welders' slag contacting contaminated AP. Several workers had stated an account of a similar incident occurring in the batch house, resulting in a tank insulation fire. An analysis of plant fires at Pepcon indicated that welding/grinding operations were the chief cause of past fires in the batch house, batch dryer building and the dryer building. About one fire incident per year was attributed to welding equipment at the plant.

A less probable cause is friction or impact ignition of sensitive product (i.e., contaminated AP) at the batch dryer equipment. Several fires have occurred in the past in this area (dryer insulation, belt friction, etc.). A previous fire at the batch dryer was due to overloaded conveyor belt friction. Early

accounts of smoke sightings through the roof of the batch house, at the same time that others have noted that the batch dryer was still operating, make these scenarios less probable.

Another less probable cause is self-heating ignition of sensitive material (i.e., contaminated AP mixed with oil-soaked desiccant). Maintenance workers used old desiccant to absorb oil spills. Perhaps such oil-soaked desiccant was disposed of in AP sweeping drums. Since no testimony has indicated such an incident in the past, the probability is assumed to be low.

Other low probability causes include overheated motors, electrical faults, presence of a gas leak and other chemical reactions. These causes have been ruled out by various fire consultants. The batch dryer motor was also suspect since it was worked on the morning of the accident.

Fire Spread In The Dryer Building

Two early observations indicate fire shooting along the floor from the north to south inside of the batch dryer building interior. This may be due to a burning drum falling over and jetting along the ground. This may have enhanced the speed of the early fire spread to other AP sweepings drums and fiberglass wall panels. A swirling flame was seen along the floor by several witnesses and may have been due to a vortex caused by the high wind conditions or horizontal jetting along the floor.

The drums involved in ignition and early fire development are assumed to have no lids. This was said to be a common occurrence

in that area. One worker stated that two drums were under the dryer at the time with lids on loosely. At least one had AP sweepings in it.

Materials which aided in early fire development include the poly drum of AP under the dryer, four other poly drums with AP sweepings, stacks of empty poly drums and lids in the northeast corner, fiber glass wall panels, and fiberglass dryer insulation.

The light fiberglass wall panels are a significant factor, having extremely high flame spread characteristics.

Reports of flames appearing early on the asphalt outside of the batch dryer building at the northeast corner are assumed to be due to melted plastic from melted poly drum lids and drums, draining out of the building. Some of the asphalt may have been burning as well (if contaminated with AP after softening). The building was designed so that it could be hosed and drained through the wall/slab lap interface openings. Drum lids and empty drums were stored in the northeast corner of the building. Wind pressure may have enhanced this effect. Such a phenomenon explains the difficulties experienced by one worker trying to extinguish the fire. Photos of the aftermath show a blue plastic residue in that

area, with evidence of melted plastic flowing through the building lap joints.

The north wall of the batch dryer building was the first exterior wall noted to burn through. AP poly drums on the outside may have ignited before the wall burned through by means of burning/melted plastic flowing out of the slab interface.

**Fire Spread Throughout The Plant/
Timeline Analysis**

A time line diagram of fire spread through the plant has been constructed and is shown in Figure 3. It illustrates the early ignition sequence, early fire spread in batch dryer and process buildings, initial small explosions, the complex spread of fire throughout the remainder of the plant, and the two major explosions.

A series of sketches, representing some snapshots of intense fire progress at various times, are shown in Figures 4a through 4e.

The most dominant fire spread was north/northeast due to wind direction, location of easily ignited AP poly drums, the close proximity (25-30 ft.) of crystallizer/dryer building walls and associated stacked poly drums alongside it (see Figure 4a). The fire continued to spread in east/northeast di-

rections following the rows of poly drums to the main bin/drum storage areas.

Flame plumes along the poly drum flame front reached heights of about 100 ft. during travel away from process buildings (Figures 4b and 4c), and as high as 200 ft. as it neared the main storage lots (Figure 4d). For a brief period of about 10 seconds, the fireball swelled to about 270 ft. in diameter as flame fronts coalesced, right before the first major explosion (Figure 4e). Thermal radiation from such extraordinary flame plumes was a major factor in the rapid fire spread throughout the plant. Fire spread from the east end of the dryer building to the poly drum storage at the eastern end of areas 16 and 17, in less than three minutes, resulting in an average easterly flame front speed of about 3.5 ft./sec.

Fire spread west through the process building was by means of fiberglass wall panels, poly drums, AP contamination, etc. The fire did spread west outside of the building and the crystallizer building and the Area 2 poly drum storage. Fire damage did not occur in the far west area of the plant where maintenance buildings were.

Fire spread southeast to the blender building was through drum storage at the south-

