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EPA/OSHA JOINT CHEMICAL ACCIDENT INVESTIGATION REPORT

Shell Chemical Company
Deer Park, Texas

REPORT

The EPA/OSHA Accident Investigation Program

EPA and OSHA work together under conditions detailed in a Memorandum of Understanding (MOU) to investigate certain chemical accidents. The fundamental objective of the EPA/OSHA chemical accident investigation program is to determine and report to the public the facts, conditions, circumstances, and causes or probable causes of any chemical accident that results in a fatality, serious injury, substantial property damage, or serious off-site impact, including a large scale evacuation of the general public. The ultimate goal of the accident investigation is to determine the root causes in order to reduce the likelihood of recurrence, minimize the consequences associated with accidental releases, and to make chemical production, processing, handling, and storage safer. This report is a result of a joint EPA/OSHA investigation to describe the accident, determine root causes and contributing factors, and identify findings and recommendations.

In the EPA accident investigation report preparation process, companies mentioned in the report are provided a draft of only the factual portions (no findings, conclusions or recommendations) for their review for confidential business information. Federal agencies are required by provisions of the Freedom of Information Act (FOIA), the Trade Secrets Act, and Executive Order 12600 to protect confidential business information from public disclosure. As part of this clearance process, companies often will provide additional factual information that EPA considers and evaluates for possible inclusion in the final report.

Chemical accidents investigated by EPA Headquarters are conducted by the Chemical Accident Investigation Team (CAIT) located in the Chemical Emergency Preparedness and Prevention Office (CEPPO) at 401 M Street SW, Washington, DC 20460, 202-260-8600. More information about CEPPO and the CAIT may be found at the CEPPO Homepage on the Internet at www.epa.gov/ceppo. Accidents investigated by the OSHA Headquarters are conducted by the Chemical Accident Response Team (CART) located in the US Department of Labor - OSHA, Directorate of Compliance Programs, Washington, DC, 20210, 202-219-8118. More information about OSHA and the CART may be found at the OSHA Homepage on the Internet at www.osha.gov.

U.S. Chemical Safety and Hazard Investigation Board (CSB)

In 1990, the U.S. Chemical Safety and Hazard Investigation Board (CSB) was created as an independent board in the amendments to the Clean Air Act. Modeled after the National Transportation Safety Board (NTSB), the CSB was directed by Congress to conduct investigations and report on findings regarding the causes of any accidental chemical releases resulting in a fatality, serious injury, or substantial property damages. In October 1997, Congress authorized initial funding for the CSB. The CSB started its operations in January 1998 and has begun several chemical accident investigations. More information about CSB may be found at the CSB homepage on the Internet at "www.chemsafety.gov".

For those joint investigations begun by EPA and OSHA prior to the initial funding of the CSB, the agencies have committed to completing their ongoing investigations and issuing public reports. Under their existing authorities, both EPA and OSHA will continue to have roles and responsibilities in responding to and investigating chemical accidents. The CSB, EPA, and OSHA (as well as other agencies) are developing approaches for coordinating efforts to support accident prevention programs and to minimize potential duplication of activities.

Basis of Decision to Investigate

An explosion and fire took place at the Shell Chemical Company Complex in Deer Park, Texas, on June 22, 1997, resulting in injuries, public sheltering, closure of transportation routes, and property damage both on and off site. EPA and OSHA undertook an investigation of this accident because of its severity, its effects on workers and the public, the desire to identify those root causes and contributing factors of the event that may have broad applicability to industry, and the potential to develop recommendations and lessons learned to prevent future accidents of this type. This investigation was conducted in conjunction with an investigation by OSHA to determine if violations of occupational safety and health laws had occurred.

Accident Investigation Report
Shell Chemical Company, Deer Park, TX, June 22, 1997

Executive Summary

On Sunday, June 22, 1997, at approximately 10:07 a.m. Central Daylight Time, a violent explosion and large fire occurred at the Shell Chemical Company plant in Deer Park, Texas. The explosion was felt and heard over ten miles away, and the ensuing fire burned for approximately 10 hours. As a result of the explosion and fire, extensive damage occurred to the facility, and several workers received minor injuries. Nearby residential property was damaged. Major transportation routes adjacent to the facility were closed for several hours, and nearby residents were advised to remain indoors.

Under the terms of the EPA/OSHA Memorandum of Understanding for Chemical Accident Investigations, a joint chemical accident investigation team (JCAIT) was formed to investigate the accident and determine its root causes. A concurrent enforcement investigation was done by OSHA to determine if any violations of occupational safety and health laws had occurred.

The JCAIT determined that the immediate cause of the accident was the internal structural failure and drive shaft blow-out of a 36-inch diameter pneumatically-assisted Clow Model GMZ check (non-return) valve. The valve was located on a high-pressure light hydrocarbon gas line installed in the process gas compression (PGC) system of Olefins Plant Number III (OP-III). The check valve's failure started a large flammable gas leak. The escaping gas formed a vapor cloud and eventually ignited, resulting in an unconfined vapor cloud explosion.

The JCAIT identified the following root causes of the accident:

- The Clow Model GMZ check valves installed in the OP-III process gas compression system were not appropriately designed and manufactured for the heavy-duty service they were subject to in OP-III. This resulted in the valves being susceptible to shaft blow-out during normal use.

- Lessons learned from prior incidents involving Clow Model GMZ check valves installed at Shell facilities and at Saudi Petrochemical Company (a Saudi facility partly owned by Shell) were not adequately identified, shared, and implemented. This prevented recognition and correction of the valve's design and manufacturing flaws at OP-III prior to the accident.

- The process hazards analysis (PHA) of the process gas compression system was inadequate; the PHA did not identify the risks associated with shaft blow-out in Clow Model GMZ check valves, and consequently no steps were taken to mitigate those risks.

- Measures necessary to maintain the mechanical integrity of Clow Model GMZ check valves installed in OP-III were not taken. This resulted in undetected damage to and eventual failure of critical internal valve components.

- Operating procedures for the start-up of the PGC system did not specifically instruct operators to re-verify the position of pneumatically-assisted check valves before restarting the compressor following unexpected automatic compressor trips; consequently, operators did not re-verify the position of the valve that failed. Re-verification might have enabled operators to observe possible indications of the fifth stage suction check valve's imminent failure on June 22, 1997.

The JCAIT identified the following factors that contributed to the accident:

- The lack of clear and immediate indications in the control room of a hydrocarbon leak contributed to the severity of the accident by significantly delaying operator action to shut down and depressurize the PGC system.

- Inadequate communications practices during the accident contributed to its severity by hindering the timely flow of information to control room operators.

The JCAIT developed recommendations addressing the root and contributing causes to prevent a recurrence or similar event at this and other facilities. While the scope of these recommendations ranges from general to very specific, companies and industry groups not specifically named should consider each recommendation in the context of their own circumstances, and implement them as appropriate. The recommendations are summarized below:

- Prior to restarting OP-III, Shell Chemical Company should replace all Clow Model GMZ check valves installed in the unit with valves not susceptible to shaft blow-out. Other Shell facilities and other companies as appropriate should review their process systems to determine if they have valves installed that may be subject to this hazard, and modify or replace those valves as necessary to prevent shaft blow-out. Companies should consult valve manufacturers or other appropriate design authorities to ensure any modifications made are safe. [Editor's note: Prior to this report being published, Shell Chemical Company replaced all Clow Model GMZ check valves installed in OP-III with valves not susceptible to shaft blow-out.]

- Shell Chemical Company should update and revalidate the process hazards analysis (PHA) at OP-III and should consider updating and revalidating other units' PHAs to ensure all operating and maintenance experience and incidents are fully evaluated. Shell should also take appropriate measures to mitigate hazards identified by the revalidated PHAs.

- Shell Chemical Company should revise OP-III PGC system operating procedures to

provide clear instructions for operators to re-verify the positions of pneumatically-assisted check valves before the PGC is re-started following any compressor trip if said check valves are at high risk of leakage or failure. Shell should also consider adding warnings or caution statements in PGC system procedures related to the circumstances and indications of check valve shaft blow-out, or other potential causes of hydrocarbon gas leaks.

- Shell Chemical Company should improve their radio communications practices at OP-III and as appropriate at other facilities to ensure operational and emergency information is transmitted in an accurate and timely fashion. Other companies that require operators to communicate in high-noise environments should also consider taking these or similar measures.

- Shell Chemical Company should implement a more rigorous mechanical integrity inspection program for valves in extreme service or with a known history of failure where the failure of such valves could result in catastrophic consequences.

- Shell Chemical Company and Shell Oil Company should develop and implement a system to ensure that lessons learned from all prior operating and maintenance accidents, incidents, and near misses at Shell facilities (including facilities partly owned by Shell) are always fully reviewed and incorporated as appropriate into the management and operation of every Shell facility.

- Shell Chemical Company and other companies that process flammable gases and volatile flammable liquids or liquefied gases must implement precautionary measures contained in OSHA's PSM standard and EPA's RMP rule to prevent flammable gas leaks from resulting in vapor cloud explosions.

- Atwood & Morrill Co., Inc. (the successor to Clow Corporation of Westmont, Illinois), should inform all customers who have previously purchased Clow Model GMZ check valves of the circumstances of this accident and of the potential for these valves to undergo shaft blow-out.

- Where feasible, companies should consider inherently safer design alternatives that limit the potential for and consequences of worst-case accidents.

- Chemical and petroleum industry trade associations should inform member companies of the circumstances in the EPA/OSHA joint report of the Shell Deer Park accident. Trade associations should also work together with individual member companies to develop and institutionalize a stronger system for sharing and implementing lessons learned from process incidents and accidents at companies in the United States and abroad.

- EPA should take appropriate follow-up actions, such as inspections, audits, or implementation of other policies to ensure that U.S. companies modify, remove, or

replace, as appropriate, all Clow Model GMZ check valves that are at high risk for shaft blow-out.

- EPA and OSHA should distribute this report and the Chemical Safety Alert entitled "Shaft Blow-Out of Check and Butterfly Valves" to affected companies (including valve manufacturers and users), industry trade associations, international organizations, Local Emergency Planning Committees (LEPCs), and State Emergency Response Commissions (SERCs). [Editor's note: Prior to publishing this report, EPA and OSHA distributed the subject Alert to affected companies, trade associations, LEPCs, and SERCs, and posted the Alert on the Internet at www.epa.gov/ceppo/. The Alert is also included as Appendix F to this report.]

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Facility Information

The Shell Deer Park Manufacturing Complex is a large multi-unit petroleum refining and chemical manufacturing center located on the south side of the Houston Ship Channel approximately 15 miles east of Houston, Texas. Shell occupies a 1400 acre plot in an area predominated by chemical and petrochemical manufacturing, refining, and storage facilities. The Shell complex is bordered by the Houston Ship Channel[1] on the north, State Route 225 on the south, and by other petrochemical company sites to the east and west. Beltway 8 (the Houston outer beltway) is located approximately ½ mile west of the complex. The nearest residential communities are Channelview, Texas, located immediately across the Houston Ship Channel to the north, and Deer Park, Texas, located just south of Route 225 (see Figure 1). About 2400 people are employed at the Shell complex.

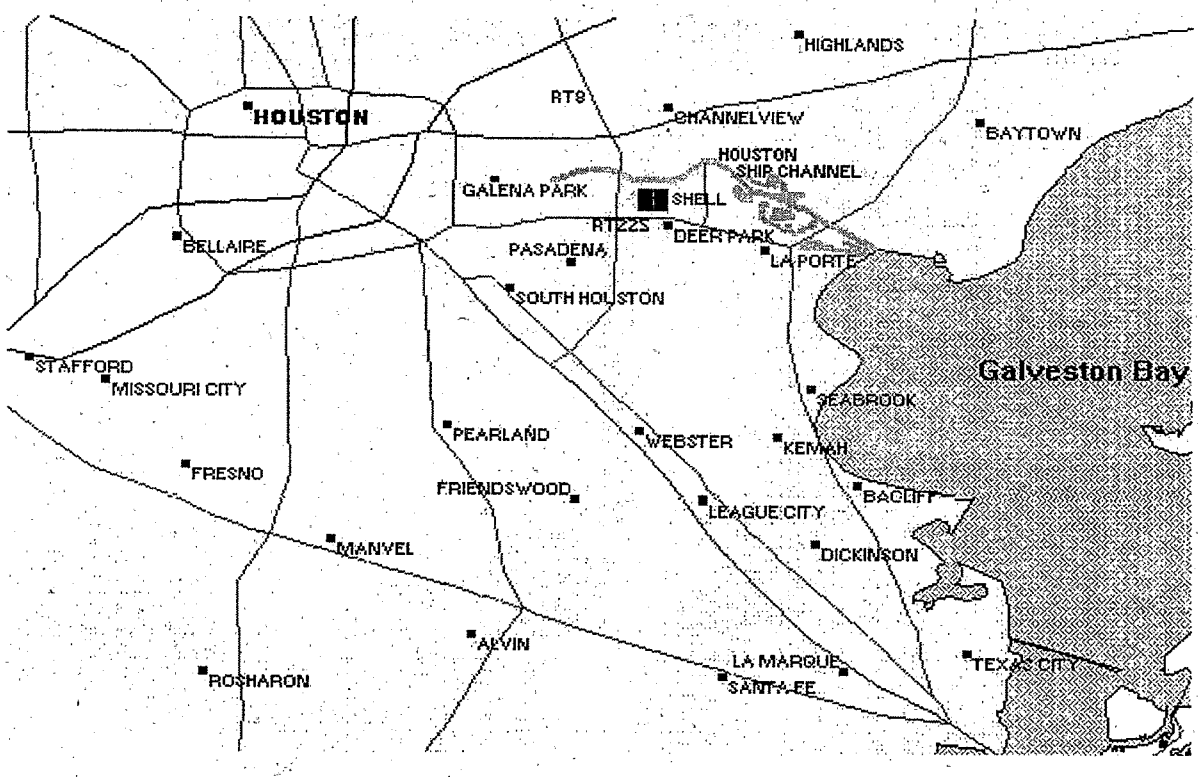

Figure 1: Geographic Area Surrounding Shell Complex

[1]The Houston Ship Channel provides a direct shipping route for oil tankers arriving from the Gulf of Mexico via Galveston Bay.

Process Overview

The Shell Deer Park Manufacturing Complex is comprised of a chemical plant and an adjacent oil refinery. The accident discussed herein took place in Olefins Plant Number III (OP-III), one of several process units in the chemical plant. OP-III produces a variety of olefinic (i.e. alkene-derived) petroleum intermediates by cracking and distilling assorted crude petroleum feed stocks. Major products include ethylene, propylene, butadiene, and isoprene. These petrochemicals are typically sold to other chemical companies who use them to synthesize a variety of finished organic products. Other outputs from OP-III include gasoline, ethane, natural gas, and other hydrocarbon derivatives. These products are either recycled, sent to other units for subsequent processing, utilized for fuel in other Deer Park process units, or sold directly. OP-III was constructed in 1976. A simplified plan-view layout of OP-III is included in Appendix A.

OP-III is roughly divided into two sequential process phases. The first phase or "hot side" of the process involves the thermal cracking of large-molecule hydrocarbon feeds into smaller molecules by mixing the crude petroleum feeds with steam in a series of high-temperature (1500 degrees F) pyrolysis furnaces. The cracked hydrocarbon molecules are then separated by boiling point (fractionated) in a large vessel at elevated temperature, where heavy oils and pitch are processed and removed. The second phase or "cold side" of OP-III involves compression and treatment of lighter hydrocarbon gases and separation of light hydrocarbon molecules by low temperature fractionation of condensed light hydrocarbons.

While the accident affected equipment and systems on both sides of the unit, the primary system involved was the process gas compression system, and investigators focused on its design and operation in determining the cause of the accident. The process gas compression system is the first process system in the cold side of OP-III. The major component in the system is the process gas compressor (PGC), which receives light hydrocarbon gases from the top of the pyrolysis fractionator and compresses the gases, condensing them to liquid for treatment and subsequent molecular separation. The PGC is a five-stage steam turbine-driven centrifugal compressor. Each compression stage has a suction drum and the final two stages have discharge drums, which are used to separate and remove condensed liquids from process gases. Condensed liquids are collected at the bottom of each suction and discharge drum and transferred to subsequent process steps or storage. Large-diameter, pneumatically-assisted swing check valves are located on the suction side of the third and fifth compressor stages and on the discharge side of the fourth and fifth compressor stages. During normal system operation, these check valves remain open to allow forward process gas flow. However, they automatically close in order to prevent PGC damage whenever reverse gas flow occurs. A simplified one-line schematic of the PGC system is shown in Appendix B.

Events Preceding the Accident

At approximately 2:15 a.m.[2] on Sunday, June 22, 1997, OP-III was operating at full production capacity under normal conditions. Shortly thereafter, all incoming electrical power to the unit was lost when a current transformer on the incoming electrical supply bus exploded, probably due to the effects of lightning from an electrical storm which passed through the area a short while earlier. OP-III receives AC power from two separate offsite sources, but the affected transformer was located on an electrical circuit which ties those sources together, and its failure resulted in the temporary loss of both incoming power sources. The total loss of incoming AC power resulted in the loss of power to vital electrical loads and necessitated the almost complete shutdown of OP-III production processes and equipment, including the PGC. The shutdown of the PGC caused its associated pneumatically-assisted check valves to rapidly shut, as designed to prevent reverse gas flow through the machine.

Some vital electrical loads which de-energized during the power outage were immediately restored by electricity supplied from emergency generating equipment, and some other equipment, such as the fractionator and fractionation furnaces, which do not require electrical power, were not immediately affected by the electrical outage, and continued to operate. OP-III hot-side and cold-side foremen[3] conferred and decided to shut down most major equipment that was still operating, such as all compressors and several furnaces, but to keep some equipment operating, including several furnaces, the fractionator, and some other support and auxiliary equipment, in order to be ready to restart the PGC and remaining OP-III unit processes when off-site electrical power was restored.

In anticipation of quickly restoring full electrical power, foremen called in additional operators to assist with plant startup. At approximately 5:00 a.m., half of off-site AC power was restored, and additional operators were present, so the OP-III cold-side foreman (hereinafter referred to simply as "foreman") began to direct prerequisite operations for PGC startup. Even though full electrical power had not yet been restored, the foreman stated that he felt some urgency to get the PGC restarted as soon as possible because as long as the PGC was shut down while some furnaces and the pyrolysis fractionator were operating, uncompressed process gases from the fractionator had to be burned off in the flare. Further, the loss of electrical power had caused the shutdown of steam generators which produce dilution steam for the flare. Consequently, a high flame and large amounts of smoke were emanating from the flare stack as the uncompressed process gas was combusted without dilution steam. This condition was considered undesirable, since it wasted resources (i.e. process gas) and also produced an unsightly smoke cloud over the facility. The foreman knew that starting the PGC would help eliminate this

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[2]All times in this report are based on the 12-hour clock and are local (i.e. Central Daylight) times.

[3]OP III has two foremen (also called team leaders), each of which are responsible for supervising and coordinating operations in one of two major sections of the plant. The "hot-side" foreman supervises operation of the pyrolysis furnaces, the pyrolysis fractionator, and associated hot-side support equipment, and the "cold-side" foreman supervises operation of plant components downstream of the pyrolysis fractionator, including, among others, the Process Gas Compression system.

problem, since process gas would no longer need to be routed to the flare.

At approximately 5:30 a.m., the foreman directed the PGC field operator [4] to place the PGC on "slow roll." "Slow roll" refers to a pre-startup condition where the PGC is rotated at low rpm in order to warm up its steam turbine and to prevent its rotor from bowing under its own static weight. The PGC is normally slow-rolled for at least two hours and usually four hours prior to being started. To protect the machine from damage, the PGC turbine has vibration sensors which automatically shut down the machine if excessive vibration is detected. According to various operator statements, between 5:30 a.m. and 8:45 a.m., the PGC tripped (i.e. automatically shut down) at least three times, and possibly as many as five times, due to high turbine vibration while on slow roll. Operators placed the machine back on slow roll after each trip. Again, each PGC trip also resulted in the automatic actuation of the pneumatic cylinders on the four pneumatically-assisted check valves located between compressor stages, shutting the valves.

At approximately 8:45 am, the foreman consulted with plant electricians who indicated that full electrical power would still not be available for several hours, but that sufficient electrical power was currently available to support PGC start-up. The foreman therefore decided to start the PGC as soon as possible, but using backup electrically-powered PGC lubricating oil and seal oil pumps instead of using the normal steam-driven oil pumps. Also, since only five pyrolysis furnaces were operating to provide load to the compressor, and the PGC is normally loaded during start up from at least 6 furnaces simultaneously, the cold side foreman directed a sixth furnace to be started using natural gas and stationed an additional operator to feed natural gas from the sixth furnace directly to the inlet of the PGC first stage in order to provide additional compressor load as needed. The foreman briefed his start-up crew regarding his intentions. The PGC field operator expressed some concern about starting the PGC without full electrical power, but agreed that the startup was feasible under existing conditions.

Operators finished pre-startup checks [5] and commenced the PGC startup sequence at approximately 9:30 a.m. The PGC field operator started the PGC and began to raise its speed. As PGC rotational speed reached approximately 1500 rpm, the PGC automatically tripped due to high vibration. Once again, this caused the pneumatically-assisted check valves to slam shut.

Operators concluded that the PGC trip was caused simply by their failure to raise the

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[4] During startup, a field operator controls the PGC from a control panel located outside on an elevated deck above the machine; after the machine is running and the system is stable, PGC control is transferred to an operator in the control room.

[5] The cold-side foreman stated that he neglected to perform one step of the pre-startup sequence involving pressurization and draining of condensate from PGC system low points and from steam turbine drains. This step is done in order to prevent liquid from entering either the compressor or the turbine, which could cause excessive vibration to the machine. The failure to perform this pre-startup step may account for the higher than normal turbine vibration observed during startup.

speed of the compressor quickly enough through its critical speed range [6], so the foreman decided to immediately restart the PGC. Since very little time had passed since the initial PGC trip, and believing he knew the cause of the trip, the foreman did not order any more pre-startup checks to be performed prior to the second PGC startup attempt. According to operators, during the second start up, PGC vibration was again higher than normal [7], and a vibration alarm occurred as PGC rotational speed passed into the critical range, but the alarm cleared as soon as speed was above the critical range, and no automatic trip occurred. By 10:00 a.m. PGC system operation appeared to be normal, and the PGC field operator was preparing to switch control of the PGC to the control room.

The Accident

From approximately 10:03 a.m. [8] until shortly after 10:07 a.m., the following sequence of events occurred (locations referred to in the following narrative are illustrated in Appendix A):

Approximately 10:03 a.m.:

- Personnel working outside in OP-III hear a loud "pop" followed by the extremely loud noise of a continuous high-pressure gas release. One person later describes the noise as a "jet engine sound."

- The foreman exits the OP-III control room and is heading toward the PGC operating deck when he hears the gas release. He contacts operators in the control room by radio and asks if they see any unusual indications on their control panels. The control room operators respond that they do not see any unusual indications (data records later revealed that PGC fifth stage flow had begun a gradual decrease and that PGC fourth stage flow increased momentarily, and then began dropping, but these changes represented a small percentage of overall PGC flow, and were not immediately detected by operators).

- The PGC field operator, who is stationed outside at the PGC deck preparing to transfer PGC control to the control room, hears the release - it is very loud and sounds to him like a 1250 psig steam relief valve opening under pressure.

- Other personnel working in the vicinity all hear a sudden loud, continuous roar. These personnel include another field operator, a trainee, and two contractor instrument

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[6]For rotating machinery, "critical speed" refers to a range of rotational speed around the fundamental or a harmonic resonant vibration frequency of the machine's structure. Lengthy operation in this speed range is undesirable because it produces excessive vibration and can result in damage to the machine.

[7]The cold-side foreman indicated that turbine vibration was about five times higher than normal (1 mil vice 0.2 mils).

[8]Times in the accident sequence description are referenced to the internal clock of the OP-III Operational Data Seryer.

technicians working in the north yard.

Approximately 10:03-10:05 a.m.:

- The foreman radios to the control room and informs operators that there has been a gas release and to activate the unit evacuation alarm. He then gets on his bicycle, and proceeds west along N. 22nd Street, toward the fractionator, and in the general direction of the noise to identify its source.

