U.S. Chemical Safety and
Hazard Investigation Board

Explosions, Fires, and Toxic Ethylene Oxide Release at Dow Louisiana Operations

Plaquemine, Louisiana | *Incident Date: July 14, 2023* | **No. 2023-03-I-LA**

Investigation Report

SAFETY ISSUES:

- **Vessel Closure Process**
- **Inerting System Control**
- **Pressure Relief System Design**

U.S. Chemical Safety and Hazard Investigation Board

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ABBREVIATIONS

ACC	American Chemistry Council
ANSI	American National Standards Institute
API	American Petroleum Institute
ASSP	American Society of Safety Professionals
CCPS	Center for Chemical Process Safety
CSB	U.S. Chemical Safety and Hazard Investigation Board
CSE	confined space entry
EPA	U.S. Environmental Protection Agency
ERT	Emergency Response Team
ES&S	Emergency Services and Security
ICHEME	Institute of Chemical Engineers
IDLH	immediately dangerous to life or health
LAO	Dow's Louisiana Operations
MET	Most Effective Technology
mJ	millijoules
NIOSH	National Institute for Occupational Safety and Health
NFPA	National Fire Protection Association
p&id	piping and instrumentation drawings
PIT	pressure-indicating transmitter
PSIG	pounds per square inch gauge
PRV	pressure-relief valve
RD	rupture disc
SDS	safety data sheet

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EXECUTIVE SUMMARY

On July 14, 2023, at approximately 9:15 p.m., a series of explosions and fires occurred at Dow Chemical Company's (Dow) Louisiana Operations' Glycol II plant in Plaquemine, Louisiana. The explosions and fires caused significant damage to nearby process equipment in the Glycol II plant and resulted in the release of over 31,000 pounds of toxic ethylene oxide. Local authorities also issued a shelter-in-place order, affecting hundreds of nearby residents.

Dow's Plaquemine facility produces ethylene oxide, a reactive and flammable chemical product and known carcinogen. This incident occurred when ethylene oxide in the Glycol II unit inadvertently entered pressure relief piping, mixed with air, and then ignited, resulting in several large fires and explosions. The ethylene oxide entered the piping after metal debris punctured a rupture disc, causing the rupture disc to partially open. The metal debris came from portable work lights that had been inadvertently left behind in a reflux drum as part of turnaround work. The work lights degraded and created debris in the drum and downstream equipment after the Glycol II unit was restarted.

Prior to the incident, leaks in the pressure relief piping caused it to lose its inert nitrogen atmosphere and fill with air. After the highly reactive and flammable ethylene oxide entered the pressure relief piping, it ignited and propagated through approximately 50 feet of piping to a pressure relief valve. The valve lifted due to the increased pressure, which then allowed the flame front to enter the vapor space of a reflux drum that contained liquid and vapor ethylene oxide. The flame front heated the ethylene oxide vapor in the drum, causing the vapor to decompose and the pressure in the drum to rise until the drum catastrophically failed, exploding and releasing its contents into the atmosphere.

SAFETY ISSUES

The CSB's investigation identified the safety issues below.

- **Vessel Closure Practices.** The incident began when work lights were inadvertently left behind in a reflux drum after the completion of turnaround maintenance and inspection activities. Due to inadequate procedures for ensuring vessel cleanliness after maintenance and inspection activities, the reflux drum was closed after the work was completed without positive confirmation that the vessel was empty, clean, and ready to be closed. The work lights degraded and broke down within the reflux drum, entered downstream equipment, and punctured the product cooler rupture disc, which was not intended to withstand impact from metal debris.

- **Inerting System Control.** At Dow's Plaquemine facility, nitrogen is generally used as an inerting gas to prevent the ignition and decomposition of ethylene oxide in process equipment. Nitrogen was pumped into the pressure relief piping during maintenance activities in 2020, but the nitrogen slowly leaked out over time and the piping unknowingly filled with air. Despite the widespread industry knowledge about the importance of using nitrogen to prevent the reaction of ethylene oxide, Dow did not adequately monitor or maintain the inert atmosphere of the pressure relief piping between the rupture disc and the process relief valve to ensure that an inerting environment persisted.

- **Pressure Relief System Design.** The product cooler pressure relief piping was vented back to the reflux drum. This allowed the ethylene oxide flame front to propagate into the vapor space of the ethylene oxide reflux drum causing a large explosion. The pressure relief was intended to protect the product cooler from a thermal expansion scenario. The system could have been modified when the product cooler was replaced in 2010 to eliminate the threat of thermal expansion and eliminate the hazard of venting ethylene oxide into the reflux drum or another location.

CAUSE

The CSB determined that the cause of the incident was the puncture of a rupture disc by metal debris that allowed the introduction of ethylene oxide into piping that contained air. The ethylene oxide ignited, and the ethylene oxide and combustion products propagated through pressure relief piping to a reflux drum that was filled with ethylene oxide. The ethylene oxide in the vapor space of the reflux drum heated and decomposed, causing the reflux drum to fail catastrophically due to increased pressure from the decomposition reaction.

Contributing to the incident was Dow's inadequate vessel closure procedures and practices, which allowed the vessel to be restarted without ensuring that it was adequately cleaned and the work lights removed. Debris from the work lights then moved downstream to the product cooler and penetrated the product cooler's rupture disc, which allowed ethylene oxide to enter the product cooler's emergency pressure relief piping's atmosphere. Also contributing to the incident was Dow's failure to maintain an inert atmosphere in the pressure relief piping and the lack of requirements to ensure that the piping segment remained inert during operation.

Contributing to the severity of the incident was the design of Dow's product cooler's emergency pressure-relief system, which discharged its pressure-relief effluent back into the reflux drum. Instead, had Dow's product cooler been designed so that pressure-relief was not necessary, the consequences of the incident would have been greatly reduced.

RECOMMENDATIONS

To The Dow Chemical Company[a]

2023-03-I-LA-R1

At all Dow ethylene oxide facilities, identify all process lines in ethylene oxide service that should be or are inerted and currently are not continuously monitored during normal operation. For all lines identified, determine whether the line can be eliminated, and if not, establish proper controls such as inerting and monitoring to ensure the process line is adequately inerted.

[a] As discussed in Section 4.1.4 of this report, as a result of the incident Dow established a new vessel closure process that includes defined steps and clear responsibilities related to vessel closure. Dow also created a *Global Foreign Materials Exclusion Standard* that sets stringent requirements for vessels over 16 inches in diameter or with manhole openings larger than 16 inches. Because of these actions, the CSB has not issued a recommendation to Dow regarding vessel closure and cleaning procedures. The CSB urges Dow to ensure that the new procedures and the new Standard are followed strictly, however.

To National Fire Protection Agency

2023-03-I-LA-R2

Update NFPA 350 *Guide for Safe Confined Space Entry and Work* to provide guidance on how to ensure that vessels that have undergone confined space entry are left clean and ready for startup after the entries are completed.

2023-03-I-LA-R3

Update NFPA 326 *Standard for the Safeguarding of Tanks and Containers for Entry, Cleaning, or Repair* to provide requirements for to ensure that vessels that have undergone confined space entry are left clean and ready for startup after the entries are completed.

To American Society of Safety Professionals

2023-03-I-LA-R4

Update *ANSI/ASSP Z117.1 Safety Requirements for Entering Confined Spaces* to provide guidance on how to ensure that vessels that have undergone confined space entry are left clean and ready for startup after the entries are completed.

1 BACKGROUND

1.1 DOW'S LOUISIANA OPERATIONS

The incident occurred in the Glycol II unit of Dow Chemical Company's (Dow) Louisiana Operations (LAO) facility located in Plaquemine, Louisiana. Dow established LAO in 1956, and at the time of the incident, the LAO site's industrial park had 23 production units manufacturing more than 50 different intermediate and specialty chemical products, including ethylene oxide [1]. On the day of the incident, LAO employed approximately 1,259 Dow employees as well as 1,400 contractors. In addition to the Dow operations, several other manufacturing tenants are located within the site's boundaries. In total, Dow owns and operates four ethylene oxide production facilities around the world: LAO; Union Carbide Corporation[a] Seadrift Operations in Seadrift, Texas; Dow Benelux Operations in Terneuzen, The Netherlands; and Union Carbide Corporation St. Charles Operations in Hahnville, Louisiana.

1.2 ETHYLENE OXIDE

Ethylene oxide is a known human carcinogen. It is a flammable, colorless gas or liquid that has a sweet, ether-like odor. Ethylene oxide boils at 50.8°F (10.4°C) at atmospheric pressure. [2] It is a highly reactive chemical, which makes it useful in creating other chemicals, but also makes ethylene oxide potentially hazardous to produce, store, and handle. Ethylene oxide is often used as an intermediate chemical in the production of other industrial chemicals, such as ethylene glycol and antifreeze. It is also used in the agricultural industry as a fumigant and in the medical industry to sterilize medical equipment and supplies [3]. In the U.S. in 2023, ethylene oxide was manufactured at 17 facilities in 12 locations, by nine companies, primarily in the states of Texas and Louisiana [4].

Ethylene oxide has a lower flammability limit of 2.6 percent and an upper flammability limit of 100 percent, meaning that it can ignite or decompose in certain conditions even when there is no oxygen present. [5, 6, pp. 229-234]. Ethylene oxide has an autoignition temperature of 833 ºF (455 ºC).

Ethylene oxide can decompose explosively and ethylene oxide in gas form has a decomposition temperature of 923 ºF at atmospheric pressure. Ethylene oxide's primary decomposition reaction has the ethylene oxide molecule (C_2H_4O) break down into carbon monoxide (CO) and methane (CH_4) with a release of energy. Once the decomposition reaction has begun, the decomposition can generate high pressures (10-20 times the initial pressure) and can propagate from the initiation source through the gas phase as a flame. Mixtures of ethylene oxide liquid and vapor decompose similarly to ethylene oxide gas but can generate even higher pressure than the gas alone. Ethylene oxide liquid can also decompose and explode if initiated by a strong ignition source. Decomposition can be minimized by using an inert gas such as nitrogen. Decomposition of ethylene oxide can propagate in piping systems as small as 2 inches in diameter.

[a] Union Carbide Corporation operates this facility but is a Dow subsidiary.

The Safety Data Sheet (SDS) for ethylene oxide provided to the CSB by Dow indicates flammability, toxicity, and reactivity hazards. The National Fire Protection Association (NFPA) hazard diamond for ethylene oxide from the SDS is shown in **Table 1** below [2].

Table 1. The NFPA Hazard Diamond for Ethylene Oxide. (Credit: CAMEO Chemicals)

Diamond	Hazard	Value	Description
	Health	3	Can cause serious or permanent injury.
	Flammability	4	Burns readily. Rapidly or completely vaporizes at atmospheric pressure and normal ambient temperature.
	Instability	3	Capable of detonation or explosive decomposition or explosive reaction but requires a strong initiating source or must be heated under confinement before initiation.
	Special		

Long-term exposure to ethylene oxide can be harmful, as it is carcinogenic and mutagenic[a] [7]. The National Institute for Occupational Safety and Health (NIOSH) considers an ethylene oxide minimum concentration in air of 800 parts per million to be immediately dangerous to life or health (IDLH) [8].[b]

1.3 Process Description

The LAO Glycol II unit contains multiple processing areas, including the ethylene oxide production unit where the incident occurred. The ethylene oxide production unit within the Glycol II unit reacts ethylene and oxygen to produce ethylene oxide. The ethylene oxide is then further processed through finishing operations, which purify the produced ethylene oxide through distillation columns and other means to between 99.9 and 100% pure ethylene oxide, which can then be sold or further used by other units in LAO.

In the ethylene oxide finishing operations section of the ethylene oxide production unit, purified ethylene oxide flows from the top of a distillation column, referred to as the finishing column, and is condensed, cooled, and sent to a reflux drum. The ethylene oxide in the reflux drum flows to multiple locations through reflux pumps.[c] The ethylene oxide can be pumped back to the finishing column to be used as reflux, recycled back to the reflux drum, or sent to storage tanks as a final product. The ethylene oxide that is sent as a final product is cooled in a heat exchanger, called the product cooler, prior to final storage. **Figure 1** provides a simplified graphical depiction of portions of the ethylene oxide finishing operations process pertinent to this incident.

The reflux drum, which failed catastrophically and exploded in the incident, was a horizontal vessel constructed of SA-285-C carbon steel. The reflex drum's maximum allowable working pressure (MAWP) was 75 pounds per square inch gauge (psig) at a temperature of 450 °F. The drum was 16 feet long and had an internal diameter of 8 feet. The drum was protected from overpressure by an emergency pressure-relief valve, which was set to relieve at 75 psig. During May to June 2023 a turnaround[d] was performed on the Glycol II unit. The reflux drum was internally cleaned and inspected as part of the turnaround work.

[a] If a substance is mutagenic, then it can damage DNA in humans [5].

[b] NIOSH defines IDLH as "the immediately dangerous to life or health air concentration values." [32]

[c] To maintain desired ethylene oxide production rates, Dow used two pumps running in parallel with one spare pump. At the time of the incident, one of the three pumps was out of service.

[d] The Center for Chemical Process Safety (CCPS) explains that a turnaround is "a scheduled shutdown period when planned inspection, testing, and preventive maintenance, as well as corrective maintenance such as modifications, replacements, or repairs is performed"

During normal production operations, the majority of the liquid ethylene oxide leaving the reflux drum was pumped back into the finishing column as reflux flow, with a smaller fraction of the liquid routed through a product cooler to one of five finished product storage tanks as finished product flow. The remainder of the reflux drum's outgoing liquid was returned to the reflux drum as recycle flow.