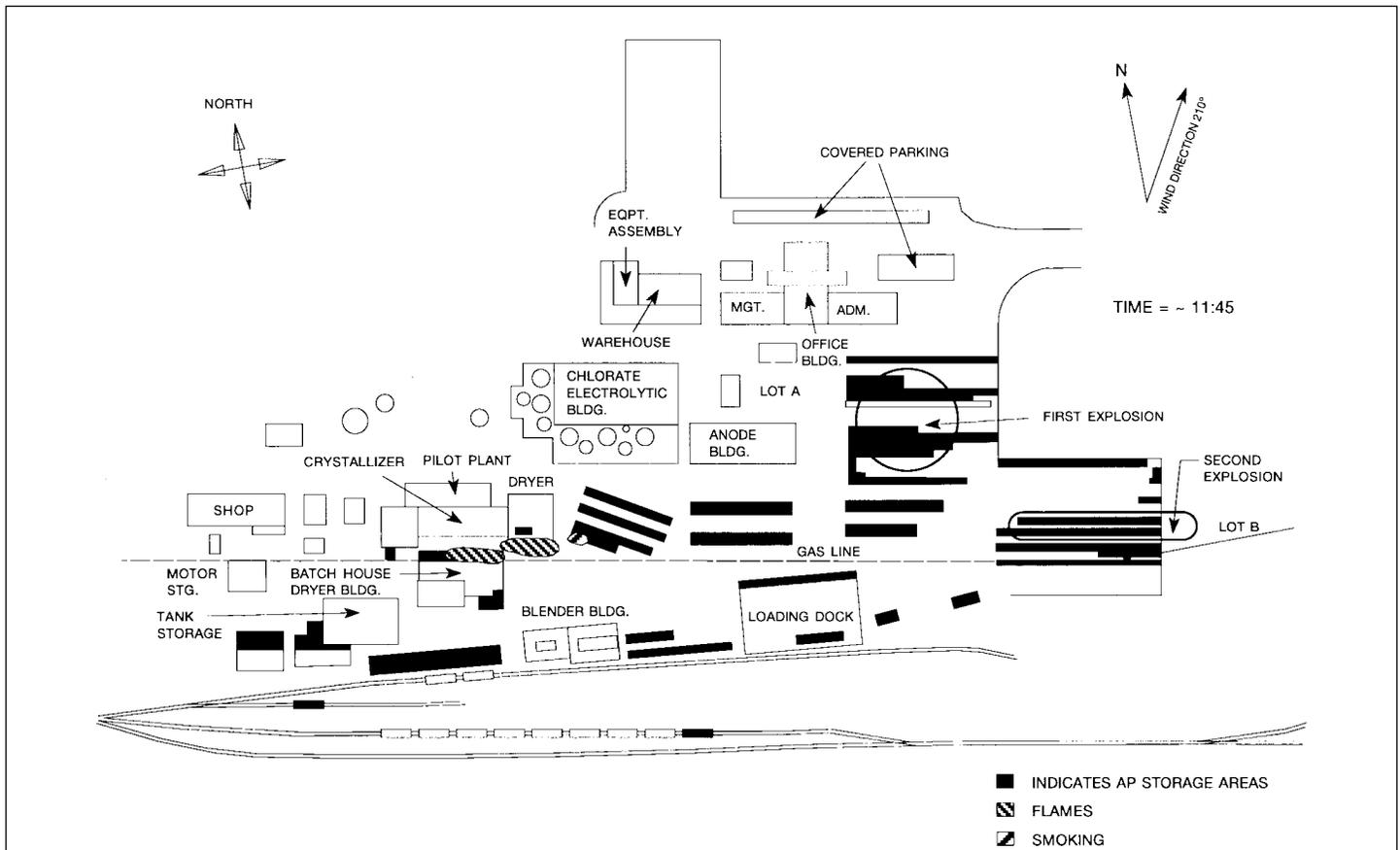


Figure 4a. Pecon Fire Progress at 11:45 A.M.

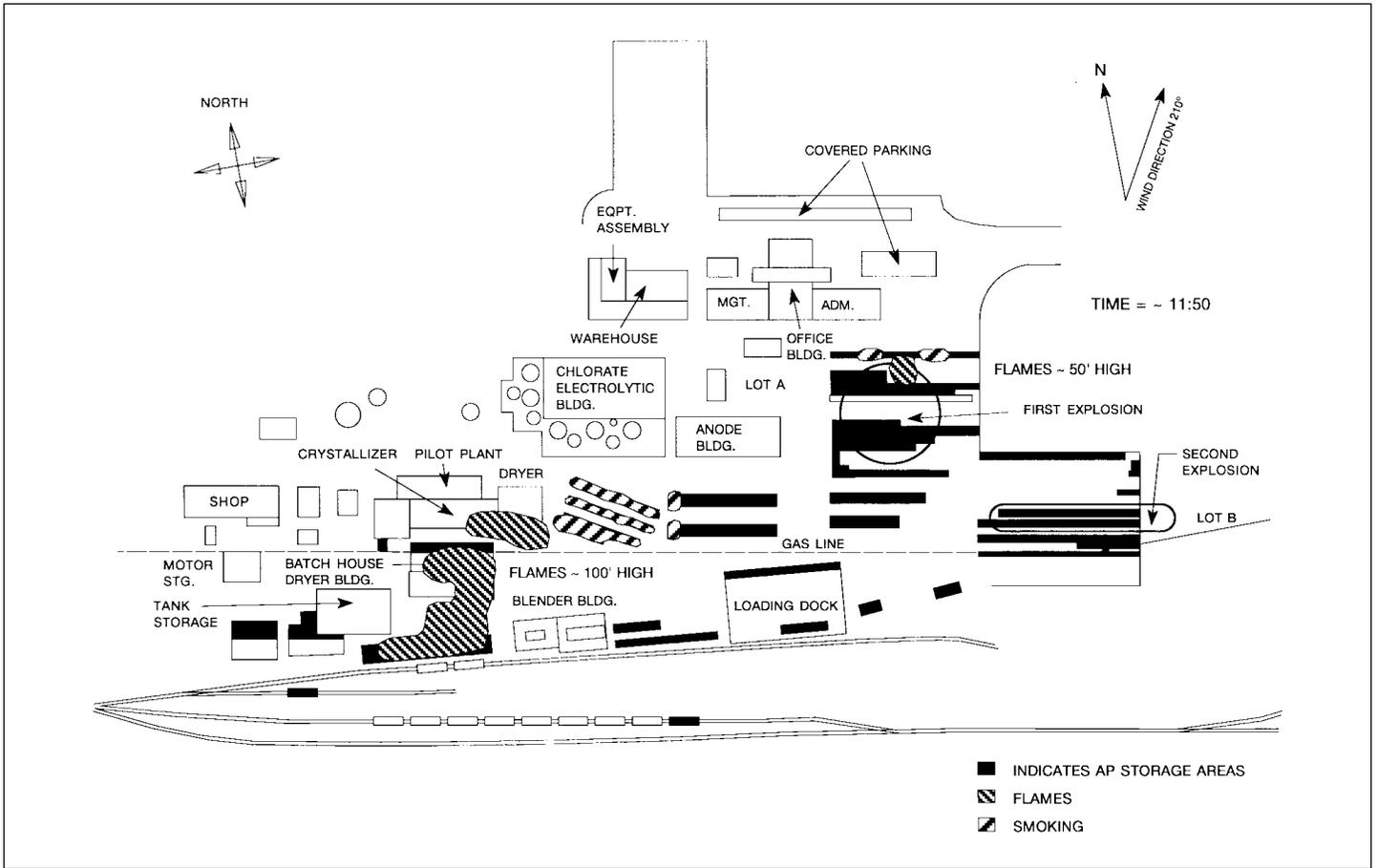


Figure 4b. Pepcon Fire Progress at 11:50 A.M.