- Control room operators have difficulty understanding the foreman's radio transmission - his voice is loud and excited and the sound of the gas release in the background masks part of the transmission. One operator hears "there's a leak in the pipe rack!"; another hears "there's a release, there's a release!"; a third operator believes he hears "Fire on the PGC!" The control room operators activate the unit evacuation alarm lights [9], radio for field operators to come in from the field to safe shelters, and call the guard at the main gate to inform him of the release and to put the fire brigade on stand-by.

- Five persons in the control room, including the fractionator operator and a furnace operator, don bunker gear (fire protective clothing) in order to exit the control room to respond to the gas release and what they believe to possibly be an ongoing fire. The fractionator operator exits first, by the west door, and hears the sound of the gas release. He judges that the release sounds very different than a fire, so he immediately re-enters the control room and informs remaining operators that there is no fire. Then he leaves the control room again and heads west down the pipe alley, toward the noise. The furnace operator and three other operators wearing bunker gear also exit the control room. The furnace operator follows the fractionator operator down the pipe alley, while the three other operators head west down N. 24th Street, looking for any sign of smoke or fire.

- The PGC field operator, located on the PGC deck, hears the report of the release on the radio. He looks west, towards the source of the noise, but cannot see anything unusual. Looking east, he sees several operators exit the control room and move west, wearing bunker gear. He remains at his station.

- A machinist supervisor and auxiliary field operator heading North past electrical substation 110 on a golf cart suddenly hear a lot of rapid, excited radio transmissions. Stopping the golf cart to listen, they hear the report on the radio: "There's a release, there's a release!", but do not hear or see any gas release. The pair decide to return to the control room, where the machinist supervisor drops off the auxiliary field operator. The auxiliary field operator runs into the control room and informs control room operators that there is a

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[9] Control room operators actuated the unit evacuation alarm, but not the plant evacuation alarm. Activating the unit evacuation alarm turns on a set of alarm lights throughout OP-III only, but does not activate the overall plant evacuation alarm. The plant evacuation alarm, on the other hand, actuates an audible signal which can be heard throughout the Deer Park Complex. Most OP-III personnel located outside during the accident stated that they did not hear or see any alarm signal.

"leak in the pipe rack."

- Other personnel working outside begin to evacuate the area and head for the nearest shelter.

Approximately 10:05-10:07 a.m.:

- The foreman passes south of the fractionator and turns north into the South Yard pipe alley. Looking east down the pipe alley, the foreman observes what he later described as a "colorless vapor" originating near the PGC fourth and fifth stage discharge drums and blowing north to south across the pipe alley. He approaches even closer and stops in the pipe alley, just south of the fourth and fifth stage discharge drums and sees a vapor cloud approximately 15 feet high and which appears as a "breeze with hydrocarbon eddies". He also smells a "sweet, light hydrocarbon smell", and realizes that the leak is probably flammable process gas. He radios the control room again and orders control room operators to "Shut down the PGC and dump everything to the flare!" - he repeats the order three times, but receives no reply.

- The machinist supervisor, after dropping off the auxiliary field operator at the control room, continues on his golf cart south along W. 35th Street toward the furnace area to notify maintenance personnel working on furnace F-1040 to leave the area and head for shelter. As he proceeds south, he looks west down N. 24th Street and sees what appear to be "heat waves" flowing to the north from the vicinity of the PGC fourth and fifth stage drums.

- The operator and trainee from the North Yard ride their golf cart east down the pipe alley and enter the control room. Meanwhile, the contractor instrument technicians ride bicycles east down N. 24th Street toward the control room. As they pass the PGC fifth stage drums, they see a "golden-yellow" vapor cloud billowing over the drums and note that the noise of the release seems to originate somewhere between the drums and the overhead cooling fans. They reach the control room as the operators wearing bunker gear are coming out.

- The fractionator operator heads west down the pipe alley and sees what he believes to be steam blowing from north to south across the alley. He also sees a safety shower sign, suspended below the pipe rack opposite the fractionator, "whipping" back and forth. From this, he judges that the release is coming from the vicinity of the PGC fourth or fifth stage drums. Still thinking the leak is steam, he continues to move west along the north side of the alley, closer to the release, followed by the furnace operator.

Approximately 10:07 a.m.:

- The vapor cloud formed by the gas release has now been generating for approximately 4

minutes. It finally reaches an ignition source, causing the vapor to ignite and explode, sending a blast wave in all directions. As the blast wave moves outward from its origin, it damages and destroys equipment and structures, rips insulation and flashing away from piping, breaks windows, blows down doors, and knocks nearby personnel off their feet and through the air.

- As he sees and smells the vapor, the foreman realizes he is in serious danger from a potential explosion, and decides to leave the area. He reverses direction (turns towards the west) and begins to ride back down the pipe alley. As he turns south to exit the pipe alley near the dilution steam generators, the explosion occurs. He sees a flash of light out of his peripheral vision and is thrown off his bike and through the air for several feet before landing in an open area adjacent to the dilution steam generators. He receives no serious injuries, but remains on the ground for a short while, disoriented.

- In the control room, operators have trouble hearing the cold-side foreman's latest radio transmission, but believe they hear him order, "Shut down the PGC and dump (garbled) to the flare". After a short discussion with other control room operators, the PGC board operator pushes the PGC shutdown button and begins to open the fifth stage flare valve (which begins to depressurize the PGC system). He gets the valve partially open when the explosion occurs.

- The fractionator operator and furnace operator continue to move west down the pipe alley until they approach to within about 70 feet of the source of the gas leak. They now see the vapor cloud, which appears as "waves of white vapor" originating just north of the pipe rack about 8 to 12 feet above the ground, and moving north to south across the pipe alley. The fractionator operator also detects a "light, sweet hydrocarbon" smell, and realizes that the leak is flammable hydrocarbon process gas and not steam. The operators now realize their danger and decide to leave the area. As they turn to leave, the explosion occurs. The fractionator operator hears a "whump", and sees a "wall of air" moving toward him, scattering debris and peeling insulation from pipes as it approaches. The blast tears portions of the fractionator operator's bunker gear off of his body and throws both operators several yards east down the pipe alley. In spite of the force of the blast and their proximity to the explosion, they escape without serious injuries.

- The PGC field operator, still located outside on the elevated PGC deck, finally decides to seek shelter; he takes two steps toward the stairs when the explosion occurs. The blast knocks him off of his feet onto the grating, but he is not seriously injured [10].

- The three other operators in bunker gear are near the PGC fourth stage suction drum and

[10] Shortly after the blast, the PGC field operator began to experience severe chest pains and shortness of breath. Fearing a heart attack, first responders sent him by ambulance to a nearby hospital for treatment. His symptoms were later diagnosed as asthma-related, and he was released.

looking towards the PGC fifth stage drums when the explosion occurs. They see a bright flash of light coming from the pipe rack in the vicinity of the PGC fifth stage drums. The blast throws the three operators backwards and to the ground. The operator furthest from the blast sees flames pass directly above the other two operators, but none of the three are seriously injured.

After the Explosion:

- The explosion starts a major fire, which is initially fed by the flammable gases still escaping through the original leak, and subsequently from other hydrocarbon lines which rupture when exposed to the intense heat of the blaze. The heat is so intense that it melts steel structural beams, and one entire section of the overhead cooling fans and supporting structure eventually collapses. The fire burns for about 10 hours.

- The PGC field operator, foreman, fractionator operator, furnace operator, and the three operators in the north yard pick themselves up and move toward the control room. The foreman, fractionator operator, and three north yard operators turn on fire monitors (fixed water turrets used for fighting fires) as they go by and aim them toward the flames.

- In the control room, operators completely depressurize the PGC system and dump its contents to the flare. Organized emergency response begins. A count of personnel is started, and some personnel leave to search for those who were outside during the explosion. Within minutes of the explosion, everyone is accounted for - the foreman is the last person to reach shelter. Several people have received minor injuries and are later treated at a local hospital, but no one is seriously injured or killed.

Response to the Accident [11]

At the sound of the explosion, the Shell Deer Park fire crew was activated and, along with OP-III operators already on scene, immediately responded to the fire. The Deer Park Complex has a dedicated fire water system which extends throughout the site, including OP-III, and operators outside during the accident activated and positioned fire monitors towards the blaze. Shell emergency responders were also able to position a pickup truck-mounted fire monitor to within feet of the center of the fire. Responders drove the portable monitor down the pipe alley from the east directly under the burning pipe rack, positioned the water cannon towards the worst part of the blaze, and abandoned the truck in place to the east of the fire with the water cannon activated. Later inspection of burn patterns and debris indicated that this single act was probably responsible for substantially mitigating the spread of the fire in that direction. The truck itself, although very near the worst part of the blaze, was protected by the water being continuously sprayed from its portable fire monitor, and suffered relatively little damage. A second truck-

[11] The scope of this EPA/OSHA joint chemical accident investigation did not include a critical analysis of the emergency response to the accident.

mounted monitor was positioned to the south of the fire, but responders were not able to place it as close to the fire as the first, and therefore it was somewhat less effective.

Shortly after the explosion, the Shell incident commander contacted the local police department and requested that State Route 225 and Route 8 be closed to traffic passing near the Shell Complex. Police complied with this request and closed sections of these roads adjacent to the complex to non-emergency traffic for approximately three hours. The incident commander also contacted local community emergency planning organizations, including the Deer Park Local Emergency Planning Committee (LEPC) to inform them of the incident. Nearby residents were advised to remain indoors during the incident. Shell officials stated that these measures were precautions taken in order to protect the public against any secondary explosions or potential toxic effects of the heavy smoke being generated by the fire, and to allow easier access to emergency vehicles on public roadways.

The smoke plume from the fire migrated towards the northwest, across the Houston Ship Channel and over the community of Channelview, Texas. Shell technicians obtained air samples in the path of the smoke plume using both automatic in-place samplers and by manual grab sample methods. Each sample was analyzed for harmful constituents, including benzene, asbestos, and other toxicants. Concentrations of all contaminants were found to be below federal and state regulatory limits.

Shell also requested and received emergency response support from the Channel Industries Mutual Aid (CIMA) organization. CIMA is an emergency response organization formed through the joint membership of the industrial companies located along the Houston Ship Channel. CIMA is organized such that all member companies agree to respond to major accidents at any other member company's site with designated emergency response resources. Emergency response personnel and equipment from CIMA member companies were integrated into Shell's response unit using the Incident Command System.

Transportation routes were re-opened to public traffic at approximately 1:00 p.m., and the fire was extinguished at approximately 8:00 p.m.

Photographs depicting the damage resulting from the accident are shown in Appendix E (figures E-1 through E-8).

The Investigation

OSHA investigators from the OSHA Houston South Area Office and an On-Scene Coordinator from EPA Region 6 arrived at the scene on the day of the accident and were joined by additional EPA and OSHA investigators on Tuesday, June 24. After inspecting the accident scene and conducting preliminary interviews, EPA and OSHA investigators decided to conduct a joint root cause investigation and convened a Joint Chemical Accident Investigation Team (JCAIT). The decision to investigate was based on the severity of the accident and its effects on

workers and the public, the fact that its causes were unknown, and the potential to gain important knowledge and lessons-learned to prevent further accidents of its type. The JCAIT consisted of members from EPA headquarters, OSHA Headquarters, EPA Region 6, and OSHA Region 6 (Houston South Area Office, Corpus Christi Area Office, and Little Rock, Arkansas, Area Office). Members of the Oil, Chemical, and Atomic Workers Union (OCAW) who were also workers at the Shell Deer Park Manufacturing Complex participated with the JCAIT as observers in the on-site fact-finding portion of the investigation. The JCAIT also employed independent expert consultants for laboratory testing and other specific investigation activities.

Shell Chemical Company also initiated an Accident Investigation Team (AIT). The Shell AIT and EPA/OSHA JCAIT cooperated in the fact-finding portion of the investigation which included collection and documentation of physical evidence, and agreed to joint access to all physical evidence for testing purposes. The two teams conducted separate witness interviews. The Shell AIT team prepared its own internal investigation report, which reached similar conclusions to this report regarding the immediate cause of the accident.

In the course of the investigation, investigators conducted numerous witness interviews, collected documentary, photographic, and physical evidence, and performed laboratory analysis of equipment and piping samples. Investigators also obtained and analyzed computer data records from the OP-III Operational Data Server (ODS), a system which automatically records and electronically stores system parameter readings for later retrieval.

The investigation was conducted roughly in two phases. In the first phase of the investigation, investigators from EPA, OSHA, and Shell collected physical evidence and conducted analyses in order to determine the immediate cause of the accident. This information is primarily contained in the following section of this report (Analyses). In the second phase of the investigation, the EPA/OSHA JCAIT evaluated Shell and OP-III safety management systems and human performance factors in order to determine the underlying root and contributing causes of the accident and to make recommendations to prevent recurrence of similar incidents. This information is contained in the subsequent sections of this report.

Analyses

Exclusions

The JCAIT excluded the following factors as being contributory to this accident:

- Sabotage: The JCAIT found no evidence of sabotage or intentional wrongdoing related to this accident. Agents from the Bureau of Alcohol, Tobacco, and Firearms questioned employees regarding the circumstances of the accident, and also found no evidence of sabotage.

- Health: The JCAIT concluded that health and fatigue of personnel was not a factor in this

accident. The JCAIT did not collect toxicological specimens from witnesses in order to test for illicit drug or alcohol impairment, but witness testimony provided no evidence of drug, alcohol, or fatigue-related impairment in the events leading up to the accident. Therefore, the JCAIT concluded that drugs, alcohol, and fatigue were not a factor in this accident.

- Weather, natural phenomena, or "Acts of God": At the time of the explosion, the weather was overcast and warm, with a light breeze from the southeast. Although lightning probably caused the power outage that occurred on the morning of the accident, the JCAIT did not conclude that this was a significant factor in the accident. In the opinion of the JCAIT, the power outage simply forced the subsequent plant startup, a relatively routine evolution. This accident could just as likely have occurred during any plant startup, whether or not it was preceded by a power outage, and possibly even during normal operating (i.e. non-startup) conditions. No evidence was found to suggest that other natural phenomena or Acts of God such as earthquakes, tornadoes, etc., contributed to the accident.

Methodology

Possible types of explosions include chemical and nuclear explosions, vessel over pressurization, boiling liquid expanding vapor explosions (BLEVEs), and vapor cloud explosions. Based on early eyewitness statements and visual inspection of the damage, investigators made a preliminary judgement that a vapor cloud explosion had occurred as a result of the ignition of a flammable gas cloud. The clear indications of a large flammable gas release immediately preceding the explosion, the fact that the area of the explosion and fire was highly congested (i.e. numerous vertical and horizontal structures extended throughout the volume affected by the explosion), along with a relative lack of missile debris or fragments (which would normally result from a vessel explosion) suggested a vapor cloud explosion.

Guidelines for Evaluating the Characteristics of Vapor Cloud Explosions, Flash Fires, and BLEVEs (Center for Chemical Process Safety of the American Institute of Chemical Engineers, 1994), specifies that several factors must be present in order for a vapor cloud explosion to occur. These include:

1. The release of a large quantity of flammable gas or vaporizing liquid from a storage tank, vessel, or pipeline. The released material must be at suitable conditions of pressure and temperature for ignition to occur in the presence of an ignition source.

2. The formation of a cloud of sufficient size prior to ignition.

3. A significant amount of the vapor cloud must be within the flammable range of the material in order to cause significant over pressure upon ignition.

4. The presence of turbulence in the released vapor. This produces the high flame propagation speeds necessary to produce significant overpressure, and normally results from either turbulence associated with the release itself (e.g. a jet release), turbulence produced by gas expansion through a congested space, or by externally induced turbulence (e.g. from objects such as ventilation systems).

5. The presence of an ignition source.

Investigators determined that large quantities of flammable material were contained in OP-III process equipment, systems, and piping prior to the explosion, and that if released in sufficient quantity and ignited, all other conditions necessary for a vapor cloud explosion were likely present. Investigators therefore focused on identifying the source and immediate cause(s) of the postulated flammable gas release, and the presence of suitable ignition sources.

Isolating the Source of the Flammable Gas Release

To determine the location and source of flammable gas released prior to the explosion, investigators first interviewed eyewitnesses to the gas release and explosion, reviewed data recordings, and collected physical evidence in and around the area of the blast. Using this information, investigators sought to narrow the range of possible leak sources for further investigation. Key evidence and significant facts identified by investigators as pertinent to determining the source and immediate cause(s) of the gas release and explosion included the following:

- Witnesses described the sound of the initial gas release as loud, sudden, and continuous, without any detectable buildup.

- Virtually every eyewitness account placed the source of the initial gas release in or near the north side of the pipe rack, in the approximate area of the PGC fifth stage drums.

- Several eyewitnesses described the odor of the escaping gas as "light and sweet".

- Eyewitness accounts of the color of the vapor cloud ranged from "colorless" to "white" to "golden-yellow".

- Wind direction at the time of the explosion was from SE to NW at approximately 9 miles per hour.

- Eyewitnesses located in or south of the pipe alley all stated that vapor observed in the pipe alley traveled from north to south (against the general wind direction). Eyewitnesses located north of the pipe alley observed a vapor cloud drifting towards the north (with the general wind direction).

- Witnesses stated that they heard only one explosion.

- Eyewitness estimates of the length of time between the start of the gas release and the explosion varied significantly. One eyewitness (the PGC field operator) estimated that the gap was only about 1 minute. Another witness (the auxiliary operator) estimated that the gap was approximately 10 minutes. Most other eyewitness estimates varied from as short as 2 minutes to as long as 7 minutes from the start of the release until the explosion.
- Analysis of process parameter trends recorded by the Operational Data Server (ODS) indicated that the leak started approximately 4 minutes before the explosion occurred (see pages 19-20 for a detailed explanation of this analysis).

- A plant security video camera monitoring the southern end of OP-III recorded the blast wave produced by the explosion and its effects. The time mark on the video camera indicated that the explosion occurred at 10:04:57 a.m. The security camera's clock was found to lag the ODS clock by approximately 2 minutes.

- Hydrocarbon leak detectors were not installed in OP-III, and no other means of automatically detecting the presence, source, or location of a flammable gas leak were present.

- The greatest explosion, fire, and heat damage occurred within approximately 200 feet of a point roughly 50 feet north of the fractionator and extended upward throughout the pipe rack. Steel structural members had warped and failed from the heat, piping had ruptured and fractured, electrical power and instrumentation cables had been incinerated, and other machinery, equipment, piping insulation, and electrical controls had been burned. One long horizontal section of overhead metal structure which supported the cooling fans (fin-fans) over the pipe rack had collapsed on top of the pipe rack, causing additional damage to components below (see Appendix E, figures E-1 through E-4).

- Among the explosion and fire damage, investigators identified and catalogued 52 openings in damaged pressure components and piping systems, each of which was considered as a potential source of the initial gas release.

- One of the 52 openings was in a 36-inch diameter Clow Model GMZ pneumatically assisted check valve located on the PGC fifth stage suction line; this valve was found to be missing its drive shaft and counterweight assembly. The hole in the valve created by the absence of the drive shaft was located 9 feet above grade, orientated directly south, and was 3.75 inches in diameter. The valve flapper was found stuck in a partially closed position, and a square bar-type metal drive shaft key was found lying loose inside the valve body. The valve was otherwise intact and relatively undamaged (investigators later conducted detailed metallurgical analysis on this valve and four other piping sections - see page 17, Metallurgical and Mechanical Findings and Analysis).

- The drive shaft and counterweight assembly from a 36-inch pneumatically assisted check valve were found located on the ground 42 feet directly south of the check valve which was missing these components, in an essentially unobstructed line of travel from the valve. The components were found lying directly on the cement ground surface (i.e. with virtually no debris beneath them), but beneath several inches of petroleum residue, tar, and other debris resulting from the explosion, fire, and firefighting efforts.

Eliminating Unlikely Leak Sources

While investigators judged that most of the 52 system openings or penetrations found among the wreckage were a secondary result of the explosion and ensuing fire, each were considered as possible candidates for the initial leak source. These 52 openings were screened against other evidence in order to eliminate impossible or unlikely alternatives and eventually narrow the list to a small number of openings, or perhaps a single opening which could have produced the flammable vapor cloud. The screening process, or process of elimination, compared each opening against the following set of criteria based upon eyewitness accounts, physical principles, metallurgical analysis, recorded data trends, and other factors:

- The opening must have been in a system which carried flammable gas or a flammable vaporizing liquid under pressure.

- The opening must have been in a system which carried "sweet" hydrocarbon (i.e. which did not contain "sour" or acid gas)[12].

- The opening must have been sufficiently large to release enough vapor over an approximate four minute time span to account for the observed explosion.

- The opening must have been in the approximate location identified by eyewitness accounts of the leak source (i.e. in or near the north side of the pipe rack in the vicinity of the PGC fifth stage drums).

- The original orientation of the opening must have conformed with eyewitness accounts of vapor cloud formation and dispersion, as well as the observed effects of the explosion.

- The physical condition of the opening must corroborate other eyewitness accounts and physical evidence. Numerous eyewitness accounts indicated that the gas release was sudden (i.e. there was no buildup) and constant, and that no fire occurred prior to the explosion. Therefore, metallurgical analysis of the component responsible for the initial

[12]Depending on the source of crude oil used as a source material, cracked hydrocarbon gas contains varying amounts of acidic gases, such as hydrogen sulfide. When present, these acidic components give the cracked hydrocarbon gas a distinctive noxious smell which operators commonly describe as "sour". In OP-III, the acid gases are "scrubbed out", or eliminated from the lighter hydrocarbon gas between the fourth and fifth compression stages, and the resulting gas is described as "sweet" because it no longer contains the noxious odors of the acid gases.

leak should indicate that the component had experienced a sudden, brittle failure, rather than a ductile rupture produced by extreme heating.

- The subject opening must account for the unusual process parameter trends recorded between the time of the release and the time of the explosion.

Investigators eliminated over 90% of the 52 possible openings from consideration as the likely leak source by using just the first five of the constraints listed above. This resulted in the following analysis:

- 18 openings were eliminated from consideration as the primary release source because their respective systems did not contain flammable materials (e.g. they carried steam, water, air, or some other non-flammable material);

- 10 openings were eliminated because their respective systems contained heavy oil mixtures, pitch, or other low-volatility hydrocarbon mixtures of insufficient volatility to vaporize and explode;

- 9 openings were eliminated because they were not large enough (in relation to system pressure) to release sufficient hydrocarbon materials within a 4 minute period to generate a vapor cloud large enough to cause the observed explosion;

- 2 openings were eliminated because they carried sour gas (such as hydrogen sulfide) - and eyewitness accounts clearly indicated that the vapor cloud smelled "sweet";

- 8 openings were considered unlikely to have caused the release because they were originally orientated in the wrong direction to account for eyewitness observations of vapor cloud formation and dispersion.

This analysis eliminated 47 of 52 openings as likely sources for the gas release [13]. Investigators focused on the remaining 5 openings as high-likelihood candidates for the source of the initial gas release, and compared them against remaining criteria and other available evidence. The remaining openings included the following:

1. A hole in a 2-inch nitrogen header connected to the PGC fifth stage suction line (the postulated hydrocarbon source for this line would be the PGC fifth stage suction header).

2. A hole in a 2-inch hydrocarbon line carrying hydrocarbon condensate from the coalescer.

3. A hole in a 2-inch hydrocarbon line carrying vent gases from the process gas drier.

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[13] Most of these 47 openings failed multiple criteria. The above analysis indicates only the primary criteria used to eliminate a particular opening.

4. A hole in a 6-inch line carrying gasoline from the coalescer to the high-pressure stripper feed heater.

5. A hole in a 36-inch pneumatically assisted check valve located in the main process gas compression line, between the fourth and fifth compressor stages.

Metallurgical and Mechanical Findings and Analyses

Each of the five remaining openings were in systems which normally contained or could have contained flammable light hydrocarbon gases under sufficient pressure to produce a large vapor cloud if released, and were located in the right area and with the right physical orientation to corroborate eyewitness accounts of the vapor cloud formation and dispersion. However, the physical condition of the pipe or component opening responsible for the initial leak must also corroborate other eyewitness accounts and physical evidence. Specifically, numerous eyewitness accounts indicated that the gas release was sudden (i.e. there was no buildup) and constant, and that no fire occurred prior to the explosion. Therefore, metallurgical analysis of the component responsible for the initial leak would likely indicate that the component had experienced a sudden, brittle failure, rather than a ductile rupture produced by extreme heating.