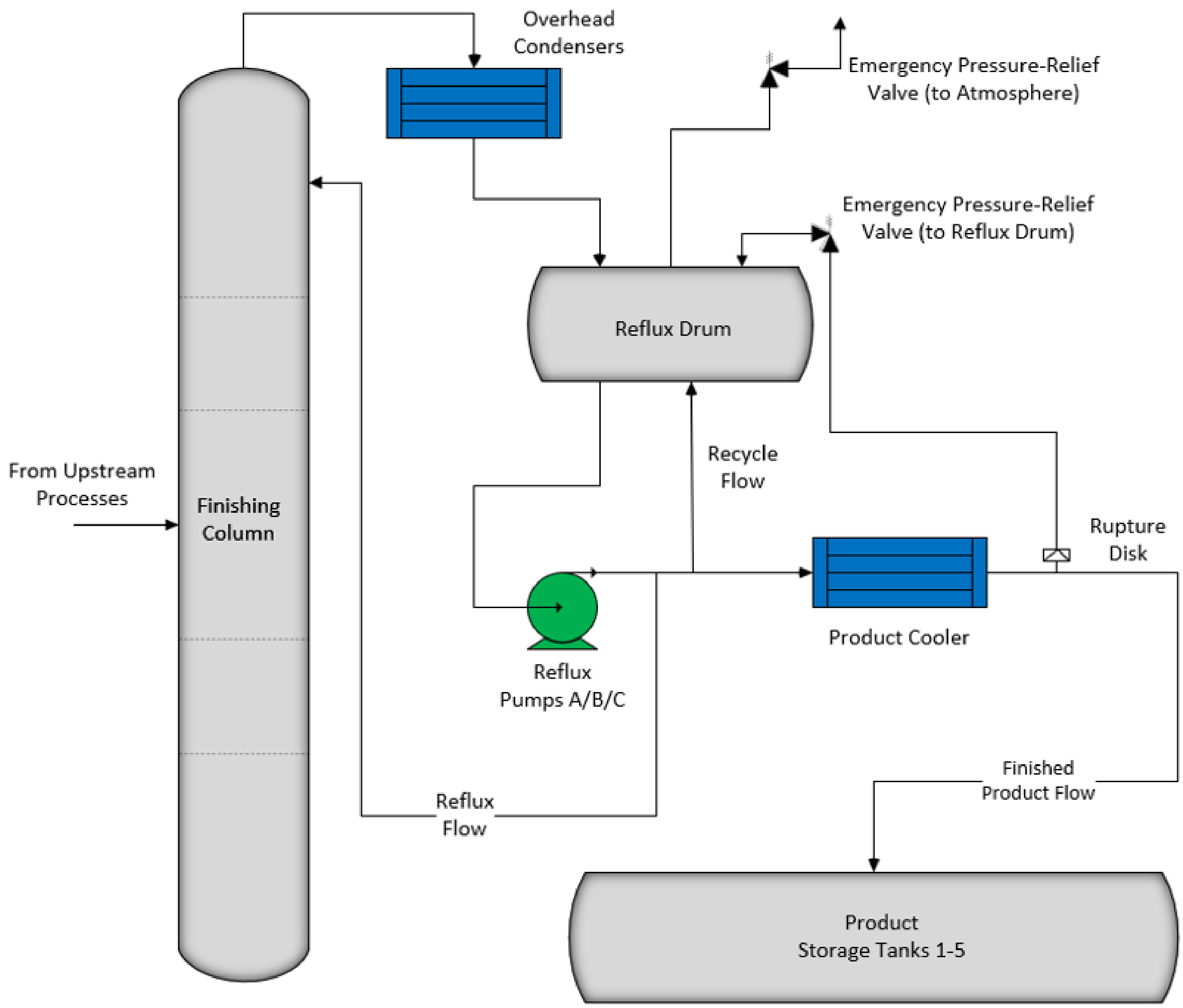


Figure 1. Simplified process flow diagram of the ethylene oxide Finishing Process. (Credit: CSB)

LAO's Glycol II unit was covered by both the U.S. Occupational Safety and Health Administration's (OSHA) Process Safety Management (PSM) standard and the U.S. Environmental Protection Agency's (EPA) Risk

Management Program (RMP) rule because it contains quantities of ethylene oxide exceeding the OSHA and the EPA thresholds[a]

1.4 PRODUCT COOLER

In 2010, Dow installed a new product cooler in the ethylene oxide finishing section. In 2010 and 2011, design changes were made to the product cooler's emergency pressure-relief system. These changes were made to protect the product cooler's integrity in the event of liquid overpressure or vapor overpressure, but they did not protect against overpressure due to thermal expansion of liquid in the product cooler. Previously, the product cooler's emergency pressure-relief discharge was routed to the atmosphere, which Dow deemed to be an unsafe location due to the risk of a vapor cloud explosion of ethylene oxide. The process was changed so that the product cooler's liquid and vapor emergency pressure-relief discharge was routed to the reflux drum. The product cooler had a maximum allowable working pressure of 570 psig on its tube side, where ethylene oxide was present.

At the time of the incident, the product cooler was protected from a thermal overpressure event by a rupture disc and an emergency pressure-relief valve (PRV) in series[b] installed downstream of the product cooler (see **Figure 2**). The rupture disc and pressure relief were intended to provide relief in the event of the product cooler being blocked in and heated at a faster rate than the ethylene oxide could safely handle.

[a] OSHA's PSM list of highly hazardous chemicals establishes the threshold quantity for ethylene oxide at 5,000 pounds [24]. EPA's List of Regulated Substances under the Risk Management Program establishes the threshold quantity for ethylene oxide at 10,000 pounds [25].

[b] For systems containing ethylene oxide guidance states: "Bursting/rupture disks can be placed on the upstream side of the pressure relief valves to help prevent accumulation of polymer in the pressure relief valve. (Non-reclosing bursting/ rupture disks are generally not used as a method of emergency relief; such devices would allow the continued escape of EO from the storage vessel.) If equipped with a bursting/ rupture disk upstream of the pressure relief valve, a method of indicating failure of the disk, such as a pressure gauge between the disk and pressure relief valve, might be considered." [8, p. 74]

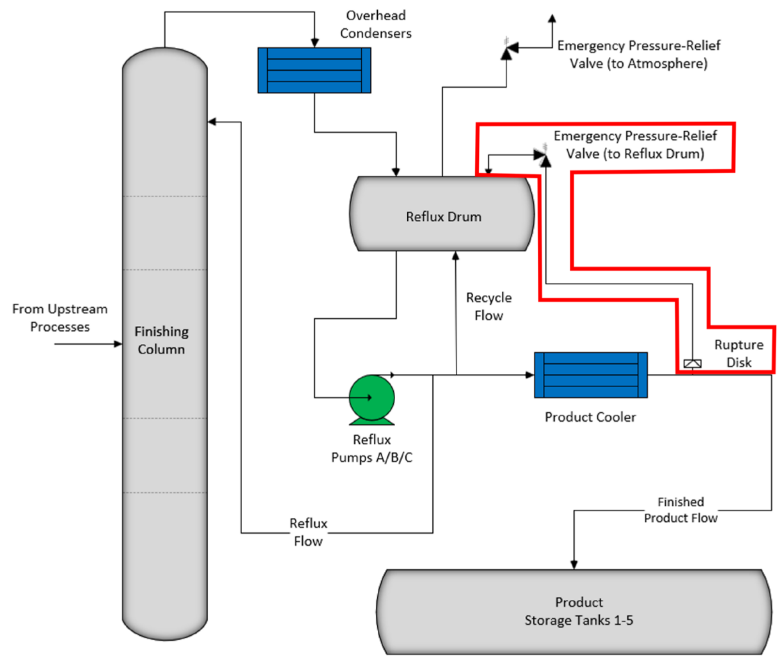


Figure 2. Simplified process flow diagram of the ethylene oxide Finishing Process, with highlighted Product Cooler's Emergency Pressure-Relief System. (Credit: CSB)

The rupture disc and the PRV were separated by approximately 50 feet of four-inch diameter pressure relief piping. Dow installed a pressure-indicating transmitter on this piping segment that included an alarm set at 80 psig to detect a disc rupture or leak.[a] Both the rupture disc and the PRV were set to relieve at 265 psig. Once the overpressured liquid or vapor was discharged from the PRV, it was routed back to the reflux drum, as shown in **Figure 3**.[b]

[a] International Code (and rupture disc manufacturers) allow for a rupture disc to be installed between a PRV and the Pressurized Equipment that is being protected, provided certain conditions are met. These conditions include requiring monitoring pressure of the space between the combined rupture disc and the PRV emergency pressure-relief in order to detect a disc rupture or leak. This is to prevent excessive backpressure from building on the rupture disc, which then would not burst at its marked bursting pressure. [34]

[b] The reflux drum had its own emergency pressure-relief system that was to open at 75 psig, and to release its' effluent into the atmosphere.

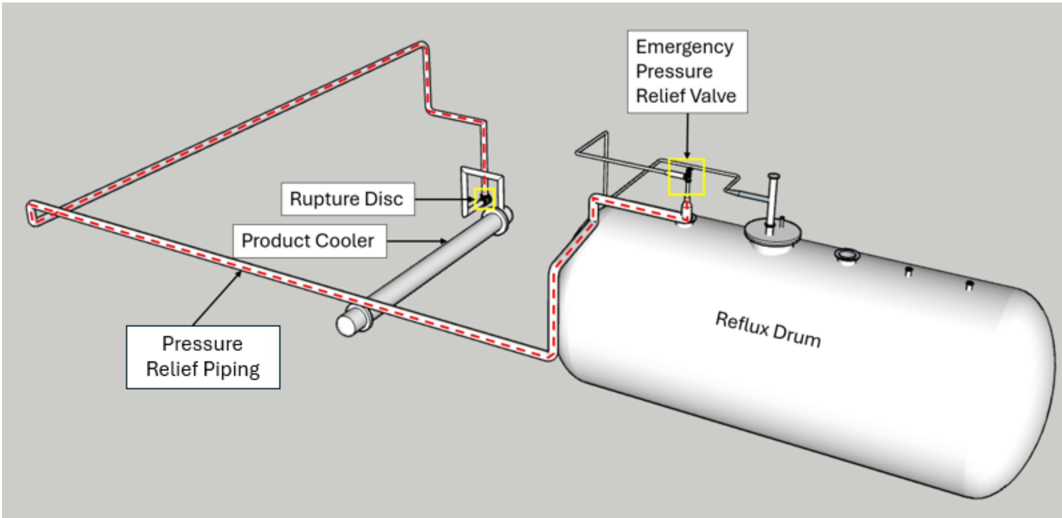


Figure 3. Schematic of product cooler and its emergency pressure-relief system components in relation to the reflux drum. (Credit: CSB)

1.5 DESCRIPTION OF THE SURROUNDING AREA – ONE-MILE

Figure 4 shows the Dow LAO site and depicts the area within one, three, and five miles of the site's boundary. Summarized demographic data for the approximate one-mile vicinity of the site is shown below in **Figure 4.** Within one mile of the site, over 9,200 people reside in nearly 4,000 housing units, most of which are single units. Detailed demographic data is included in **Appendix B: Description of Surrounding Area**.

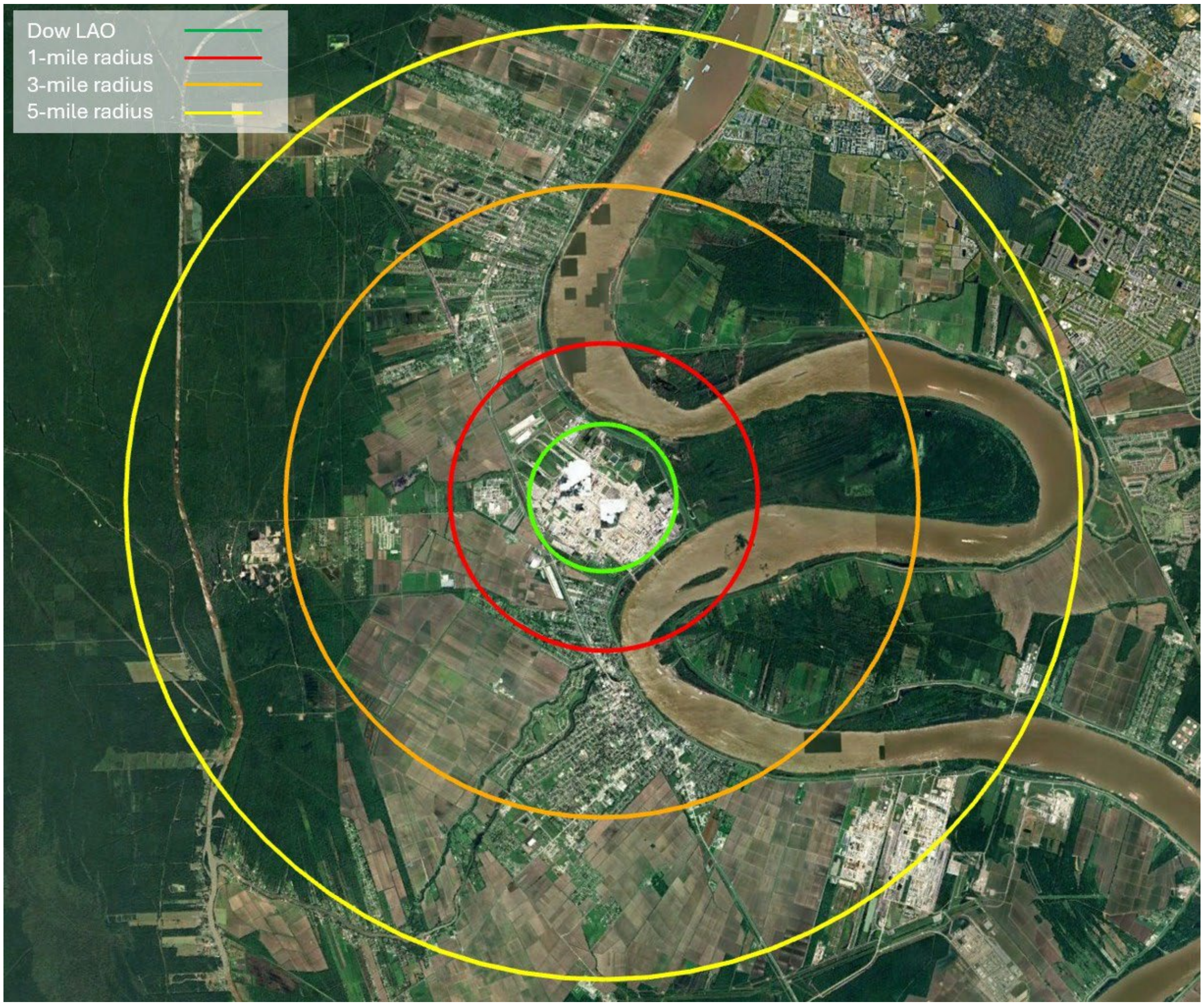


Figure 4. Overhead satellite image of the Dow site and the surrounding area.
(Credit: Google Earth, annotated by the CSB)

