U.S. Chemical Safety and Hazard Investigation Board

Furnace Explosion and Fire at Shell Polymers

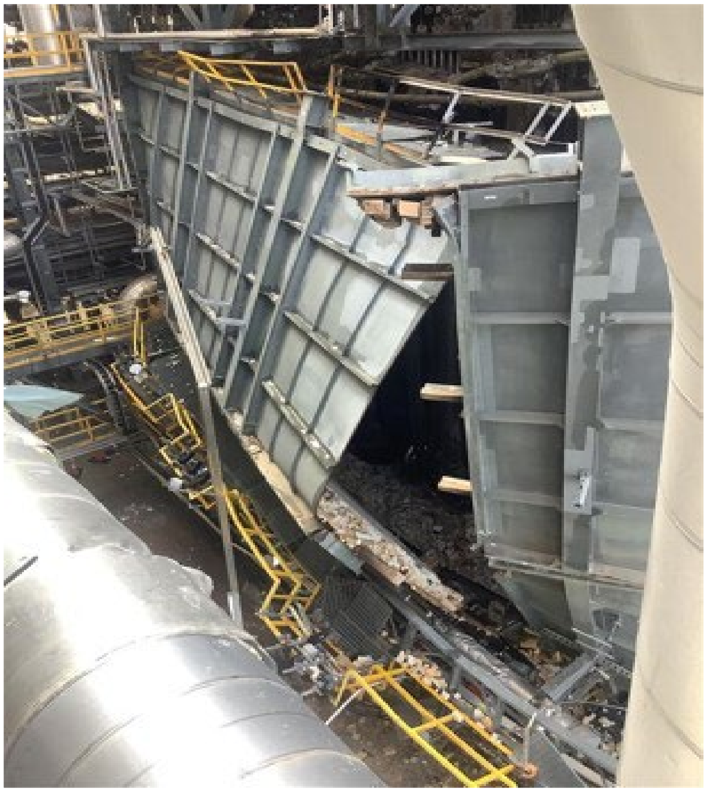
Monaca, Pennsylvania | *Incident Date: June 4, 2025* | **No. 2025-05-I-PA**

Investigation Report

September 2026

SAFETY ISSUES:

- **Reliance on Administrative Controls**
- **Human Machine Interface**



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ABBREVIATIONS

°F	degrees Fahrenheit
ANSI	American National Standards Institute
BPCS	Basic Process Control System
CAMEO	Computer-Aided Management of Emergency Operations
CCPS	Center for Chemical Process Safety
CSB	U.S. Chemical Safety and Hazard Investigation Board
EPA	U.S. Environmental Protection Agency
ECU	Ethane Cracking Unit
ESD	Emergency Shutdown
HMI	Human-Machine Interface
HSSB	Hot Steam Standby
ID	Induced Draft
IEC	International Electrotechnical Commission
ISA	International Society of Automation
MOV	Motor-Operated Valve
NAICS	North American Industry Classification System
NFPA	National Fire Protection Association
NIOSH	National Institute for Occupational Safety and Health
OSHA	Occupational Safety and Health Administration
PACO	Process, Automation, Control, and Optimization
PHA	Process Hazard Analysis
PID	Proportional-Integral-Derivative

PPE	Personal Protective Equipment
psig	pounds per square inch (gauge)
PSM	Process Safety Management
RMP	Risk Management Program
RPM	Revolutions per Minute
SDS	Safety Data Sheet
SIF	Safety Instrument Function
SIL	Safety Integrity Level
SIS	Safety Instrumented System
TR	Technical Report
TRI	The Refractories Institute

EXECUTIVE SUMMARY

On June 4, 2025, at 2:21 p.m., flammable cracked gas backflowed into the firebox of an ethane cracking furnace (identified as Furnace 5) at the Shell Polymers Monaca ("Shell") facility in Monaca, Pennsylvania, and then ignited and exploded. Furnace 5 was severely damaged by the explosion, and an ensuing fire led to the evacuation of 15 employees who were in the area. Shell estimated that this incident resulted in $95 million in property damage.

At the Monaca facility, Shell converts ethane to ethylene via a high-temperature reaction in its ethane cracking unit, which has seven furnaces, called Furnace 1 through Furnace 7. A byproduct of this reaction is a solid carbon residue, called coke, which is deposited into a large vertical pipe, called a coke trap, to prevent it from moving through the rest of the process. Before the incident, Shell determined that the coke traps of all seven of its furnaces needed to be cleaned out. None of the coke traps had ever been cleaned since the facility started up in November 2022. To clean the Furnace 5 coke trap, Shell isolated the furnace by closing two motor-operated valves (MOVs) in series between the furnace and a quench tower.

On the day of the incident, Shell was returning Furnace 5 to operation after cleaning its coke trap. During the return to operation, a process control engineer (also called a PACO engineer), who had never previously performed the task involved in this procedure, inadvertently opened a valve during the start-up sequence, leading to an unintended flow path of flammable cracked gas between the downstream quench tower and Furnace 5. Four of the other seven furnaces were actively producing cracked gas, and the flammable cracked gas backflowed from the quench tower to the furnace. Roughly just 6 minutes after the PACO engineer sent the inadvertent open command to the valve, cracked gas entered the firebox, contacted the lit pilots, and ignited.

The explosion ruptured a firebox wall in Furnace 5. Shell estimated that 5,100 pounds of ethylene and combustion products were released by this incident. Furnace 5 was repaired and returned to service seven months after the explosion.