Piping or component sections containing the five high-priority line openings were removed from their respective systems and transported to a local Shell laboratory facility for detailed metallurgical and mechanical analyses. Both Shell and EPA/OSHA investigators conducted standard metallurgical and mechanical testing of equipment samples and shared the results. Testing conducted included macroscopic and microscopic visual examination, fractography, hardness testing, and dimensional measurement.

Analysis of samples numbered 1 through 4 above indicated that their failure occurred by ductile rupture following high temperature oxidation, corrosion, and fire damage to each pipe's external surfaces. In other words, *these failures all resulted from the fire, and therefore could not have caused it.*

Analysis of sample number 5, the 36-inch diameter Clow Model GMZ check valve (and its internal components), revealed that it had suffered little or no heat damage. Analysis also indicated the following (see Figures 2 and 3 on pages 25-26 for an illustration of the valve):

Fractured Dowel Pin

- a 2 inch long, ½ inch diameter cylindrical steel dowel pin which connected the valve's drive shaft to its disk had fractured and sheared.

- The end of the dowel pin had been drilled and tapped and a .25-inch diameter threaded machine screw had been inserted in the hole. The purpose of the threaded hole was apparently to allow later removal of the pin after its insertion in the shaft and disk ear.

- The fracture occurred through the transverse (circular) cross section of the dowel pin and through the drilled hole.

- The fractured dowel pin had been case-carburized on the outside diameter and on the inside surface of the threaded screw hole. The carburized case structure consisted of tempered martensite and small amounts of retained austenite. The core structure of the pin contained Widmenstatten ferrite and unresolved pearlite.

- The morphology of the pin fracture surface indicated failure occurred by brittle overload. No evidence of cleavage separation (ductile overload) was observed. No evidence of arrest lines or fatigue striations was observed. The "rock candy" fracture morphology was consistent with hydrogen embrittlement failure mode (see Appendix E, figure E-20).

Drive Shaft Key Clearance Too Large

- Although the shaft key (which was much larger than the dowel pin) was intended to transmit torque from the drive shaft to the valve disk, it fit too loosely in its key slot (see Appendix E, figure E-14). The total clearance (slack) of the key was between .045 and .050 inch. The dowel pin had an interference fit (no clearance). This caused the dowel pin to carry all of the rotational torque load transferred between the drive shaft and valve disk.

- Hardness measurements of the shaft key indicated that the material used to fabricate the key was relatively soft and ductile.

- The gap between the disk ear and valve body as measured was sufficient to allow the shaft key to fall out of its keyway as the unrestrained shaft translated outward under system pressure.

- The valve's drive shaft key was found, unattached, lying inside the body of the valve. Combined with the dowel pin's failure, the displacement of the key essentially disconnected the drive shaft from the valve disk. No other retaining mechanism (other than friction) prevented the drive shaft from being expelled from the valve by internal system pressure.

Analysis showed that the dowel pin's failure was caused by the excessive stress placed on the pin as it transferred essentially all operating torque from the drive shaft to the valve disk (a function which should have been performed by the much larger shaft key). Since the dowel pin was not designed to carry such high stress, it eventually failed. The dowel pin was also found to

have experienced hydrogen embrittlement which contributed to its fracturing. [14]

In summary, metallurgical and mechanical analyses indicated that the fifth stage suction check valve likely underwent drive shaft blow-out (i.e. violent ejection of the drive shaft out of the valve body) resulting from the brittle fracture of the drive shaft dowel pin and subsequent displacement of the drive shaft key. Once the drive shaft was unrestrained, it was expelled from the valve under the force created by internal system pressure acting on the end of the drive shaft. Since no evidence was found to indicate that the valve's failure was caused by the fire, investigators inferred from the above facts that the fifth stage suction check valve was the likely primary failure point and the likely source of the initial flammable gas release.

Appendix E contains photographs of various components analyzed in the laboratory and details of metallurgical and mechanical findings (Figures E-9 through E-22).

Analysis of Process Parameter Trends

Analysis of process parameter trends allowed investigators to accurately determine the elapsed time between the start of the gas leak and the explosion and confirmed investigators' theory that the fifth stage suction check valve was the source of the initial gas leak. Investigators desired to accurately determine the elapsed time between the start of the gas leak and the explosion in order to estimate the amount of gas in the vapor cloud prior to its ignition and to model the vapor cloud explosion. However, witness statements related to the elapsed time varied widely enough that no single witness estimate was considered to be reliable. The most accurate indication of elapsed time between the start of the gas release and the explosion was obtained by analysis of PGC system parameter levels around the approximate time of the accident. These parameter levels were automatically recorded by the OP-III ODS roughly every minute during the PGC startup and until the explosion. Process parameters recorded by the ODS showed the following significant trends around the time of the gas release and explosion:

- PGC fifth stage discharge pressure: Increased normally during PGC startup and stabilized at 9:52 a.m. at approximately 500 psig, where it remained until 10:03 a.m. Between 10:03 and 10:07 a.m., PGC fifth stage discharge pressure dropped steadily from 500 psig down to 470 psig (i.e. a total change of 30 psi). Immediately thereafter, fifth stage discharge pressure (as well as all other PGC pressure readings) abruptly dropped to zero.

- PGC fourth stage discharge pressure: Increased normally during PGC startup to a peak of 316 psig at 10:03 a.m. Between 10:03 a.m. and 10:07 a.m., pressure dropped steadily from 316 psig to 263 psig (i.e. a total change of 49 psi). Immediately thereafter, fourth stage discharge pressure abruptly dropped to zero.

[14] Hydrogen embrittlement is a form of chemical attack on steel where atomic hydrogen diffuses into steel, forming molecular hydrogen in intergranular voids in the steel. The buildup of molecular hydrogen inside these voids can generate internal pressures of up to several thousand psi. The steel consequently suffers a loss of ductility, develops micro fissures at grain boundaries, and eventually cracks, all of which lead to a loss of strength.

- PGC fifth stage suction pressure: Increased normally during PGC startup to a peak of 314 psig at 10:03 a.m. Between 10:03 and 10:07 a.m., pressure dropped steadily from 314 psig to 290 psig (i.e. a total change of 24 psig, or about half the change observed in fourth stage discharge pressure). Immediately thereafter, fifth stage suction pressure abruptly dropped to zero.

- PGC mass flow rate: Between 10:03 and 10:07 a.m., PGC fifth stage discharge flow rate steadily dropped by approximately 20,000 lbs/hr. PGC fourth stage discharge flow, however, abruptly increased at 10:03 a.m. by approximately 120,000 lbs/hr, and then steadily decreased until 10:07. After 10:07 a.m., both PGC fourth and fifth stage discharge flow rates abruptly dropped to zero.

These trends indicate that PGC system pressures increased normally during the final PGC startup, and remained normal until approximately 10:03 a.m. Immediately thereafter, system pressures began a gradual and abnormal decline through 10:07 a.m.. This indicates that the gas leak began at or shortly after 10:03 a.m. and before 10:04 a.m. At 10:08 a.m. virtually all relevant parameter readings (pressures, levels, flow rates, etc.) abruptly drop to and remain at zero, indicating that the explosion occurred after the 10:07 reading and before the 10:08 reading (the explosion destroyed parameter sensing instruments and transmission lines, causing all subsequent readings to fail to zero). Therefore, the elapsed time between the start of the gas leak and the explosion was roughly 4 minutes.

Analysis of parameter trends also indicated that the gas leak occurred somewhere between the fourth and fifth compressor stages, and therefore corroborated the theory that the leak occurred at the fifth stage suction check valve (which was located just upstream of the fifth stage suction drum). The following two parameter trends support this conclusion:

1) At 10:03 a.m., with the PGC still running at full speed, an abrupt increase in fourth stage flow rate occurred, while fifth stage flow rate simultaneously began to decrease. This indicated that a leak had occurred downstream of the fourth stage, but not downstream of the fifth stage.

2) Between approximately 10:03 and 10:07 a.m., PGC fourth stage discharge pressure dropped about twice as fast as fifth stage suction drum pressure (the two pressures normally differ by only 3 or 4 psi during normal operations) and nearly twice as fast as fifth stage discharge drum pressure. This indicated that a leak had occurred upstream of both fifth stage drums, since if the leak was downstream of either fifth stage drum, that drum would have depressurized relatively faster than the fourth stage discharge drum.

Vapor Cloud Explosion Modeling

Investigators carried out analyses to model the formation and explosion effects of the presumed vapor cloud produced by the gas released from the 3.75-inch diameter hole in the fifth

stage suction check valve. The modeled vapor cloud was then compared to observed blast effects in order to determine if the two were consistent. Specifically, investigators sought answers to the following questions:

- What weight of gas was released from the failed check valve?
- What fraction of the gas released was involved in the explosion and what was its TNT equivalent?
- Would the vapor cloud explosion modeled by these parameters be consistent with observed effects?

Using several different methods to model gas release rates and explosion effects, investigators concluded the following:

- Approximately 15,000 pounds of process gas was released from the hole in the fifth stage suction check valve prior to the explosion.
- Approximately 3,000 pounds of gas was involved in the explosion (for a yield factor of 0.2), which was equivalent to about 31,000 pounds of TNT [15].
- A vapor cloud containing this much gas, if rapidly released into a highly congested area with a volume of about 20,000 cubic meters (the estimated congested volume of the vapor cloud) and ignited, would likely generate overpressures sufficient to produce the effects observed at Shell.

In short, vapor cloud explosion models based on a theoretical gas release from the hole in the fifth stage suction check valve were consistent with the actual blast effects observed at OP-III, further confirming the theory that the gas release originated at the subject valve. Appendix D contains details of vapor cloud modeling and analyses.

Other Corroborating Evidence

Other evidence and analysis also validated the theory that the leak began at the fifth stage suction check valve:

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[15] While vapor cloud explosions are commonly converted to TNT-equivalent explosions for purposes of comparison, TNT explosions and vapor cloud explosions have different characteristics. The destructive power of an explosion is based on numerous factors, including explosive parameters such as characteristic detonation velocity and pressure, confinement, tamping, method of initiation, impulse profile, and brisance value, and site parameters such as stand-off distance from surfaces. Specifically, the overpressure at the center of a vapor cloud explosion is much less than that at the center of an "equivalent" TNT explosion. So, even though approximately 31,000 pounds of TNT would have been necessary to produce the far-field (< 1 psi overpressure) blast effects observed at Shell, a much smaller amount of TNT would have produced equivalent near-field effects.

- After the fire, the shaft and counterweight from the fifth stage suction check valve were found partially buried beneath several sections of damaged piping and several inches of debris and sludge. However, the shaft and counterweight were lying directly on the ground surface with virtually no debris underneath them. This indicated that they landed at or near the beginning of the accident and were subsequently covered by debris from the explosion and fire.

- Engineering calculations indicated that the unrestrained drive shaft and counterweight assembly, with a combined weight of approximately 200 pounds, if ejected from the valve under normal operating pressure (300 psig), would travel a minimum of 12 feet, and probably much farther before striking the ground. The shaft and counterweight were found 42 feet directly south of the valve, in an unobstructed line of travel.

- A gas release from the drive shaft hole in the 5th stage suction check valve would account for the various eyewitness statements related to vapor cloud formation and dispersion. Eyewitnesses located underneath the pipe rack and south of the valve observed vapor blowing rapidly to the south, which is consistent with the direction of the high velocity gas jet emanating from the failed valve. Once the vapor cloud expanded out of the direct path of the gas jet, however, it would have drifted upward due to both the updraft produced by the overhead cooling fans and the fact that a substantial fraction of it was less dense than air. The cloud would also have started drifting northward with the prevailing breeze. This accounts for the observations of witnesses located to the north of the pipe rack, who observed vapor billowing over the 5th stage drums and drifting roughly to the north.

- To locate the approximate explosion center, Shell investigators conducted a bolt-stretch analysis. This was done by measuring the plastic deformation of metal anchor bolts of large equipment structures surrounding the blast area. Strain calculations indicated that the explosion center was located approximately 80 feet directly south of the PGC fifth stage suction drum. This point is almost directly in the path of the vapor jet that would have been produced by the gases escaping from the hole created by the absence of the drive shaft in the fifth stage suction check valve.

- The PGC automatically tripped between five and seven times on the morning of June 22, 1997 before the accident (3 to 5 trips from slow roll and 2 trips while at or near full speed). Each compressor trip actuated the four Clow Model GMZ check valves, which quickly slammed shut (as designed to prevent compressor damage from reverse gas flow). These events placed large and repeated stresses on internal valve components.

- Maintenance records showed that the fifth stage suction check valve was the only one of the four Clow Model GMZ pneumatically-assisted check valves installed in the PGC system never to have been inspected and repaired. The other three check valves had been inspected and repaired following a 1991 incident at OP-III (see page 26), and were found to be generally intact following the explosion and fire.

- Investigators determined that failure of Clow Model GMZ check valves was a factor in several other incidents at Shell facilities, including one serious gas release occurring in 1991 at a facility in Saudi Arabia partly owned by Shell. The circumstances preceding some of these prior incidents were remarkably similar to those in this accident (see pp 26-28).

Ignition Sources

Guidelines for Evaluating the Characteristics of Vapor Cloud Explosions, Flash Fires, and BLEVEs (Center for Chemical Process Safety of the American Institute of Chemical Engineers, 1994), states that, "In general, ignition sources must be assumed to exist in industrial situations." This is because in many industrial settings, ignition sources are ubiquitous and extremely difficult or even impossible to completely eliminate. Common industrial plant ignition sources include hot steam lines, sparks from friction between moving parts of machines, and open fire or flames from furnaces, heaters, or flares. Consequently, while plant designers strive to minimize ignition sources, the primary strategy for preventing vapor cloud explosions in chemical plants, refineries, and the like is to prevent formation of flammable vapor clouds [16].

Investigators determined that several ignition sources were present in the area of the OP-III explosion. These included at least the following: exposed piping flanges on the 1250 psig steam header in the south yard pipe rack, exposed hot surfaces of kerosene furnace transfer lines at their entrance to the fractionator, exposed hot surfaces of the dilution steam superheater and associated steam piping, and exposed surfaces of the fuel oil stripper stripping steam super heater. Other ignition sources, such as sparking electric apparatus, or friction between moving parts of nearby machines, may also have been present. The JCAIT was unable to determine which of these ignition sources actually ignited the vapor cloud.

Immediate Cause of the Accident

Based on the evidence and analysis hereinbefore presented, the JCAIT concluded that the flammable gas release was caused by the internal structural failure and drive shaft blow-out of the 36-inch diameter Clow Model GMZ check valve located on the suction side of the PGC fifth stage. Due to the failure of the drive shaft dowel pin and displacement of the shaft retaining key, the drive shaft of the valve detached from the valve disk and was expelled out of the valve body under system pressure. The absence of the drive shaft left a 3.75-inch diameter hole in the valve and allowed the compressed gases in the PGC system to escape at high velocity. The gases were released as a turbulent jet into an area congested by numerous vertical and horizontal structures, forming a flammable vapor cloud which subsequently ignited and exploded. Appendix C contains an Events and Causal Factors Chart of the accident sequence and subsequent events.

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[16] This is in contrast to measures taken to prevent vapor explosions within aircraft fuel tanks, where the primary strategy has historically been to eliminate all possible ignition sources.

Clow Model GMZ Check Valve Information[17]

The JCAIT determined that four Clow Model GMZ pneumatically-assisted check valves were installed in the OP-III process gas compression system and were located on the suction lines of the third and fifth compressor stages and on the discharge lines of the fourth and fifth compressor stages. The check valves were installed in 1976 as original plant equipment and were designed to permit process gas flow in only the forward direction. This is accomplished through the action of the valve's hinged disk, or flapper, which swings open during forward process gas flow and swings shut when gas begins to flow in the reverse direction (hence the common name "swing" check valve). A pneumatic system is interlocked with the PGC shutdown system and operates during an automatic compressor trip or manual shutdown. The pneumatic system applies a moderate force to hold the valve closed to minimize valve leakage and valve swinging following a compressor shutdown.

Reverse flow is the natural result of stopping a centrifugal compressor; compressed gas in the high pressure section of the plant tends to flow back to the low pressure section. Reverse gas flow is an undesired condition. It can damage a centrifugal compressor, such as the PGC. Also, any hydrocarbon that flows backward from the high pressure section of the plant to a lower pressure section may be vented to prevent the equipment in the low pressure section of the plant from over pressuring when the compressor is stopped. Check valves are installed to prevent this reverse flow in the event of a planned shutdown or trip of a centrifugal compressor.

The potential for reverse flow also exists in upset operating conditions commonly referred to as "compressor surge" or "surging". Surging can occur when a centrifugal compressor has insufficient gas flow, and the process flow rapidly switches from normal forward flow, to reverse flow, back to forward flow. During these rapid flow reversals, the check valves in the compressor suction and discharge pipe rapidly and repeatedly close and open. This often produces a forceful, loud "slamming" of the valve disk against the valve seat. The instant the valve closes, a very high unbalanced pressure can develop in the pipe due to the rapid interruption of the reverse flow. The combination of the high, unbalanced pressure, plus the valve disk slamming can cause significant temporary deflection in the pipe. In such cases, operators have described the valve and attached pipe as "jumping" out of the saddles.

Clow Model GMZ check valves (see Figure 2) contain a two-piece stem in which one

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[17]Clow Model GMZ Check Valves were manufactured by the Clow Corporation of Westmont, Illinois, and were marketed under the TRICENTRIC® trademark. The Clow Corporation of Westmont Illinois no longer exists, having been purchased by the C&S Valve Company, which itself was later purchased by Atwood & Morrill, Inc., of Salem Massachusetts. Atwood & Morrill, Inc., still markets valves under the TRICENTRIC ® trademark, and is therefore referred to later in this report as the "successor" to the Clow Corporation of Westmont, Illinois. The TRICENTRIC® trademark refers specifically to a unique triple offset seat and seal design used in certain valves and is unrelated to drive shaft retention. It in no way implies that products marketed by Atwood & Morrill Company, Inc. under the TRICENTRIC® trademark may be subject to the same failure as the Clow Model GMZ valves described in this report. The Clow Corporation of Westmont Illinois should not be confused with the currently existing Clow Valve Company of Oskaloosa, Iowa.

stem piece functions as a drive shaft and connects the internal valve disk to an external air-assist cylinder and flapper counterweight assembly. The other stem piece, or idler shaft, simply functions as a hinge for one side of the flapper. The drive shaft penetrates the pressure boundary through a stuffing box. The exterior portion of the drive shaft is connected to the pneumatic piston and counterweight, and the interior portion of the shaft is coupled directly to the valve disk using a cylindrical hardened steel dowel pin and a steel rectangular bar key (see Figure 3). This arrangement provides a counter weight to partially balance the weight of the valve disk, and provides the pneumatic power assist to maintain the valve closed as described above.

The Clow Model GMZ check valve installed as the PGC fifth stage suction check valve had an internal diameter of 36 inches and weighed 3.2 tons. The valve had a design limit pressure of 480 psig, and a design limit temperature of 115 degrees Fahrenheit. The JCAIT found no evidence that these limits were exceeded at any time prior to or during the accident.

Simplified cross-sectional view of check valve (flow direction is into page)

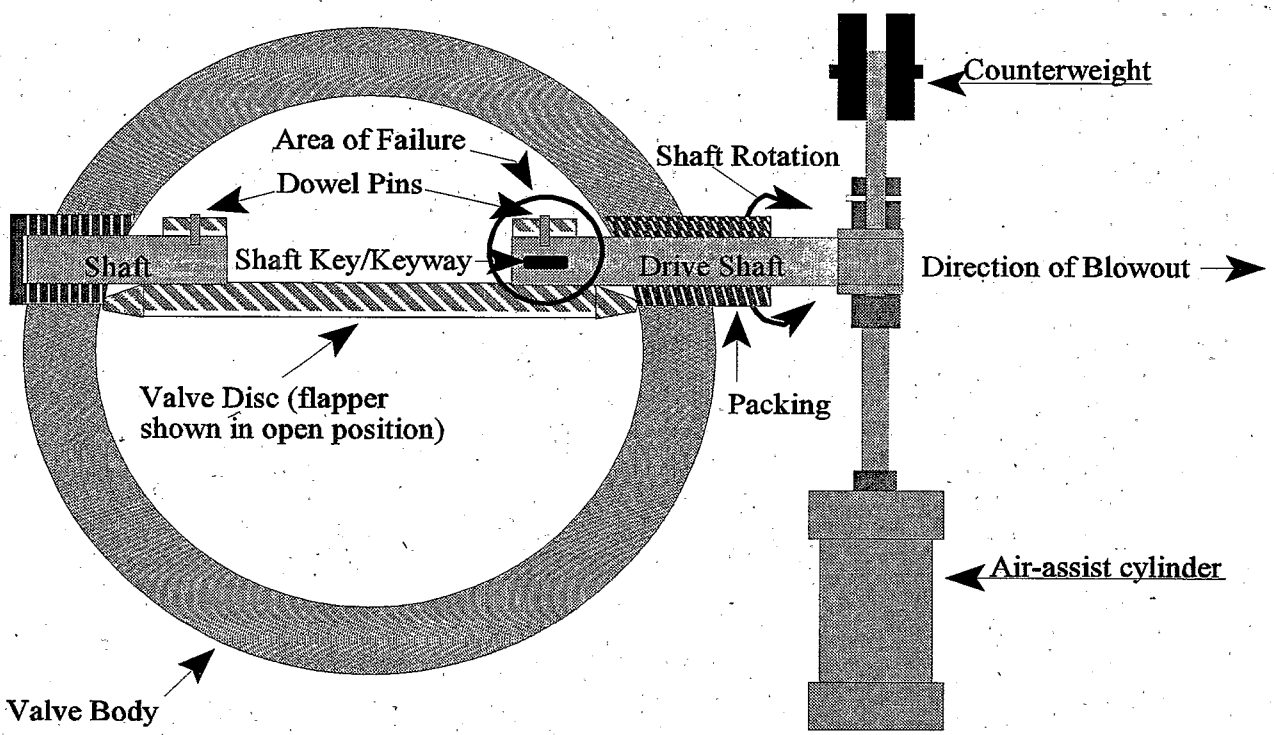

Figure 2: Clow Model GMZ Pneumatically-Assisted Check Valve

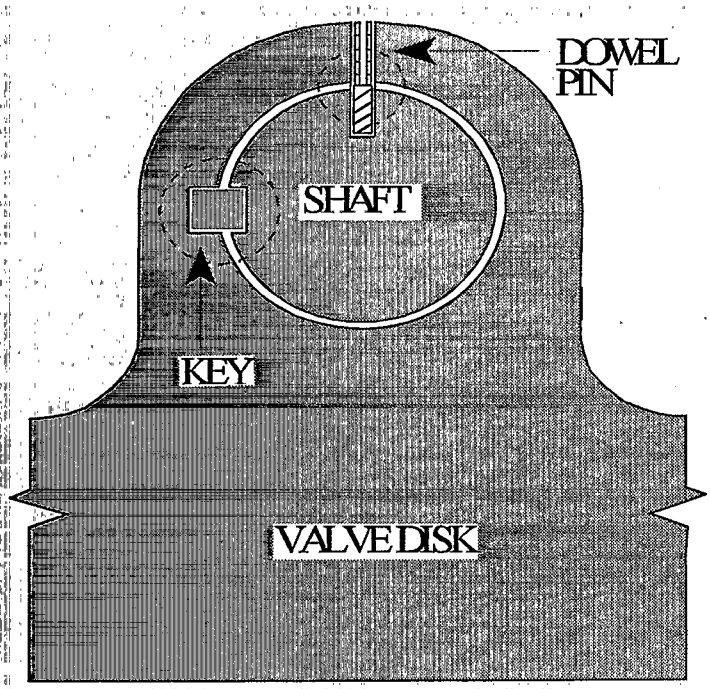

Figure 3: Expanded View of Check Valve Disk/Shaft/Key/Dowel Pin Arrangement

Previous Incidents Involving Clow Model GMZ Check Valves at Shell Facilities

In addition to this accident, several other incidents involving malfunctioning Clow Model GMZ check valves have occurred at Shell facilities. These included the following:

May, 1991 Clow Model GMZ Check Valve Malfunction at OP-III

In May 1991, OP-III was being started up following a five-week maintenance period. Operators started the PGC with gas flow from four fractionation furnaces. After the PGC was brought up to full speed, operators observed that the compressor began to surge [18]. The intermittent reverse gas flow caused the check valves located between compressor stages to repeatedly slam shut and re-open. One operator noticed that one of the check valves, located on the compressor third stage suction line, was slamming shut every ten to fifteen seconds with such force that the 36-inch diameter steel pipe to which the valve was connected noticeably "jumped", or deflected upward and downward with each cycle of the valve. A different check valve located on the fourth stage discharge line was also observed to slam shut and re-open several times, but not as often or as forcibly as the third stage suction check valve.