Table 2. Summarized Demographic Data for Approximately One-Mile Vicinity of Dow site.
(Credit: CSB using data obtained from Census Reporter)

Population	Race & Ethnicity		Per Capita Income	% Persons Below Poverty Line	Number of Housing Units	Types of Housing Units	
9,209	White	54%	$ 39,076	7.7%	3,990	Single Unit	77%
	Black	42%				Multi-Unit	14%
	Native	0%				Mobile Home	10%
	Asian	1%				Boat, RV, Van, etc.	0%
	Islander	0%					
	Other	2%					
	Two+	1%					
	Hispanic	1%					

2 INCIDENT DESCRIPTION

2.1 NOVEMBER 2020 MAINTENANCE ACTIVITIES

On November 20, 2020, the rupture disc protecting the product cooler was replaced as part of regular maintenance and inspection activities. Upon completing the installation of the rupture disc, Dow workers pressurized the pressure relief piping between the rupture disc and PRV with 2.4 psig of nitrogen, which was used as an inerting gas in the Glycol II unit to prevent ethylene oxide decomposition and reaction. Over the next two months, unbeknownst to Dow, the nitrogen pressure in the rupture disc discharge piping gradually decreased, eventually reaching atmospheric pressure and even showing negative gauge pressure for periods of time, indicating a slight vacuum in the pressure-relief piping. No additional nitrogen was added to the pressure relief piping between the November 2020 maintenance activities and the incident.

2.2 MAY TO JUNE 2023 TURNAROUND ACTIVITIES

In May 2023, the Glycol II unit underwent a turnaround. One of the turnaround activities included cleaning out and performing an internal inspection of the reflux drum. The work order for this activity included tasks to "install low voltage lights" prior to the work beginning and "remove internal low voltage lights" after the work was completed inside of the reflux drum.[a] According to the work order, these tasks were to be performed by contractor electricians and were executed under a confined space entry (CSE) permit. Portable work lights with magnetic bases were checked out during this turnaround, but five of these lights were never returned following the turnaround. **Figure 5** shows one of the portable work lights inside the reflux drum during the May 2023 turnaround.

[a] Each portable work light that was used in the reflux drum, during the May 2023 turnaround, was a Bayco Products, Inc., NightStick XPR-5592 rechargeable LED scene light powered by a lithium-ion battery pack.

Figure 5. Photo of the inside of the reflux drum during the May 2023 turnaround, with highlighted portable work light (Credit: Dow) and the portable work light, NightStick XPR-5592 (Credit: Bayco Products, Inc. [9])

The internal cleaning and inspection of the reflux drum occurred on May 21, 2023. Following the planned task to remove the portable work lights, the work order called for circulating and signing a "Vessel/Nozzle Closure Form". The Glycol II unit used the Vessel/Nozzle Closure Form as an administrative tool to ensure, in part, that no debris or tools remained in a vessel following an inspection or repair. The last signature on the closure form was from a "Final Closure Witness," whose responsibility was to confirm that the "vessel/nozzle [was] clean and free of debris". The Final Closure Witness typically was an operator.

Dow required the Final Closure Witness to "be present and visually observing the…closure at least up to [four] bolts being installed." The Final Closure Witness's signature indicated that the reflux drum manway was closed on May 28, 2023. Unbeknownst to the workers, some of the portable work lights from the turnaround work were left behind in the reflux drum. After the turnaround work was complete, the ethylene oxide unit was started up and began operating without issues. During this time, the reflux drum filled with ethylene oxide, and the reactive chemical began to degrade the work lights.

2.3 Night of the Incident

When the night shift began on July 14, 2023, the Glycol II unit was operating under normal conditions. At approximately 6:52 p.m., one of the reflux pumps shut down due to a high-high vibration interlock[a], indicating that the pump was experiencing excessive vibrations. An operator was sent to troubleshoot the pump in the field. The operator found what looked like a scrap piece of insulation on the vibration probe wiring. After presuming this to be causing the pump shutdown, the operator was able to restart the pump successfully. Post-incident analysis determined that the vibrations were likely caused by work light debris working its way through the unit.

The reflux pump was returned to operation at approximately 6:54 p.m. The vibrations continued at a high rate, but they level did not reach the high-high vibration level and the pump did not shut back down automatically.

As a result of the reflux pump shutdown, the ethylene oxide finishing operations experienced numerous process upsets resulting from the rising liquid ethylene oxide level[b] in the reflux drum. The liquid level in the reflux drum rose as less liquid was pumped out.

Process operators attempted to stabilize the liquid levels, principally in the finishing column and reflux drum until approximately 9:17 p.m., when an explosion occurred in the vicinity of the reflux drum.

[a] A vibration interlock on a pump detects vibration and automatically shuts down the pump to prevent damage to the pump system.

[b] The Dictionary of Chemical Engineering defines a "process upset" as "a sudden, gradual, or unintended change in the operational behaviour of a process [23, p. 300]."

After the explosion, two process operators who were working in the unit immediately evacuated the area following the initial explosion. One of the process operators announced the presence of a fire over the radio while they evacuated. The lead process operator reported the fire to the site's Emergency Services and Security (ES&S)[a] department dispatcher at 9:18 p.m. The ES&S department then mobilized the site's emergency response team. ES&S personnel witnessed multiple explosions in the Glycol II unit and a "fireball" (see **Figure 6**).

Figure 6. Surveillance footage of the explosion at approximately 9:17 p.m. (Credit: Dow)

At 9:20 p.m., ES&S responders arrived at the scene to fight the fire and establish the Incident Command. At 9:21 p.m., the Glycol II unit reported to ES&S that all of its personnel were accounted for. At approximately the same time, control room operators executed the Glycol II unit's automatic procedure to shut down the unit.

2.4 Incident Consequences

Dow reported that approximately 31,525 pounds of ethylene oxide were released during the incident, which included the ethylene oxide de-inventorying from process equipment that followed the fire. Dow also reported that its property damages were estimated to be $43 million. No injuries were reported as a result of the incident.

After the explosion the Iberville Parish Council Office of Emergency Preparedness issued a shelter-in-place order for residents living within a half-mile of the Dow site. The shelter-in-place order was lifted at approximately 3:40 a.m. on July 15, 2023 [10].

[a] As part of emergency services and security, this department also had the responsibility for site firefighting response

3 Technical Analysis

The explosion occurred when a reflux drum containing liquid and vapor ethylene oxide failed catastrophically. The chain of events began when metal debris from portable work lights that had been left in the drum impacted a rupture disc, causing it to partially open, allowing ethylene oxide to flow into pressure relief piping, which contained air. The ethylene oxide ignited and propagated through the pressure relief piping into the reflux drum. The heat from the flame front caused the liquid ethylene oxide within the drum to decompose, and the subsequent pressure rise caused the drum to fail.

Figure 7 below shows a simplified overview of the incident.

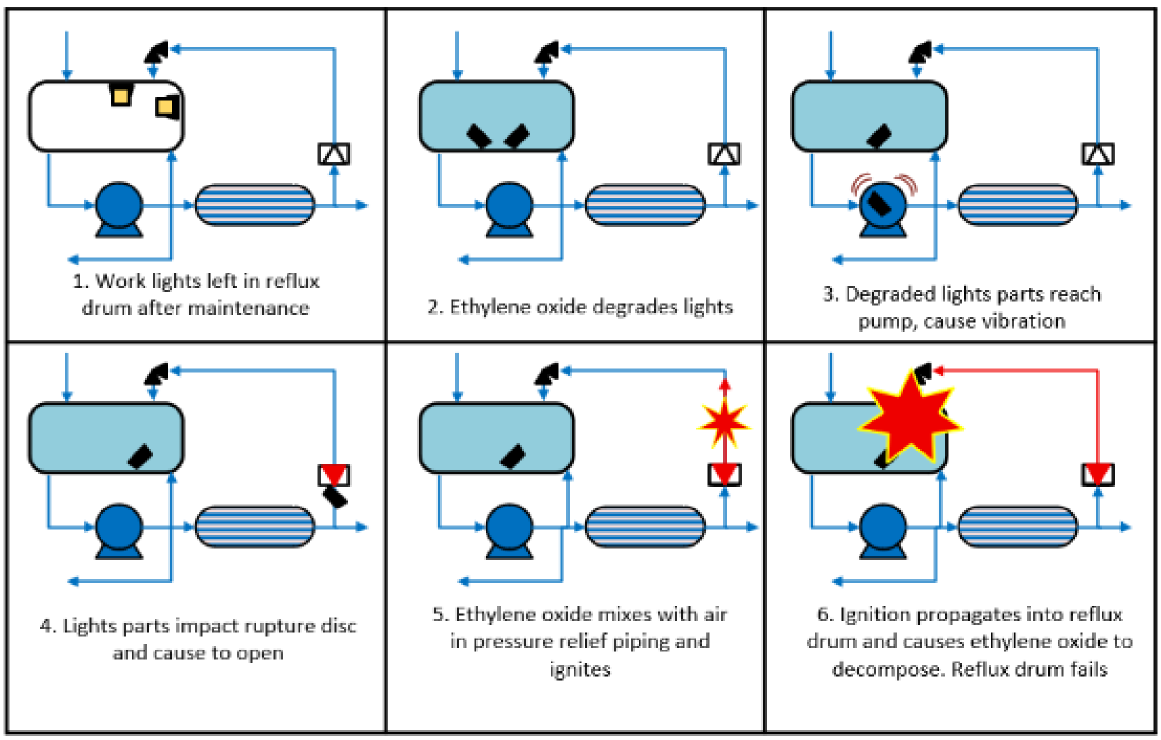


Figure 7. Chain of events of the incident (Source: CSB)

3.1 Work Light Debris

As shown in the figure above, the incident began when work lights were left in the reflux drum after maintenance work and the lights degraded when ethylene oxide was reintroduced to the drum. Following the incident, foreign material consistent with the work lights was discovered inside multiple pieces of equipment in the Glycol II unit. Multiple pieces of rubber and metal debris, including metal fragments, plastic pieces, and batteries, were discovered after the explosion in and around the reflux drum, inside the reflux pump, and in one of the product coolers' heads. The recovered debris from these areas is consistent with components of the portable work lights that were used in the reflux drum during the May 2023 turnaround. For instance, degraded circuit board pieces were found inside the product cooler, which were identical to exemplar pieces from other portable work lights (**Figure 8**). The metal portions were also consistent with the metal found embedded in the failed rupture disc.

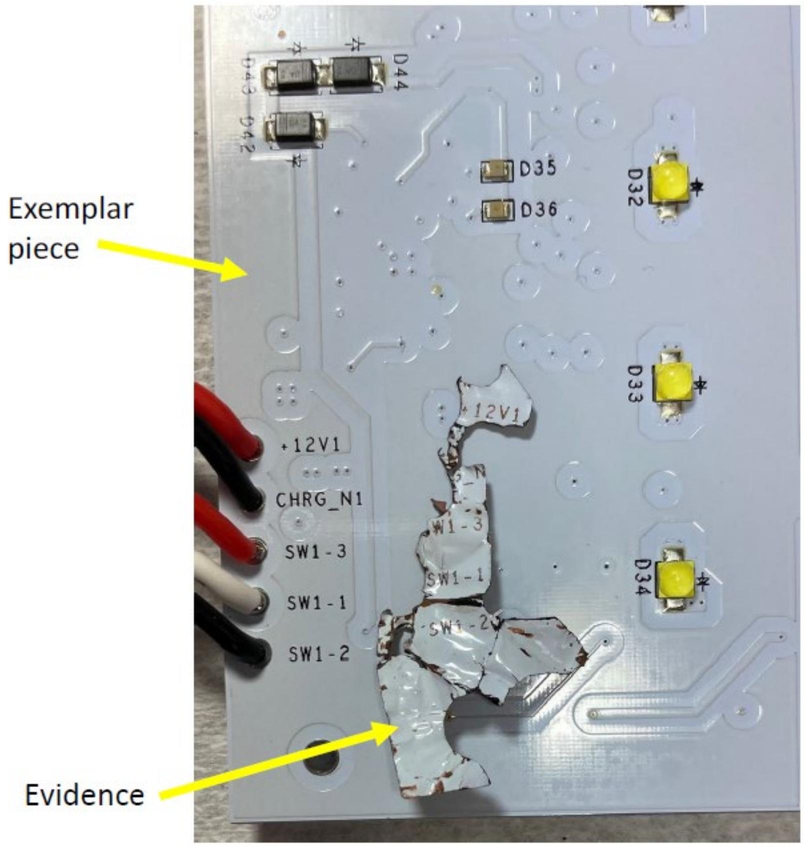


Figure 8. Metallic debris found with process equipment post-incident, along with portable work light exemplar circuit board (Source: Dow)

The presence of debris from the portable work lights in the reflux drum and in other downstream equipment indicates that at least three portable work lights used in the May 2023 turnaround were not removed from the reflux drum before returning it to service. The condition of some of the portable work lights' parts indicates that the reaction of the work lights with the pure ethylene oxide in the reflux drum likely caused the parts to deteriorate, breaking them into smaller pieces of debris.