SAFETY ISSUES

Although many factors contributed to the incident, this report addresses the two primary safety issues:

- **Reliance on Administrative Controls.** Shell relied on 11 controls that the facility had in place that it believed should have prevented the explosion but failed to. However, each of these controls was a purely administrative control that relied on management's and workers' awareness of what Shell's policies required and their compliance with them. In its process hazard analyses (PHAs), Shell identified the backflow of cracked gas as a potentially fatal explosion hazard when an isolation valve was open during the coke removal process. However, instead of implementing engineered controls to prevent backflow while the furnace was in the double-isolated state, Shell chose to rely solely on administrative controls. Additionally, although the furnace technology licensor, Selas Linde North America, provided engineered controls to prevent backflow into the firebox using a local field control panel, Shell did not set up the control panel so that the panel could be used when removing the double isolation of the valves from the furnace. (Section 3.1)

- **Human-Machine Interface.** Shell's human-machine interface (HMI) for operating furnace MOVs combined three nearly identical valves on a single logic screen. Although the valves were identified by unique tags and were positioned separately, they differed only by the last digit of the tag name, and the logic screen was not sufficiently intuitive or clear to facilitate valve identification. The furnace MOV interface in the safety system lacked clear labeling, adequate separation of complex logic, and safeguards such as confirmation steps, thereby increasing the likelihood of human error. Industry standards such as ANSI/ISA 101.01-2015: *Human-machine interfaces for Process Automation Systems* call for structured displays, error-avoidance methods, and task analyses. Without implementing available interface standards guidance, the PACO engineer who had been assigned to bring the furnace back into operation unintentionally created a hazardous flow path that allowed flammable cracked gas to enter a furnace with lit pilots. (Section 3.2)

CAUSE

The CSB determined that the cause of the incident was the inadvertent simultaneous opening of both motor-operated valves that were being used to isolate the furnace. Opening both valves created a path for cracked gas to backflow and accumulate in the furnace's firebox, where an existing flame ignited the flammable vapors, resulting in the explosion. Contributing to the incident was assigning a PACO engineer with limited process knowledge to manipulate the valves, as well as Shell's use of ineffective administrative controls to prevent the backflow hazard and subsequent explosion. Also contributing to the incident was the safety instrumented system logic human-machine interface Shell used at the time of the incident to open the motor-operated valves, which combined all three valves on a single diagram without clear labels to distinguish them.

RECOMMENDATIONS

To Shell Polymers Monaca[a]

2025-05-I-PA-R1

Review the Shell Polymers Monaca Ethane Cracking Unit process hazard analysis to identify process deviations that are addressed solely with administrative controls. Implement an inherently safer design or an engineered control for any scenario identified that could result in a fatality, serious injury, or substantial property damage.

2025-05-I-PA-R2

Based on licensor input and good industry practices, such as ANSI/ISA-61511-2-2018 / IEC 61511-2:2016*, Functional Safety – Safety Instrumented Systems for the Process Industry Sector – Part 2: Guidelines for the application of IEC 61511-1:2016* and *Part 3: Guidance for the Determination of the Required Safety Integrity Levels*, implement and maintain an engineered control to prevent backflow of cracked gas into a furnace during all modes of furnace operation.

[a] As discussed in **Section 3.1.4** herein, after the incident, Shell implemented new controls that enable operations staff to open and close the furnace-side, decoking, and tower-side MOVs on Furnace 5 from a local field control panel, eliminating the need for a PACO engineer to manipulate any of the furnace MOV valves. Shell also implemented new SIS logic that keeps the Furnace 5 tower-side MOV closed if a field operator mistakenly opens the furnace-side MOV. Additionally, Shell issued -- and provided training on -- a new operating procedure that provides written step-by-step instructions and information for opening or closing either the furnace-side or tower-side MOV. Because of Shell's corrective actions, the CSB is not making any recommendations to Shell regarding these issues. However, the CSB urges Shell to ensure that the new controls are fully implemented and consistently adhered to for all the furnaces at the facility. Further, although the CSB is not making a recommendation to Shell regarding maintenance of the furnace coke traps, the CSB urges Shell to ensure that the furnace coke traps are cleaned on a periodic basis and in accordance with guidance provided by Linde.

1 BACKGROUND

1.1 SHELL

Shell plc is a global group of energy and petrochemical companies, with operations in more than 70 countries [1, p. 9]. In 2022, Shell Chemical Appalachia, LLC, a subsidiary of Shell plc, completed construction of a 386-acre petrochemical complex in Monaca, Pennsylvania [2], roughly 30 miles northwest of Pittsburgh. This large-scale petrochemical facility, called Shell Polymers Monaca, produces plastics by converting ethane into ethylene and is known as an "ethane cracker" or "cracker plant" [2, 3]. Subsidiaries of Shell plc also operate ethane crackers in Deer Park, Texas; Norco, Louisiana; Germany; and the Netherlands, with a total ethylene production capacity of 11.4 billion pounds annually [1, p. 64].

Shell Polymers Monaca ("Shell") includes an ethane cracking unit (**Section 1.2**), three polyethylene plastic production units, a cogeneration power plant, a water treatment facility, and extensive storage with railcar and truck loading capabilities (**Figure 1**) [4]. The facility began operations in November 2022, using regionally sourced ethane, and can produce 3.3 billion pounds of polyethylene pellets annually [1, pp. 63-64, 5, 6]. The incident on June 4, 2025, occurred in the ethane cracking unit, as indicated by the yellow star in **Figure 1** [7]. There were 351 Shell employees, 529 contractors, and 2 visitors at Shell on the day of the incident.

Figure 1. Shell Polymers Monaca in Monaca, Pennsylvania, approximately 30 miles northwest of Pittsburgh. (Credit: Shell [8], annotated by CSB)

1.2 ETHANE CRACKING

In the United States, ethane is consumed almost exclusively in the petrochemical industry as feedstock for steam crackers to produce ethylene [9]. There are approximately 35 ethane cracking facilities in the United States.[a] These facilities are concentrated in the Gulf Coast region of Texas and Louisiana, with additional production capacity in the Ohio River Valley region and the upper Midwest along the Mississippi River [10].

In March 2025, the U.S. Energy Information Administration reported that domestic ethane consumption rose by eight percent in 2024 to a record 2.3 million barrels per day [9]. The rise in consumption was driven by higher cracker operating rates in 2024 compared with 2023, as no new crackers became operational in the United States in 2024 [9]. Ethane consumption on the U.S. Gulf Coast rose five percent to 2.1 million barrels per day in 2024. On the East Coast, consumption nearly tripled to 103,000 barrels per day in 2024 as Shell Polymers Monaca continued to ramp up its production after starting up in November 2022 [9].