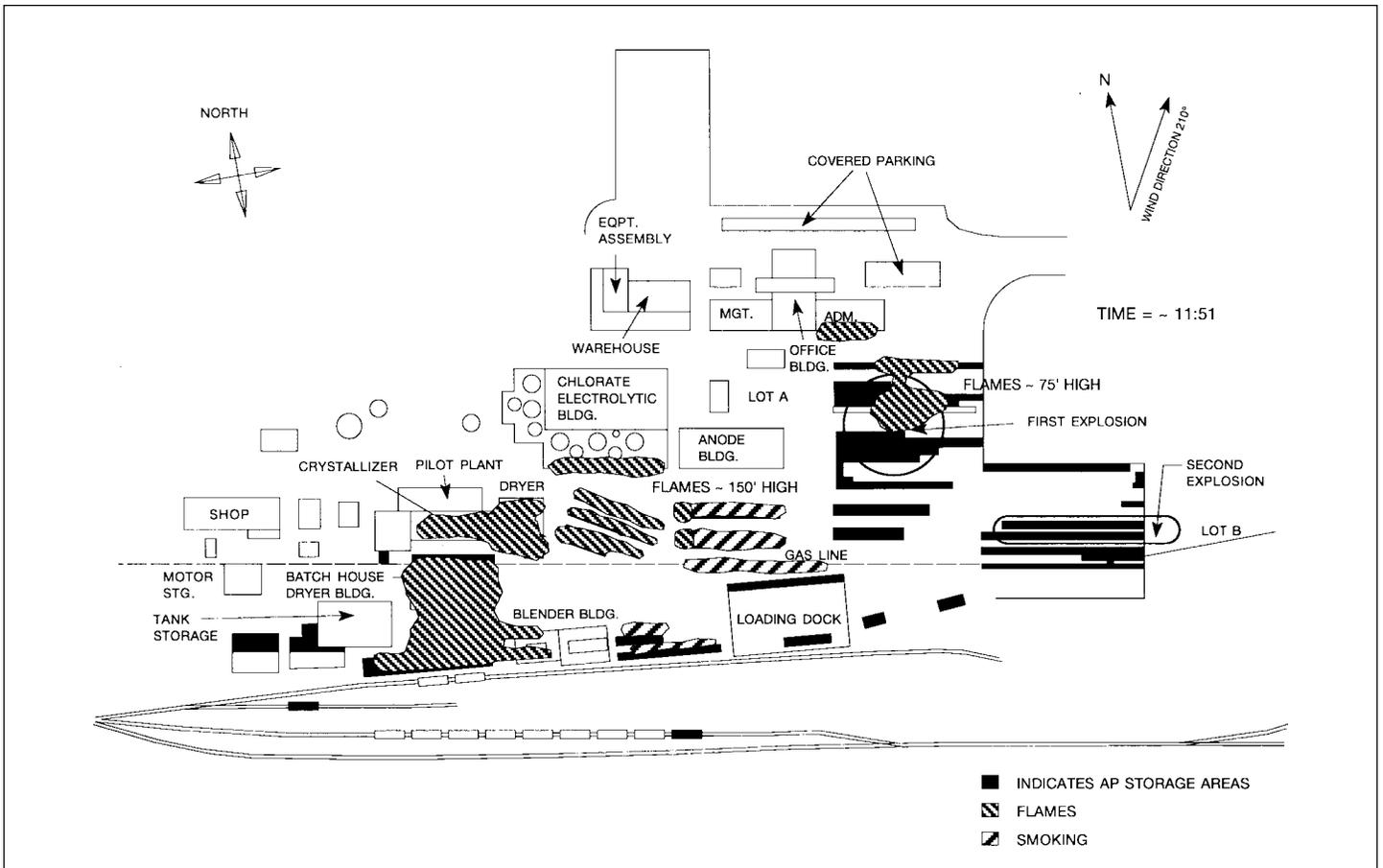


Figure 4c. Pepcon Fire Progress at 11:51 A.M.