The presence of debris from portable work lights in the reflux pump and the product cooler also indicates that some of this debris was carried from the reflux drum into process equipment further downstream. This debris likely caused the pump vibrations that occurred in the unit prior to the explosion, as the debris worked its way from the reflux drum through the pumps. As pieces of the work lights impacted the internal components of the pump, they likely caused the pump vibrations to increase, setting off the high-high vibration pump alarms.

The CSB concludes that work lights were left behind in the reflux drum during the May 2023 turnaround and degraded in the process, allowing metal debris to flow downstream.

3.2 RUPTURE DISC FAILURE

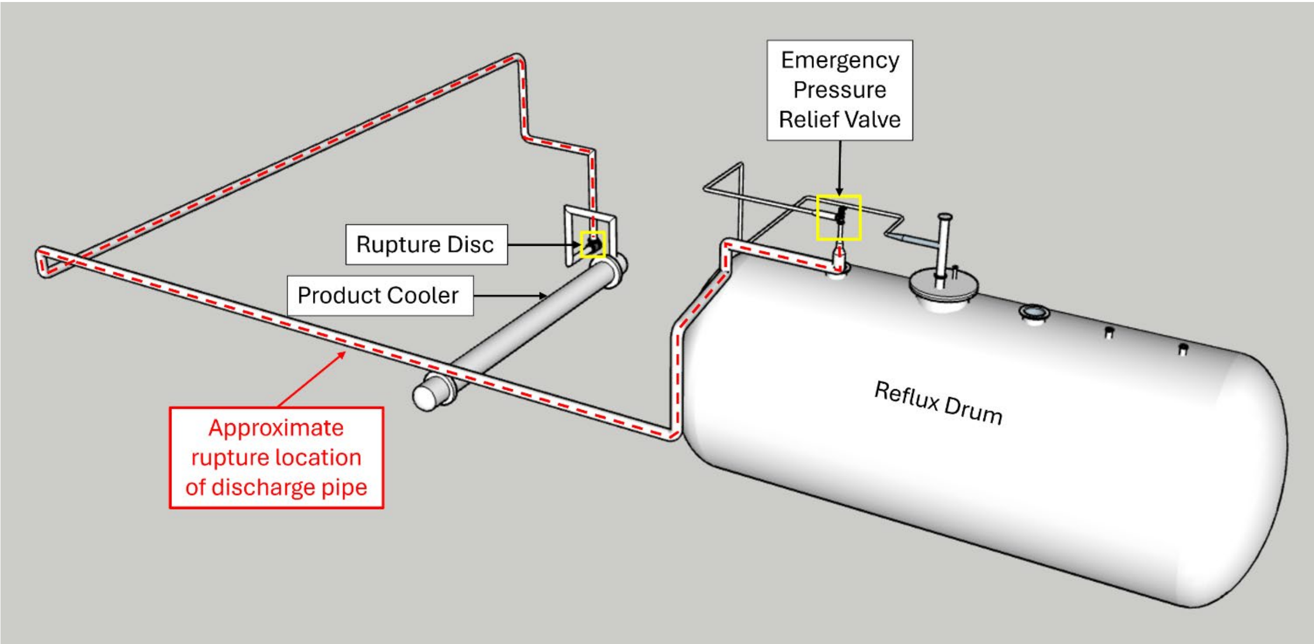


Figure 9. Schematic of product cooler and its emergency pressure-relief system components in relation to the reflux drum, with highlighted approximate location of the product cooler's emergency pressure-relief rupture disc discharge piping rupture. (Credit: CSB)

The first mechanical failure in the chain of events leading to the fire and explosion was the failure of the product cooler rupture disc (shown in **Figure 9** above). This allowed the ethylene oxide to enter the pressure relief piping which contained air and ignite. After the incident, the rupture disc was tested and analyzed by Dow to understand its part in the incident. Initial inspection determined that the rupture disc had partially opened and would have allowed flow into the pressure relief piping (see **Figure 10**). The pressure transmitter located on the pressure relief piping system showed increased pressure immediately prior to the explosion, which indicates the rupture disc opened immediately before the reflux drum failed.

The rupture disc was a forward-acting scored rupture disc, which uses scoring on the metal surface to control the burst pressure and opening pattern. The purpose of the rupture disc, in combination with the PRV on the other end of the pressure relief piping, was to provide overpressure protection to the product cooler during a thermal expansion scenario in the event that the liquid ethylene oxide on the tube side of the product cooler was blocked in and the ethylene oxide became overheated and began to expand.

Figure 10. Damaged product cooler's rupture disc (left), compared to an intact product cooler's rupture disc which did not open during the incident[a] (right), both photos post-incident. (Credit: Dow)

Metallurgical testing and post-incident analysis determined that the rupture disc did not fail in the designed and intended manner as it would in a regular overpressure event. Rupture discs are designed to open in the event of a pressure event in a symmetrical fashion and with minor deformation (**Figure 11**). A "normal" rupture disc opening would have all four portions of the rupture disc open in a symmetrical pattern. The asymmetry of the rupture disc involved in this incident indicates that it likely did not burst from a consistent pressure increase inside the product cooler, but opened through a different mechanism.

[a] The Glycol II unit had two separate emergency pressure-relief systems for the product cooler, "A" and "B." Each system had its own rupture disc and PRV in combination, a nitrogen sweep on the product cooler's PRV discharge piping [8, p. 75], and any associated piping. The systems were designed to be used separately in order to allow for the maintenance of one system without having to shut down the Glycol II unit.

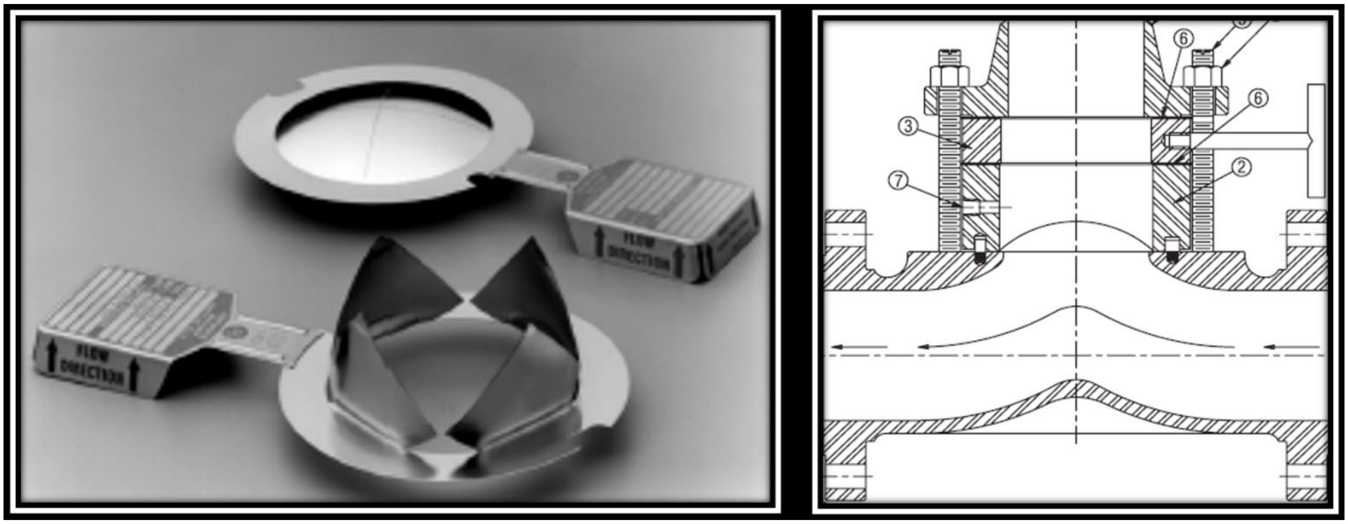


Figure 11. Rupture disc of the type used in the product cooler pressure relief line (left) before (above) and then after (lower) a full rupture [11] and a cross-section schematic of the rupture disc holder (right) [12]. (Credit: Continental Disc Corporation)

Post-incident metallurgical testing of the rupture disc identified small pieces of corroded carbon steel embedded in the rupture disc body. The presence of these small pieces of debris. together with the manner in which the rupture disc opened. indicates that a small hard piece of metal debris likely impacted the rupture disc, causing a hole in the surface of the rupture disc, which resulted in the partial opening of the disc. As the rupture disc was designed for liquid ethylene oxide service and was not intended to withstand metal debris, it most likely failed below the design burst pressure.

The corroded carbon steel embedded in the rupture disc was the same material as some of the work light debris found in the reflux drum and product cooler, indicating that the metal embedded in the rupture disc likely came from portable work lights that were inadvertently left in the reflux drum after the May 2023 turnaround.

The CSB concludes that the product cooler rupture disc opened in a non-intended manner below its burst pressure and allowed ethylene oxide to reach the pressure relief piping due to impact from metal debris.

3.3 Ethylene Oxide Ignition

After the rupture disc partially opened, the liquid ethylene oxide entered the pressure relief piping between the rupture disc and the PRV and mixed with the air in the pressure relief piping segment. The air was present due to a lack of inerting gas – i.e., the nitrogen that had leaked. This mixture of ethylene oxide and air then ignited within the pressure relief piping. After the initial ignition, the heat of the initial ignition caused continued ignition and decomposition of ethylene oxide as it propagated through the pressure relief piping.

As discussed in Section 2.1, the rupture disc protecting the product cooler was replaced in November 2020 as part of regular maintenance and inspection activities. Upon completing the installation of the new rupture disc, workers closed the pressure relief piping and pressurized it with approximately 2.4 psig of inert nitrogen. Inert gas minimizes the risk of ethylene oxide ignition and decomposition and is regularly used for that purpose in the Glycol II unit. Following the 2020 maintenance activities, the nitrogen pressure in the pressure relief piping gradually decreased, eventually reaching atmospheric pressure and even showed negative gauge pressure. The pressure between the rupture disc and PRV was recorded by a transmitter but was not adequately monitored by Dow. Although there was a high-pressure alarm, there was no low-pressure alarm present on the pressure indicator. Moreover, operators were not instructed to ensure that the piping maintained pressure by periodically checking the pressure in the piping segment.

The pressure transmitter on the pressure relief piping was designed to read psig, which at atmospheric pressure would indicate 0 psig. In the years preceding the incident, the transmitter frequently showed negative readings (i.e. -0.073 psig), which indicated that the pressure relief piping was under a slight vacuum. During these times, air would have entered the pressure relief piping through the leaks which allowed the nitrogen to vent, filling the piping with air. With the loss of the inerting gas in the pressure relief piping, the ethylene oxide mixed with air and ignited when it reached the pressure relief piping.

As discussed in Section 1.2, ethylene oxide is a reactive chemical and can react or combust energetically. Under standard atmospheric conditions, the energy required to ignite pure ethylene oxide vapor (minimum ignition energy) is around 1,000 millijoules (mJ). However, ethylene oxide at certain mixtures with oxygen has a minimum ignition energy of only 0.06 mJ, which is lower than the minimum ignition energy of gasoline (0.24 mJ) and even lower than the static electricity that a person generates (1-50 mJ) when they walk across a carpet and create a static electricity spark.

The CSB concludes that the pressure relief piping between the product cooler rupture disc and PRV did not have adequate inerting nitrogen to prevent the ignition of ethylene oxide within the piping system. As a result, when the rupture disc ruptured, ethylene oxide was able to combust and propagate through the piping to the reflux drum.

3.4 Propagation to Reflux Drum

As stated earlier, the pressure relief piping was about 50 feet long and consisted of a 4-inch diameter line with multiple elbows. As the ethylene oxide and combustion products flowed through the pressure relief piping, it continued to combust and generate pressure within the system. This pressure increase ultimately ruptured portions of the pressure relief piping. The ethylene oxide flame front and combustion gas reached the PRV and the increased pressure of the combusting ethylene oxide in the pressure relief piping caused the PRV, which had a set pressure of 265 psig, to lift. The PRV pressure relief piping discharged to the reflux drum, releasing the heated ethylene oxide and combustion products into the reflux drum.

When the ethylene oxide and associated combustion gas flame front reached the reflux drum, which contained liquid and vapor ethylene oxide, it caused the ethylene oxide within the drum to heat and begin to decompose, and the pressure quickly rose faster than it could be relieved, causing the reflux drum to fail catastrophically (**Figure 12**).

Figure 12. Reflux Drum, post-incident.[a] (Credit: CSB)

The CSB concludes that the ethylene oxide ignited within the pressure relief piping and propagated toward the PRV, which lifted, and the hot ethylene oxide and combustion products then initiated a reaction in the vapor phase of the reflux drum, causing the drum to overpressure catastrophically.

4 Safety Issues

4.1 Vessel Closure Practices

The series of events that culminated in the explosion of the reflux drum began when portable work lights were left behind in the reflux drum after turnaround maintenance and cleaning activities. The work lights subsequently degraded and produced metal debris in the drum. This section will discuss the failures and actions that resulted in the work lights being left in the reflux drum.

[a] This image of the reflux drum was taken after its re-location from the incident site. Note the welded beams around the sides and on the inside were not present on this drum at the time of the incident. Instead, the beams were added for structural support during transportation and inspection to maintain the drum's as-found condition post-incident.