At Shell, ethane is thermally cracked into ethylene, hydrogen, and other byproducts in a cracking furnace at 1,545 degrees Fahrenheit (°F) in the presence of steam [11]. The general ethane cracking chemical reaction is shown in **Figure 2**.

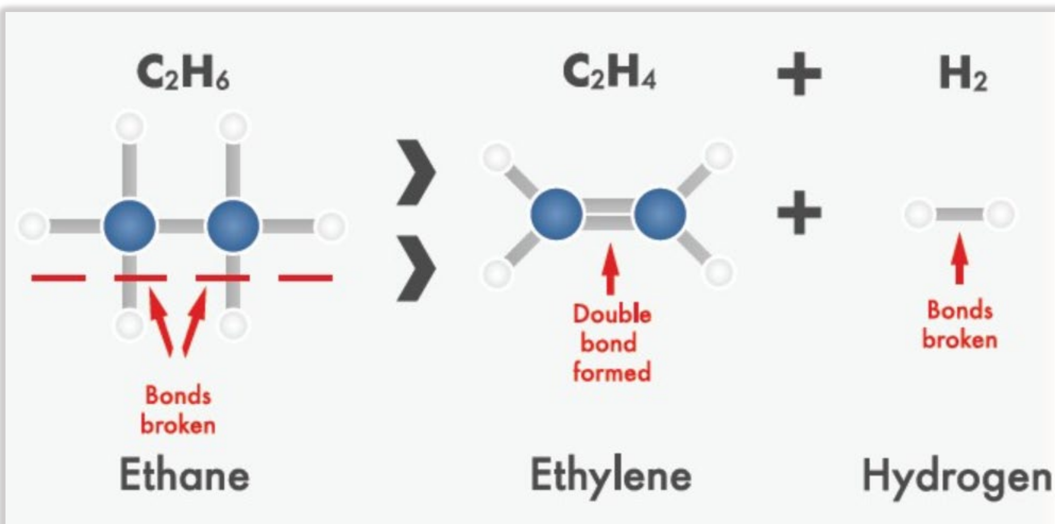

Figure 2. Simplified ethane cracking reaction. (Credit: Shell [12])

Figure 3 shows a simplified process flow diagram of an ethane cracking furnace at Shell. Shell licensed the furnace technology from Selas Linde North America, a division of Linde Engineering Americas, part of Linde plc ("Linde").[b] The cracking furnace functions as a chemical reactor [13, p. 16]. Steam cracking furnaces can face combustion safety challenges, particularly during start-up and transitions between operating modes (**Section 1.3**) [14, p. 46].

[a] *See* FracTracker Petrochemical Data Portal [60].

[b] Linde is a company name used by Linde plc and its affiliates. The words Linde and PYROCRACK® are trademarks or registered trademarks of Linde plc or its affiliates [54].

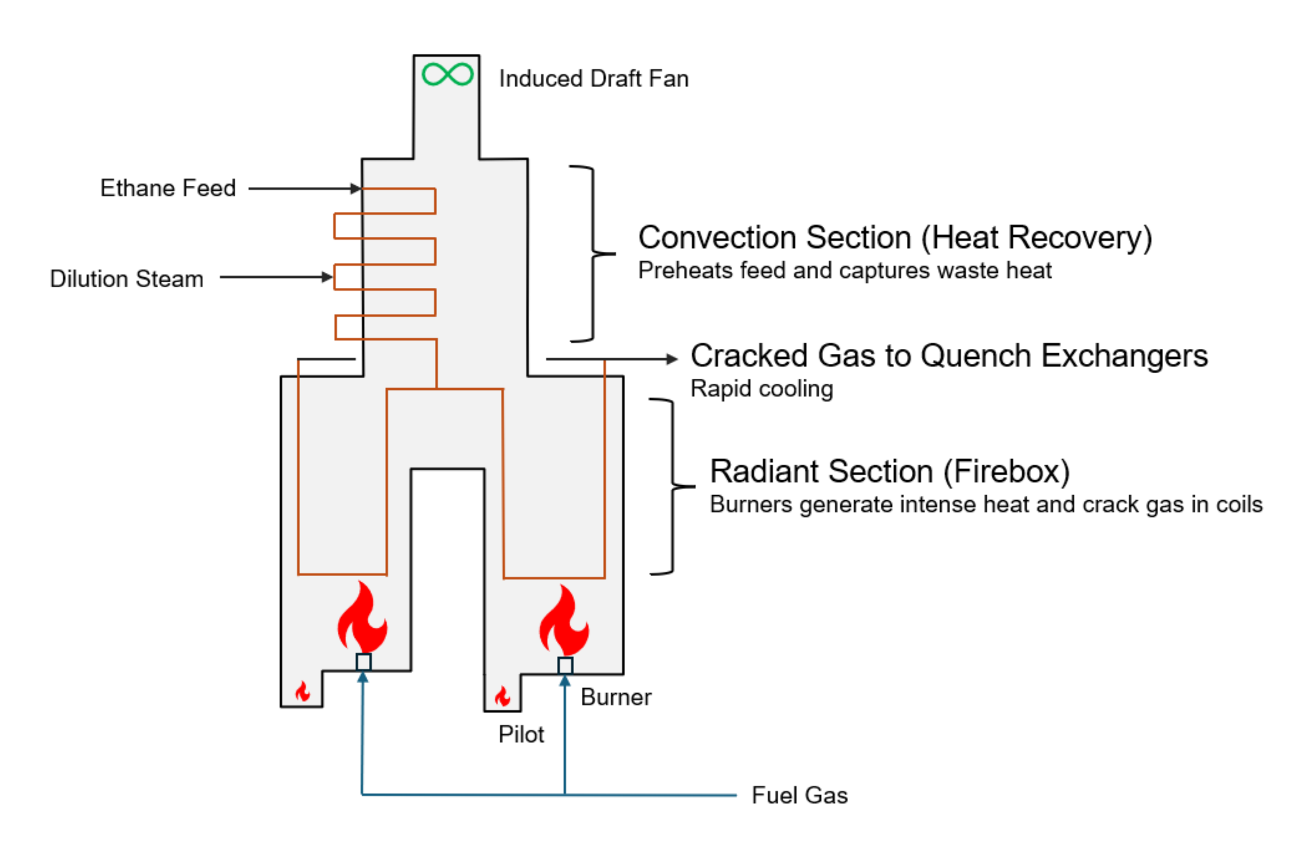

Figure 3. Simplified process flow diagram of an ethane cracking furnace at Shell. (Credit: CSB)