[18] The surging (reverse gas flow) in this event likely resulted from the fact that four furnaces provided insufficient gas load to the PGC. Operating practices were later changed to require the PGC to be fed process gas from at least six furnaces.

On closer inspection, operators observed several indications that the third stage suction check valve was malfunctioning. These indications included a small but noticeable amount of gas leaking out of the valve around its drive shaft, a slight outward axial displacement of the drive shaft, and the erratic operation of the valve, which was observed to operate independently of its external drive mechanism. Because of these indications, employees inspected the three other Clow check valves installed in the PGC system for similar problems. Employees noted that two of the three remaining valves (fourth and fifth stage discharge check valves) had gas leakage through the idler (non-drive) shaft packing and packing end plate. The fourth valve (fifth stage suction check valve) appeared to be functioning normally.

In spite of the indications that one check valve in the system was malfunctioning and two other valves had packing leaks, plant startup continued. About one hour after the first compressor surging was noted, two additional pyrolysis furnaces were brought on line (for a total of six) to add additional load to the PGC. This prevented further reverse gas flow and stabilized the compressor.

Upon further evaluation of the malfunctioning third stage suction check valve, maintenance technicians concluded that an internal dowel pin and shaft key in the valve had failed, allowing the disk to open and shut independently of its drive shaft, and allowing the axial movement of the drive shaft. Because of this fact and the leaks observed in two of the three remaining check valves, employees decided to shut down the PGC and remove the third stage suction check valve for repair and to remove the other two leaking check valves for inspection and possible repair. Employees decided not to remove and inspect the fifth stage suction check valve (the subject valve of this report), since it appeared to be functioning normally.

The next morning, the PGC was shut down and the one malfunctioning valve and the two valves with leaks were removed. At the time of the shutdown, the drive shaft on the third stage suction check valve was protruding approximately 3/4-inch out of the valve. Subsequent internal inspection of the third stage suction check valve revealed that two internal metal dowel pins designed to connect the drive shaft and non-drive shaft to the valve disk had sheared, and that a shaft key which coupled the drive shaft and disk was missing. With guidance from an experienced engineering representative of the valve's manufacturer, maintenance technicians fabricated replacement dowel pins and a shaft key in the machine shop and repaired the third stage suction check valve.

The two valves with leaks were disassembled and inspected. The dowel pins and shaft keys on both of these valves did not appear to be damaged, but since the valve's shaft packing material had become brittle and was crumbling, causing the leakage from the non-drive end of the valves, technicians decided to replace it with new packing. Since packing replacement required the removal of the drive end and non-drive end shafts, it was necessary for technicians to remove the old dowel pins which held the shafts in place, so these dowel pins were also replaced with newly fabricated pins. Original shaft keys for these valves were re-used.

The three check valves were reinstalled on Wednesday, May 22, 1991, and the OP III was started without further incident. The JCAIT found no evidence to indicate that further maintenance or internal inspections were ever performed on any of the PGC system pneumatically-assisted check valves prior to the 1997 accident, and various witnesses confirmed that none ever occurred.

December, 1991 Propane Gas Release in Saudi Arabia

In December 1991, Saudi Petrochemical Company (SADAF), a chemical plant located in Saudi Arabia and partly owned by Shell Chemical Company, experienced a release of propane gas when a Clow Model GMZ check valve experienced shaft blow-out. Many circumstances in this incident were similar to those in both the June 1997 accident and May 1991 incident. The incident occurred following a process upset in the facility's ethylene plant, where the inadvertent shutdown of a cracked gas compressor resulted in downstream flow instabilities and initiated a 13-hour period of surging in the unit's propane refrigeration compressor. During this period, the Clow Model GMZ check valves installed in the propane refrigeration compression system slammed shut repeatedly.

The shaft of the compressor's third stage discharge valve eventually separated from its disk and was partially ejected from the valve. The shaft was not fully ejected because its path was blocked by an adjacent steam line inches away from the valve, keeping about 70 mm of the shaft's length within the valve body. Propane gas began to leak out of the valve around the gap between the shaft and its stuffing box until operators discovered the leak and shut down the compressor. Operators also discovered that the valve's drive shaft counterweights had broken off of the drive shaft and had been propelled approximately 16 meters from the valve.

The facility was fortunate in this case. An adjacent steam line kept the shaft from being fully ejected from the valve, thus limiting the leak rate and preventing an accident of potentially much greater severity. It was also fortunate that no one was struck by the counterweights when they were propelled from the valve.

A subsequent investigation by SADAF and analysis of the check valve's internal components revealed that the dowel pin which secured the drive shaft to the valve flapper had sheared, and the shaft key had fallen out of its keyway (the same failure mode identified in the 1997 accident at Deer Park).

The SADAF investigation report also revealed that facility maintenance records indicated a long history of problems with the Clow Model GMZ check valves installed there. The valves were installed in 1982, and due to continuing valve malfunctions, underwent repair or modification in 1984, 1986, 1987, 1989, and 1990. These repairs and modifications included replacement of damaged counterweight arms, replacement of seals and gaskets, replacement of dowel pins and internal keys, and installation of external shaft "keepers". The investigation report indicates that the purpose of the external shaft keepers was to limit shaft "float" (minor shaft

movement). SADAF and Shell personnel stated that the keepers were not specifically intended to prevent shaft blow-out. Nevertheless, since they functioned to limit axial shaft movement, the external keepers might have prevented shaft blow-out. Ironically, when valve internals were serviced in 1990, the external keepers were no longer thought necessary and were therefore removed and never reinstalled.

1980 and 1994 Incidents at Shell Facility in Norco, Louisiana

In 1980 and 1994, a Shell facility in Norco, LA experienced failures involving Clow Model GMZ check valves. In both cases, shaft-disk separation occurred when the dowel pin fastening the valve's drive shaft to its disk sheared (in the 1980 case the pin was possibly never installed by the manufacturer), and a rectangular key fell out of its keyway, disconnecting the drive shaft from the disk. Although separation of the shaft and disk occurred in both of these cases, it did not result in shaft blow-out in either case. This may have been because the valves in these instances were installed in lower-pressure service, or because the malfunctions were identified before complete shaft blow-out occurred. In both cases, the malfunction was identified when employees noted that the external piston rod connecting the air-assist cylinder to the drive shaft had broken due to outward axial movement of the drive shaft.

Lessons Learned by Shell from Previous Check Valve Incidents

The JCAIT reviewed maintenance records from the 1980, May 1991, and 1994 check valve malfunctions. Shell personnel stated that these events were treated as maintenance actions and were not considered "accidents" or "incidents". Therefore, no formal investigations were conducted to determine their root causes or to determine lessons learned from the events. Consequently, other than the immediate repair of the malfunctioning components and a later change in operating practice requiring that the PGC be fed process gas from at least six furnaces (to limit compressor surging), no actions were apparently ever taken to prevent future incidents involving Clow Model GMZ check valves at Shell Deer Park. The JCAIT did not determine whether or not such actions were ever taken at other Shell facilities as a result of these events.

In the case of the December 1991 check valve incident in Saudi Arabia, a significant propane gas leak had occurred and facility personnel recognized that the incident could have been much more severe than it was. A formal investigation by SADAF personnel was conducted in order to determine the causes of the incident and to make recommendations to prevent recurrence of similar incidents. However, although a Clow Model GMZ check valve was determined to be the source of the leak in this event, the SADAF investigation did not specifically identify check valve design deficiencies as a cause of the event. Instead, investigators attributed the check valve's failure as the secondary result of a malfunctioning "kickback" valve [19] which caused compressor surging and repeated check valve slamming. Consequently, the majority of

[19] "Kickback" valves function to feed back a portion of the discharge gas flow from a given compressor stage to the inlet of that stage in order to artificially increase compressor gas load and thereby prevent reverse flow or "surging".

recommendations in the report focused on preventing compressor surging rather than the check valve itself. The report states:

> "The importance of limiting surge cycles to an absolute minimum can not be over-emphasized, therefore the recommendations listed below should be dealt with the utmost priority."

While the subsequent recommendations focused primarily on eliminating compressor surging, one recommendation was specifically relevant to the Clow check valves. This recommendation was:

> "Evaluate the need to retrofit dampening devices as well as pull and inspect all NRV's on 11K2 and 11K3 during the next ethylene plant T/A"[20]

Additionally, although not specifically recommended in the report, the JCAIT determined that after the incident, *a full external restraining bracket* was built around the valve with the intention of providing secondary containment of the shaft should the internal restraining mechanisms ever completely fail. The JCAIT did not attempt to verify whether or not the other recommendations from the SADAF incident investigation were implemented at that facility, but three things are clear:

1) Dampening devices were never installed on Clow Model GMZ check valves at OP-III,

2) None of the Clow check valves were ever "pulled and inspected" following the repairs performed subsequent to the May 1991 event at OP-III, and;

3) External restraining brackets were never installed on the Clow check valves at OP-III.

The JCAIT found no evidence that any of the lessons-learned or recommendations resulting from the SADAF incident were ever implemented at Deer Park or shared with other Shell facilities.

Other Information

<u>Shell Chemical Company Analysis of OP-III Process Hazards</u>

The JCAIT determined that Shell Chemical Company performed a Process Hazards Analysis (PHA) for the OP-III PGC system in 1991. The JCAIT also determined that Shell was in the midst of performing this PHA when the May, 1991 check valve malfunction event occurred

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[20] "NRV" is an abbreviation for Non-Return Valve, another term for check valve. "11K2" and "11K3" are facility designations for the ethylene and propane compression systems, respectively. "T/A" is an abbreviation for "turnaround", which is industry jargon meaning planned maintenance period.

at OP-III. In fact, employees stated that the PHA was suspended while the three check valves were repaired, since the engineers responsible for performing the PHA were also needed to repair the malfunctioning valves[21]. However, a review of the PHA showed no evidence that check valve failure or shaft blow-out was considered in the analysis, and the JCAIT found that no measures were taken as a result of the PHA to prevent a potential check valve shaft blow-out accident.

Operating Procedures

The JCAIT reviewed OP-III operating procedures for the PGC system to determine if the procedures or related operator actions were a likely factor in the accident. The JCAIT determined that written procedures for starting up the PGC in various modes existed, that operators were knowledgeable of the procedures, and intended to start-up the PGC in accordance with applicable written procedures on June 22, 1997. The JCAIT determined the following significant facts related to PGC operating procedures:

- Operating procedures did not contain any warnings, caution statements, or safety measures related to preventing check valve shaft blow-out, flammable gas releases, or vapor cloud explosions. The "Safety Precautions" section of the procedures addressed only hazards related to steam leaks, chemical exposure, and high noise.

- Operating procedures identified the possibility of a compressor trip due to high vibration, but did not contain any contingency actions in case such a compressor trip actually occurred. Operators stated that automatic compressor trips occasionally occurred during PGC start-ups (as was the case on the morning of June 22).

- Operating procedures required operators to confirm that all air-assisted check valves were open by visually inspecting the valves prior to starting the PGC. However, operating procedures did not specifically instruct operators to re-verify the position of these valves following an inadvertent compressor trip occurring during startup.

- Operators stated that they verified the position of all air-assisted check valves prior to the next to last PGC startup on June 22, but did not re-verify the positions of the check valves (or perform any other pre-startup checks) after the compressor subsequently tripped due to high vibration.

Root Causes and Contributing Factors

Root causes are the underlying prime reasons, such as failure of particular management systems, that allow faulty design, inadequate training, or deficiencies in maintenance to exist. These, in turn, lead to unsafe acts or conditions which can result in an accident. Contributing

[21] The PHA was actually suspended twice during 1991. Once for the repair of the check valves, and on an earlier occasion in order to allow the PHA team to assist with a scheduled maintenance period.

factors are reasons that, by themselves, do not lead to the conditions that ultimately caused the event; however, these factors facilitate the occurrence of the event or increase its severity. The root causes and contributing factors of this event have broad application to a variety of situations and should be considered lessons for industries that operate similar processes, especially the chemical and petroleum refining industries.

The JCAIT used a variety of analytical techniques to determine the root causes and contributing factors of the accident, and to generate recommendations to prevent recurrence. These techniques included events and causal factors charting, fault tree analysis, root cause tree analysis, and professional judgement. The JCAIT identified the following root causes and contributing factors of the accident:

Root Causes

1) Inadequate Valve Design

The Clow Model GMZ check valves installed in the OP-III PGC system were not appropriately designed and manufactured for the heavy duty service they were subject to in OP-III. This resulted in the valves being susceptible to shaft blow-out during normal use.

"Normal" use of Clow Model GMZ check valves at OP-III included periods of high cyclic loading. Operating practices during routine startups of the process gas compression system and during recovery from process upsets subjected the system to intermittent automatic compressor trips and occasional periods of surging (rapid flow reversals) which placed high stresses on the check valves by slamming them shut. On the morning of June 22nd, 1997, the valves slammed shut after compressor trips on at least five and possibly as many as seven separate occasions. Each of these cycles placed peak stresses on the fifth stage suction check valve and its internal components, including the drive shaft dowel pin, and caused existing intergranular cracks to propagate through the dowel pin, eventually fracturing it completely and initiating the shaft blow-out. The fact that Clow Model GMZ check valves had experienced the same mode of failure under similar circumstances on several previous occasions further confirms that they are not appropriately designed for severe-duty applications.

A number of design factors contributed to the fifth stage suction check valve's failure, including:

- The valve was inherently susceptible to shaft blow-out. This resulted primarily from the following two design elements: the valve's "stub-shaft" design and its lack of secondary shaft-retention features. The term "stub-shaft" denotes a valve having a shaft piece that penetrates the pressure boundary and terminates inside the pressurized portion of the valve. This feature results in an unbalanced axial thrust on the shaft which tends to force it out of the valve. Since the fifth stage suction valve was located in a relatively high-pressure portion of the PGC system (300 psig), the drive shaft was subject to a large axial

thrust during system operation. The valve also did not contain any secondary shaft-retention feature or device, such as a split-ring annular thrust retainer or a shaft with an internal diameter larger than the internal diameter of its stuffing box. Therefore, when the drive shaft separated from the disk, nothing (other than friction) prevented it from being ejected out of the valve.

- The shaft dowel pin carried too much stress load. The shaft key was intended to transfer all of the torque between the drive shaft and disk. However, the excessive looseness of the shaft key in its keyway combined with the tight fit of the shaft dowel pin resulted in the relatively small diameter dowel pin (which was further weakened by the threaded screw installation and the effects of hydrogen embrittlement) transferring all torque between the shaft and the disk. The relatively large gap between the shaft key and its keyway also permitted the key to fall completely out of the keyway as the drive shaft moved outward. The excessive looseness of the shaft key in its slot was either the result of inadequate design (e.g., inadvertently designing a key with a too-loose fit), inadequate manufacturing (e.g., machining the key and keyway with more looseness than design specifications called for), or both.

- The shaft dowel pin was susceptible to hydrogen embrittlement. Metallurgical analysis indicated that the dowel pin was manufactured from case-hardened carbon steel and was used in a hydrogen-rich environment, conditions leading to hydrogen embrittlement. This probably led to the formation of intergranular cracks which propagated inward from the exposed surfaces to the core of the dowel pin. This weakened the dowel pin, which was already carrying more load than it was intended to carry. Other materials or other types of steel not susceptible to hydrogen embrittlement should have been chosen for fabrication of the dowel pins.

2) Failure to Learn from Prior Incidents

Lessons learned from prior incidents involving Clow Model GMZ check valves installed at Shell facilities and at Saudi Petrochemical Company (SADAF), a Saudi facility partly owned by Shell, were not adequately identified, shared, and implemented. This prevented recognition and correction of the valve's design and manufacturing flaws at OP-III prior to the accident.

Information available to Shell as early as 1980 suggested that Clow Model GMZ check valves were problematic. In 1991, however, the two potentially very serious incidents involving Clow Model GMZ check valves occurring within a period of eight months should have been clear warnings that the valves presented a significant hazard. Both incidents involved very similar circumstances and required the respective operating units to be shut down specifically for repair of the Clow check valves.

However, while the investigation of the incident in Saudi Arabia identified numerous causal factors involved in that event, it did not focus on the failed Clow Model GMZ check valve

itself and therefore the report did not identify all factors involved in the valve's failure. For example, even though equipment records from the Saudi plant indicated a long history of problems with the Clow Model GMZ check valves, the investigation report did not identify check valve design features as possible factors in the shaft blow-out incident. Nevertheless, the fact that a full external restraining bracket was installed around the valve after the incident indicates that facility engineers recognized the valve's design flaws. If external restraining brackets had been installed on the Clow check valves at Deer Park, the 1997 accident would almost certainly have been avoided. Also, at least one of the Saudi incident report's recommendations (i.e., to install dampening devices), if implemented at Deer Park, might have prevented the 1997 accident.

At least one person at the Saudi plant recognized the potential severity of the valve's failure. A handwritten note on the cover page of the company investigation report from the incident reads:

"Could have been serious!"[sic]

In spite of this, The JCAIT found no evidence that any actions were ever taken at the Deer Park plant to prevent future incidents of this type. Lessons learned from the incident in Saudi Arabia may not have been adequately communicated to, or understood by, Deer Park personnel; for some reason they were simply not applied at OP-III.

3) Inadequate Process Hazards Analysis

The process hazards analysis (PHA) of the process gas compression system was inadequate; the PHA did not identify the risks associated with shaft blow-out in Clow Model GMZ check valves, and consequently no steps were taken to mitigate those risks.

Formal hazard evaluations, such as PHAs, should identify potential failure areas that need to be addressed by safeguards such as equipment design, engineering controls, maintenance, and standard operating procedures. When conducting a PHA, companies should consider previous incidents related to the subject process and its equipment. However, during the 1991 PHA at OP-III, Shell did not consider relevant previous incidents that had occurred at OP-III and other Shell facilities. Shell consequently missed an early opportunity to eliminate or minimize the hazards created by the check valves in the PGC system and avoid this accident.

The failure of the PHA to identify and address the hazards associated with Clow Model GMZ check valves is particularly remarkable since the PHA (a process which required a Shell engineering team several months to complete) was temporarily suspended specifically in order to allow engineers on the PHA team to repair the Clow Model GMZ check valves that malfunctioned in May, 1991.

4) Inadequate Mechanical Integrity Measures

Measures necessary to maintain the mechanical integrity of Clow Model GMZ check valves installed in OP-III were not taken. This resulted in undetected damage to and eventual failure of critical internal valve components.

The JCAIT found that the PGC fifth stage suction check valve had not been inspected for internal mechanical integrity and had not received any internal maintenance since its original installation, a period of over 20 years. The JCAIT also determined that the other three Clow Model GMZ check valves installed in the PGC system had been inspected and repaired only once - after the 1991 malfunction of the third stage discharge check valve. In his book, *What Went Wrong? Case Histories of Process Plant Disasters* (Kletz, 1994), author and industrial safety expert Trevor Kletz states:

> "Check valves have a bad name among many plant operators. However, this is because many of them are never inspected or tested. No equipment, especially containing moving parts, can be expected to work correctly forever without inspection and repair."

In spite of the fact that OP-III and Shell's Norco, LA facility had experienced significant mechanical integrity problems with these valves, and of the fact that the Saudi Petrochemical facility (partly owned by Shell) had documented a long history of mechanical problems with the valves, the OP-III mechanical integrity inspection program did not include periodic internal inspections of PGC system check valves or any other measure to evaluate or ensure their integrity. If such inspections or other mechanical integrity measures such as periodic preventive maintenance had been conducted, the Deer Park accident would likely have been prevented.

5) Inadequate Operating Procedures

Operating procedures for the start-up of the PGC system did not specifically instruct operators to re-verify the position of pneumatically-assisted check valves before restarting the compressor following unexpected automatic compressor trips, nor did they contain warnings or caution statements related to prevention of hydrocarbon leaks or check valve shaft blow-out. Consequently, operators did not re-verify the position of the valve that failed. Re-verification might have enabled operators to observe possible indications of the fifth stage suction check valve's imminent failure on June 22, 1997.

The JCAIT found that operators were knowledgeable of PGC startup procedures and generally followed them when conditions were normal. However, since the procedures did not address unexpected situations or contain steps required to correct upset conditions such as power outages or compressor trips, foremen and operators used their own discretion in deviating from or adapting the procedures during upset or abnormal conditions. Such was the case on June 22, 1997; since PGC operating procedures did not contain specific requirements for re-verification of equipment status following an unexpected automatic compressor trip or any warnings related to

check valve shaft blow-out, operators elected to immediately re-start the compressor after a high-vibration trip, without performing any further equipment checks.

While other root causes presented herein address factors farther upstream in the chain of events leading to the accident, the final possible opportunity to avoid the accident was for operators to have visually inspected the pneumatically-assisted check valves before the final compressor startup. In the May 1991 check valve malfunction event at OP-III, operators visually detected the partial ejection of the drive shaft from the third stage discharge check valve in time to take action to prevent complete blow-out of the drive shaft. This was also true in the 1980 and 1994 events at Shell's Norco, LA facility. In the 1997 accident, it was likely that the drive shaft from the fifth stage suction check valve had become unrestrained (i.e., the dowel pin had fractured and the shaft key had fallen out) during one of the several check valve closures that occurred earlier that morning. Consequently, it is possible, and in consideration of past events perhaps even likely, that if operators had visually inspected the position of the check valves immediately prior to the final compressor startup attempt on the morning of June 22, they might have observed indications of the PGC fifth stage suction check valve's imminent shaft blow-out and taken actions to prevent the accident.

Contributing Factors

1) No Indication of Hydrocarbon Leak / Delayed Operator Response to Leak

The lack of clear and immediate indications in the control room of a hydrocarbon leak contributed to the severity of the accident by significantly delaying operator action to shut down and depressurize the process gas compression system. This is another aspect of inadequate process hazards analysis, but is addressed in detail here due to the large role it played in the release.

Once operators were aware that a large process gas leak had occurred, they immediately (and correctly) acted to shut down and depressurize the PGC system. However, if these actions had occurred immediately after the gas release began, rather than approximately four minutes later, the vapor cloud explosion would likely have been either averted entirely or of much smaller magnitude. Each minute that the leak continued with the PGC running at full speed contributed nearly two tons of additional flammable gas to the vapor cloud, substantially increasing the likelihood and force of the subsequent explosion. In *Loss Prevention in the Process Industries* (Lees, 1996), the author cites an analysis conducted by Trevor Kletz (1977) which concludes that small hydrocarbon vapor clouds, even if they ignite, are not likely to explode. Kletz states:

> "... the probability of an explosion certainly appears to be much less if the quantity is small. ... if there are 10 tons of vapour (sic), the probability of explosion is at least 1 in 10, whereas if there is 1 ton or less, the probability of explosion is of the order of 1 in 100, or, more likely, one in 1,000."

The main reason for the four minute delay in responding to the leak was that control room operators were unaware that a flammable gas leak had occurred. Various operator statements conveyed their initial belief that the accident was either a fire or a high-pressure steam leak, and not a flammable process gas leak. Since the rate of leakage from the PGC system was too small to be easily differentiated from the normal process gas flow rates indicated on control room instruments, and no other indications of flammable gas leakage were available in the control room, operators there decided to wait for verbal reports from on-scene personnel before taking action.