4.1.1 Reflux Drum Closure

Figure 13. Debris from a portable work light found in the reflux drum post incident with scale showing inches (Source: Dow edited by CSB)

As discussed in Section 3.1, portable work lights were left in the reflux drum after the May 2023 turnaround work in the drum had concluded. Debris consistent with the work lights was found in the reflux drum, the downstream pumps, the product cooler, and the rupture disc after the incident (**Figure 13**).

The work done inside the reflux drum during the May 2023 turnaround constituted multiple confined space entries into the vessel. Dow required that all confined space entries "have adequate lighting" present, and the work lights were placed in the drum to meet this requirement during the turnaround. Light installation was the first step of the work order for the reflux drum after it was safe for entry and a ladder was installed inside. Removal of the lights was also the last step in the work order prior to signing the vessel closure form and sealing the reflux drum back up. **Figure 14** shows the work lights in the reflux drum during the turnaround.

Figure 14. Portable work lights within the reflux drum during the turnaround (Source: Dow)

At the time of the incident, Dow's vessel closure process had no official procedure in place related to tracking equipment placed inside a vessel during maintenance and inspection activities requiring confined space entries. Tools and equipment, such as work lights, that were checked out to be used during the turnaround were not tracked based on the specific equipment on which the work was being conducted (i.e. the reflux drum), but rather just for the overall unit where the work was done (i.e. the Glycol II unit). When tools and equipment were checked out for use, Dow tracked what was out and what had been returned for the entire unit. For the Glycol II unit in the May 2023 turnaround, five of the magnetic portable work lights that were checked out were not returned. Along with the missing five work lights, a number of batteries, radios, gas detectors, and a fire extinguisher were also checked out but not returned during the turnaround.

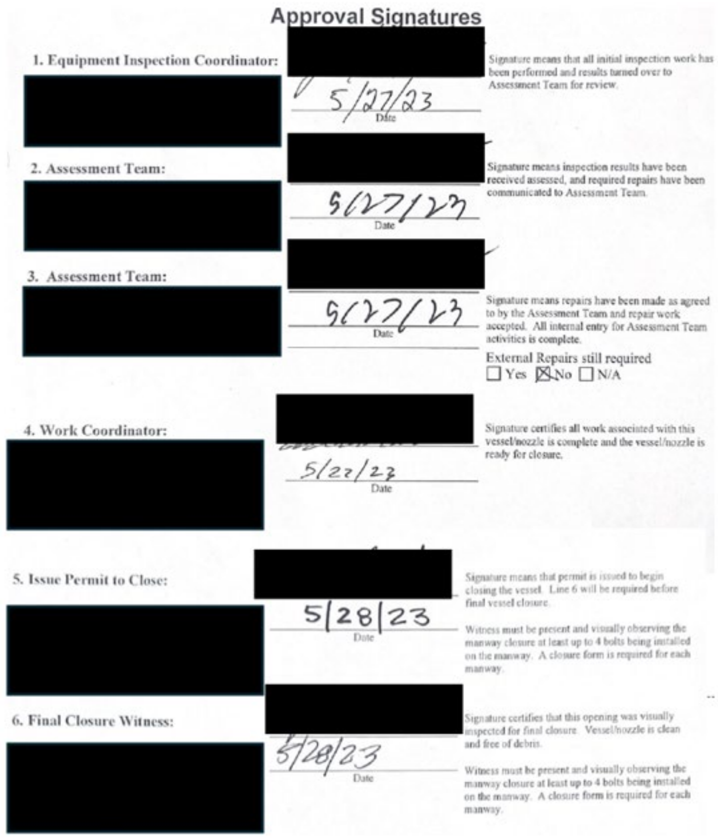
Dow's vessel closure process and practices did not adequately identify whether the reflux drum was clean and empty after maintenance was completed and no search for tools left behind was effectively conducted for this vessel during the May 2023 turnaround. This failure made it possible for the Glycol II unit to start back up with equipment still present in the reflux drum and for operations to be unaware of the potential that these lights were inside their unit.

The CSB concludes that Dow's lack of an effective system to ensure process vessels were clean and empty after maintenance work was completed during the May 2023 turnaround contributed to work lights being left behind in the reflux drum. This allowed the work lights to degrade and cause the rupture disc to open, initiating the incident.

4.1.2 Dow Closure Process

At the time of the incident, Dow had few procedures in place to ensure that debris was not left behind after confined space entries and work in vessels. The Dow *Confined Space Entry Standard* provided guidance on safety and health requirements for confined space entries such as air monitoring, energy isolation, and ventilation, but did not have any guidance on ensuring proper clean-up of equipment upon completion of work. The Glycol II unit's procedure for ensuring that no debris or tools were left inside equipment after inspections or maintenance was outlined in a document titled the *Vessel/Nozzle Closure Form*. This two-page form was intended to "ensure that a vessel or large bore pipe is closed without any debris, tools, etc., left inside after it has been opened for inspection or repair." The form provides no guidance on how operators are expected to check for debris or what steps to take to ensure a vessel is "clean and free of debris." Instead, it simply serves as a checklist to indicate that the activity has been completed rather than providing steps to complete the process. **Figure 15** below shows a portion of the form detailing the approvals necessary to ensure that the work for the reflux drum was completed and that the vessel was cleaned prior to closing it.

At the Glycol II unit, the operator responsible for closing vessels after the completion of maintenance and inspection work inside the vessel is called a permit writer. The permit writer's signature is one of the two signatures required on the form for the reflux drum work to certify that the vessel was empty and the work completed prior to the vessel's closure. In addition to the permit writer, a witness also was required to sign for the final closure of the vessel. This document did not give any additional guidance related to ensuring the cleanliness of the equipment beyond the statements shown in the figure below. Nor does the document tell the operator what steps to follow or what it means for a vessel to be "clean" means.



Approval Signatures

1. Equipment Inspection Coordinator: [redacted]
[redacted]
5/27/23
Date
Signature means that all initial inspection work has been performed and results turned over to Assessment Team for review.

2. Assessment Team: [redacted]
[redacted]
5/27/23
Date
Signature means inspection results have been received assessed, and required repairs have been communicated to Assessment Team.

3. Assessment Team: [redacted]
[redacted]
5/27/23
Date
Signature means repairs have been made as agreed to by the Assessment Team and repair work accepted. All internal entry for Assessment Team activities is complete.
External Repairs still required
☐ Yes ☒ No ☐ N/A

4. Work Coordinator: [redacted]
[redacted]
5/22/23
Date
Signature certifies all work associated with this vessel/nozzle is complete and the vessel/nozzle is ready for closure.

5. Issue Permit to Close: [redacted]
[redacted]
5/28/23
Date
Signature means that permit is issued to begin closing the vessel. Line 6 will be required before final vessel closure.
Witness must be present and visually observing the manway closure at least up to 4 bolts being installed on the manway. A closure form is required for each manway.

6. Final Closure Witness: [redacted]
[redacted]
5/28/23
Date
Signature certifies that this opening was visually inspected for final closure. Vessel/nozzle is clean and free of debris.
Witness must be present and visually observing the manway closure at least up to 4 bolts being installed on the manway. A closure form is required for each manway.

Figure 15. Dow Vessel Closure form for the reflux drum (Credit: Dow with CSB annotations)

For the reflux drum during the May 2023 turnaround, the Dow inspection work coordinator, an employee separate from the permit writer, certified that all of the work in the reflux drum was completed on May 27, 2023. The next day, two Dow operators certified that they visually inspected the drum for final closure and ensured that it was "free of debris." After this certification was made, the manway into the reflux drum was bolted closed, and there was no opportunity thereafter to find any equipment that may have been left behind in the drum.

During a turnaround such as the one in May 2023, many pieces of equipment were opened and had work done inside them. To cover the large amount of permits entailed in the turnaround, there were multiple permit writers within the Glycol II unit who were responsible for managing the work permits, including vessel closure. As part of the vessel closure process, the permit writer would be "looking for anything visible to the eye that could be in the drum." The permit writer would use a flashlight to inspect the inside of the vessel without actually entering the vessel. If the permit writer did not see anything in the vessel, the permit writer would order the vessel to be bolted and closed. However, not only did the operators not actually enter the vessel, they also did not use inspection mirrors or other means, such as a boroscope, to check the inside of the vessel.

The final Dow operator who attested that the reflux drum was empty and free of debris also was not expected to physically enter the equipment and perform a confined space entry to make sure that the vessel was clean and empty. Instead, the operator simply needed to look through the manway, which provided only a limited view of the drum's interior. The operator responsible for the final closure of the reflux drum involved in this incident stated to the CSB that "at the final closure portion of the closure form...I only can see what the man[way] allow[s] me to." As a result, the operator was largely trusting that the personnel who had entered the vessel during the work had completely removed all their tools, equipment, and debris.

The manner in which Dow performed vessel close-out often meant that a contractor was frequently the last person to be inside the vessel after maintenance and inspection work. During the course of the May 2023 turnaround, multiple contractors would have performed confined space entries into the reflux drum. For this turnaround, the reflux drum required scaffolders, electricians, boilermakers, and inspectors. Each of these sets of contractors would have had their own tools and equipment that they would bring in and out of the reflux drum. It was not made clear on the Vessel Closure form whether the Dow permit writer was required to confirm that contractors had gathered all their materials, or even to ask them if they had seen anything left behind in the vessel. Also, as discussed earlier, Dow only tracked equipment that was checked out at the unit level and did not track based on the vessel where the equipment was being used. As a result, an operator had no exact way to ensure that all equipment that entered a vessel had been removed without physically entering the vessel.

Figure 16 below shows the limitations of performing a last check visually from the largest manway of the reflux drum. As shown by the shaded areas of the reflux drum, the operator likely would not have been able to visually inspect a large portion of the vessel. The portable work lights used in the reflux drum were magnetic and could be attached to the side of the vessel. If the lights were turned off and stuck to the wall, it is unlikely that a visual inspection from the manway would identify any lights left behind, no matter how thoroughly the operator looked through the manway. This is especially the case since Dow did not require the operator to use an inspection mirror or other inspection device.

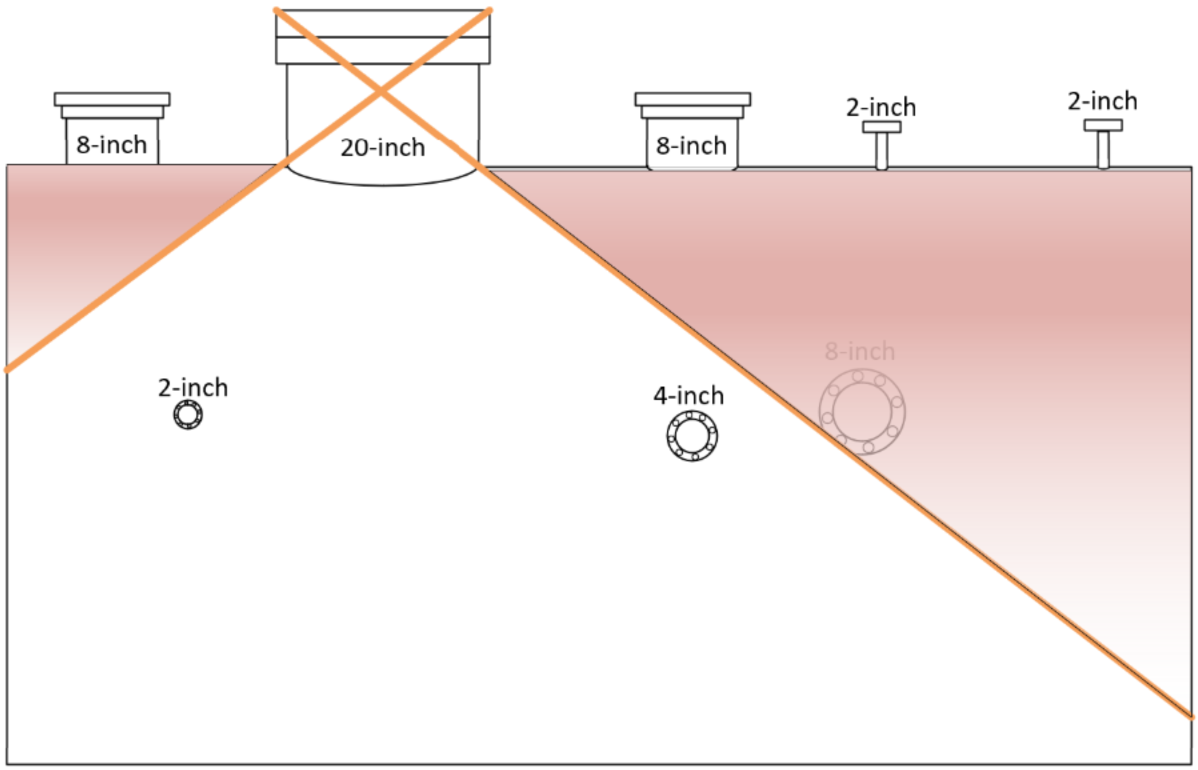


Figure 16. Approximate drawing of reflux drum (Source: CSB)

Dow's vessel closure procedure did not provide adequate steps to ensure that tools, equipment, and debris were not left behind. As a result, there was no adequate process in place to prevent the work lights from remaining behind in the reflux drum.

The CSB concludes that Dow's reliance on a visual inspection without the aid of inspection tools or a confined space entry to ensure that nothing was left in the equipment after maintenance and inspection work allowed the work lights left in the reflux drum to be missed and remain in the reflux drum. The work lights then degraded and caused the rupture disc to fail, initiating the incident.