The ethane feed enters the furnace through tubes at the top (convection section), where it is preheated by the hot gases removed from the furnace by an induced draft (ID) fan [15, p. 482]. The ethane is then mixed with steam, which increases ethylene production and minimizes the formation of byproducts, such as coke [16]. The ethane and steam mixture is then further heated in the furnace convection section.

As shown in **Figure 3**, the furnace has two radiant sections connected to a common convection section [15, p. 488]. The preheated feed mixture inside the tubes enters the lower section of the furnace (radiant section), where burners generate heat, raising the temperature of the mixture to the desired 1,545 °F, which causes the hydrocarbon molecules to "crack" [15]. The mixture flows through a network of long metal tubes, called coils, suspended inside the lower section, where the cracking reaction occurs [15, p. 470]. Hydrogen-rich "tail gas" containing methane is recovered from the ethylene manufacturing unit and combined with natural gas to fuel the furnace burners [13, p. 18].

Immediately after leaving the coils, the hot gas mixture is rapidly cooled in a series of three heat exchangers to stop the cracking reactions as quickly as possible and prevent excessive formation of undesired byproducts (**Figure 4**) [16]. There are three quench heat exchangers: the primary quench exchanger, the secondary quench exchanger, and the tertiary quench exchanger [15, p. 494].

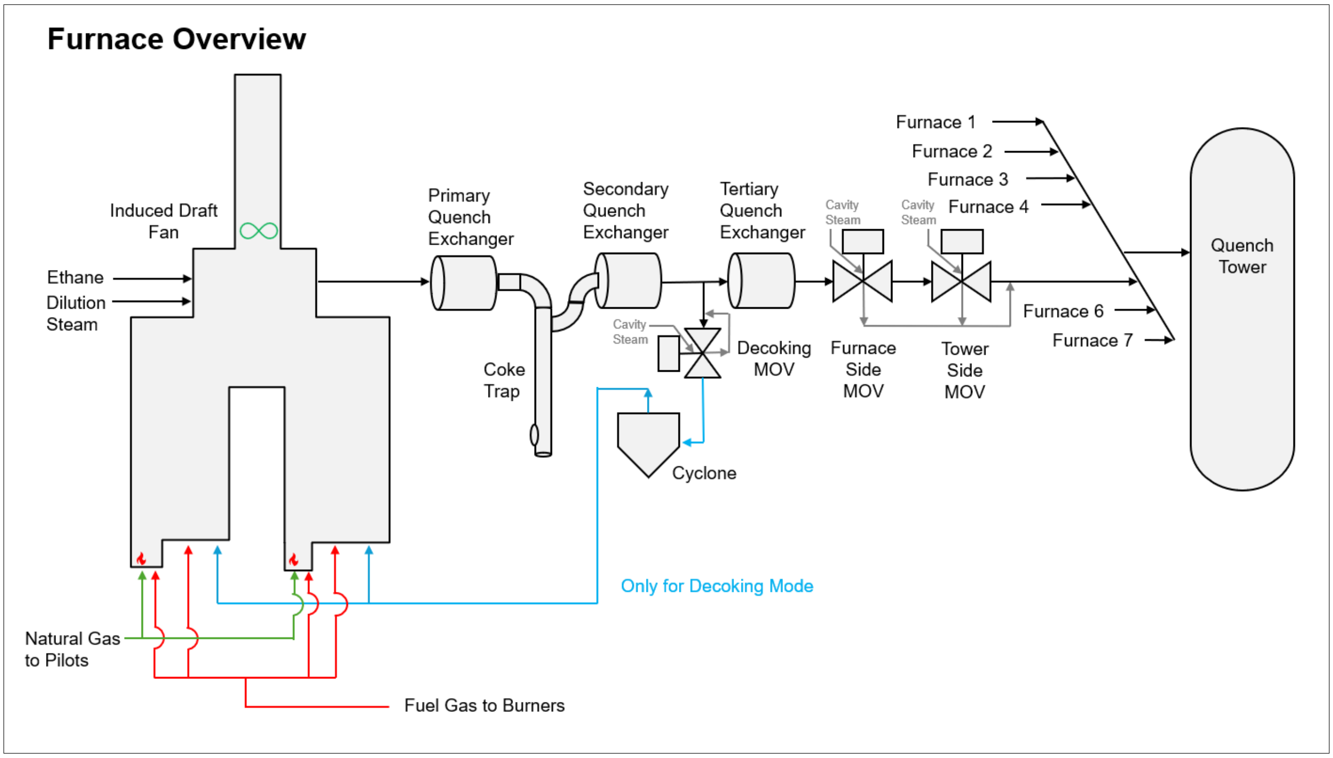

Figure 4. Simplified schematic of the ethane cracking unit showing Furnace 5 effluent being cooled and combined with the other six furnaces to feed the quench tower. (Credit: CSB)

Ethane cracking also produces carbon, which deposits as coke in the furnaces' tubes and polymerizes into carbon compounds, such as coke residue and tar [13, p. 16]. A large, vertical pipe, called a coke trap, is located between the primary and secondary quench exchangers [17]. Here, the cooled gas leaving the primary quench exchanger is forced to flow downward before being redirected upward to enter the secondary quench exchanger [18, p. 3]. Coke particles fall into the coke trap and accumulate there, while the gas continues to the secondary quench exchanger (**Figure 5**). The coke traps at Shell were supposed to be cleaned on a regular basis and were designed with a manway to allow removal of the coke; however, until the incident, none of the coke traps at the Monaca facility had ever been cleaned, with the other furnaces in operation since the facility started up in November 2022 (*See* **Appendix A** at **April 2025 – May 2025**).[a]

[a] Linde's guidance for Shell was that coke trap cleaning would be notionally annually at full production capacity. The facility, which began operations in November 2022, was not fully functional during 2023 due to operational and start-up challenges, which were resolved during the first quarter of 2024. In 2025, an additional defect intermittently impacted utilization and was subsequently corrected [1, p. 61].