If flammable gas detection equipment had been installed in OP-III and monitored in the control room, operators would have immediately recognized the nature of the accident and would likely have taken actions to mitigate or prevent the subsequent vapor cloud explosion. Flammable gas detectors are commercially available today that are intrinsically safe (i.e, they do not present an ignition or explosion hazard), such as ultraviolet or infrared optical point and open-path hydrocarbon gas detectors. It is even possible to link such detectors directly to emergency shutdown systems.

In light of the continuing difficulties associated with the PGC in the hours preceding the accident, it is possible that once the machine had (apparently) successfully been started, operators were reluctant to shut it down without clear indications of a serious malfunction. Nevertheless, the JCAIT noted that the strategy of control room operators to take no action without definite indications as to the nature of the accident was not appropriate. In this case, the worst accident scenario potentially indicated by the leak in the pipe rack was a vapor cloud explosion resulting from a process gas leak (a fact that should have been particularly evident since the PGC system had just been started), and operators should have immediately shut down and depressurized the PGC system to prevent or mitigate this accident. The adverse safety consequences associated with taking these actions immediately were minimal, but the consequences of *not* taking them immediately were severe.

2) Inadequate Communications Practices

Inadequate communications practices during the accident contributed to its severity by hindering the timely flow of information to control room operators. This caused confusion among control room operators regarding the circumstances of the accident, unnecessarily placed additional operators in jeopardy from the impending explosion, and further delayed mitigating actions by control room operators.

Control room operators and operators in the field stated that they had difficulty understanding radio transmissions from the cold-side foreman due to the excited nature of his reports and the high background noise in the area of the leak. The cold-side foreman, in turn, stated that control room operators failed to acknowledge several of his emergency reports and orders during the gas leak. Various control room operators also stated that they were unsure of the exact meaning of the foreman's reports and orders. Uncertainties resulting from these difficulties in communication prompted control room operators to discuss among themselves their

understanding of various reports and orders. This, (along with the lack of clear flammable gas leak indications), contributed to delays in mitigating action.

The confusion in the control room also led five employees to leave the shelter of the control room and place themselves in great danger because they did not understand the nature of the hazard. These employees, as well as the foreman and PGC field operator, were fortunate in that they did not suffer any indirect effects of the explosion (e.g., impact of indirect fragments, structural collapse, or blunt object trauma).

Recommendations

The JCAIT developed recommendations addressing the root and contributing causes of the accident to prevent a recurrence or similar event at this and other facilities. The scope of these recommendations ranges from general to very specific, and companies and industry groups not specifically named should consider each recommendation in the context of their own circumstances, and implement them as appropriate. The recommendations are as follows:

1) Prior to re-starting OP-III, Shell Chemical Company should replace all Clow Model GMZ check valves installed in the unit with valves not susceptible to shaft blow-out. If immediate valve replacement is impossible or impractical, Shell should immediately modify the valves to prevent shaft blow-out. Other Shell facilities and other companies as appropriate should review their process systems to determine if they have valves installed that may be subject to this hazard, and modify or replace those valves as necessary to prevent shaft blow-out. Companies should consult valve manufacturers or other appropriate design authorities to ensure any modifications made are safe. [Editor's note: Prior to this report being published, Shell Chemical Company replaced all Clow Model GMZ check valves installed in OP-III with valves not susceptible to shaft blow-out.]

2) Shell Chemical Company should update and revalidate the process hazards analysis (PHA) at OP-III and should consider updating and revalidating other units' PHAs to ensure all operating and maintenance experience and incidents are fully evaluated. Shell should also take appropriate measures to mitigate hazards identified by the revalidated PHAs.

3) Shell Chemical Company should revise OP-III process gas compression system operating procedures to provide clear instructions for operators to re-verify the positions of pneumatically-assisted check valves before the process gas compressor is re-started following any compressor trip if said check valves are at high risk of leakage or failure. Shell should also consider adding warnings or caution statements in process gas compression system procedures related to the circumstances and indications of check valve shaft blow-out, or other potential causes of hydrocarbon gas leaks.

4) Shell Chemical Company should improve their radio communications practices at OP-III and as appropriate at other facilities to ensure operational and emergency information is transmitted in an accurate and timely fashion. Shell should consider instituting communication verification

measures such as mandatory repeat-backs for all operational reports and orders, and should consider obtaining communications equipment capable of being used effectively in high-noise environments. Other companies that require operators to communicate in high-noise environments should also consider taking these or similar measures.

5) Shell Chemical Company should implement a more rigorous mechanical integrity inspection program for valves in extreme service or with a known history of failure where the failure of such valves could result in catastrophic consequences. Where possible, these inspections should include detailed examinations of critical internal components for damage or failure. Where indicated by inspections or operating history, additional measures should be taken to maintain valve integrity. Such measures may include periodic replacement of critical internal components (e.g., dowel pins), material substitution for critical internal components, installation of shaft or stem retention devices, complete valve substitution, or periodic valve replacement.

6) Shell Chemical Company and Shell Oil Company should develop and implement a corporate information communication system, or improve existing systems, to ensure that lessons learned from all prior operating and maintenance accidents, incidents, and near misses at Shell facilities (including facilities partly owned by Shell) are always fully reviewed and incorporated as appropriate into the management and operation of every Shell facility (not just the facility where the incident occurs).

7) Shell Chemical Company and other companies that process flammable gases and volatile flammable liquids or liquefied gases must implement precautionary measures contained in OSHA's PSM standard and EPA's RMP rule to prevent flammable gas leaks from resulting in vapor cloud explosions. These measures may include the following (other measures than these may also be advisable, depending on each facility's particular risk factors):

- Installing hydrocarbon or flammable gas detectors which provide immediate and positive leak indication to field and/or control room operators;

- Installing active vapor cloud suppression equipment in high-risk plant areas; and,

- Conducting process operational drills which train operators to quickly recognize and take immediate actions to prevent worst-case accidents such as vapor cloud explosions. In some cases, operators should be trained to immediately act even when presented with ambiguous accident indications. For example, in a situation where operators are unable to immediately determine whether a loud and unexpected gas leak in a system is steam or hydrocarbon gas, they would be trained to immediately take at least the appropriate actions for a hydrocarbon gas leak if it constitutes the most potentially severe accident. Readers should understand that this is not intended to encourage companies to take reckless actions or to perform uncontrolled or emergency shutdowns "at the drop of a hat". The JCAIT recognizes that in some circumstances, emergency shutdowns can have adverse consequences and are therefore not to be undertaken lightly. Each facility must

evaluate their own circumstances and prepare and implement emergency procedures, including emergency shutdown procedures, which account for those circumstances. However, when the adverse consequences of taking emergency shutdown actions are minimal in relation to the risk of not taking those actions (as was true in this case), such actions should be taken without delay.

8) Atwood & Morrill Co., Inc. (the successor to Clow Corporation of Westmont, Illinois), should inform all customers who have previously purchased Clow Model GMZ check valves of the circumstances of this accident and of the potential for these valves to undergo shaft blow-out.

9) Where feasible, companies should consider inherently safer design alternatives. For example, process designs that reduce or eliminate extreme equipment cycles such as check valve slamming should be considered, as well as designs which eliminate the possibility or minimize the potential consequences of worst-case accidents such as vapor cloud explosions.

10) The American Petroleum Institute, the National Petroleum Refineries Association, the Chemical Manufacturers Association, and other related industry trade associations in the U.S. and abroad should inform member companies of the circumstances in the EPA/OSHA joint report of the Shell Deer Park accident.

11) Chemical and petroleum industry trade associations and individual member companies should work together to develop and institutionalize a stronger system, or improve existing systems, for sharing and implementing lessons learned from process incidents and accidents at companies in the United States and abroad.

12) EPA should take appropriate follow-up actions, such as inspections, audits, or implementation of other policies to ensure that U.S. companies modify, remove, or replace, as appropriate, all Clow Model GMZ check valves that are at high risk for shaft blow-out.

13) EPA and OSHA should distribute this report and the Chemical Safety Alert entitled "Shaft Blow-Out of Check and Butterfly Valves" to affected companies (including valve manufacturers and users), industry trade associations, Local Emergency Planning Committees (LEPCs), and State Emergency Response Commissions (SERCs). The Alert counsels process facilities, including chemical, petrochemical, power generation, compressed gas, and others to review their process systems to identify valves which may be susceptible to shaft blow-out and, in consultation with valve manufacturers, replace or modify those valves as necessary to prevent an accident. EPA and OSHA should also distribute this report to international organizations such as the Organization for Economic Cooperation and Development (OECD) and the United Nations Environment Programme (UNEP) so that these organizations may inform member countries of the circumstances of this accident. Valve manufacturers should consider the risk factors described in the alert and this report and modify current valve designs as appropriate to prevent shaft blow-out accidents. [Editor's note: Prior to publishing this report, EPA and OSHA distributed the subject Alert to affected companies, trade associations, LEPCs, and SERCs, and posted the Alert

on the Internet at www.epa.gov/ceppo/. The Alert is also included as Appendix F to this report.]

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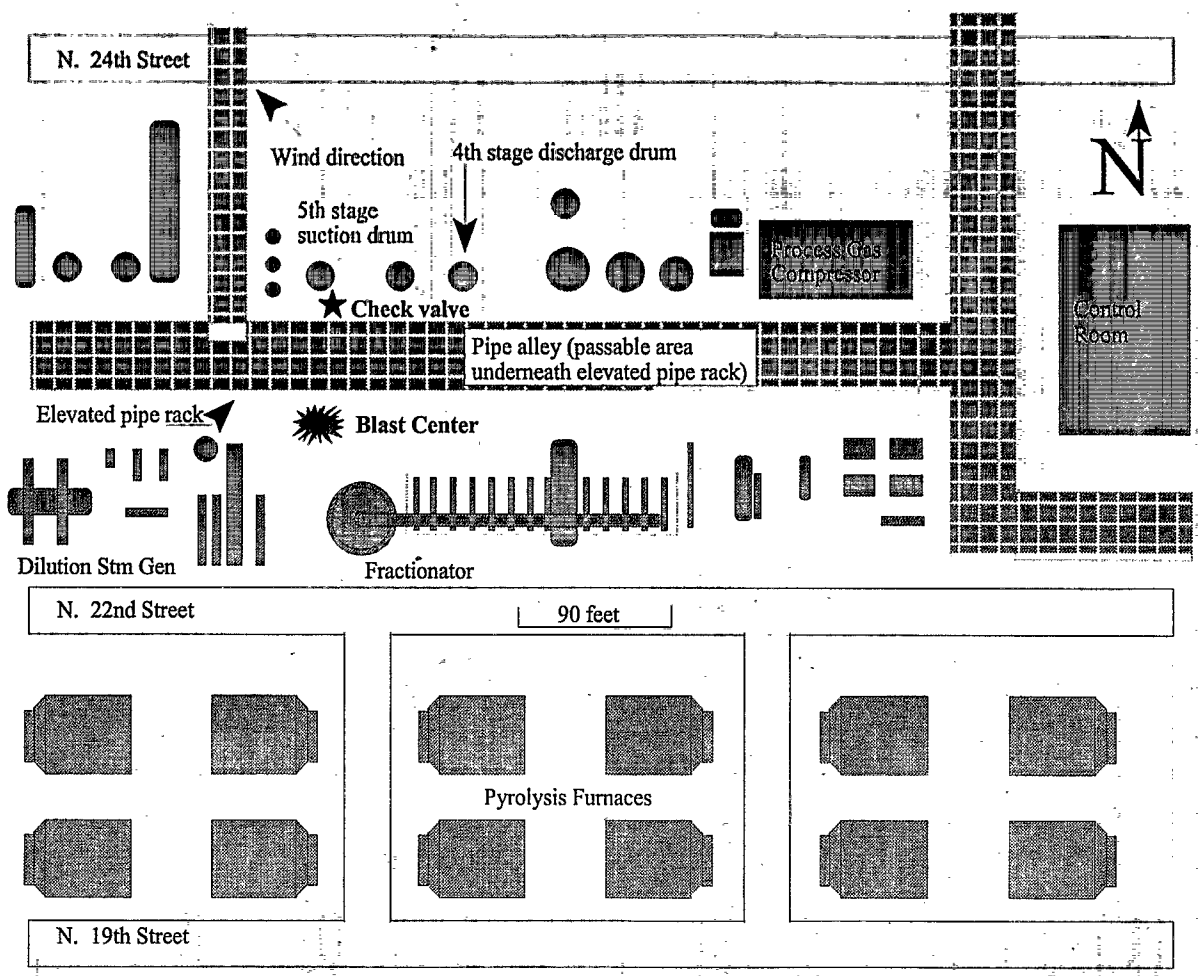
List of JCAIT Members

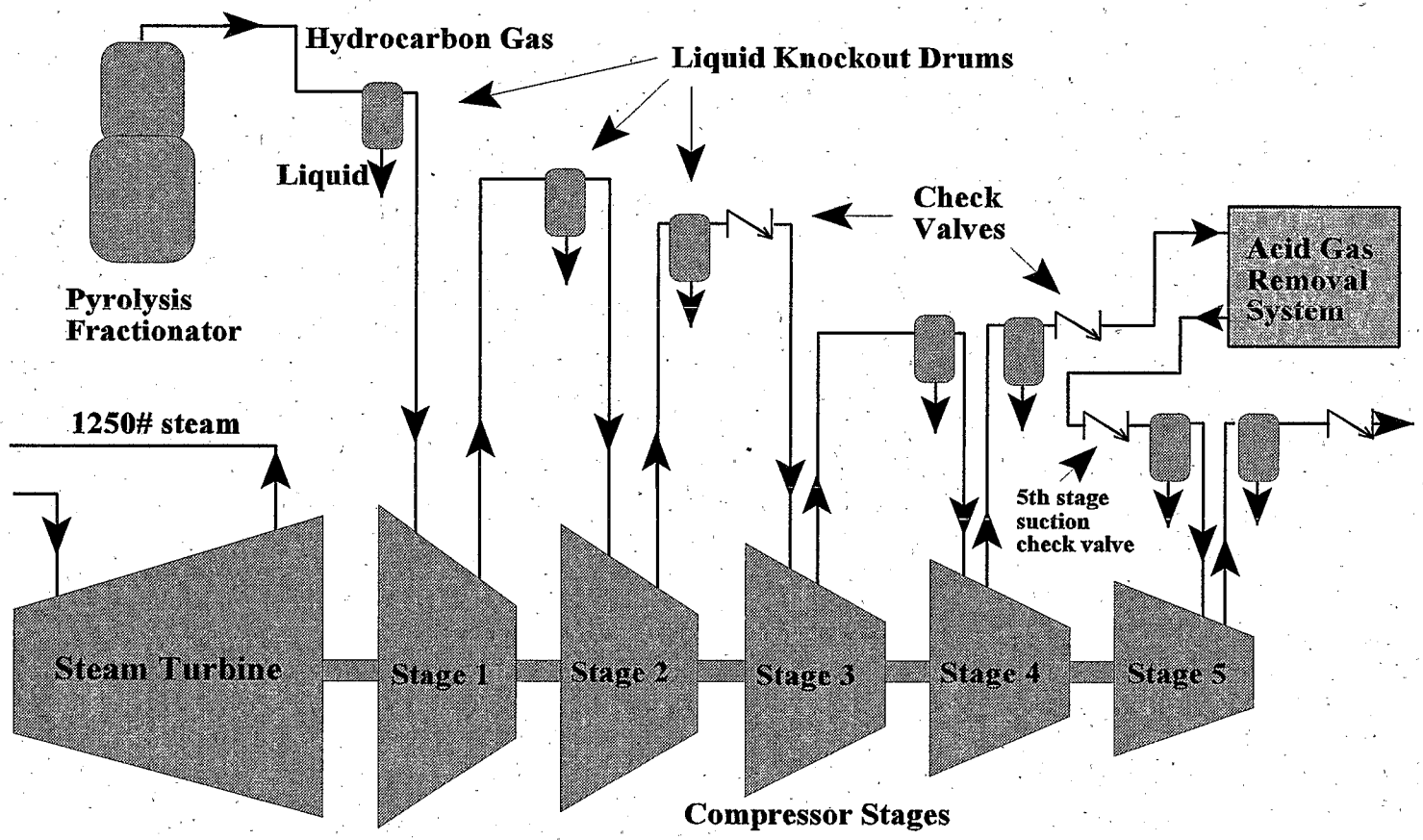
Name / Organization	Position
James Belke / EPA Headquarters	JCAIT Co-leader
Mark Briggs / OSHA Houston South Area Office	JCAIT Co-leader
Kevin Rockwell / OSHA Houston South Area Office	JCAIT Lead Investigator
Kim Nguyen / OSHA Houston South Area Office	JCAIT Investigator
Russ Elveston / OSHA Houston South Area Office	JCAIT Investigator
Craig Weber / OSHA Corpus Christi Area Office	JCAIT Investigator
Richard Watson / OSHA Little Rock Area Office	JCAIT Investigator
Mike Marshall / OSHA Headquarters	JCAIT Investigator
Steve Mason / EPA Region 6	JCAIT Investigator
Jack Stark / EPA Region 6	JCAIT Investigator

Appendix A: OP-III Layout



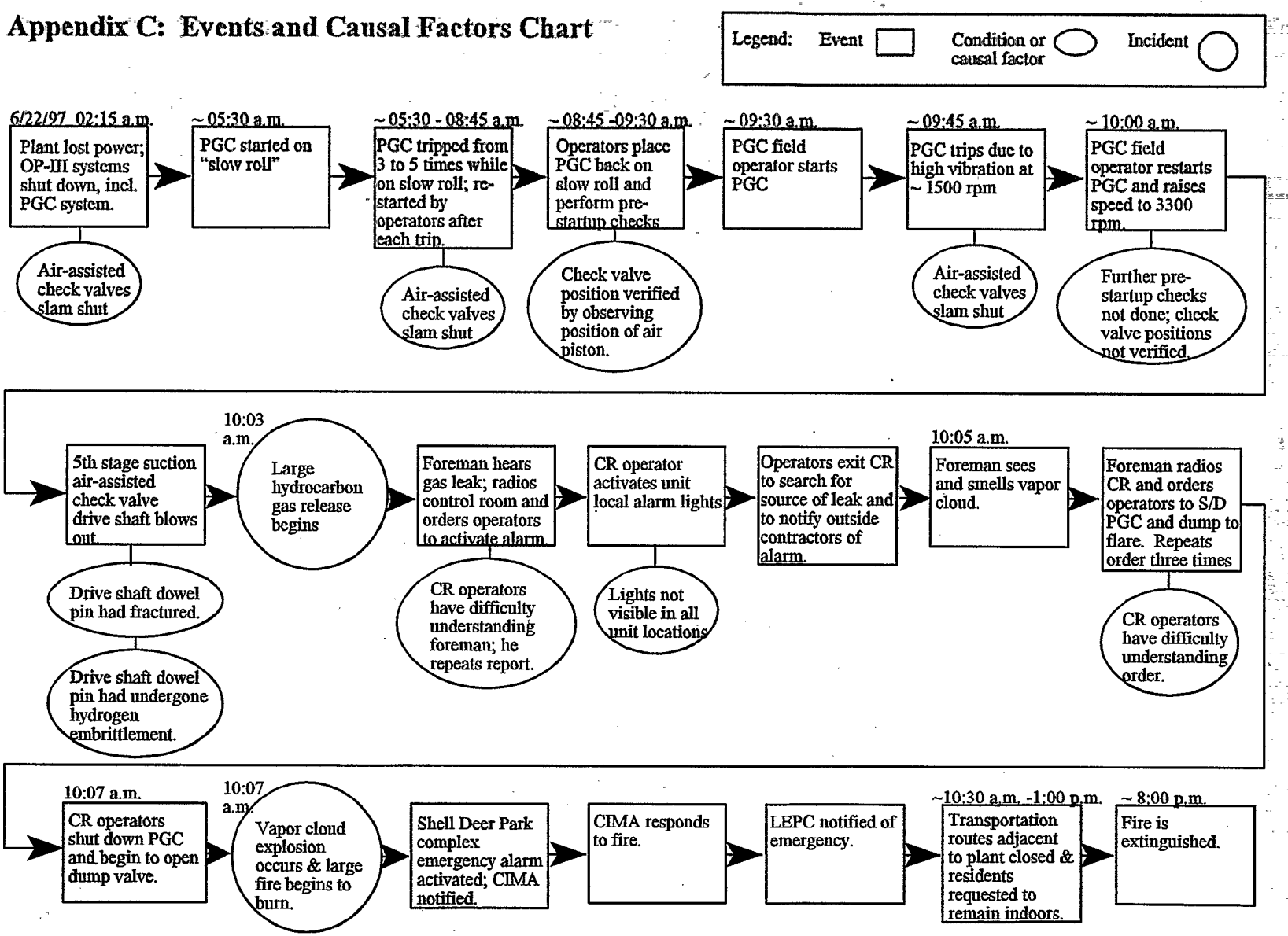
Appendix B

Process Gas Compression System - Simplified Flow Diagram*



* Diagram shows only selected components in main flow path. Subsystems and other components, including low & high pressure stripping systems, refrigeration system, discharge coolers, condensate pumps, feed heaters, gas dryers, etc.. are not shown.

Appendix C: Events and Causal Factors Chart



Appendix D: Vapor Cloud Explosion Modeling

The JCAIT carried out analyses to answer the following questions concerning the gas release and explosion that occurred at Shell on June 22, 1997:

- What weight of gas was released from the failed check valve?
- What fraction of the gas released was involved in the explosion and what was its TNT equivalent?
- Would the vapor cloud explosion modeled by these parameters be consistent with observed effects?

The rate and total quantity of process gas released through the 3.75-inch diameter hole in the check valve was estimated using the calculation methods and models discussed in section 1 below.

To estimate overpressures that resulted from the Shell explosion, window breakage observed at Shell was analyzed and compared with the overpressures reported to result in breakage of windows of similar size and thickness. These estimates are discussed in section 2.

The effects of a vapor cloud explosion resulting from the quantity of released gas determined in section 1 were estimated using two different models, the TNT-equivalent model and the multi-energy model. The TNT-equivalent model is a widely used model that relates the blast effects of an explosion of flammable gas to the blast effects of TNT. The multi-energy model is more recently developed, and models nodes of explosive atmospheres in a confined space. These models and modeling results are discussed in sections 3 and 4.

A comparison of the results of vapor cloud explosion modeling described in sections 3 and 4 to the estimated overpressures for the window breakage observed at Shell is discussed in section 5.

1. Release Rate and Quantity Released

Three methods were used to estimate the rate of release of flammable gas through a hole, as follows:

- The method developed for *RMP Offsite Consequence Analysis Guidance* (OCA Guidance) (May 24, 1996 draft);
- The World Bank Hazard Analysis (WHAZAN) model; and
- The Automated Resource for Chemical Hazard Incident Evaluation (ARCHIE) model.

To use these methods, a set of "composite" chemical properties was developed, based on the properties of the pure substances making up the chemical mixture that was released at OP-III and the fraction of each substance in the mixture. For purposes of comparison, the same calculations were performed assuming that the entire mixture had the properties of ethylene, the major component of the mixture.

The three methods used to estimate the release rate have the same theoretical basis and give similar results. As presented in the OCA Guidance, the equation for an instantaneous discharge under non-choked flow conditions is:

$$m = C_d A_h \sqrt{2 p_0 \rho_0 \left(\frac{\gamma}{\gamma - 1}\right) \left[\left(\frac{p_1}{p_0}\right)^{\frac{2}{\gamma}} - \left(\frac{p_1}{p_0}\right)^{\frac{\gamma+1}{\gamma}}\right]}$$

where: m = Discharge rate, kg/s
C_d = Discharge coefficient
A_h = Opening area, m^2
γ = Ratio of specific heats
p_0 = Tank pressure, Pascals
p_1 = Ambient pressure, Pascals
ρ_0 = Density, kg/m^3

Under choked flow conditions (maximum flow rate), which would apply in the case of the release at Shell, the equation becomes:

$$m = C_d A_h \sqrt{\gamma p_0 \rho_0 \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{\gamma-1}}}$$

For all three methods, the discharge coefficient was assumed to be 0.8.[1] The gas pressure was assumed to be the average absolute pressure calculated from the pressure differential across the hole recorded at the start of the leak and after four minutes. The temperature was assumed to be constant at 95 of (308 K). The release rates determined by these three methods, based on composite chemical properties, and the quantities estimated to be released in four minutes, are in good agreement, as shown below. Release rates and quantities calculated using the properties of ethylene were very similar.