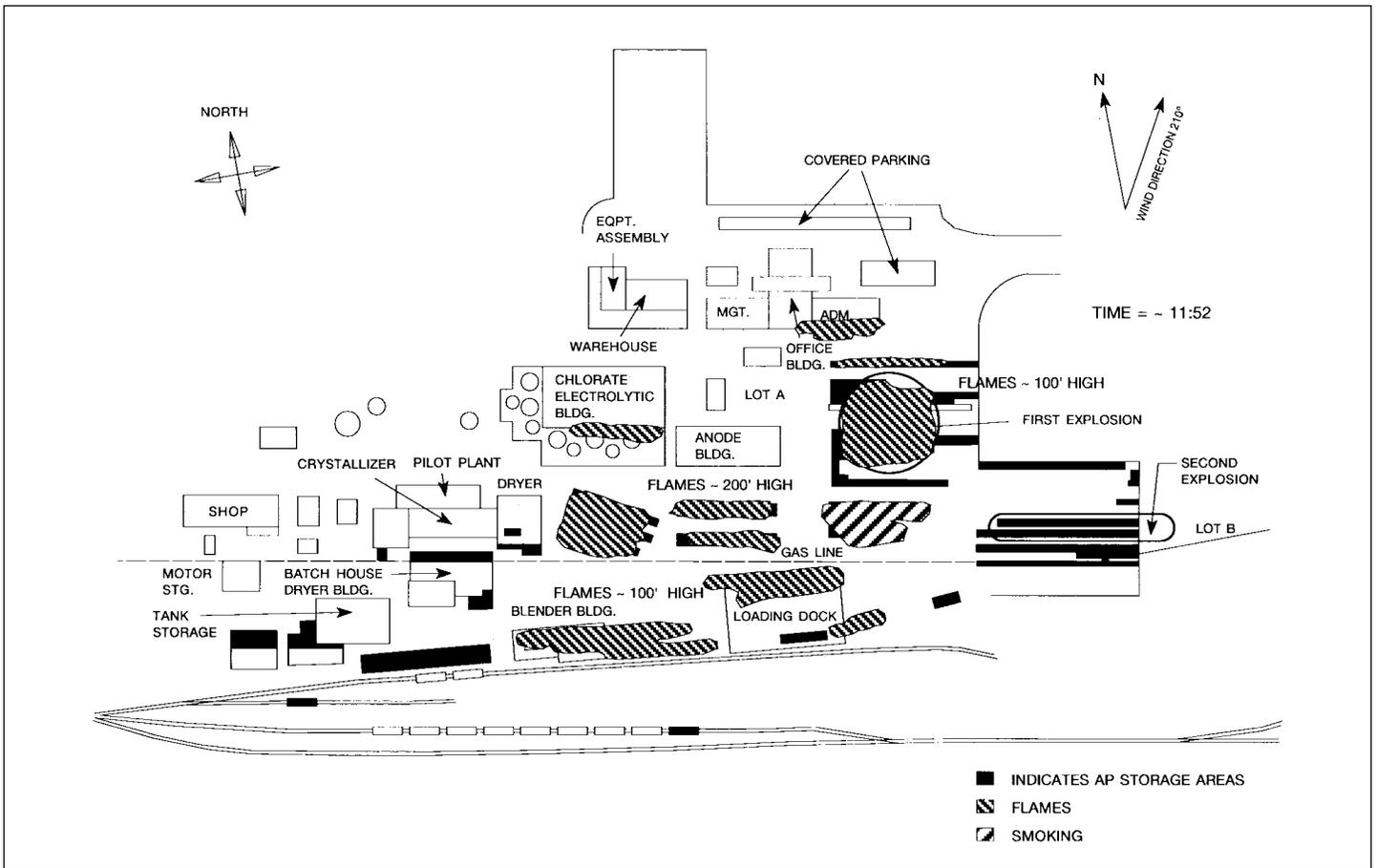


Figure 4d. Pepcon Fire Progress at 11:52 A.M.

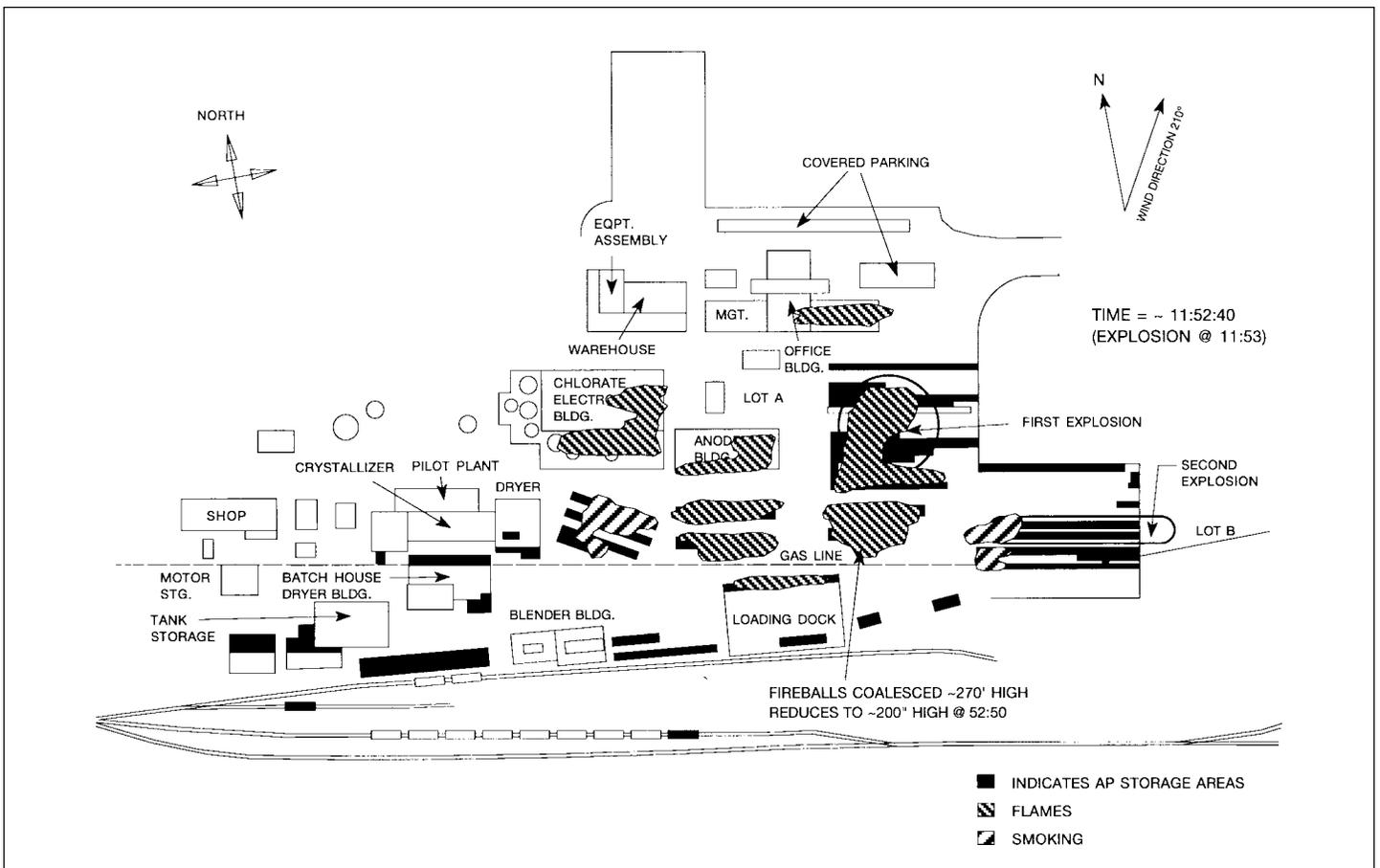


Figure 4e. Pepcon Fire Progress at 11:52:40 A.M.

east corner of the batch dryer building and close proximity of the blender building (30-40 ft.).