Figure 5. Coke trap after an ethane cracking furnace primary quench exchanger at Shell. (Credit: Shell, annotated by CSB)

After leaving the heat exchangers, the cracked gases from all the furnaces are combined into a single stream. This stream enters a process tower known as the quench tower, where it is further cooled so that it can be compressed (**Figure 4**) [13, p. 16].

1.3 Furnace Operating Modes

The Shell ethane cracking unit has seven ethane cracking furnaces operating in parallel to produce ethylene (**Figure 6**) [13, p. 16]. All of Shell's ethylene production at Monaca can be achieved with six operating furnaces, while the seventh furnace is either decoking[a], in hot steam standby (HSSB) mode, or offline for maintenance [13, p. 16].

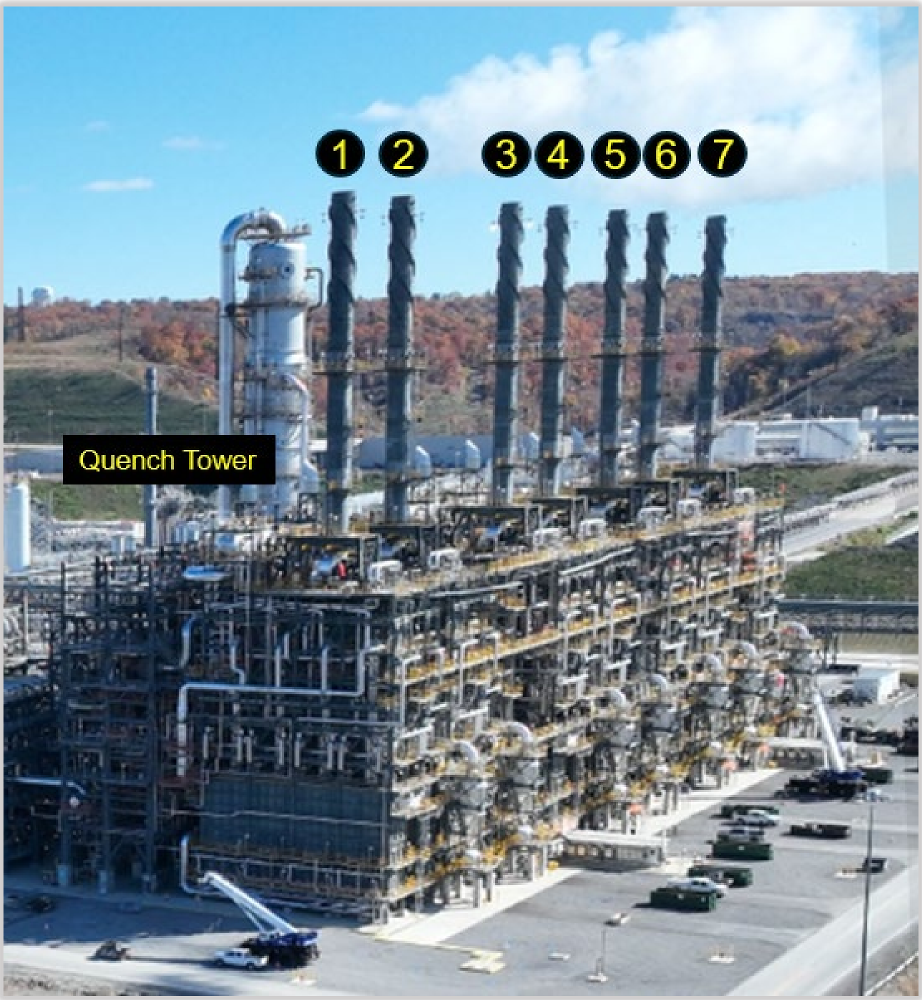

Figure 6. The seven ethane cracking furnaces and the quench tower at Shell Polymers Monaca. (Credit: Shell, annotated by CSB)

The cracking furnaces have multiple operating modes, including [13, pp. 18-19]:

Ethane cracking: This is the normal operating mode for a cracking furnace when it is being used to crack ethane into ethylene, described in **Section 1.2**.

[a] Every 30 to 60 days, a cracking furnace at Shell undergoes decoking for approximately 36 hours to remove the coke buildup from the tubes of the furnace.

Cold startup and shutdown: These modes cover the operation of a cracking furnace when it is initially started up after a turnaround, and the period following when feed is taken out of a cracking furnace until it is shut down. In a cold startup, when none of the cracking furnaces are in ethane cracking mode, natural gas is used to fuel the furnaces until ethane cracking begins and tail gas becomes available to fuel them.

Decoking: During the ethane cracking mode, coke forms within the radiant tubes of the cracking furnace. Coke buildup eventually leads to high tube wall temperatures, requiring decoking of the cracking furnace. Every 30 to 60 days, a cracking furnace undergoes decoking, which lasts for approximately 36 hours. The coke buildup is removed from the tubes of a cracking furnace during this mode of operation.

Decoking is accomplished by injecting steam into a cracking furnace's tubes while progressively raising the concentration of air introduced into the tubes to achieve controlled combustion of the coke in the tubes. The gas stream exiting the tubes passes through a cyclone separator to remove large particulates before it is routed into the cracking furnace's firebox, where any carbon monoxide and remaining particulates in the stream are combusted.

The heat input rate required during decoking is approximately 30 percent of the cracking furnace's maximum heat input. After a cracking furnace completes a decoking cycle, it is placed in HSSB mode until another cracking furnace shuts down or begins decoking.