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[1]The value of the discharge coefficient is determined by two factors: friction between the gas and the sides of the opening, and contraction of the gas as it flows into the opening. Various sources cite coefficients for circular orifices ranging from 0.62 to 0.98. Therefore, 0.8 was chosen as an average coefficient for a circular orifice. The calculated release rate varies linearly with the value of the discharge coefficient, so other C_d values would result in slightly higher or lower release rates.

Method	Release Rate (Pounds per Minute)	Quantity Released (Pounds)
OCA Guidance	3,956	15,820
WHAZAN	3,661	14,640
ARCHIE	3,620	14,480

Based on these results, the vapor cloud was estimated to contain 15,000 pounds of gas for the purposes of TNT-equivalent modeling.

2. Overpressure for Window Breakage

The blast overpressure that will cause windows to break depends on a number of factors, including the area of the window, the thickness of the glass, the type of glass, and the orientation of the window with respect to the blast[2]. Window breakage is reported by various sources[3] for blast overpressures of about 0.15 psi to 1.0 psi. According to one study, overpressures of 0.09 to 0.9 psi will cause 50 percent window failure for most windows oriented face-on to the blast[4]. This study provides a graph (reproduced in Figure D-1) that shows the overpressures that will cause 50 percent window breakage as a function of pane area for glass of six different thicknesses.

At the Shell site, one of two windows, 0.59 centimeter (cm) thick, with an area of 1.58 square meters (m^2), was broken at a distance of 3,200 feet from the center of the blast. Based on the graph in Figure D-1, an overpressure of about 0.6 psi was necessary to cause this breakage. Other data from the explosion site indicate that this overpressure may be an overestimate. Windows at about 2,950 feet (somewhat closer to the blast), that were 0.32 cm thick (i.e., thinner than the glass that broke) and 0.9 and 0.6 m^2 in area, were not broken by the blast. These windows faced in the same direction (south) as the windows that failed and had the same general orientation to the blast. Based on the graph, these windows would have failed if the overpressure actually reached 0.6 psi. At an overpressure of 0.3 psi, these windows would not be predicted to fail, but at overpressures not significantly higher, breakage would be expected. The windows that broke may have been subject to some factor (e.g., strain on the glass, faulty window frames, etc.) that caused them to break at an overpressure lower than predicted. Based on limited number of windows involved, given the fact that some south-facing windows broke and others did not, the overpressure at a distance of approximately 3,000 feet from the blast center may have been between 0.3 and 0.6 psi.

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[2] E. Royce Fletcher, Donald R. Richmond, and John T. Yelverton, "Glass Fragment Hazard from Windows Broken by Airblast," Report Prepared for Defense Nuclear Agency, May 30, 1980.

[3] U.S. EPA, *Flammable Gases and Liquids and Their Hazards*, EPA 744-R-94-002, February 1994.

[4] Fletcher, Richmond, and Yelverton, *op.cit.*

Likewise, at a distance of about 2,800 feet, some windows failed, while others with the same thickness and similar areas did not. Figure D-1 indicates that side-on windows (west-facing at Shell) would experience 50 percent failure at about 0.5 psi. Since west-facing windows at Shell experienced about 17 percent failure, the actual overpressure was probably slightly less than 0.5 psi, because some windows that would be predicted to have failed did not. The overpressure at 2,800 feet could therefore be estimated to be between 0.3 and 0.5 psi.

At less than 500 feet from the center of the blast, 100 percent window breakage was recorded for windows facing in all directions. Based on the window damage at 2800-3000 feet, 100 percent failure would be expected for windows even farther than 500 feet from the blast center, since the pressure wave was more intense closer to the blast center. The overpressure that would cause this amount of damage at a distance of 500 feet likely would be greater than 1 psi, but there is no way to estimate from available window breakage data alone how much greater it was.

3. Vapor Cloud Explosion -- TNT Equivalent Model

A TNT equivalent model was used to estimate the results of a vapor cloud explosion involving the quantity of 15,000 pounds estimated in section 1. The TNT equivalent model relates the blast effects of the explosion of a cloud of flammable gas to the blast effects of an equivalent quantity of TNT. Because the entire cloud of flammable gas does not participate in the explosion (since only a fraction of the cloud contains the necessary fuel-air ratio to support ignition), a "yield factor" is applied to estimate the portion of the cloud that explodes. The quantity in the vapor cloud, the yield factor, and the heat of combustion of the flammable gas compared to the heat of explosion of TNT are used to estimate the quantity of TNT equivalent to a given quantity of flammable gas. Empirical relationships derived for TNT explosions are then used to determine overpressures and distances from a blast involving the flammable vapor cloud. For this analysis, a composite heat of combustion was estimated from the heats of combustion of individual gas components and several different yield factors were assumed for the explosion.

Yield factors for vapor cloud explosions are reported to range commonly from 1 percent to 10 percent, but may be much higher in some cases. In this case, a relatively high yield factor is appropriate for a number of reasons, including the following:

- The vapor cloud contained a large amount of hydrogen (approximately 19% by volume),
- The vapor was released as a high-velocity jet, and,
- The vapor was released into a highly congested area (the pipe rack).

Vapor clouds of hydrogen and hydrogen-rich hydrocarbon mixtures have higher flammable ranges and higher laminar flame speeds, both of which tend to increase the vapor cloud yield factor. The last two factors caused a large amount of turbulence and high confinement in the exploding vapor cloud, resulting in higher flame front acceleration and therefore higher explosive yield factor. Based on these, a high yield factor is appropriate, and this analysis

estimates distances for various yield factors of 3 to 20 percent to provide a range for comparison with the results of the overpressure analysis discussed in the previous section.

Results of TNT-equivalent modeling are presented in the table below. To allow comparison of the results of TNT-equivalent modeling with the results reported for window breakage at Shell, the table shows distances to overpressures of 0.15 to 1.0 psi. Overpressures in this range are reported to result in window breakage, as noted in the previous section. Yield factors of 0.03, 0.1, 0.15, and 0.2 were assumed in order to provide a reasonable range.

The release quantities calculated by the three methods discussed above were used as the quantity of gas in the vapor cloud.

Quantity in Cloud (lbs)	Yield Factor	Distance (feet) to Overpressure						
		0.15 psi	0.2 psi	0.3 psi	0.4 psi	0.5 psi	0.6 psi	1.0 psi
15,000	0.2	6,360	4,610	2,470	2,230	1,830	1,670	1,350
	0.15	5,780	4,190	2,240	2,020	1,660	1,520	1,230
	0.1	5,050	3,660	1,960	1,770	1,450	1,330	1,070
	0.03	3,380	2,450	1,310	1,180	970	890	720

The results shown in the table for the yield factor of 0.2 agree better than the results for the lower yield factors with the overpressure previously estimated for glass breakage at Shell. For all four yield factors, the overpressure at about 500 feet from the blast, where all the windows failed in the blast at Shell, is greater than 1 psi, which is consistent with 100 percent window breakage. Based on glass thickness and area, estimated overpressures were from 0.3 to 0.6 psi at about 2,800 to 3,200 feet, as discussed in the previous section. The results for a yield factor of 0.2 show an overpressure of 0.3 psi at a distance of about 2,500 feet, which is close to the distance of 2,800 where an overpressure of between 0.3 and 0.5 psi was estimated. The results for the yield factor of 0.2 and overpressure of 0.15 also indicate that windows could have been broken at distances of more than a mile from the Shell site. Windows in private residences were, in fact, broken at various distances more than 1 mile from the blast center, so this is consistent with the yield factor of 0.2.

4. Vapor Cloud Explosion -- Multi-Energy Model

The multi-energy model presented in *Methods for the Calculation of Physical Effects Resulting from Releases of Hazardous Materials* was used to carry out calculations of the effects of a vapor cloud explosion, based on the characteristics of the portion of OP-III where the vapor cloud formed. The multi-energy model for vapor cloud explosions does not consider the total quantity of flammable substance in the vapor cloud. Instead, it takes into account the

characteristics of the area into which a flammable vapor is released. In particular, it considers portions of the area where a strong blast could occur, such as congested and obstructed regions, and only considers the quantity of flammable gas/air mixture that could be found in these regions. The volume of such regions and the combustion energy of stoichiometric fuel-air mixtures within these regions are used in calculating the effects of a vapor cloud explosion. A "blast class" must be assigned, based on the ignition energy, the degree of obstruction, and the presence or absence of parallel plane confinement. A factor is derived for any chosen distance, based on the distance, the combustion energy within the congested region, and the ambient pressure. Using this factor and a graph, a scaled overpressure can be found for the chosen distance and blast class, and the overpressure at that distance can be estimated.

For the analysis of the Shell explosion, the volume of the congested area was estimated to be 19,550 cubic meters, and a stoichiometric heat of combustion of 3.5 million Joules per cubic meter (a value applicable to most hydrocarbon mixtures) was used. For low ignition energy (which would apply to the hot surfaces which served as likely ignition sources at Shell) and high obstruction, the blast class would fall into the range of 3 to 7. The degree of parallel plane confinement also affects the blast class. Since detailed information about parallel plane confinement was not collected but the degree of confinement was qualitatively estimated to be quite high (based on the high density of parallel structures in the pipe rack where the vapor cloud formed), it was conservatively assumed that a blast class of 7 was appropriate for the analysis.

The analysis was conducted for distances of 500 to 5,000 feet, including 2,800 feet and 3,200 feet, distances at which less than 100 percent glass breakage occurred at Shell. Results of the multi-energy analysis using a blast class of 7 are shown in the table below. (Blast classes of 6 and 7 gave the same result, so the table lists blast classes 6-7.) Cloud volume for this analysis was

Blast Class	Distance (feet)	Overpressure (psi)
6-7	500	2.9
	1,000	1.1
	2,000	0.5
	2,800	0.32
	3,200	0.26
	5,000	0.17

assumed to be 19,550 cubic meters (equivalent to the estimated volume of the congested region), and total cloud energy was calculated as 68,430 million Joules, based on the cloud volume and the stoichiometric heat of combustion.

At 2,800 to 3,200 feet from the center of the blast, the multi-energy model predicts an overpressure of about 0.3 (0.32-0.26) psi, which is consistent with the overpressure of 0.3 to 0.6 that we estimated at these distances based on the glass breakage observed at Shell. This result is also consistent with the TNT-equivalent modeling results assuming a yield factor of 0.2. At 1,000 feet or less from the center of the blast, the multi-energy model predicts overpressures greater than 1 psi. Again, this result is consistent with the 100 percent glass failure reported at Shell at about 500 feet.

5. Comparison of Vapor Cloud Explosion Modeling Results with Blast Effects at Shell

An overpressure of 0.3 psi at about 2,500 to 3,200 feet is predicted by both the TNT-equivalent model (assuming a yield factor of 0.2) and the multi-energy model (assuming a blast class of 6-7). This overpressure is consistent with the overpressure of 0.3 to 0.6 psi that was estimated for the 50 percent glass breakage recorded at Shell at approximately 3,000 feet, as discussed earlier. These modeling results are in agreement with the lower end of the estimated overpressure range, when conservative assumptions were used regarding the yield factor for TNT-equivalent modeling and the blast class for multi-energy modeling. Larger releases (for the TNT-equivalent model) and larger cloud volumes (for the multi-energy model) also would give results that would fall into the estimated overpressure range for the observed effects.

Based on the results of the foregoing release rate and vapor cloud explosion modeling, the questions posed at the beginning of this analysis can reasonably be answered as follows:

- The release of about 15,000 pounds of gas is consistent with the blast effects observed at Shell.
- About 3,000 pounds of gas was involved in the explosion (for a yield factor of 0.2), which was equivalent to about 31,000 pounds of TNT.
- A vapor cloud containing about 15,000 pounds, rapidly released into a highly congested area with a volume of about 20,000 cubic meters, could generate overpressures sufficient to produce the effects observed at Shell.

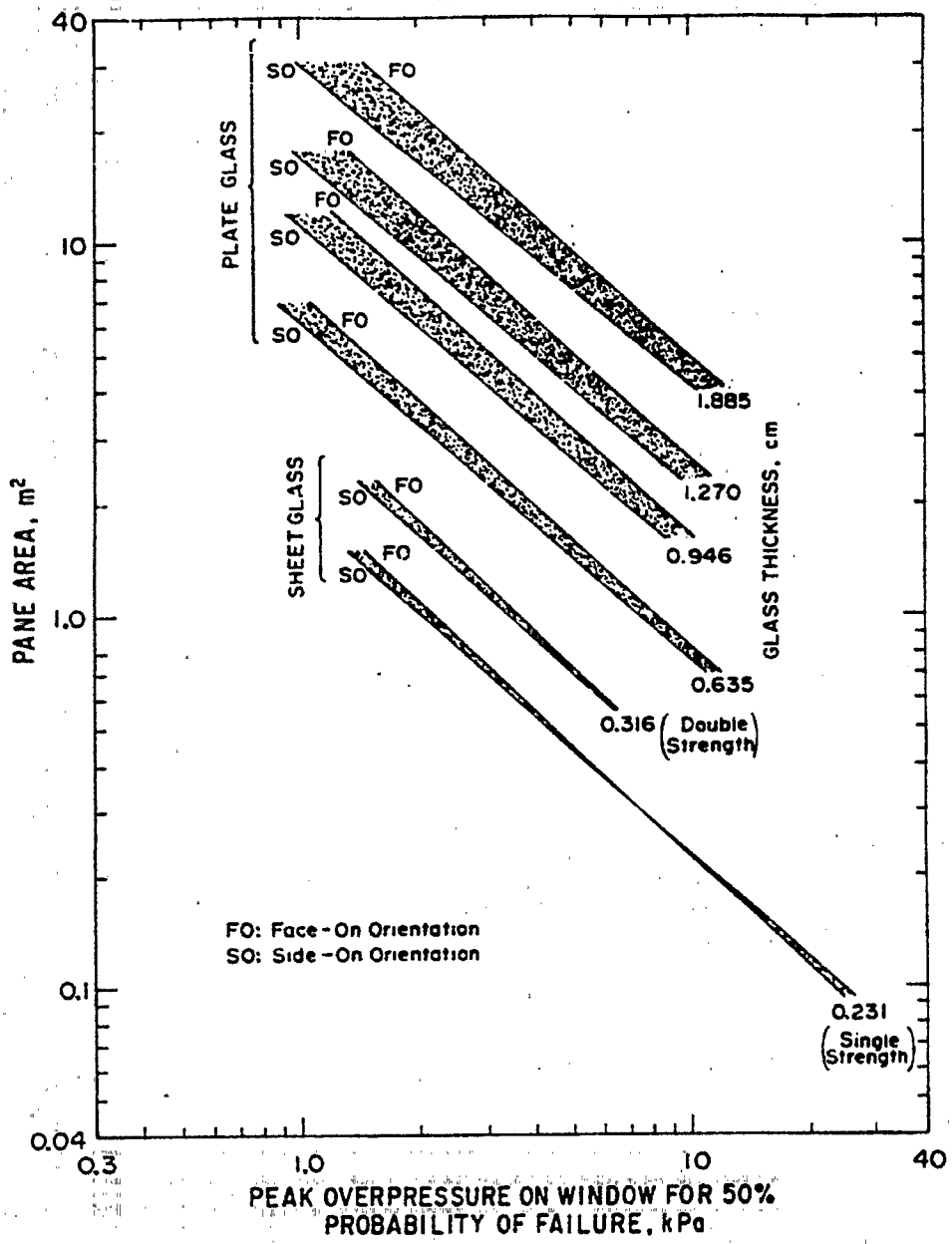


Figure D-1
Peak Blast-Wave Overpressure on a Window for 50-Percent Probability of Failure

Source: E. Royce Fletcher, Donald R. Richmond, and John T. Yelverton, "Glass Fragment Hazard from Windows Broken by Airblast," Report Prepared for Defense Nuclear Agency, May 30, 1980.

Appendix E: Photographs of Shell Chemical Company OP-III Unit Damage

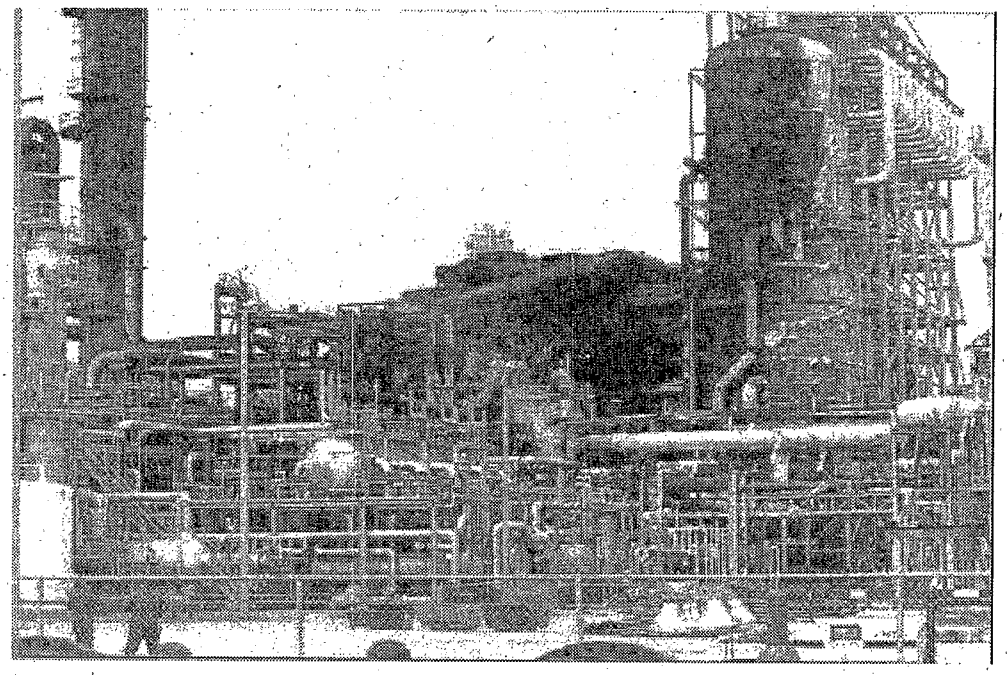


Figure E-1: Photograph of the damage resulting from the explosion and fire at Shell Olefins Plant Number 3 (view from west of blast area). Note the heavy structural damage in the rear center of the photograph.

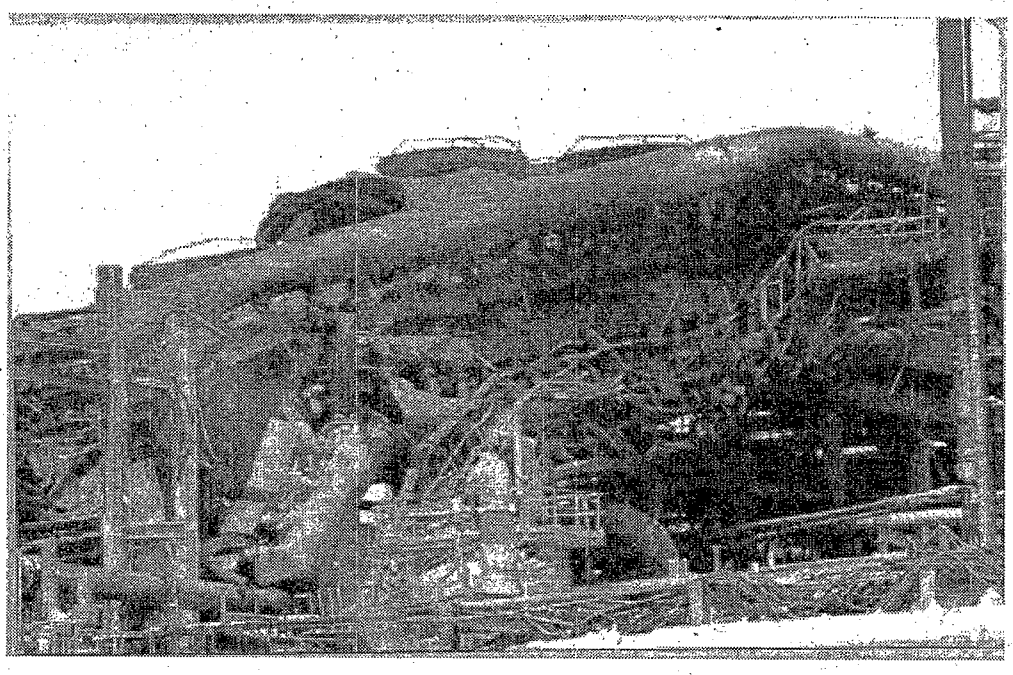


Figure E-2: Close-up of OP-III damage. The structure supporting the overhead cooling fans melted due to the intense heat of the fire and collapsed on top of the pipe rack.

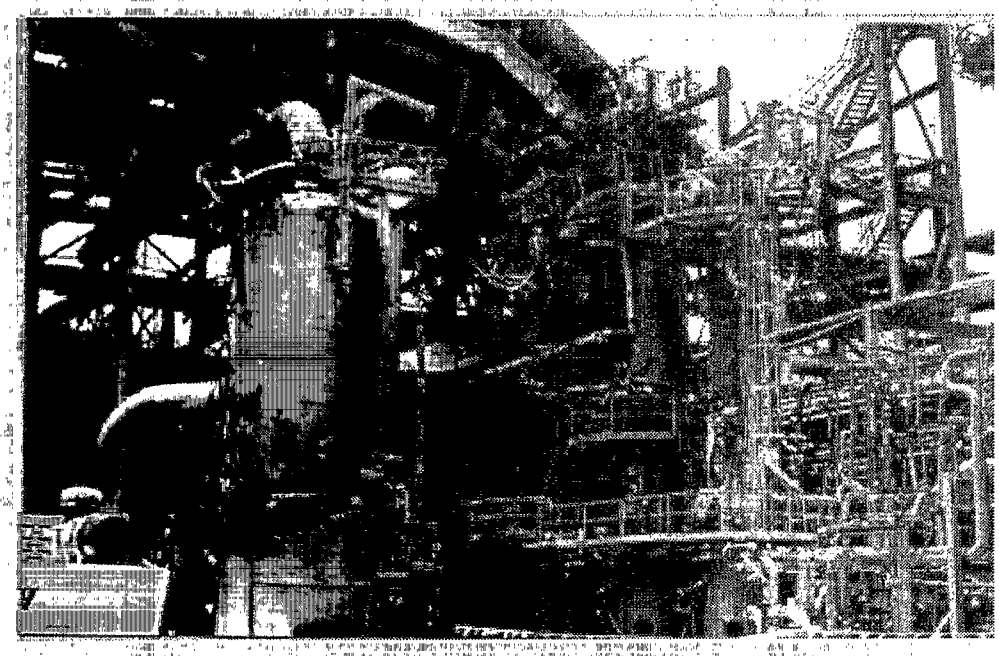


Figure E-3: Photograph of explosion and fire damage at OP-III as seen from the north side of the blast zone.

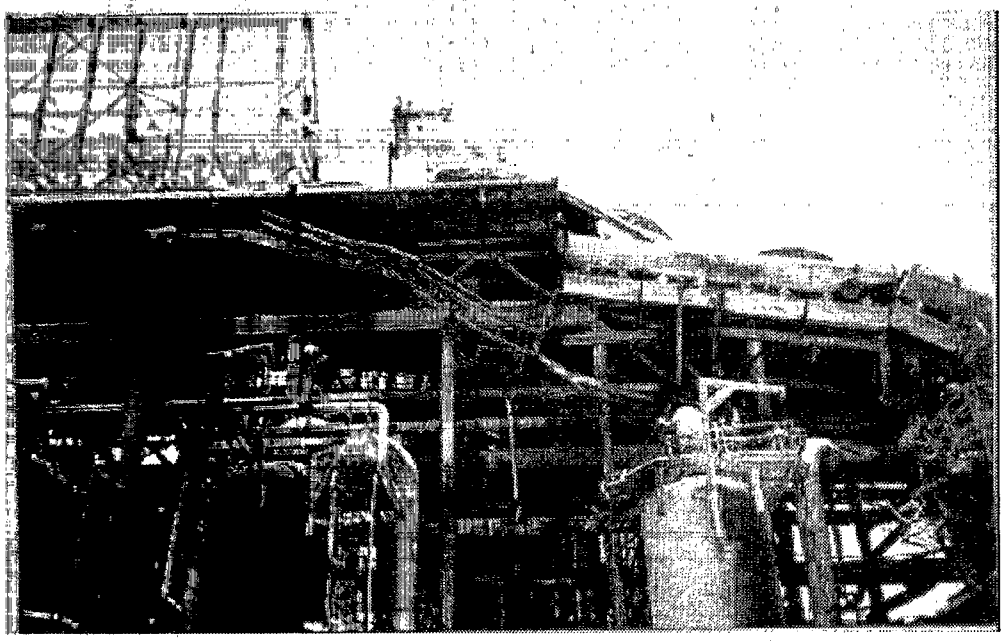


Figure E-4: Photograph of explosion and fire damage at OP-III as seen from north side of pipe rack, looking upward.