Fire spread to the south (against wind direction) by means of fire brands, rocketing poly barrels or thermal radiation, into the reprocess storage drum field (60 ft. away), which provided an extremely intense early fire.

An unusual factor of significance in plant fire spread was the early rocketing of AP poly drums and cell cans across the plant, acting as fire bombs. Early photographs of fire development show this phenomenon (see Figure 5). One major fire at the northeast corner of the plant, just south of the office/administration buildings, at the far end of the Lot A storage field is assumed to have been started in such a manner. One worker witnessed the "popping" of drums along the north wall of the batch dryer building early in the fire development. Others described the flight of drums across the plant, and a large fireball that landed near a building. Others describe early fire appearing near the office buildings, far from the dryer buildings.

Another factor of significance in the plant fire spread was large firebrands lofted by high plume currents in the larger flame plumes. This is clearly evident on the video tape.

The occurrence of the initial explosion in the plant also hastened early fire spread through that section of the plant by means of blast wave dispersal of burning fragments.

Initial Explosions

Several small explosions or "pops" occurred before the two large explosions in the storage fields. Initiation of the first small explosion occurred in or near the batch dryer, within the batch dryer building. This explosion is thought to have originated in the batch dryer. Since several close observers were not knocked down or hearing impaired during this explosion, it is surmised that it was not a detonation, and probably was an AP deflagration pressure rupture of the batch dryer (due to external heating of the dryer, and subsequent AP decomposition gas buildup). A worker within 12 ft. of the batch dryer claimed he heard a hissing sound prior to the explosion and then saw the cover of the batch dryer fly off during the explosion. From a distance, this explosion probably sounded as a "pop". The time of this event was approximately 11:50.

A more significant explosion is noted slightly later in the same area at about 11:50



Figure 5. Early fire development.

(from numerous testimony). This explosion shook the administration building and knocked down ceiling tiles and light fixtures. Most observers describe the location of that blast as southwest of the administration building, or near the batch dryer building. Assuming a blast overpressure of about 1 psi necessary to cause such effects in the administration building at a 500 ft. distance, a detonation of several thousand pounds of AP is necessary.

A small crater was reported in the northeast corner of the batch dryer house. This may be the location of the explosion.

This early explosion (not on the video tape) was a significant factor in early fire spread since burning particles (presumed to be fiberglass particles) were raining throughout the area after its occurrence.

Major Explosion Occurrence And Propagation

Two major explosions occurred during the incident.

Initiation of the first major explosion at 11:53 occurred in Lot A, just south of the Administration Building. This field had been burning and subjected to intense radiant heating prior to initiation. Blast wave propagation velocity, from the video records, is consistent with that developed from a few hundred tons of TNT equivalent explosive. Bins, drums and fiberglass bags in Lot A were involved in a sympathetic detonation at that location. Analysis of a topographic map of the post accident site showed

cratering in rows 3-13 of that lot, with deepest cratering along row 12.

Immediately after this explosion (about 1.11 sec. later) a second explosion occurred in the crystallizer/dryer building, and a third explosion (about 1.14 sec. later) occurred in the chlorate building.

A Sandia report (Reed) states that the first major explosion was preceded by a fuel/air explosion. However, this phenomena has not been verified.

Several small bin/drum explosions occurred prior to the second major explosion. At 11:55:23.81, a small explosion occurred in Lot A. At 11:55:31.71, an explosion occurred near or on the loading dock. Five seconds later (11:55:36.87), another explosion occurred on the same loading dock. Another small Lot A explosion occurred at 11:56:54.54.

The second major explosion occurred at about 11:57 in Lot B, at the southeastern end of the plant. Initiation appears to have occurred at the northeast end of that field, judging from the video tape record and a cursory study of fragment patterns. Blast wave propagation velocity, from the video records, is again consistent with that developed from a few hundred tons of TNT equivalent explosive. Analysis of a topographic map of the post accident site shows cratering and severe ground disturbance throughout the lot, with the deepest cratering along rows 18-35. A Southwest Gas transmission line buried under the storage field ruptured during the severe

cratering of this explosion, resulting in a large post explosion flame plume.

The initiation of the AP in these explosions is thought to be of a thermal nature, since there is no evidence of any other means. Significant preheating of storage fields by radiant plant fires enhanced the probability of initiation and tendency to sympathetically detonate the storage bins and drums. Mixing of dispersed AP with fuels such as asphalt and polyethylene may have produced a much more sensitive explosive than AP alone.

ANALYSIS OF ACCIDENT PHENOMENA

Combustion and Explosive Properties Of AP

AP undergoes combustion at a temperature of about 440°C (824°F). However, it will not necessarily burn by itself at atmospheric pressure. In a review of AP combustion phenomena (Jacobs), it is noted that incident radiation levels of about 10 cal/cm²-sec (418 Kw/m²) are necessary for combustion of AP at atmospheric pressure, without contaminants. This level is on the order of that achieved with flame impingement or very close proximity to a large radiant flame plume. Thus, uncontaminated AP is not expected to burn by itself except when surrounded/impinged by flames or radiated upon by flames.

When small amounts of contaminants such as fuels, metal oxides, etc., are added to AP, combustion becomes much more easily self-supporting at atmospheric pressure.

Detonation properties of AP are best described by Price. It is a Group 2 type explosive, which means it does not follow classical explosive material behavior properties (i.e., its behavior is more ideal at low densities than high densities). Its sensitivity is considerably less than TNT, and can be ranked slightly less than commercial ANFO, but greater than slurry explosives. The critical diameter of 200 micron AP is about 5-6 inches. Its experimental detonation velocity is about 5248-13,120 ft./sec. depending on the charge size. Experimental detonation pressure is about 23 Kbar.