Hot steam standby (HSSB): After a cracking furnace has been decoked, it is placed in HSSB until needed for cracking, possibly when another cracking furnace requires decoking. In this mode, a furnace is being heated below 50 percent of its maximum firing rate with no ethane feed and a coil outlet temperature greater than or equal to 1,382 °F [13, p. 16].

Pilots Only Operation: A mode in which a cracking furnace is heated only by pilots, and there is no hydrocarbon feed to the furnace.

1.4 Motor-Operated Valves

Each ethane cracking furnace has two 36-inch motor-operated valves (MOVs) in series to isolate the furnace from the downstream quench tower (**Figure 7**). The MOV closest to the furnace (furnace-side valve) is followed by the MOV closest to the quench tower (tower-side valve). Although the use of one furnace-exit MOV remains an industry practice for current-state-of-the-art systems and is in place at other Shell ethane cracking facilities, Shell requested that Linde provide a two-MOV exit at Monaca. The second valve, the tower-side MOV, was added with the intent that it would be redundant if the furnace-side MOV became inoperable or required maintenance.

Figure 7. Furnace-side and tower-side 36-inch motor-operated valves after an ethane cracking furnace. (Credit: Shell, annotated by CSB)

A third MOV, the decoking valve, is used to route gases produced by the decoking process back to the furnace. **Figure 8** illustrates the decoking configuration with the furnace-side valve fully closed, and the decoking valve and tower-side valves fully open.

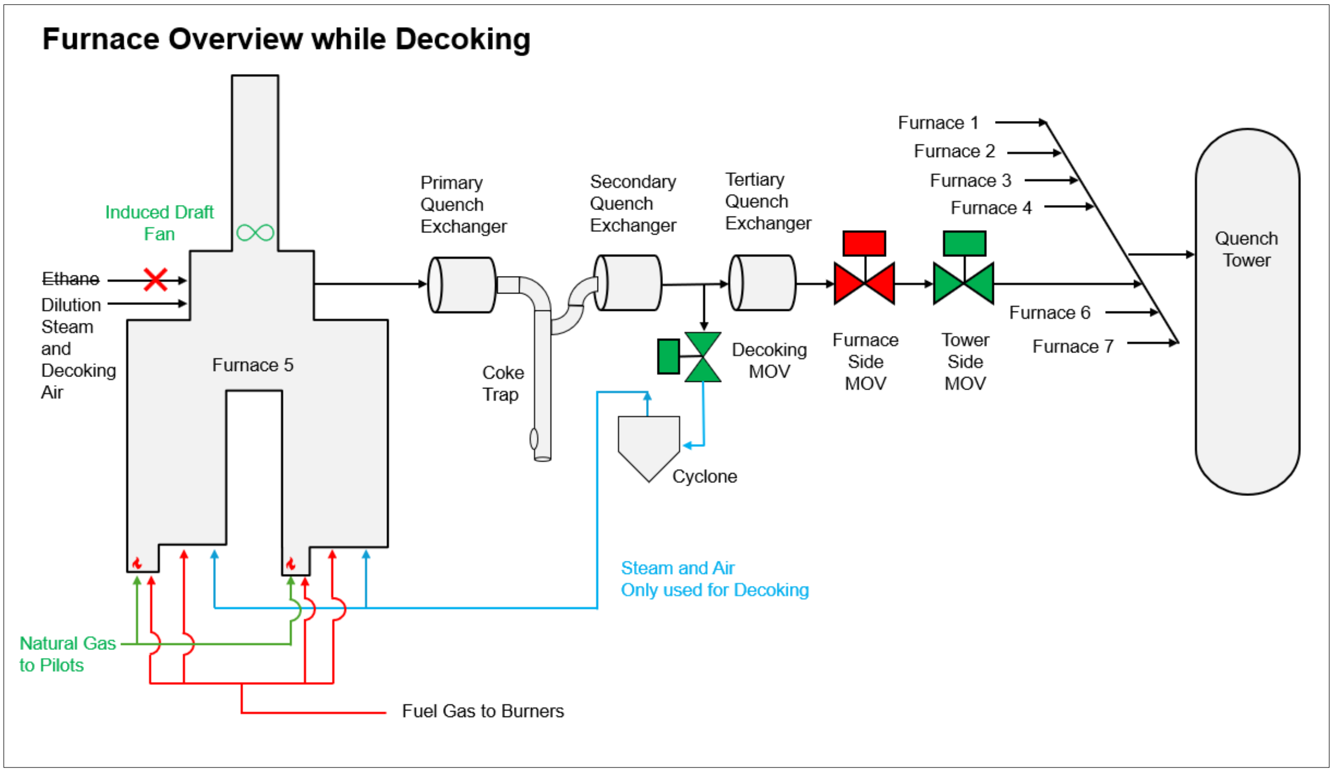

Figure 8. Simplified process diagram of a Furnace 5 decoking. A green MOV indicates that the valve is open, while a red MOV indicates that the valve is closed. (Credit: CSB)

Each MOV is a double-gate valve with an expanding wedge, which provides an active mechanical sealing force to drive the gates against hard surfaced seats to provide a leak-tight seal. The valve body is smooth so that the coke does not accumulate within it [19]. Each MOV is a double-block-and-purge valve because steam at a higher pressure than the process pressure flows through the cavity between the gates and back to the process, as shown in **Figure 4**. The steam purge provides an additional layer of protection against the backflow of cracked gas to the furnace when the MOV is closed.

The transition from ethane cracking to decoking requires simultaneous operation of the MOVs. While the furnace is in ethane cracking mode, both the furnace-side MOV and the tower-side MOV are fully open, and the decoking MOV is fully closed. To transition from the ethane cracking mode to decoking mode, the furnace-side MOV is slowly closed while the decoking MOV is slowly opened. The two MOVs work in tandem such that when one is open, the other is closed.