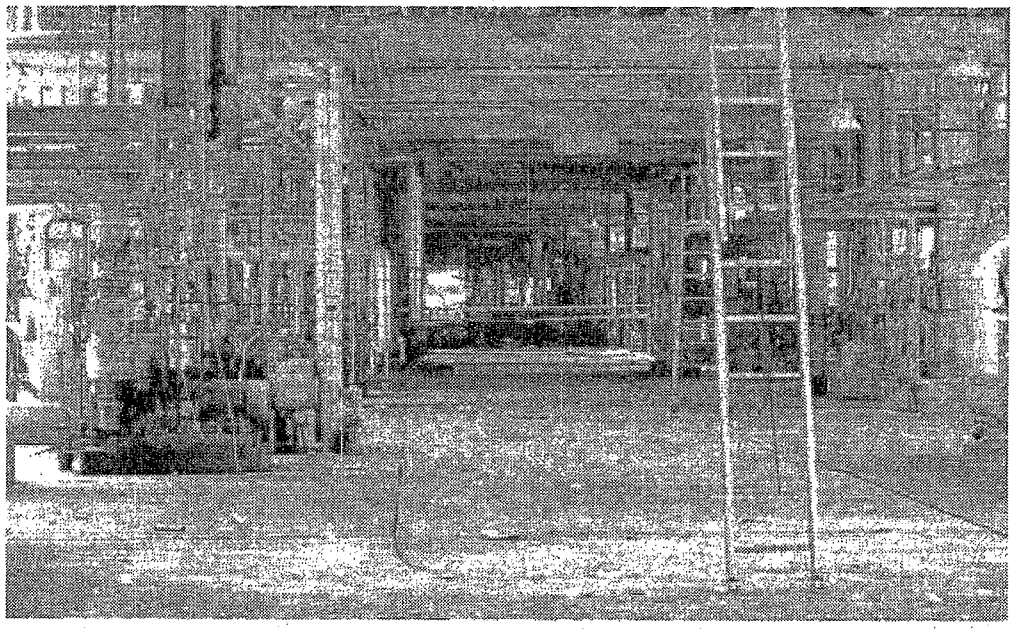


Figure E-5: Photograph looking down pipe alley (passable area underneath pipe rack) where explosion occurred.

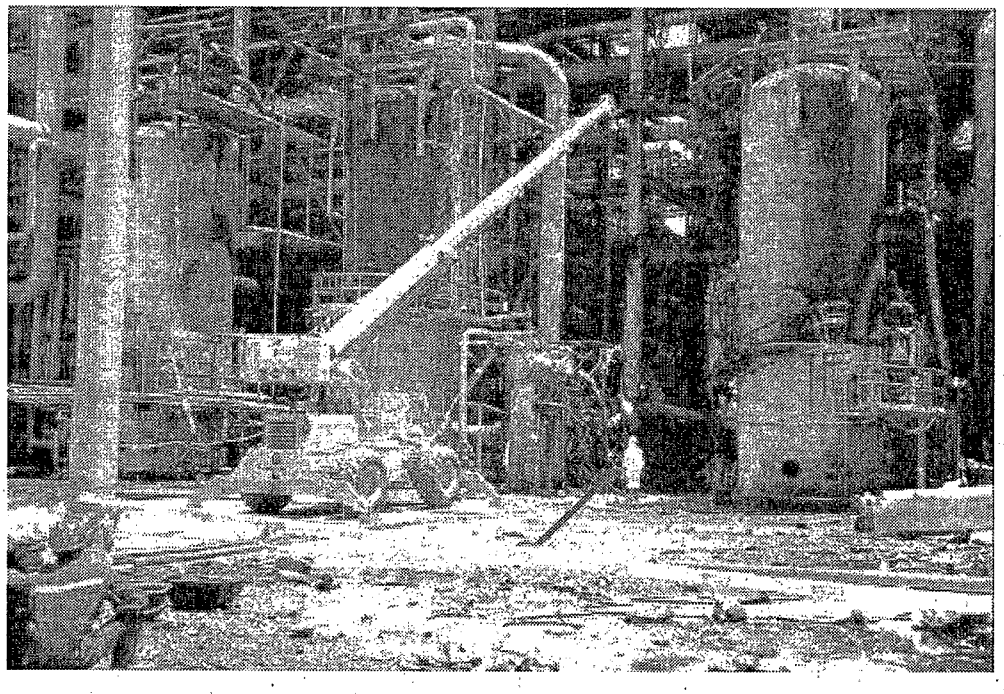


Figure E-6: Photograph of explosion and fire damage in the area of the PGC fifth stage suction and discharge drums (viewed from the north). The man in the lower center provides a reference to the scale of the surrounding structures. The failed check valve was located behind the drum to the man's right.

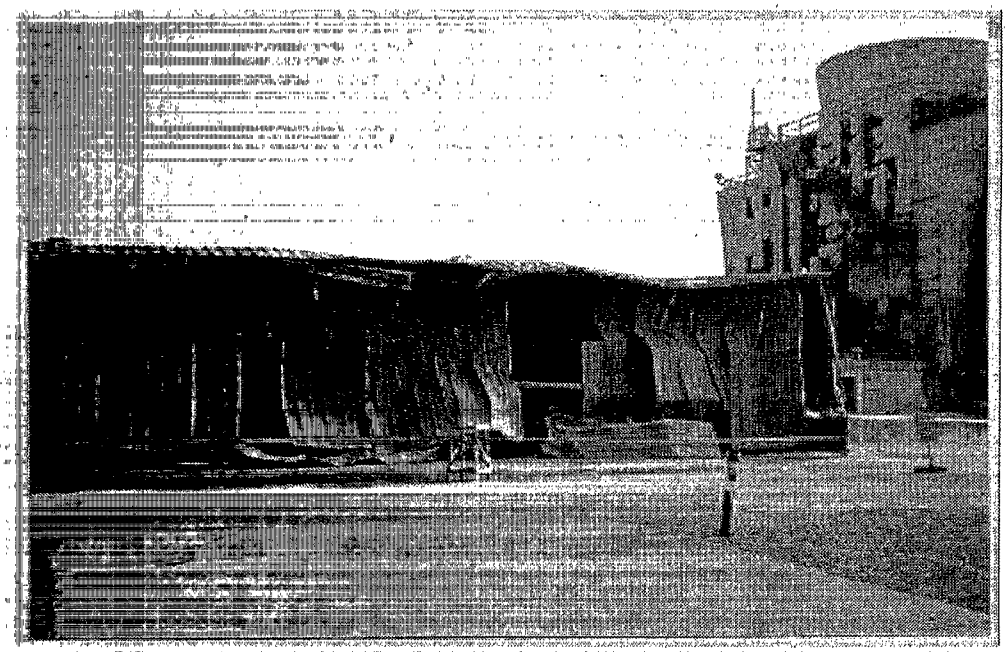
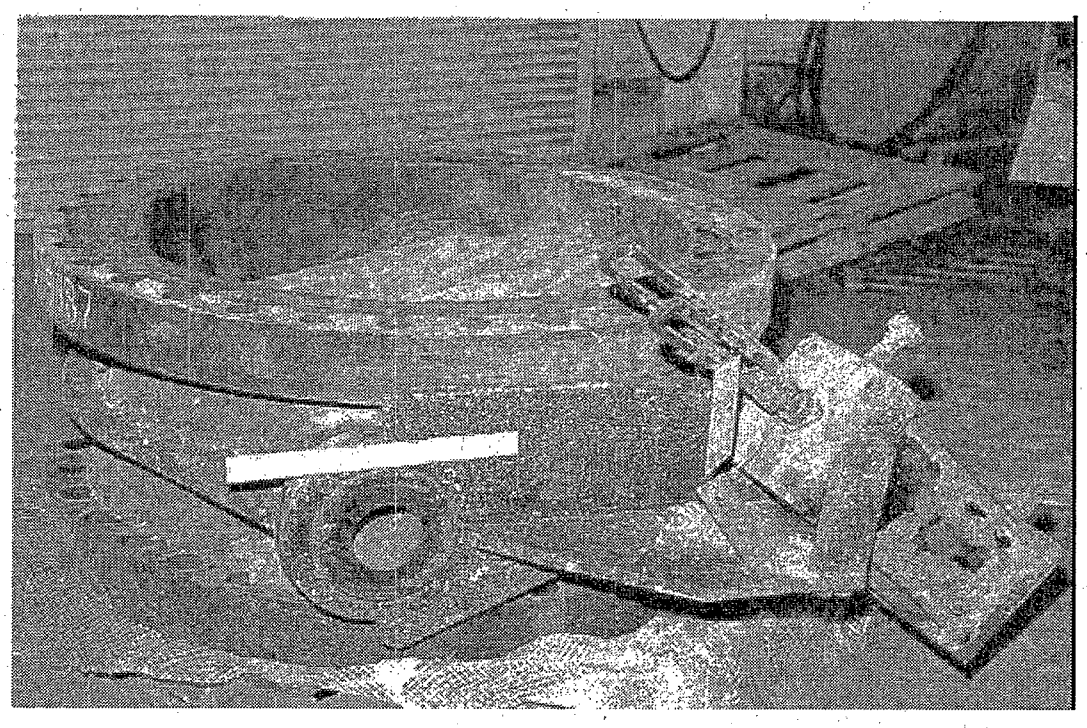
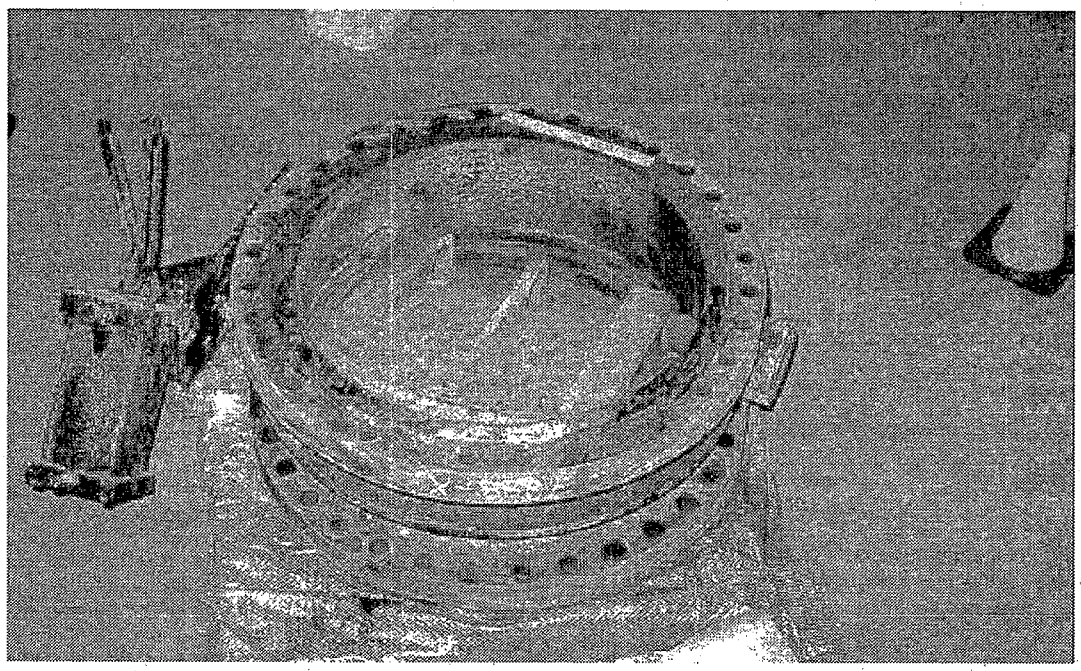


Figure E-7: Photograph of blast damage to buildings and structures in the vicinity of the explosion. Note the buckled metal walls of the storage building in the center and the panels missing from the cooling tower on the right. These buildings were located approximately 500 feet north of the blast center.

Figure E-8: Photograph of damage to a pickup truck parked near the blast site. Most automobiles parked in this company lot during the accident suffered damage.





Figures E-9 and E-10: Photographs of two views of the disassembled subject 36" Clow check valve. The pneumatic actuator assembly can be seen in both views. In the lower photograph, the hole directly below the 12-inch ruler formerly contained the valve's drive shaft. This is where the shaft blow-out and flammable gas release occurred.

Figure E-11: Photograph shows the drive shaft and counterweight that were ejected from the 36" Clow check valve.

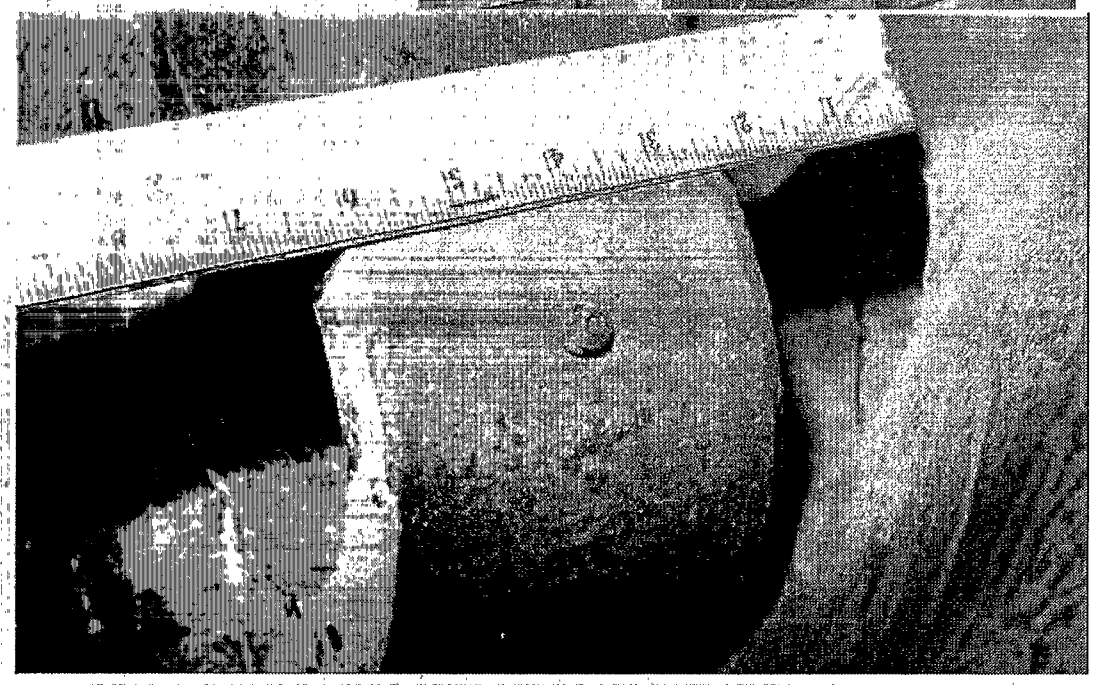


Figure E-12: Photograph shows the head of the machine screw protruding from the portion of the fractured pin. The pin is shown extended slightly out from the surface of the flange, or disk "ear", from which the valve shaft was ejected.

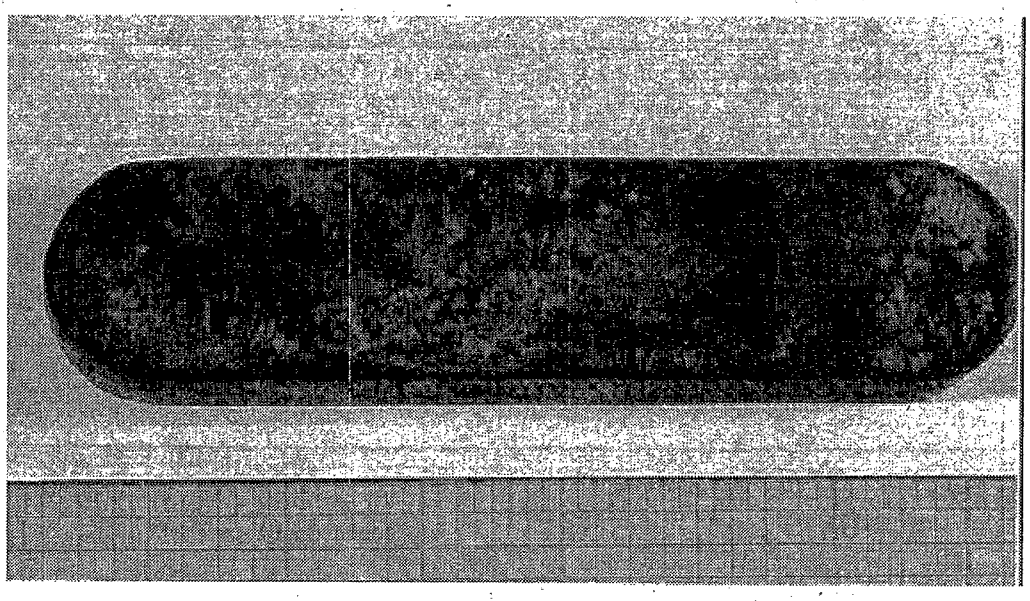


Figure E-13: Photograph shows the metal key intended to help mechanically connect the drive shaft to the valve disk.

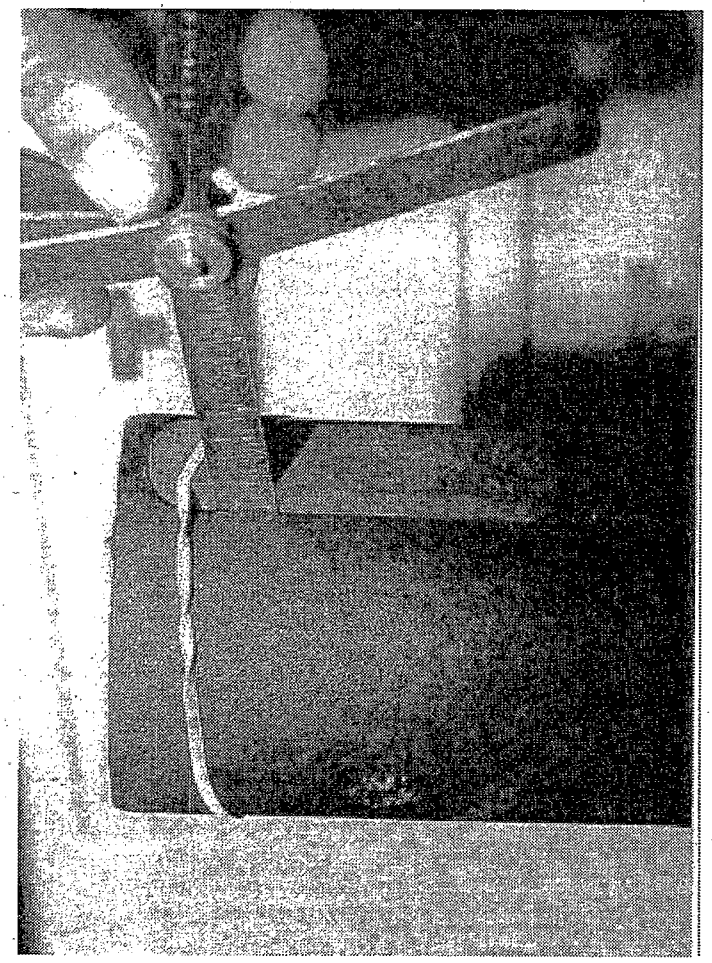


Figure E-14: Photograph depicts the measured looseness of the key within its machined slot, or keyway. The key was intended to transfer torque between the shaft and the valve disk, but the key's loose fit forced the much smaller dowel pin to transfer virtually all drive shaft torque. The key eventually fell out of its slot as the drive shaft moved outward after the dowel pin fractured.

Figure E-15: Photograph shows the general configuration of the intact dowel pin removed from the idler shaft, and a portion of the fractured pin. Both pins exhibit the threaded machine screws, which were placed in holes drilled in the center of each pin to allow later pin removal.

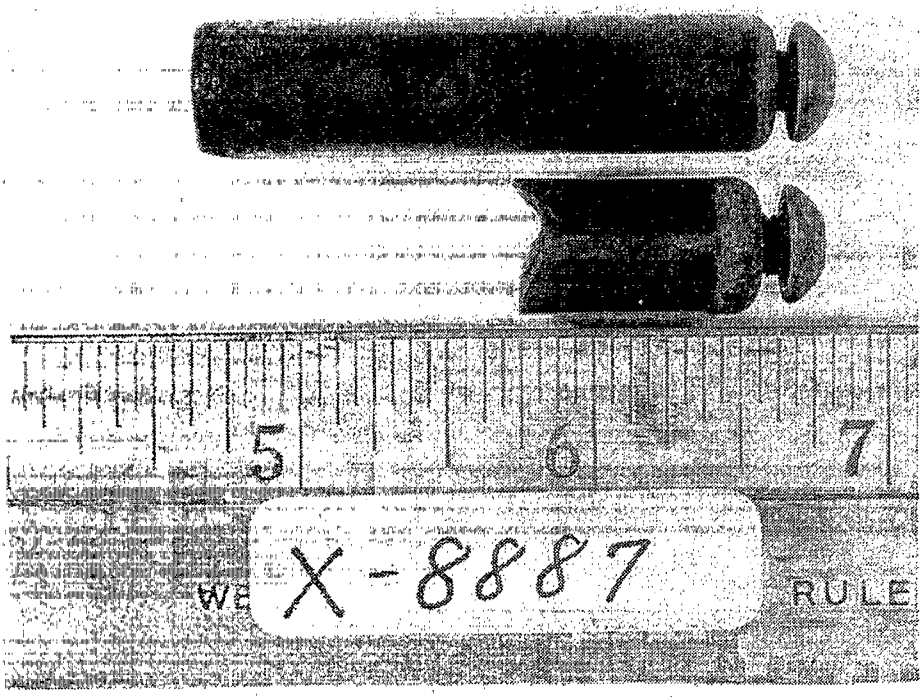
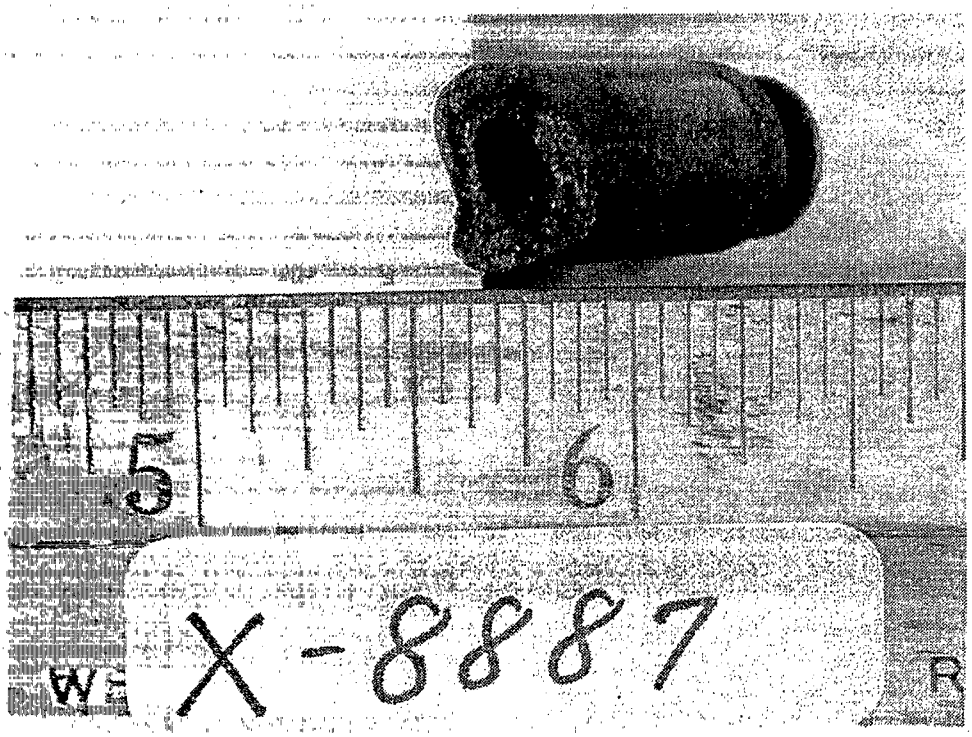


Figure E-16: Perspective view of the fractured dowel pin showing the fracture face extending through the drilled hole within the center of the pin.