4.1.3 Industry Guidance

A number of other incidents have involved material that was inadvertently left behind in a vessel at a chemical facility. For example, in March 2024, a major fire occurred at the ExxonMobil Baytown refinery in Baytown, Texas, when debris, including fire blankets and insulation material, was left behind in a fired heater. The debris restricted flow through the fired heater tubes and ultimately led to tube failure and a release of 250,000 pounds of hydrogen and naphtha, which ignited and caused the fire. The incident also resulted in $32 million in estimated property damage. Additionally, a 2003 study of distillation tower incidents identified five incidents that were caused by debris left in distillation columns after maintenance or inspection activities [13]. Although some general industry guidance exists discussing the importance of performing safe vessel closure after maintenance and inspections are performed inside, no guidance currently provides specific requirements and information for ensuring that vessels are clean and empty of debris after maintenance activities are completed.

4.1.3.1 National Fire Protection Association

The NFPA has two documents which discuss safety considerations for confined space work. NFPA 326 *Standard for the Safeguarding of Tanks and Containers for Entry, Cleaning, or Repair* provides requirements for "safeguarding of tanks or containers operating at nominal atmospheric pressure that contain or have contained flammable or combustible liquids or other hazardous substances." [14] Also, NFPA 350 *Guide for Safe Confined Space Entry and Work* provides guidance for conducting confined space entry and work, specifically on how to identify, evaluate, assess, and mitigate hazards present during confined space work. [15]

NFPA 326 provides requirements for confined space work on vessels that have contained hazardous chemicals, such as ethylene oxide. The standard goes into great detail on what steps must be taken to ensure that such a vessel is safe prior to human entry, including appropriate lockout/tagout, cleaning, isolation, and atmospheric monitoring. [14] NFPA 326 also discusses requirements for permits needed prior to vessel entry and the appropriate steps for accessing these vessels. The standard requires that a visual inspection must be done prior to vessel entry but provides no guidance on inspections to be done after the work has been completed. The standard focuses on preparing a vessel for entry but does not address any steps necessary to ensure that it is safe to close.

NFPA 350 provides guidance on multiple aspects of confined space work, including pre-entry evaluation of the confined space, permitting of work, hazard mitigation during confined space work, and training requirements for confined space work participants. The standard states that it is intended to provide "best practices for eliminating, mitigating, or controlling hazards that either already exist in or around confined spaces or are created during entry into and/or working in or around confined spaces." [15] The standard's focus, however, is largely on planning for confined space work and safety considerations during the work itself and not on ensuring that the space is clear of material thereafter.

While NFPA 326 and 350 have extensive guidance on evaluating confined spaces prior to entry, ensuring the space is safe for human occupancy, they provide no guidance on ensuring that a confined space has been cleaned appropriately after work has been completed. The standards provide requirements and guidance for creating a permit to begin work in a confined space and have detailed instructions for what to monitor during confined space work, but they provide no guidance or requirements for closing a permit and what must be done before sealing a vessel. Specific guidance and requirements on how to close vessels safely is needed to help industry users understand the hazards of the final portion of confined space entry work and prevent serious incidents from occurring in the future.

The CSB recommends that NFPA update NFPA 350 *Guide for Safe Confined Space Entry and Work* to provide guidance on how to ensure that vessels that have undergone confined space entry are left clean and ready for startup after the entries are completed. The CSB also recommends that NFPA update NFPA 326 *Standard for the Safeguarding of Tanks and Containers for Entry, Cleaning, or Repair* to provide requirements to ensure that vessels that have undergone confined space entry are left clean and ready for startup after the entries are completed.

4.1.3.2 American Society of Safety Professionals

The American Society of Safety Professionals (ASSP) and the Approved American National Standard (ANSI) organization also have guidance for working in confined spaces titled *ANSI/ASSP Z117.1 Safety Requirements for Entering Confined Spaces*. [16] This document is intended to provide "minimum safety requirements to be followed while entering, exiting, and working in confined spaces". [16, p. 12]

ANSI/ASSP Z117.1 has similar requirements to NFPA 350 and provides guidance on multiple aspects of confined space work, such as hazard identification and evaluation prior to entering a confined space, atmosphere testing, hazardous energy isolation, emergency response, and training requirements. Like NFPA 350, however, the standard provides no guidance on how to ensure that a confined space is clean after work has been completed. . It also only provides guidance on hazard identification and mitigation prior to and during confined space work.

The CSB recommends that ASSP update *ANSI/ASSP Z117.1 Safety Requirements for Entering Confined Spaces* to provide guidance on how to ensure that vessels that have undergone confined space entry are left clean and ready for startup after the entries are completed.

4.1.3.1Institute of Chemical Engineers

The Institute of Chemical Engineers (IChemE), a UK-based organization for chemical, biochemical, and process engineers, has published guidance titled *Chemical and Process Plant Commissioning Handbook: A Practical Guide to Plant System and Equipment Installation and Commissioning* that addresses how to properly commission, or start up, vessels after initial installation and maintenance [17], including ensuring that vessels are clean prior to start-up. For vessels or piping larger than 30 inches in diameter, such as the reflux drum, the Handbook recommends that personnel physically enter the vessel to remove debris:

> "Manual cleaning and subsequent visual inspection are often the only methods which can be used in some columns and vessels. The commissioning mechanical or systems engineer should carry out a final cleanliness inspection post the cleaning prior to closure of the piece of equipment." [17]

The Handbook recommends that a check sheet be used with the "main and important sign-off being that of final closure prior to operation." The Handbook specifies that this final check should ensure that the vessel is "free of debris". It also stresses the importance of having appropriate personnel present for the final closure to minimize the potential of process upsets due to debris being left inside equipment. [17, p. 241] While the Handbook suggests that visual inspection can be made from the manway of vessels in some cases, it stresses that each piece of equipment is different and that the requirements for each individual situation must be considered. Although this guidance is intended for UK industry and focuses on facilities that are starting up for the first time or after a significant process change, the lessons could have been more broadly applied to vessel closures and could have prevented this incident.

4.1.3.2 American Petroleum Institute

The American Petroleum Institute (API) has published guidance on vessel closure related specifically to aboveground petroleum storage tanks. API has a standard titled *API Standard 2015 Requirements for Safe Entry and Cleaning of Petroleum Storage Tanks* that provides guidance on how to safely close out petroleum storage tanks after maintenance and cleaning activities.[18]. While API 2015 is focused specifically on atmospheric low-pressure petroleum storage tanks, the guidance provides useful guidance which could help prevent incidents involving other vessels if followed.

KEY LESSON

Companies should have robust systems in place to ensure that vessels are cleaned of all equipment, tools, and debris after confined space entries occur. Operations should have strict controls in place to ensure that any equipment that enters the vessel and is not necessary for the operation of the vessel also leaves the vessel.

API 2015 requires companies to develop and implement procedures for returning a tank back to service, including inspecting the tank to ensure that "all temporary equipment has been removed" and that "the tank is properly cleaned of debris, tools, etc.". API 2015 requires each company to designate a qualified person to "thoroughly inspect the tank prior to the reinstallation of tank opening (manway) covers" [18, p. 59]. The inspection must include a verification that all equipment, tools, materials, and debris have been removed from inside the tank. If Dow had required either a more thorough visual inspection using adequate tools to ensure full visibility of the interior, confined space entry as the final check, or a verification of all equipment, tools, materials, and debris, this incident could have been prevented.

4.1.4 Post Incident Changes

After the incident, the Dow internal investigation team made a recommendation to improve the vessel closure process within the Glycol II unit to address:

- Inventory of tools and equipment that have entered the equipment
- Vessel closure steps
- Roles and responsibilities for the vessel closure process
- Specific sign-off for final cleanliness
- Criteria for performing final closure inspections (potentially including confined space entry)

The investigation team also recommended that Dow "create a Global Process/Standard for enhanced Equipment Closure Management."

In June 2024, in order to close these recommendations from the company's internal investigation, Dow created a new vessel closure process that was more robust than the previous two-page document and included defined steps and clear responsibilities related to vessel closure. The new process included defined steps on managing vessel closure, the roles and responsibilities of vessel closure permit signatories, and steps to perform tool inventory after work is concluded. Dow also created a *Global Foreign Materials Exclusion Standard* that provided stringent requirements for vessels over 16 inches in diameter or with manhole openings larger than 16 inches. For vessels with "high consequence" chemicals, such as ethylene oxide, operators must either perform a confined space entry to conduct a final inspection to ensure the cleanliness of the vessel or, where a full final inspection was not possible, an enhanced worker, tool, and material reconciliation process was added to ensure that nothing was left behind.

4.2 Inerting System Control

As discussed in Section 3.3, after the rupture disc was punctured and ethylene oxide entered the pressure relief piping, the ethylene oxide ignited when it mixed with air. Ethylene oxide is flammable and explosive, and decomposes readily under certain conditions. It is also toxic, carcinogenic, and mutagenic. Due to the reactive nature of ethylene oxide, special precautions must be taken by facilities to ensure that it does not ignite or react violently. Multiple industry guidance documents, as well as Dow's own internal documents, recommend that steps be taken to mitigate the hazard of ethylene oxide, forming an explosive mixture with air. The Center for Chemical Process Safety (CCPS) guidance document *Guidelines for Safe Storage and Handling of Reactive Materials* states that extra precautions must be taken for equipment that contains ethylene oxide in addition to the usual precautions related to safely handling flammable vapors and liquids [19, p. 229]. One such safeguard recommended by the CCPS is to use an inert gas (such as nitrogen) to prevent the ignition of the ethylene oxide in any vapor space present in the equipment. The CCPS guidelines state:

> "Air can lead to ignition of ethylene oxide under milder conditions than for the pure vapor. Proper inerting of ethylene oxide will prevent flame propagation from an initiation site" [19, p. 232]

The CCPS goes on to state that ethylene oxide liquid discharged into the vapor space of properly inerted equipment or piping will not carry sufficient energy to ignite the vapor in the absence of oxygen. When the rupture disc partially opened in this incident, the ethylene oxide most likely would not have combusted if the pressure relief piping had an inert atmosphere, and there would have been no fire or subsequent explosion.

4.2.1 Dow Nitrogen Inerting

At Dow's LAO Plaquemine facility, nitrogen is generally used as the inerting gas to prevent the ignition or decomposition of ethylene oxide. The Glycol II unit at the facility has a nitrogen system used for purging, inerting, and pressure control utilizing nitrogen supplied to the site by an industrial gas supplier. At the facility, nitrogen is one of the primary safeguards to ensure any large vessel with large quantities of ethylene oxide that contained a vapor phase, such as in the final product storage drums, would not react or combust in the vapor space. The reflux drum vapor space is kept inerted through a nitrogen "blanket" which is controlled by a control system and pressure is maintained by continually pumping nitrogen into the reflux drum from a plant nitrogen header through the discharge of the product cooler PRV. Leading up to the incident, no nitrogen was continually supplied to the piping between the rupture disc and the product cooler PRV (shown in **Figure 17** as the piping with the dotted red line), however. Instead, nitrogen would be manually charged into this piping segment whenever the pressure relief piping was opened for maintenance or inspection, and no procedure required regular charging of nitrogen.

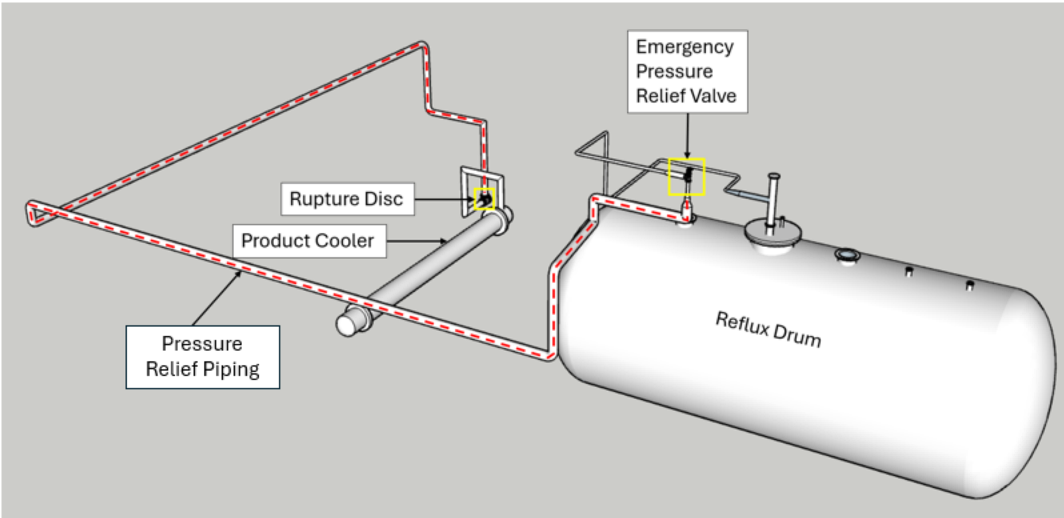


Figure 17. Pressure relief piping between the product cooler and the reflux drum. The dotted red line shows the portion of the pressure relief piping that was not kept inerted when the incident occurred (Credit: CSB)

As discussed later, the product cooler was replaced in 2011, partly to mitigate the risk involved with the pressure relief system relieving to the atmosphere. At no point was a continuous nitrogen flow considered for the pressure relief piping between the rupture disc and PRV.

The CSB concludes that Dow failed to ensure that an inert atmosphere was maintained in the pressure relief piping between the rupture disc and PRV protecting the product cooler. As a result, when ethylene oxide entered this piping it was able to mix with air, ignite, and propagate toward the reflux drum.