The addition of small amounts of contaminants such as fuels, metal oxides, etc. to AP can increase its sensitivity greatly to that of conventional explosives such as RDX. Thus, from a fire/explosive safety viewpoint, it is vital to avoid the contamination of AP.

Combustion Of Plant Fuels With AP

There are four general fuels (aside from AP) within the plant which played a significant role in the fire: fiberglass building panels, polyethylene drums, bulk fiberglass bags, and asphalt pavement surfaces. Quantities of those fuels consumed in the fire were estimated (Merrill) as:

FUEL	QUANTITY
<i>fiberglass siding</i>	<i>22,000 lbs.</i>
<i>poly drums</i>	<i>365,000 lbs.</i>
<i>asphalt</i>	<i>40,000 lbs.</i>

Fiberglass wall panels played an important role in early fire spread due to its low ignition temperature and high flame spread characteristics, though little fiberglass/ AP combustion is assumed to have occurred. However, much AP/asphalt and AP/polyethylene combustion has obviously occurred in the accident. Due to the dispersive nature of AP decomposition and the low melting point of polyethylene and asphalt fuels, it is easily seen that intimate mixing is possible. High flame temperatures (4940°F) are possible with such mixtures.

Combustion of AP/poly drums is a significant combination. The stoichiometric mass fuel/oxidizer ratio of an AP filled drum is about 1:9, which is 122% oxidizer rich. Two hundred and twenty five (225) lbs. of AP is necessary to achieve a balanced combustion of a polyethylene drum. Thus, one would expect such combustion to proceed violently, like a roman candle, as polyethylene melts and diffuses and wicks into the AP. Some AP should be left over due to excess oxidizer. In some areas, "pillars of salt" were seen to be still standing. In these cases, when the plastic fuel is spent and incident radiation levels are too low to support the AP combustion, the reaction dies out. Thus, an exterior fire on a poly drum may actually keep the interior AP cool, due to the latent heat of the polyethylene layer, till the layer is spent.

A similar stoichiometric ratio exists with asphalt and AP. since the stoichiometric mass fuel/oxidizer ratio is about 1:9, only a thin layer of melted asphalt is necessary for balanced combustion with dispersed AP. However, asphalt pavement is actually only about 25% asphalt (i.e., remainder is rock). So, about 1/2" asphalt pavement thickness is estimated as necessary for complete combustion of each inch of AP layer, assuming similar densities.

Bulk polypropylene bags are a fuel quite similar to polyethylene. Bag weight was

estimated as 33 lbs. each, from a description of its components. The stoichiometric mass fuel/oxidizer ratio of an AP filled poly bag is about 1:9, which is 752% oxidizer rich. Two hundred and ninety (290) lbs. of AP is necessary to achieve a balanced combustion of a polyethylene drum.

Plastic desiccant holders in the aluminum bins may have played a significant role. These include two 6" diameter PVC tubes installed in one type of bin and a 2 lb. plastic net installed in another type of bin. These fuels certainly add to the overall fuel/oxidizer load and may have served to enhance the early fire spread through the bin storage fields.

Steel/iron in building structures was burned in some locations, according to post-accident descriptions of the site. This is evidence of extremely high flame temperature in some areas. AP probably aided in the combustion of those materials. It is not assumed that iron/steel combustion contributed significantly to the fires because of the relatively low mass of that material consumption.

Aluminum bins do not appear to be a relevant fuel, except in the fully developed stages of the fire where fuel/AP flame temperatures were hot enough to exceed the melting point of the aluminum oxide coatings (3716° F).

Most of the aluminum is expected to melt and run down to the ground rather than combust. Verneker indicates that AP combustion flame temperatures (1652-1787°F) will not initiate aluminum in the same mix, even when the aluminum is in particulate form. Some other fuel is necessary to raise the flame temperature high enough to melt the aluminum oxide coating (3716°F, Markstein). Also, Verneker indicates that aluminum particles larger than 100 microns do not participate in the AP/Al reaction. Therefore, without the presence of other nearby fuels, aluminum bins filled with AP should not burn intensely even when exposed to high incident radiation. Rather, the aluminum should melt away, and AP should disperse, smoke and partially burn like a weak propellant.

Thermal Initiation Of AP Detonations

Radiant heating calculations showed that significant preheating of drums/bins in Lots A and B had occurred before initiation of detonation. Calculations consisted of a radiant flame plume model coupled with a

one dimensional conduction heat transfer model of a bin. Due to the bins' large bulk and orientation with respect to flame plumes, an assumption of modeling the bin as a semi-infinite solid was taken as adequate.

Emphasis was placed on model of aluminum bins in center row of Lot B. The model allowed for two advancing flame plumes and changing plume shape. Rectangular plume shapes of constantly changing size and distance were utilized. Thus, simple radiation shape factors out of any heat transfer text could be utilized for this geometry. The heat of fusion was utilized to estimate melting effects of the aluminum bins in the semi-infinite solid conduction target model.

Forced convective cooling from the wind was included. The radiation temperature of AP/asphalt AP/polyethylene was estimated, since experimental data is not available. This temperature was conservatively estimated as 314°F, which is about 25% higher than the "effective" radiation temperature of the fuel alone (25% is a typical increase with balanced fuel/oxidizer combustion with hydrocarbons). The actual flame temperature is much higher; the "effective" radiation temperature is that estimated assuming theoretical black body radiation.

Results of modeling the 3 minute period before the first explosion indicates aluminum bin melting at the western boundary, together with AP deflagration temperature zone (824°F) down to a depth of about 1/2". Middle lot location results indicate high aluminum bin temperatures, beginning to melt, but AP deflagration temperature zone is about a 1/4" depth. East end lot location results indicate significant heating of AP only at aluminum skin boundaries (600°F).