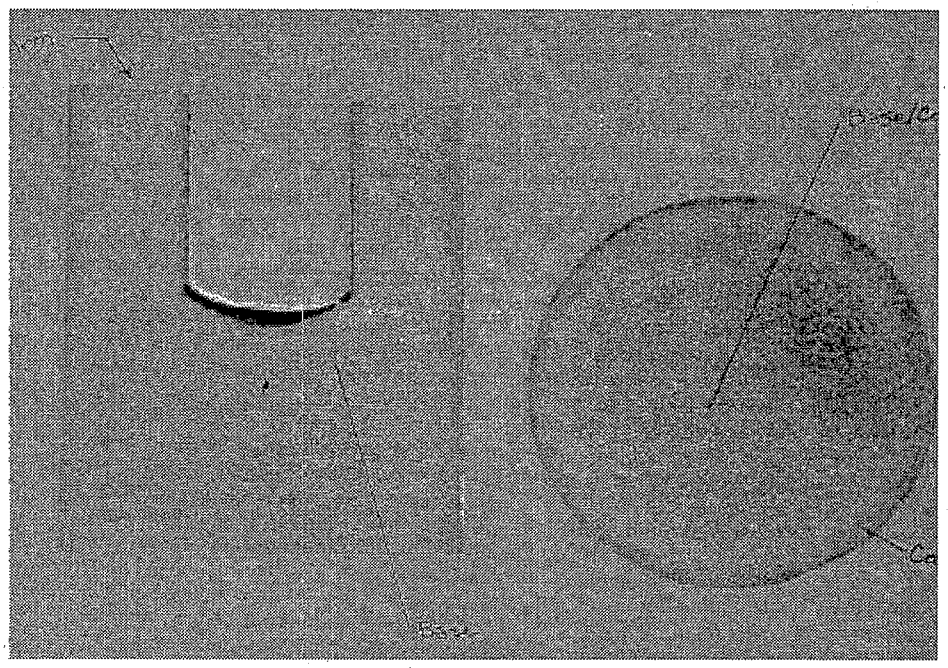


Figure E-17: Views of the longitudinal and transverse cross-sections taken through the intact dowel pin showing the carburized case at both the outside diameter of the pin and within the drilled hole.

Figure E-18: 25X magnification fractograph displaying a portion of the fracture face of the dowel pin which broke in the service of the 36" Clow check valve.

Figure E-19: 100X magnification scanning electron microscope (SEM) fractograph depicting the intergranular fracture at the carburized surface of the dowel pin.

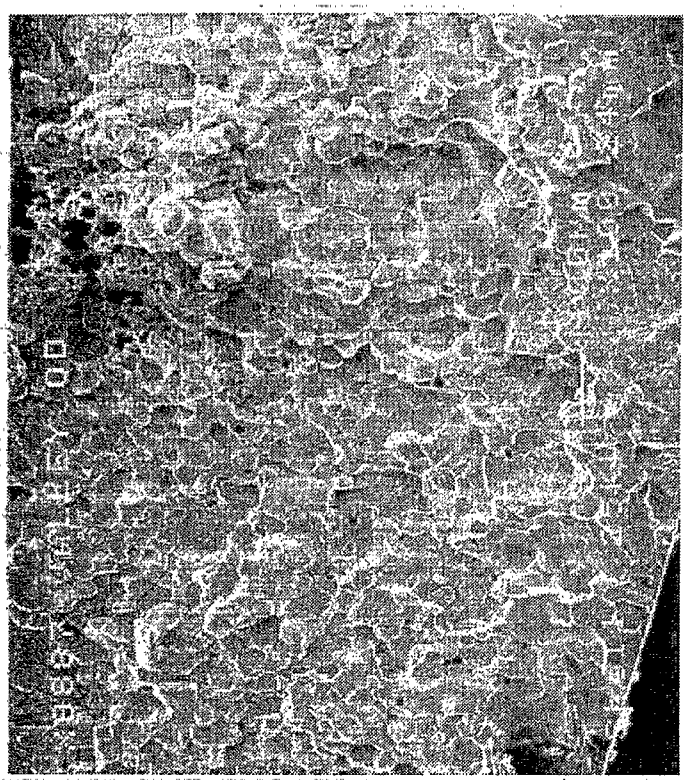
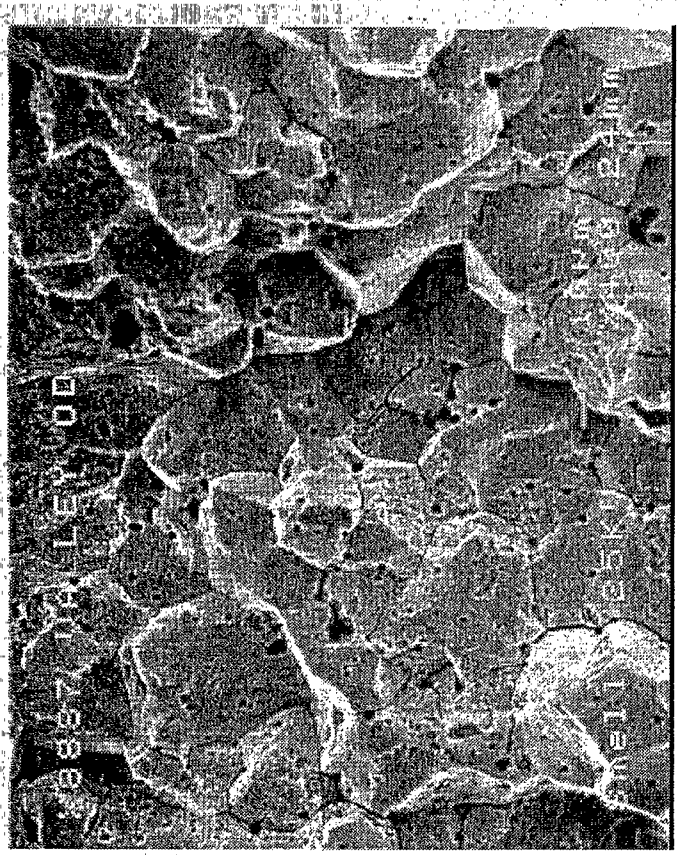


Figure E-20: 400X magnification SEM fractograph of the dowel pin shows details of the intergranular "rock candy"fracture surface at the outside diameter of the dowel pin, a characteristic of hydrogen embrittlement failure mode.



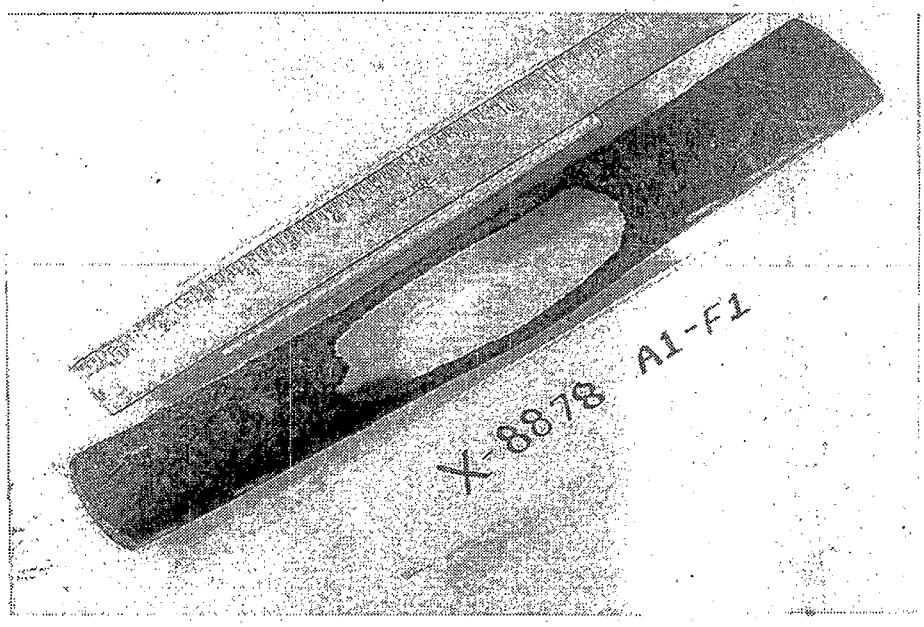


Figure E-21: A view of pipe section X-8878, one of four pipe sections removed from OP-III in addition to the Clow check valve for laboratory analysis as possible sources of the initial flammable gas leak.

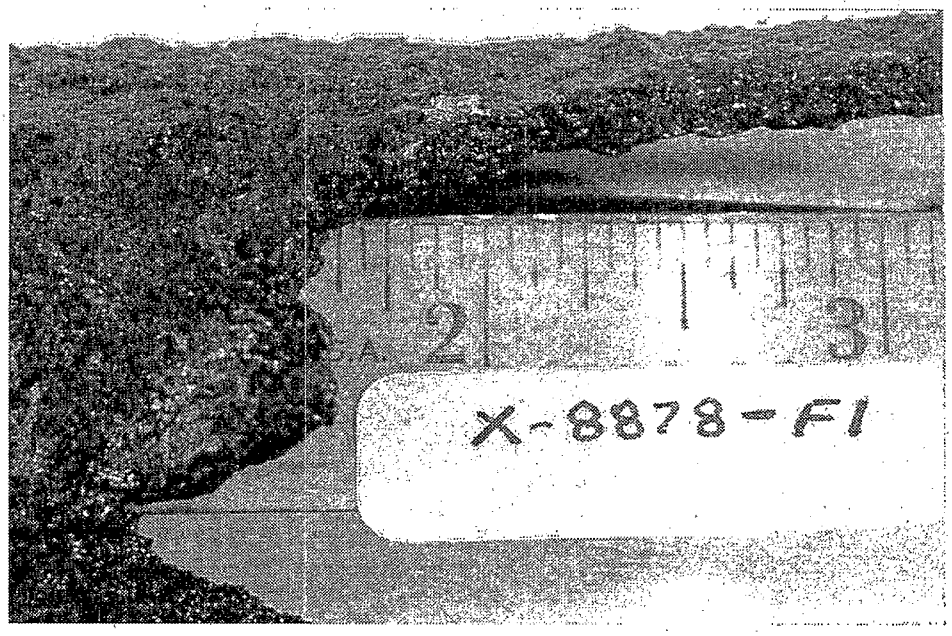


Figure E-22: At higher magnification, this macrograph shows the high temperature oxidation and fire damage around the opening in the pipe section. Laboratory analysis of this and each of the other three pipe sections revealed similar fire-induced failure modes, indicating that none were the likely source of the initial flammable gas leak.

Appendix F:
EPA/OSHA Chemical Safety Alert
"Shaft Blow-Out Hazard of Check and Butterfly Valves"

United States
Environmental Protection
Agency

United States
Occupational Safety and
Health Administration

EPA 550-F-97-002F
September 1997

EPA
CEPP
OSHA

SHAFT BLOW-OUT HAZARD OF CHECK AND BUTTERFLY VALVES

The Environmental Protection Agency (EPA) and Occupational Safety and Health Administration (OSHA) are issuing this *Alert* as part of their ongoing efforts to protect human health and the environment by preventing chemical accidents. Under CERCLA, section 104 (e), the Clean Air Act (CAA), and the Occupational Safety and Health Act (OSH Act), EPA and OSHA have authority to conduct chemical accident investigations. Additionally, in January 1995, the Administration asked EPA and OSHA to jointly undertake investigations to determine the root cause(s) of chemical accidents and to issue public reports containing recommendations to prevent similar accidents. EPA and OSHA have created a chemical accident investigation team to work jointly in these efforts. Prior to the release of a full report, EPA and OSHA intend to publish *Alerts* as promptly as possible to increase awareness of possible hazards. *Alerts* may also be issued when EPA and OSHA become aware of a significant hazard. It is important that facilities, SERCs, LEPCs, emergency responders and others review this information and take appropriate steps to minimize risk.

CHEMICAL SAFETY ALERT

PROBLEM

Certain types of check and butterfly valves can undergo shaft-disk separation, and fail catastrophically or "blow-out", causing toxic and/or flammable gas releases, fires, and vapor cloud explosions. Such valve failures can occur even when the valves are operated within their design limits of pressure and temperature.

ACCIDENT HISTORY

In a 1997 accident, several workers sustained minor injuries and millions of dollars of equipment damage occurred when a pneumatically assisted Clow stub-shaft Model GMZ check (non-return) valve in a 300 psig flammable gas line underwent shaft blow-out. The valve's failure caused the rapid release of large amounts of light hydrocarbon gases which subsequently ignited, resulting in a large vapor cloud explosion and fire.

The check valve was designed with a drive shaft that connects the internal valve disk to an external pneumatic cylinder (see diagram on next page). The valve failed when a dowel pin designed to fasten the drive shaft to the disk sheared and a key designed to transfer torque from the drive shaft to the disk fell out of its keyway, disconnecting the drive shaft from the disk. System pressure was high enough to eject the unrestrained drive shaft from the valve, carrying with it the external counterweight assembly, weighing over 200 lbs., a distance of 43 feet away.

The absence of the drive shaft left a hole in the valve body the diameter of the shaft (3.75 inches) directly to atmosphere, and initiated a high-pressure light hydrocarbon leak. The leak continued for approximately 2 to 3 minutes, forming a large cloud of flammable light hydrocarbon vapor. The vapor cloud ignited, resulting in an explosion felt and heard over 10 miles away. The explosion and ensuing fire caused extensive damage to the facility, completely or partially destroying many major components, piping systems, instruments, and electrical systems, and requiring the complete shut-down of the affected unit for cleanup and repair. Minor damage occurred to nearby residences and automobiles (mostly broken glass and minor structural damage due to the blast wave). Nearby highways were closed for several hours. Damage cost to the facility alone is estimated at approximately 90 million dollars. Fortunately, no fatalities and only minor injuries to workers resulted from the accident.

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Previous malfunctions involving check valves of the same or similar design occurred at facilities in 1980, 1991, and 1994. In each case, the affected check valve was located in a large diameter (36-inch or greater) pipe in a hydrocarbon gas compression system. Also in each previous case, a dowel pin fastening the valve's drive shaft to its disk sheared (in the 1980 case the pin was possibly never installed) and a rectangular key fell out of its keyway, disconnecting the drive shaft from the disk. Although shaft-disk separation occurred in each previous case, it did not result in shaft blow-out or catastrophic failure. This may be because the valves in these instances were installed in lower-pressure service, or because the malfunctioning valves were identified before shaft blow-out occurred.

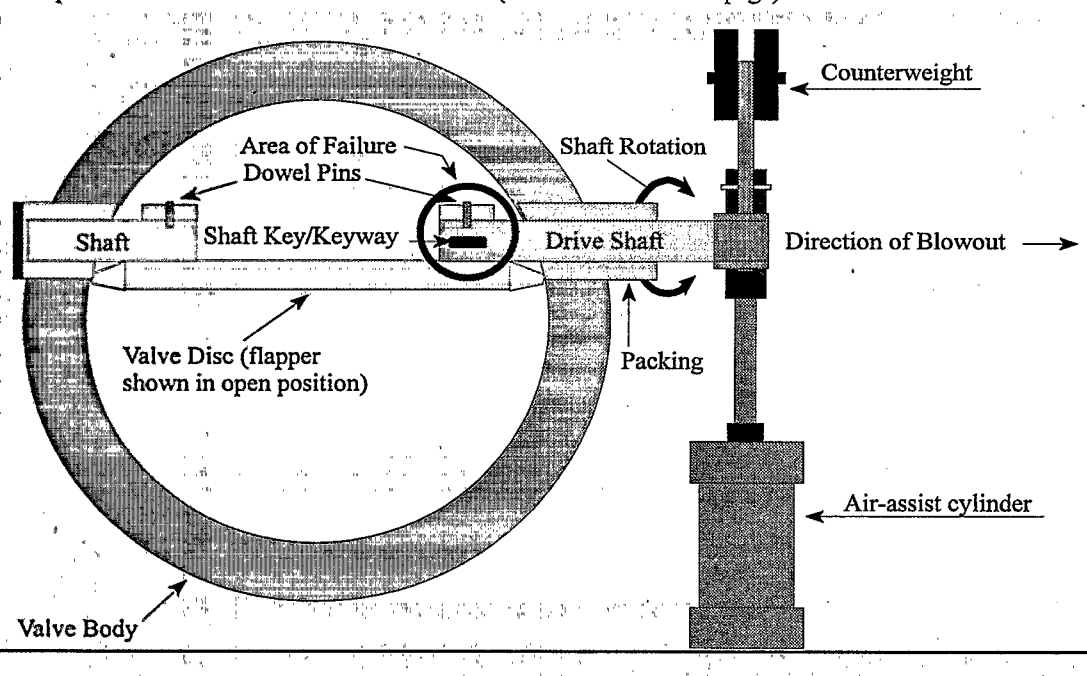
In the 1991 incident, the malfunction was manifested by the erratic operation of the valve, which was observed to operate independently from its external drive mechanism. System pressure was low enough (70 psig) that the failure was detected before the shaft was expelled out of the valve body. (At the time the malfunctioning valve was identified, the valve shaft was protruding about 0.75 inches out of the valve body.) In the 1980 and 1994 cases, the malfunction was identified when workers noted that the external piston rod connecting the air-assist cylinder to the drive shaft had broken due to axial movement of the drive shaft.

Hazard Awareness

Check and butterfly valves are used in many industries, including refineries, petrochemical plants, chemical plants, power generation facilities, and others. Most modern valve designs incorporate features that reduce or eliminate the possibility of shaft blow-out. However, older design check and butterfly valves with external appendages such as pneumatic-cylinders, counterweights, manual operators, or dashpots may be subject to this hazard. Shaft blow-out may be of particular concern wherever these valves are installed in systems containing chemicals leading to hydrogen embrittlement.

Valves subject to this hazard may be designed with a two-piece valve stem (sometimes referred to as a "stub-shaft" design). In each of the cases described above, the malfunctioning component was a Clow stub-shaft Model GMZ pneumatically assisted swing check valve (see diagram below). In these check valves, one stem piece functions as a drive shaft that connects the internal valve disk to an external air-assist cylinder and counterweight assembly. The drive shaft penetrates the pressure boundary through a stuffing box. The exterior portion of the drive

Simplified cross-sectional view of check valve (flow direction is into page)



shaft is connected to a pneumatic piston and counterweight, and the interior portion of the shaft is coupled directly to the valve disk using a cylindrical hardened steel dowel pin and a rectangular bar key. This arrangement provides a power-assist to close the valve during compressor shut down, preventing reverse flow of compressed gases. These particular valves have probably not been produced since 1985, but still exist in some process facilities constructed before that date. Similar valves currently or previously produced and sold by other valve manufacturers may also be subject to this hazard.

Factors in Valve Failure

A number of design and operational factors may contribute to this hazard. These include the following:

Design Factors

- The valve has a shaft or stem piece which penetrates the pressure boundary and ends inside the pressurized portion of the valve. This feature results in an unbalanced axial thrust on the shaft which tends to force it (if unconstrained) out of the valve.

- The valve contains potential internal failure points, such as shaft dowel-pins, keys, or bolts such that shaft-disk separation can occur inside the valve.

- The dimensions and manufacturing tolerances of critical internal parts (e.g., keys, keyways, pins, and pin holes) as designed or as fabricated cause these parts to carry abnormally high loads (e.g., in the 1997 accident, the dowel pin rather than the key transmitted torque from the shaft to the disk).

- The valve stem or shaft is not blow-out resistant. Non blow-out resistant design features may include two-piece valve stems that penetrate the pressure boundary (resulting in a differential pressure and unbalanced axial thrust as described above), single-diameter valve shafts (i.e., a shaft not having an internal diameter larger than the diameter of its packing gland) or shafts without thrust retaining devices, such as split-ring annular thrust retainers.

Operational Factors

- The valve is subject to high cyclic loads. In all of the above incidents, the valve repeatedly slammed shut with great force during compressor trips and shutdowns. Such repeated high stresses may cause propagation of intergranular cracks in critical internal components, such as dowel pins.

- The valve is subject to low or unsteady flow conditions, such that disk flutter or chatter occur, resulting in increased wear of keys, dowel pins, or other critical internal components.

- Valves in high-pressure service lines may be more likely to undergo shaft blow-out (in the 1997 accident, system pressure at the failure point was approximately 300 psig).

- Valves used in hydrogen-rich or hydrogen sulfide-containing environments may be more susceptible to blow-out due to hydrogen embrittlement of critical internal components, particularly if these are made from hardened steel (as was the dowel pin in the 1997 accident).

Hazard Abatement

Facilities should review their process systems to determine if they have valves installed that may be subject to this hazard. If so, facilities should conduct a detailed hazard analysis to determine the risk of valve failure. Check valves or butterfly valves which are subject to several or all of the above design and operational factors are at high risk for shaft blow-out. Detailed internal inspections may be necessary in order to identify high-risk valves. Facilities should consider replacing high-risk valves at the earliest opportunity with a blow-out resistant design. Several blow-out resistant designs of check and butterfly valves are available. If immediate valve replacement is impossible or impractical, facilities should consider immediately modifying the valves to prevent shaft blow-out. Valve manufacturers should be consulted in order to ensure that any modifications made are safe.

Information Resources on Valve Safety

Some sources of information on valve safety are listed below.

General References

Information on cases of valve failure can be found in T. Kletz, *What Went Wrong?*, 3rd Edition, Gulf Publishing Co., Houston (1994). This reference contains general information related to check valve failure (pp 127, 129, and 175) and cites one specific case of check valve failure (page 124) similar to those described in this *Alert*.

Information on hydrogen embrittlement can be found in F.P. Lees, *Loss Prevention in the Process Industries: Hazard Identification, Assessment, and Control*, 2nd edition, Butterworth-Heinemann Publishing, Oxford (1996), pp 12/82-83.

Codes, Standards, and Regulations

The American Society of Mechanical Engineers (ASME) has a standard for valves.

American Society of Mechanical Engineers
345 East 47th Street
New York, NY 10017
or
22 Law Drive
Fairfield, NJ 07007-2900
Phone: (800) 843-2763
Web site: http://www.asme.org

Relevant ASME standards include:
ASME B16.34-1996 — Valves - Flanged, Threaded, and Welding End, an American National Standard.

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The American Petroleum Institute (API) has several relevant standards and Recommended Practices.

American Petroleum Institute
1220 L Street NW
Washington, DC 20005
Phone: (202) 682-8000
Web site: http://www.api.org

Relevant API standards include:

API 598-1996 — Valve Inspection and Testing

API 570-1993 — Piping Inspection Code: Inspection, Repair, Alteration, and Rerating of In-Service Piping Systems

API 941-1991 — Steels for Hydrogen Service at Elevated Temperatures and Pressure in Petroleum Refineries and Petrochemical Plants

Relevant API Recommended Practices include:

RP 574-1992 — Inspection of Piping, Tubing, Valves and Fittings

RP 591-1993 — User Acceptance of Refinery Valves

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Applicable regulations include:

29 CFR 1910.119 Process Safety Management of Highly Hazardous Chemicals; Explosives and Blasting Agents.

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For More Information...

Contact EPA's Emergency Planning and Community Right-to-Know Hotline

(800) 424-9346 or (703) 412-9810
TDD (800) 553-7672

Monday-Friday, 9 AM to 6 PM, eastern time

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Visit the EPA CEPPO Home Page on the World Wide Web at:

http://www.epa.gov/swercepp/

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Visit OSHA's Home Page on the World Wide Web at:

http://www.osha.gov/

NOTICE

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