4.2.2 Nitrogen Inerting During the 2020 Maintenance

As discussed earlier in Section 2.1, the pressure and amount of nitrogen present in the rupture disc discharge pressure relief piping gradually decreased after being inerted and pressurized with nitrogen in 2020 after the rupture disc was replaced during a turnaround. Dow had a procedure which provided guidance on how to manage inerting this specific pressure relief line during maintenance on the rupture discs or pressure relief devices, such as the work carried out in 2020. This procedure required that operators, when performing work on a rupture disc in part:

- Sweep the pressure relief piping between the rupture disc and the PRV with 90 psig nitrogen for at least 10 minutes, and continue until less than 1% oxygen is detected in the vapor exiting the piping
- With the pressure relief piping blocked in at 90 psig, check for leaks; if any leaks are found, repair the leaks
- Reduce the pressure in the pressure relief piping to 5 psig before closing the system

The pressure reduction from 90 psig to 5 psig was needed to ensure that there was no back pressure on the rupture disc that might prevent it from opening at the intended burst pressure. The procedure did not specify a time period to hold at 90 psig to ensure all leaks were identified, but it did specify soaping flanges to check for leaks. The procedure listed potential consequences that could occur from deviation from the procedure, including worker exposure to ethylene oxide and improper commissioning of the pressure relief system. However, there was no warning in the procedure about the importance of maintaining the inert nitrogen atmosphere within the piping system. In fact, the importance of maintaining an inert atmosphere is not mentioned at all in the document.

For the 2020 maintenance activities, Dow could not provide documentation detailing whether the procedure for checking for leaks in the piping system and inerting the pressure relief piping was followed, but process data shows that the piping was left with only 2.4 psig instead of the required 5 psig of pressure at the end of the maintenance work and that the pressure slowly declined over the next two months, indicating that leaks were occurring. There is no evidence that an operator or management official checked the pressure in the system in the two-plus years between the rupture disc work in 2020 and the incident in 2023, or that any management system prompted them to do so. Even when the pressure transmitter was reading negative gauge pressure, indicating the intrusion of air into the system, no alarm was set off.

4.2.3 DOW PRESSURE RELIEF GUIDANCE FOR ETHYLENE OXIDE SERVICE

At the time of the incident, Dow had multiple standards that detailed pressure relief requirements in general, as well as specific to ethylene oxide service. However, these standards did not prevent the Glycol II unit from operating a pressure relief piping system that did not maintain an inert atmosphere.

At the time of the incident, a Dow company standard titled *Installation of Pressure Relief Devices* required that there must be a means of detecting pressure build-up between the rupture disc and the PRV for every pressure relief system that had a rupture disc and a PRV in combination. The Dow standard recommended that a pressure transmitter with an alarm that sounded in the unit control room be installed to detect a pressure increase to enable operators to know whether a rupture disc had burst and potentially needed replacing. The Dow standard recommended that this alarm be given a set point of 5 psig, which would be high enough to show when the process leaked past the rupture disc while avoiding nuisance alarms.

The Dow pressure relief standard did not discuss situations where inert gas may be required between the rupture disc and the PRV, however. Also, there were only requirements for high-pressure alarms. There were no low-pressure alarm requirements or requirements for monitoring the pressure transmitter periodically when the alarm was not in an alarm state. The recommended, but not required, alarm set point of 5 psig indicates that Dow did not anticipate scenarios where inerting gas might be present at 5 psig within the piping system, as required by the rupture disc replacement procedure.

At the time of the incident, Dow also had a global standard that was specific to pressure relief technology related to ethylene oxide, titled *Most Effective Technology for Ethylene Oxide Process Safety Valve Installations* (MET). This standard was intended to "define best practices for proper PRV operation" for ethylene oxide service. Like Dow's *Installation of Pressure Relief Devices* standard, the MET required that a rupture disc and PRV in combination should have a pressure alarm between the devices. The MET standard stated that "installation of the rupture disc without a pressure alarm between the rupture disc and the safety valve does not comply with the intent of this standard." The MET required that for a system with a rupture disc and PRV in combination, there must be nitrogen inerting on the outlet of the PRV. There were no requirements for inerting on the piping between the rupture disc and PRV, however.

KEY LESSON

Companies should ensure that information that is vital to the safe operation of a facility, such as the condition of an inert atmosphere, is collected and acted on to mitigate the risk of an ignition or reactive incident.

In alignment with Dow's pressure relief standards, the rupture disc discharge piping involved in the incident was equipped with a pressure transmitter that relayed the pressure reading within the pressure relief piping between the rupture disc and the PRV. The pressure transmitter had a high-pressure alarm set at 80 psig, but it was not equipped with an alarm to indicate a loss of pressure. Dow also did not require operations personnel to periodically check the pressure in the rupture disc discharge piping.

Finally, Dow did not install oxygen monitors or other similar devices on the rupture disc discharge piping that could detect oxygen in the pipe and alert operators to its presence. As a result, Dow had no system in place to ensure that nitrogen inerting remained within the pressure relief piping, either through a constant nitrogen purge or through monitoring the pressure between the rupture disc and the PRV. As a result, Dow personnel were unaware that in the two months after the maintenance on the rupture disc was performed, the inerting nitrogen in the pressure relief piping was lost, and the vapor space in the empty piping was slowly filling with air.

The CSB concludes that Dow did not have an effective system in place to alert operations about the presence of or lack of an inerting atmosphere in the pressure relief piping. As a result, operations were unaware that a segment of piping which could contain ethylene oxide was filled with air. Furthermore, Dow did not design a system that would continuously ensure that an inert atmosphere persisted in the piping.

The CSB recommends that Dow at all Dow ethylene oxide facilities, identify all process lines in ethylene oxide service that should be or are inerted and currently are not continuously monitored during normal operation. For all lines identified, determine if the line can be eliminated, if not, establish proper controls such as inerting and monitoring to ensure the process line is adequately inerted.

4.2.4 Process Hazards Analysis

As discussed, Dow had no adequate corporate or site policy or procedure related to ensuring that the piping between rupture discs and pressure relief devices in ethylene oxide service maintained an inert atmosphere. Also, between 2011, when the new product cooler was installed, and the incident in 2023, no process hazard analysis (PHA) or risk assessment associated with the product cooler pressure relief system identified the need for an inerting atmosphere between the rupture disc and PRV.

Dow did perform risk assessments to ensure that sufficient nitrogen was in place to prevent an explosion in the vapor space of some ethylene oxide-containing equipment. A 2023 PHA (**Figure 18**) conducted prior to the incident asked the PHA team to ensure that tanks and vessels are properly inerted. Although Dow had multiple robust procedures to maintain nitrogen inerting blankets on many critical pieces of equipment, piping systems were not considered in the PHA.

[redacted]		Are all tanks and vessels properly inerted or are they maintaining a non-ignitable atmosphere according to [redacted] during normal, startup, and shutdown operations?	X			EO storage tanks and railcars have N2 pad in vapor space

Figure 18. Excerpt from Glycol II 2023 PHA (Source: Dow)

Also, when the PHA team was prompted to analyze "vent streams", which could include pressure relief piping, or tank head spaces to determine whether they could have flammable atmospheres, the PHA team documented hazards considering only nitrogen purges on tanks and did not document any analysis of pressure relief piping (**Figure 19**).

Do any of the vent streams or tank head spaces in the facility operate in or near the flammable range?		X		All tanks are inerted with N2 and LOPA scenarios have identified risk areas where a flammable vapor space would occur.

Figure 19. Excerpt from Glycol II 2023 PHA (Source: Dow)

The CSB concludes that Dow's process hazards analysis overlooked the risk and potential consequences of pressure relief piping systems losing their inert atmosphere.

4.2.5 Industry Guidance

There are multiple guidance documents that provide general guidance on pressure relief requirements and specific guidance on ethylene oxide considerations related to pressure relief scenarios, as well as inerting systems for flammable and reactive chemicals.

Several guidance documents recommend or require that an indicator, such as a pressure transmitter, is needed between a rupture disc and a PRV to indicate a ruptured disc when the two devices are used in combination. The ASME Section VIII Boiler Code requires that the space between the rupture disc installed between a PRV and the vessel it is protecting be equipped with something that allows the detection of a ruptured rupture disc. [20, pp. UG-127] Moreover, API 520 Part II *Sizing, Selection, and Installation of Pressure-relieving Devices* states that "when a rupture disk device is used between the [PRV] and the protected vessel, the space between the rupture disk and the [PRV] shall have a free vent, pressure gauge, trycock, or other suitable tell tale indicator." [21, p. 35] The ACC ethylene oxide guidance manual also recommends that pressure relief systems with a rupture disc in combination with a PRV should have an indicator, such as a pressure transmitter, to alert the facility when the rupture disc has ruptured.

Despite the requirement for a pressure transmitter between the rupture disc and PRV, there is no requirement (or even a recommendation) in industry guidance for a low-level alarm in addition to the high-pressure alarm requirement. Dow's pressure transmitter provided high pressure alerts consistent with the industry guidance documents, but there was no mechanism to detect the low-pressure condition that led to the 2023 incident.

NFPA 69 *Standard on Explosion Prevention Systems* is an industry standard that applies "to the design, installation, operation, maintenance, and testing of systems for the prevention of explosions." [22] NFPA 69 requires that facilities evaluate multiple factors when designing an inert purge system including considering "reduced effectiveness of purge gas due to equipment leakage." NFPA 69 states that inerting purge gas "shall be obtained from a source that is capable of continuously supplying the required amount of purge gas". The standard further requires that instrumentation, such as a pressure transmitter, be installed in as many places as necessary to ensure that the atmosphere remains inert. It also requires that the oxygen concentration shall be checked on "a regularly scheduled basis." The pressure relief piping between the PRV and rupture disc in the LAO Glycol II unit did not have a continuous supply of nitrogen, did not have instrumentation or procedures in place that were meant to alert operators of a loss of inerting gas, and did not have effective means of ensuring that nitrogen did not leak out of inert equipment as required by NFPA 69.

The CSB concludes that if Dow had implemented the requirements of NFPA 69 for the pressure relief piping involved in the incident, the inert atmosphere would not have been compromised, and the ethylene oxide would not have ignited, preventing the incident.

4.2.6 Post Incident Changes

After the 2023 incident, the Dow investigation team recommended that the product cooler system be redesigned to remove the piping system between the rupture disc and the PRV completely. The Dow investigation team also recommended that the Glycol II unit perform an analysis to identify other locations in ethylene oxide service that may also require inerting and should have periodic pressure and oxygen checks.

Ultimately, Dow eliminated the rupture disc and PRV system involved in the incident entirely. The product cooler was altered to eliminate the need for pressure relief, and it was raised to eliminate a ground fire overpressure threat. Additionally, a minimum flow line to the reflux drum was added to remove the risk of a thermal expansion overpressure event. This minimum flow line eliminates the possibility of liquid within the product cooler from becoming blocked in potentially expanding and increasing pressure. Because the blocked-in thermal expansion hazard has been mitigated, no pressure relief system is needed for the product cooler.

Dow also performed an analysis of the Glycol II unit to find any process lines that may require inerting. As a result of this effort, the Glycol II unit identified two other locations that required inerting gases and did not have them. Like the product cooler pressure relief piping system, both of these locations had requirements to leave 5 psig of inert nitrogen in piping after maintenance. One of the locations was eliminated completely, and blinds were installed on the other to ensure that ethylene oxide would not inadvertently enter the location.

As discussed in Section 1.1, Dow operates multiple ethylene oxide facilities, and the risk of a piping system being inadequately inerted is possible at all of them.

The CSB recommends Dow at all Dow ethylene oxide facilities identify all process lines in ethylene oxide service that should be or are inerted and currently are not continuously monitored during normal operation. For all lines identified, determine if the line can be eliminated, if not, establish proper controls such as inerting and monitoring to ensure the process line is adequately inerted.

4.3 PRESSURE RELIEF SYSTEM DESIGN

After the ethylene oxide ignited within the pressure relief piping, the flame front built pressure as it propagated toward the PRV and the reflux drum. When this flame front reached the reflux drum, it heated and ignited the large quantity of ethylene oxide present in the drum, which decomposed and significantly increased the severity of the incident when the reflux drum exploded (**Figure 20**). This was possible because the pressure relief piping from the product cooler vented to the reflux drum.

Figure 20. Explosion when the reflux drum catastrophically failed (Source: Dow)

As discussed in Section 1.4, the product cooler was replaced in 2011. The pressure relief system between the product cooler and the reflux drum was put in place when the new product cooler system was installed. The product cooler was replaced to allow more flow and be more efficient. The project planned to remove the product cooler's existing pressure relief system, which discharged to the atmosphere and posed a safety risk of a vapor cloud explosion. The new product cooler was planned to be elevated high enough to eliminate two of the identified pressure relief scenarios, a pump generating excessive pressure and water hammer pressure surges. However, the risk of liquid thermal expansion still existed if the product cooler was blocked in and pressure relief was still required. To avoid this risk, the pressure relief had to be directed somewhere to mitigate the risk of a vapor cloud explosion. No documentation was provided of any analysis related to designing the system so that the pressure relief needed was eliminated completely.

The plan to upgrade the product cooler was originally designed in 2007 but was not funded until 2009 when two water hammer incidents in the Glycol II unit made it more pressing to change the product cooler and remove the risk of a PRV lift to the atmosphere caused by a water hammer event. The new product cooler with the altered pressure relief system was authorized and began construction in June 2010 and was completed in 2011. The 2009 design had the new pressure relief piping from the product cooler vent into downstream ethylene oxide final product storage tanks. However, there was concern that a water leak in the product cooler could flow through the pressure relief piping to the final product storage tank and compromise the product or potentially cause the reactive ethylene oxide to have a runaway reaction. As a result, Dow looked into routing the pressure relief to other equipment, including the reflux drum. In 2011, Dow determined that venting the pressure relief to the final product storage tanks represented risks that were commiserate with the original problem of a vapor cloud explosion and decided to vent the pressure relief piping to the reflux drum. The possibility that ethylene oxide could ignite within the pressure relief piping and cause an overpressure of the reflux drum or process piping was not documented at any point in the design process.