Actually, before aluminum skin melts on a filled bin, the bin should hydrostatically burst, due to the products of AP pyrolysis reactions pressurizing it. The bin has an approximate burst pressure of about 5-6 psig. Any heating of an AP layer above 440°C (824°F) is likely to result in pressure buildup due to the production of decomposition gases. As pressure is relieved, only burning is possible within the bin and much AP is then dispersed outside of the bin due to the turbulent relief of gases.

Dispersed AP settled on melted/vaporizing asphalt and polyethylene fuels. When properly mixed, this mixture will form an extremely sensitive mixture which is much

easier to initiate to detonation than AP itself. Thus, the likely initiation mechanism for the explosions is that of an AP/ fuel thermal initiation. The critical thickness for such a mixture is very thin, about 1 cm or less.

Tote-bin thermal initiation calculations, based on Frank-Kamenetskii theory (Bowes), showed that the outer surface of a large AP cube with the dimensions of a tote-bin, steel drum or poly drum need to be brought to a temperature of about 700°C (1292°F) for about 100 sec. to achieve burning/deflagration/detonation. This is only possible from either direct flame impingement or very close proximity to high thermal radiation. This is significant, in that the accident time frame supports this. The first major explosion occurred after a 2-3 minute exposure of bins/drums to flames. However, it is believed that the stimulus for the detonations was overheated fuel-contaminated AP.

The radiation/conduction model described above was also exercised for the case similar to that of a DOT test with a substitution of hydrocarbon fuel instead of wood. Several such tests in the past have shown that such a scenario will result in a low order detonation after a period of about 20-30 minutes. Results indicate that it takes about 20 minutes to achieve critical deflagration temperatures in a 2.5" thickness. However, it is not known what the critical thickness of AP is at these temperatures.

Sympathetic Detonation Propagation

Two major explosions occurred during the incident.

Initiation of the first major explosion at 11:53 occurred in Lot A, just south of the Administration Building. This field had been burning and subjected to intense radiant heating prior to initiation. Blast wave propagation velocity, from the video records, is consistent with that developed from a few hundred tons of TNT equivalent explosive. Bins, drums and fiberglass bags in Lot A were involved in a sympathetic detonation at that location. Analysis of a topographic map of the post accident site shows cratering in rows 3-13 of that lot, with deepest cratering along row 12.

The second major explosion occurred at about 11:57 in Lot B, at the southeastern end of the plant. Initiation appears to have occurred at the northeast end of that field, judging from the video tape record and a cursory study of fragment patterns. Blast wave propagation velocity, from the video

records, is consistent with that developed from a few hundred tons of TNT equivalent explosive. Analysis of a topographic map of the post accident site shows cratering and severe ground disturbance throughout the lot, with the deepest cratering along rows 18-35.

Based on the inventory records, aluminum bins full of AP were involved in this sympathetic detonation.

Analysis of the explosive effects (damage to windows, etc.) by Reed has implied an estimate of the largest explosion yield of about 250 tons of TNT equivalent.

It was estimated that sympathetic detonation propagation velocity in the two explosions was about 10,000 ft./sec. At that rate, it traverses each field in about 30 milliseconds or the equivalent of one frame of video. Therefore, there should only be one main flash apparent on the video of each explosion, which was found to be true.

There is no question that the drums and bins can propagate a detonation (based on literature) to adjoining items when spaced only a few inches apart, as was the case in the storage field rows. However, there are some questions regarding propagation from one row to another, and across several rows (tens of feet).

A review of pertinent nonclassified literature is as follows:

Analysis of accidental detonations from the past (Kinney) result in a Q-D formula for estimating unprotected (or lightly protected) explosive items. From this expression, the 50:50 sympathetic detonation distance for 550 lb. drums is about 8.5 ft.; for 4500 lb. bins is 17.14 ft.

Cook's analysis is based on small scale test extrapolation and is not necessarily valid for metal fragments, since his theory is based on gaseous product wave initiation. His results indicate that the 50:50 sympathetic detonation distance for 550 lb. drums is 2.25 ft.; for 4500 lb., bins is 5.25 ft. (recommends spacing at twice that level). This analysis is not seen to be valid, from what we know presently.

Van Dolah conducted a large scale test program using AN (ammonium nitrate), a less sensitive material than AP. Test sizes ranged up to and larger than the 5000 lb. size.

Applicable 50:50 sympathetic detonation distances are as follows:

5000 lb. AN;	metal skin	35 ft.
5000 lb. AN;	PE skin	20 ft.
5000 lb. AN;	barricaded	7.5 ft.
500 lb. AN;	metal skin	9 ft.
500 lb. AN;	PE skin	7 ft.
500 lb. AN;	barricaded	4 ft.

Since AP is more sensitive than AN, one would expect the above distances to increase somewhat. Also, distances are expected to increase due to bin preheating (some tests by Van Dolah confirm this).

Video analysis of the second major explosion indicates that from the initiation point, the sympathetic detonation must span across 47 ft. to propagate across all rows. From the above discussion, it appears that this may be possible, especially since they were preheated.

The Role Of Natural Gas In The Accident

Three workers stated a belief that natural gas was a factor in the early fire. One (a) claimed that he smelled natural gas while fighting the fire. Another (b) claimed that he saw burning in the air, that is uncharacteristic of ordinary fires, and may be gas. One (c) stated that he thought there was natural gas leakage in the storage field, because when the explosion occurred, the asphalt disappeared; which he felt was not a natural phenomena characteristic of normal explosives. The claim (b) made is unfounded in that several observers have described the existence of burning particles in the air. Claim (c) is unfounded and based on an ignorance of explosion phenomena.

None of the other statements of plant workers described the odor of natural gas in the area prior to the accident, which is to be expected if it were a factor. Descriptions of natural gas leaks throughout the plant in the past are minimal and are what is expected in a large plant facility.

A theory was proposed that a gas leak migrated up through the drain lines at the northeast corner of the batch house building and through vent-like structures at foundation walls. In order for such a theory to be credible, a gas leak from the distribution line or house line near the batch dryer building is necessary.