Closing the furnace-side MOV too quickly can cause excessive pressure and low flow through the furnace, potentially overheating the process tubes. Opening the decoking MOV too quickly can drop furnace pressure below the quench tower pressure, causing backflow from the furnaces in ethane cracking mode to the furnace in decoking mode. This is because a decoking furnace operates at atmospheric pressure, while the quench tower operates at approximately five pounds per square inch gauge (psig).

A computer program (transition computer) manages the changeover sequence and controls the differential pressure across the furnace-side MOV to ensure flow from the furnace to the downstream quench tower. Operators direct the transition computer from a local field control panel adjacent to the MOVs after completing a key-enforced, procedural isolation of ethane from the furnace (**Figure 9**). After decoking is complete, the process is reversed using the same transition computer to revert to the ethane cracking mode.

Figure 9. Local field control panel for furnace motor operator valves. (Credit: Shell, annotated by CSB).

Shell would occasionally close the furnace-side and tower-side MOVs to isolate a furnace from the others for maintenance work. This was done as an alternative to installing a 36-inch line blind on the furnace's outlet for energy isolation. The project design team assumed that only one MOV would be closed at a time to provide isolation, primarily the furnace-side valve.

The local field control panel was not set up to open both the furnace-side and tower-side MOVs. This was the case because only operating modes, such as decoking, were considered in the logic design. After completing a maintenance activity, the tower-side valve cannot be reopened by operators at the local field control panel. It can only be opened by a process control engineer, known as a PACO engineer at Shell,[a] typically from an engineering workstation in a room adjacent to the control room.

The PACO engineer could view the MOV status from a simplified process flow graphic using an operating console in the engineering room. After the tower-side valve is opened, a console operator can transition the

[a] At Shell, PACO stands for Process, Automation, Control, and Optimization [73].

furnace-side and decoking MOVs to bring the furnace back to ethane-cracking mode. The practice of closing both MOVs to isolate a furnace for maintenance, followed by a PACO engineer commanding the open tower-side MOV and Shell's Operations department using the furnace-side MOV to bring the furnace online, had been successfully performed 19 times at Shell before the incident.

1.5 Ethylene

Ethylene (C_2H_4) is a simple yet highly reactive hydrocarbon molecule consisting of two carbon atoms connected by a double bond [14]. This double bond makes ethylene highly versatile, serving as a key precursor to produce plastics, chemicals, and other essential materials [14].

Shell maintains a Safety Data Sheet (SDS) for ethylene that warns it is a flammable gas. The primary hazard concern if there is a spill or leak is that a fire and/or explosion could occur due to ethylene's extremely flammable properties [20]. The National Fire Protection Association (NFPA) diamond for ethylene shows that its flammability hazard is a 4, the most severe NFPA hazard rating [21, 22] (**Figure 10**).

Diamond	Hazard	Value	Description
	Health	2	Can cause temporary incapacitation or residual injury.
	Flammability	4	Burns readily. Rapidly or completely vaporizes at atmospheric pressure and normal ambient temperature.
	Instability	2	Readily undergoes violent chemical changes at elevated temperatures and pressures.
	Special		

Figure 10. The NFPA diamond for ethylene [21]. (Credit: CAMEO[a] Chemicals)

Ethylene is a colorless gas with flammability (explosive) limits reported as low as 2.7 and as high as 36 (volume percent) [23, p. 9]. The relative vapor density of ethylene is 0.975 (air is equal to 1.0) [23, p. 10].

1.6 Federal Safety Regulations

1.6.1 OSHA Process Safety Management Standard

The U.S. Occupational Safety and Health Administration (OSHA) Process Safety Management (PSM) standard was promulgated on May 26, 1992. According to OSHA, the PSM standard:

> [E]stablishes procedures for process safety management that will protect employees by preventing or minimizing the consequences of chemical accidents involving highly hazardous chemicals. Employees have been and continue to be exposed to the hazards of toxicity, fires, and explosions from catastrophic releases of highly hazardous chemicals in their workplaces. The requirements in this standard are intended to eliminate or mitigate the consequences of such releases [24].

[a] Computer-Aided Management of Emergency Operations (CAMEO) is a system of software applications used to plan for and respond to chemical emergencies [51].

Shell considered its ethane cracking unit covered by the OSHA PSM standard[a] because the chemical quantities used or stored in the process exceeded the threshold quantity of 10,000 pounds of flammable gas set forth in the standard.[b]

1.6.2 EPA Risk Management Program

The U.S. Environmental Protection Agency (EPA) Risk Management Program (RMP) rule requires an owner or operator of a stationary source with a process that has more than a threshold quantity of a regulated substance to develop a risk management plan prior to initial operations and update the plan at least once every five years [25, 26].[c] According to EPA, a facility's risk management program includes a facility's responsibility to:

- Conduct hazard evaluations: Regularly identify and analyze potential points of failure in equipment or human processes that could lead to a chemical release;
- Maintain safety systems: Implement maintenance, testing, and inspection schedules for all equipment and controls;
- Standardize operations: Develop written operating procedures and provide training for employees and contractors on how to handle chemicals safely; and
- Coordinate with emergency responders: Establish an emergency response program that includes planning, equipment, and coordination with local emergency responders.

The EPA's RMP rule defines three Program levels (Program 1, 2, or 3) based on the potential consequences to the public and the effort needed to prevent accidents [27]. Of these three Program levels, Program 1 is the least stringent, and Program 3 is the most rigorous. Because Shell included ethane and ethylene in its risk management plan and identified the North American Industry Classification System (NAICS) code for the ethane cracking unit as Petrochemical Manufacturing, the facility was subject to Program Level 3, the most stringent [28, p. 9].[d]

Shell filed its initial risk management plan on April 6, 2022, [29] and has since submitted two updates of the plan to EPA, on December 20, 2023, [30] and October 22, 2024 [28]. Shell's risk management plan submission identified that its Monaca facility is regulated by both the EPA RMP rule and the OSHA PSM standard [28, p. 3].

In its initial risk management plan and both resubmissions, Shell stated that it had identified fire, explosion, overpressure, and equipment failure as major hazards in a 2019 process hazards analysis (PHA) [29, p. 27, 30, p. 35, 28, p. 39]. Both resubmissions include the date of the latest review of operating and maintenance procedures as December 2021 [29, pp. 28-29, 30, p. 37, 28, p. 41].