KEY LESSON

When designing original pressure relief systems or making changes to existing pressure relief systems, companies should consider the impact of the new venting scenario and understand all hazards associated with a potential overpressure release.

As discussed in Section 4.2.6, after the incident, the pressure relief piping from the product cooler into the reflux drum was eliminated completely. Dow raised the product cooler above grade level sufficiently to eliminate a pool fire overpressure scenario and installed a minimum flow line back to the reflux drum to eliminate the thermal expansion scenario, eliminating the need for pressure relief specific to the reflux drum. If this analysis had been conducted prior to the incident, the incident would have been avoided.

The CSB concludes that Dow's decision to vent the product cooler's pressure relief to the reflux drum contributed to the severity by the incident by causing a large volume of ethylene oxide to combust and the reflux drum to fail. Dow did not adequately assess the risk of venting to a vessel full of reactive ethylene oxide and did not analyze safeguards needed to mitigate ignition within the pressure relief piping.

5 Conclusions

5.1 Findings

Technical Analysis

1. The product cooler rupture disc opened in a non-intended manner below its burst pressure and allowed ethylene oxide to reach the pressure relief piping due to impact from metal debris.
2. The pressure relief piping between the product cooler rupture disc and PRV did not have adequate inerting nitrogen to prevent the ignition of ethylene oxide within the piping system. As a result, when the rupture disc ruptured, ethylene oxide was able to combust and propagate through the piping to the reflux drum.
3. The ethylene oxide ignited within the pressure relief piping and propagated toward the PRV, which lifted, and the hot ethylene oxide and combustion products then initiated a reaction in the vapor phase of the reflux drum, causing the drum to overpressure catastrophically.

Vessel Closure Practices

1. Work lights were left behind in the reflux drum during the May 2023 turnaround and degraded in the process allowing metal debris to flow downstream.
2. Dow's lack of an effective system to ensure process vessels were clean and empty after maintenance work was completed during the May 2023 turnaround contributed to work lights being left behind in the reflux drum. This allowed the work lights to degrade and cause the rupture disc to open, initiating the incident.
3. Dow's reliance on a visual inspection without the aid of inspection tools or a confined space entry to ensure that nothing was left in the equipment after maintenance and inspection work allowed the work lights left in the reflux drum to be missed and remain in the reflux drum. The work lights then degraded and caused the rupture disc to fail, initiating the incident.

Inerting System Control

1. Dow failed to ensure that an inert atmosphere was maintained in the pressure relief piping between the rupture disc and PRV protecting the product cooler. As a result, when ethylene oxide entered this piping it was able to mix with air, ignite, and propagate toward the reflux drum.
2. Dow did not have an effective system in place to alert operations about the presence of or lack of an inerting atmosphere in the pressure relief piping. As a result, operations were unaware that a segment of piping which could contain ethylene oxide was filled with air. Furthermore, Dow did not design a system that would continuously ensure that an inert atmosphere persisted in the piping.

3. If Dow had implemented the requirements of NFPA 69 for the pressure relief piping involved in the incident, the inert atmosphere would not have been compromised, and the ethylene oxide would not have ignited, preventing the incident.

4. Dow's process hazards analysis overlooked the risk and potential consequences of pressure relief piping systems losing their inert atmosphere.

Pressure Relief System Design

1. Dow's decision to vent the product cooler's pressure relief to the reflux drum contributed to the severity by the incident by causing a large volume of ethylene oxide to combust and the reflux drum to fail. Dow did not adequately assess the risk of venting to a vessel full of reactive ethylene oxide and did not analyze safeguards needed to mitigate ignition within the pressure relief piping.

5.2 Cause

The CSB determined that the cause of the incident was the puncture of a rupture disc by metal debris that allowed the introduction of ethylene oxide into piping that contained air. The ethylene oxide ignited, and the ethylene oxide and combustion products propagated through pressure relief piping to a reflux drum that was filled with ethylene oxide. The ethylene oxide in the vapor space of the reflux drum heated and decomposed, causing the reflux drum to fail catastrophically due to increased pressure from the decomposition reaction.

Contributing to the incident was Dow's inadequate vessel closure procedures and practices, which allowed the vessel to be restarted without ensuring that it was adequately cleaned and the work lights removed. Debris from the work lights then moved downstream to the product cooler and penetrated the product cooler's rupture disc, which allowed ethylene oxide to enter the product cooler's emergency pressure relief piping's atmosphere. Also contributing to the incident was Dow's failure to maintain an inert atmosphere in the pressure relief piping and the lack of requirements to ensure that the piping segment remained inert during operation.

Contributing to the severity of the incident was the design of Dow's product cooler's emergency pressure-relief system, which discharged its pressure-relief effluent back into the reflux drum. Instead, had Dow's product cooler been designed so that pressure-relief was not necessary, the consequences of the incident would have been greatly reduced.

6 RECOMMENDATIONS

To prevent future chemical incidents, and in the interest of driving chemical safety excellence to protect communities, workers, and the environment, the CSB makes the following safety recommendations:

6.1 The Dow Chemical Company

2023-03-I-LA-R1

At all Dow ethylene oxide facilities, identify all process lines in ethylene oxide service that should be or are inerted and currently are not continuously monitored during normal operation. For all lines identified, determine if the line can be eliminated, if not, establish proper controls such as inerting and monitoring to ensure the process line is adequately inerted.

6.2 National Fire Protection Association

2023-03-I-LA-R2

Update NFPA 350 *Guide for Safe Confined Space Entry and Work* to provide guidance on how to ensure that vessels that have undergone confined space entry are left clean and ready for startup after the entries are completed.

2023-03-I-LA-R3

Update NFPA 326 *Standard for the Safeguarding of Tanks and Containers for Entry, Cleaning, or Repair* to provide requirements to ensure that vessels that have undergone confined space entry are left clean and ready for startup after the entries are completed.

6.3 American Society of Safety Professionals

2023-03-I-LA-R4

Update *ANSI/ASSP Z117.1 Safety Requirements for Entering Confined Spaces* to provide guidance on how to ensure that vessels that have undergone confined space entry and are left clean and ready for startup.

7 KEY LESSONS FOR THE INDUSTRY

To prevent future chemical incidents and in the interest of driving chemical safety excellence to protect communities, workers, and the environment, the CSB urges companies to review these key lessons:

1. Companies should have robust systems in place to ensure that vessels are cleaned of all equipment, tools, and debris after confined space entries occur. Operations should have strict controls in place to ensure that any equipment that enters the vessel and is not necessary for the operation of the vessel also leaves the vessel.

2. Companies should ensure that information that is vital to the safe operation of the facility, such as the condition of an inert atmosphere, is collected and acted on to mitigate the risk of an ignition or reactive incident. When an inert environment is required to prevent ignition, monitors should be in place to show when that safeguard is lost.

3. When designing original pressure relief systems or making changes to existing pressure relief systems, companies should consider the impact of the new venting scenario and understand all hazards associated with a potential overpressure release.

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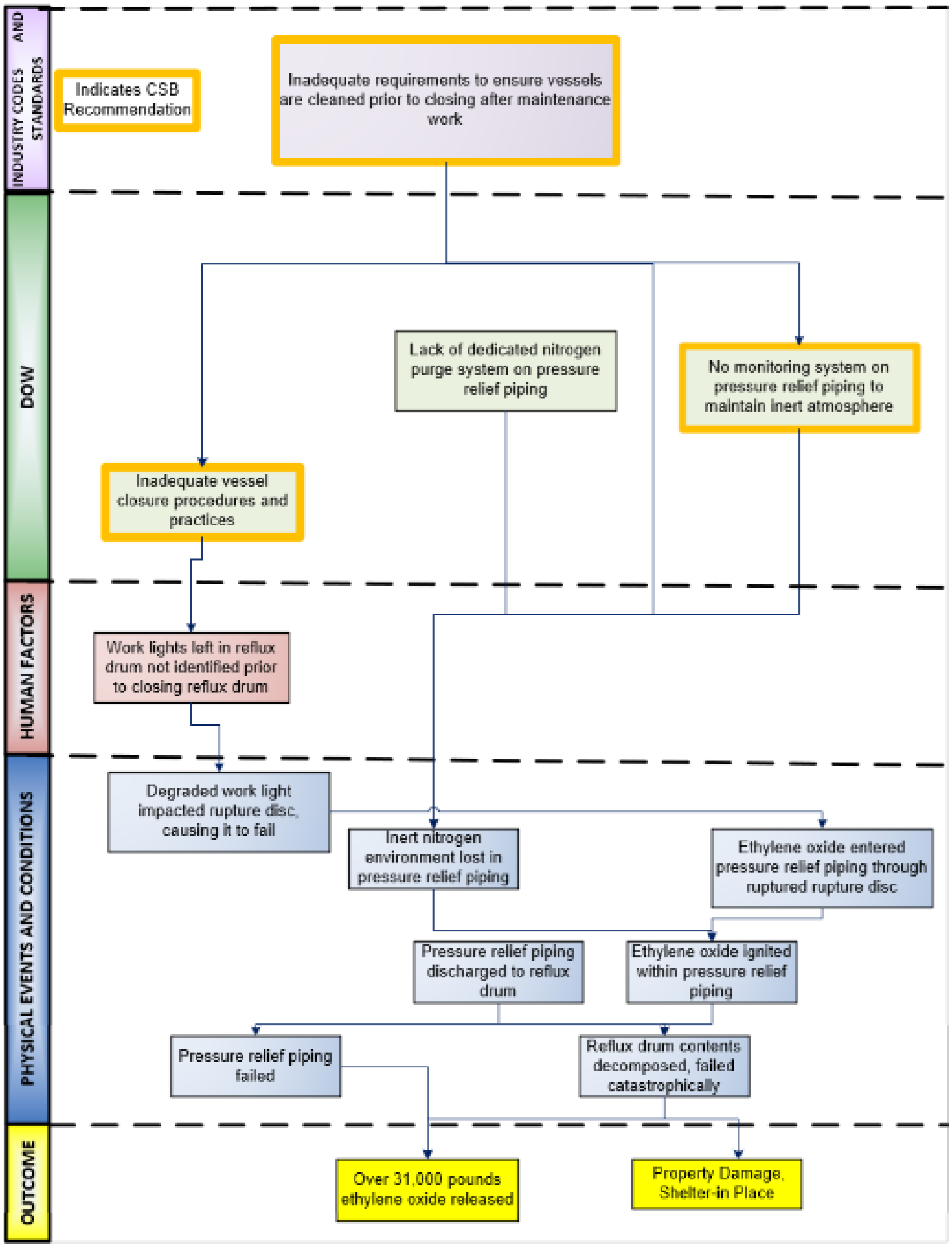
APPENDIX A- SIMPLIFIED CAUSAL ANALYSIS (ACCIMAP)



APPENDIX B- DESCRIPTION OF SURROUNDING AREA

Figure 21 shows the census blocks immediately surrounding the Dow Plaquemine facility. The census information for the blocks is presented in **Table 2** [23].

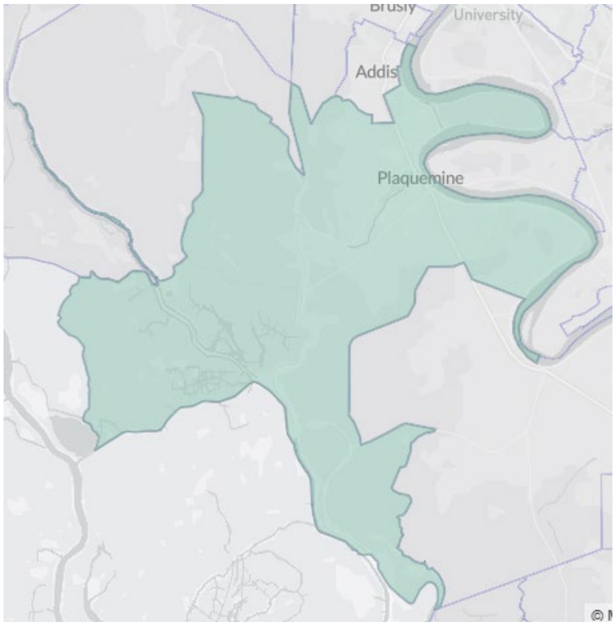


Figure 21. Census block within one-mile distance from Dow Plaquemine facility [23]. (Credit: Census Reporter)

Table 2. Tabulation of demographic data for the populations within the census blocks shown in **Figure 21**.

<table>
<tr><th>Tract Number</th><th>Population</th><th>Median Age</th><th colspan="2">Race and Ethnicity</th><th>Per Capita Income</th><th>% Persons Below Poverty Line</th><th>Number of Housing Units</th><th colspan="2">Types of Structures</th></tr>
<tr><td rowspan="8">1</td><td rowspan="8">15,046</td><td rowspan="8">42</td><td>50.0%</td><td>White</td><td rowspan="8">$31,846</td><td rowspan="8">10.7%</td><td rowspan="8">7,419</td><td>79%</td><td>Single Unit</td></tr>
<tr><td>39.0%</td><td>Black</td><td>4%</td><td>Multi-Unit</td></tr>
<tr><td></td><td>Native</td><td>17%</td><td>Mobile Home</td></tr>
<tr><td></td><td>Asian</td><td></td><td>Boat, RV, van, etc.</td></tr>
<tr><td></td><td>Islander</td><td colspan="2" rowspan="4"></td></tr>
<tr><td>1.0%</td><td>Other</td></tr>
<tr><td>5.0%</td><td>Two+</td></tr>
<tr><td>4.0%</td><td>Hispanic</td></tr>
</table>