Southwest Gas records indicated a drop in pressure prior to the accident, but attributed it to improper time calibration of

the recorders, as well as other factors. Readings at different stations indicated different times of pressure drop, which confirm that there was a time calibration problem. It was not possible to sort out from these records whether or not there was such a pressure drop.

Post-accident leakage testing by Southwest Gas, together with other parties, of the remaining portions of the pipeline running through the plant, indicated no leaks. However, leaks were found in the house line system. Leaks in the house line system are expected to occur after a serious fire or explosion.

Another testing phase, using helium leakage measurement, also revealed no leaks in the remaining distribution line.

A forensic firm (for Pepcon) conducted tests on portions of the remaining pipeline to test their "annular ring migration theory," that gas may have migrated from a failure in the distribution line in the crater area to the batch dryer building by means of the annular space between the pipeline and surrounding soil. Results showed the theory to be inappropriate. A diffusion theory is stated as more appropriate. Also, it was shown that asphalt has significant permeability, which does not support the theory of gas reservoir formation under the storage areas. The testing has shown gas dilution of several orders of magnitude within 100 ft. of a leak.

Extensive soil gas analysis on July 10, 1989 revealed no significant concentrations of methane above usual background levels. Slightly higher levels were found near the batch house, which were attributed to anaerobic bacteria due to ammonia in the soil from spills. Later testing, using a new Petrex test method, was inconclusive.

Gas distribution experts and gas reservoir experts indicate such a theory to be very unlikely. Gas migration from a leak is not a long distance phenomenon. The pavement above a leak may help to form an underground gas reservoir, though the path of least resistance is usually followed (which in this case would be to the south). Personnel would have smelled the gas throughout the plant (barring an odorization problem). Occasionally, gas does migrate along "annular pipe ring" spaces and enter building foundations, resulting in fires and explosions.

The possibility of heat transfer from the intense fire damaging the pipeline was analyzed using semi-infinite slab heat transfer calculations, similar to that found in any

good heat conduction text (Carlslaw). It was concluded that even with direct ground impingement of an intense fire, a pipeline buried 3 ft. or more under the ground will see virtually no heat.

Based on the above analysis, there does not appear to be any strong evidence of natural gas involvement in the accident.

HIGHLIGHTS OF PERTINENT SAFETY STANDARDS AND RECOMMENDED SAFETY PRACTICES APPLICABLE TO THE PEPCON FACILITY

Three documents represent the general state of knowledge of AP safety in standards and guides at the time of the accident: DOD 4145.26M, NFPA 43A, CPIA 394 and DOT (49 CFR 172). Some highlights of those documents, which are directly related to the severity of the accident, are as follows with relevant comments.

DOD 4145.26M:

- Classifies the bulk AP used by Pepcon as a 1.3 or 1.4 explosive, depending on whether it is stored in a shipping container or not.
- AP in poly drums is defined as a 1.3 explosive, one with a mass fire hazard with little chance of being extinguished.
- AP in shipping bins is defined as a 1.4 explosive, one with a fire hazard but not blast hazard.
- Quantity-Distance (Q D) distances are specified for each category, which are much higher than that implemented at Pepcon.
- Also, it is spelled out that natural gas pipelines should not be installed under explosive storage areas or near processing buildings; minimum separation is 80 ft.

NFPA 43A:

- Classifies bulk AP as a class 4 oxidizer, which is one which can undergo an explosive reaction when catalyzed or exposed to heat, shock or friction.
- States that oxidizers shall be stored to avoid contact with incompatible materials such as ordinary combustibles, flammable liquids, greases, etc.
- States that water supplies for fire protection of oxidizer storage should be capable of 750 gpm (about 7, 1.5" hose streams); this was clearly not met since 3 hose streams overtaxed the system.
- States that when AP is stored in quantities greater than 10 lbs, storage should be in accordance with NFPA 495, the code for explosive material, which requires magazine storage and the appropriate separation distances.

- Drum storage separation requirements are stated, which were much more conservative than Pepcon practices.

CPIA 394:

- States that AP will explode when involved in a fire.
- States that AP will explode before melting.
- States that fires involving AP alone may be fought from an explosion-resistant location.

DOT 49 CFR 172:

- States that AP is classified as an oxidizer for transportation, unless the average particle size is less than 45 microns, where upon it is classified as a 1.1D explosive.

One major problem was that until recently, AP has been classified as an oxidizer, not an explosive, for purposes of transportation by the Department of Transportation (DOT). DOT listed AP as an oxidizer for particle sizes greater than 45 microns. Pepcon produced larger particle sizes, ranging from 90 to 400 microns.

CONCLUSIONS

The most significant factors involving ignition in the plant included (1) high sensitivity of AP and other chlorate compounds, (2) the quality of housekeeping, (3) possible open drums of product wastes, (4) inadequate welding procedures in high hazard areas, and (5) the high wind conditions.

The most significant factors involving the extremely rapid fire development included (1) inadequate water supply for early fire fighting, (2) the lack of an organized fire brigade, (3) lack of a sprinkler system in a high hazard area, (4) severe fire spread properties of fiberglass wall panels, (5) quality of housekeeping, (6) presence of fuels close to AP storage, such as polyethylene and asphalt (and favorable fuel/AP mixtures), (7) extremely high rate of combustion of fuel/AP mixtures, (8) extraordinary high flame plumes and high radiation flame temperatures from combustion of fuel/AP mixtures, (9) the high gas output "jetting" nature of

AP/fuel combustion, (10) the close proximity of bulk AP storage within the plant and storage fields, (11) high wind conditions, and (12) a lack of understanding of the explosive properties of AP.

Today, an accident in such a plant may be less likely due to requirements imposed by OSHA in its new 29 CFR 1910.119, "Process Safety Management of Highly Hazardous Chemicals." A complete process safety management program is now required including various levels of training, operating procedures, emergency response plan and a process hazards analysis to identify any unreasonable hazards.

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