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[a] 29 C.F.R. § 1910.119 - Process safety management of highly hazardous chemicals.

[b] The PSM standard covers chemicals deemed hazardous because of their chemical composition and quantity (listed in Appendix A of 29 C.F.R § 1910.119) or because of their flammability characteristics. *See* 29 C.F.R. 1910.119 (a)(1)(ii).

[c] 40 C.F.R. § 68.10.

[d] There are ten NAICS codes that automatically require a facility with potential offsite impact to comply with Program Level 3, including NAICS Code 32511 Petrochemical Manufacturing [66, 53, p. 3].

1.7 DESCRIPTION OF SURROUNDING AREA

Figure 11 shows the Shell Polymers Monaca facility and depicts the area within 1, 3, and 5 miles of the facility boundary. Summarized demographic data for the approximate 1-mile vicinity of the Shell Polymers Monaca facility is shown below in **Table 1**.

There are 787 people residing in 377 housing units within 1 mile of the Shell Polymers Monaca facility. Detailed demographic data is included in **Appendix B** of this report.

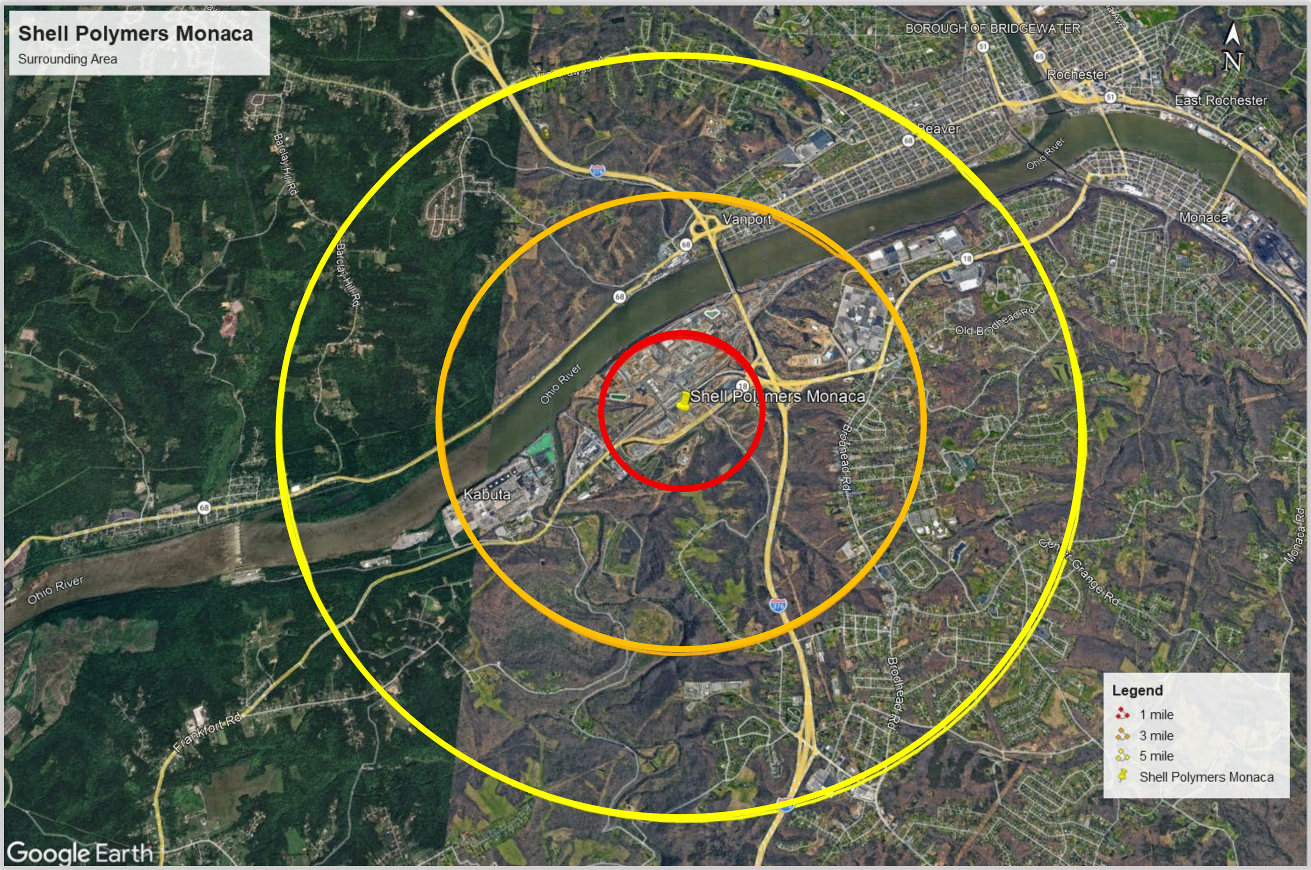


Figure 11. Overhead satellite image of the Shell Polymers Monaca facility and the surrounding area (Credit: Google Earth, annotated by CSB).

Table 1. Summarized demographic data for approximately 1-mile vicinity of Shell Polymers Monaca facility (Credit: CSB using data obtained from U.S. Census Bureau, 2024 American Community Survey)

Population	Race and Ethnicity (%)		Per Capita Income ($)	Persons Below Poverty Line (%)	Number of Housing Units	Types of Housing Units (%)	
787	White	89	$41,485[a]	3	417	Single Unit	81
	Black	4				Multi-Unit	18
	Native	0				Mobile Home	1
	Asian	0				Boat, RV, Van, etc.	0
	Islander	0					
	Other	0					
	Two+	3					
	Hispanic	3					

[a] Census Reporter reports that Monaca's per capita income was $39,340 and the overall per capita income for the United States from 2020-2024 was $44,673 [50].

2 INCIDENT DESCRIPTION

A timeline of events is provided in **Appendix A** of this report.

2.1 COKE TRAP CLEANING

In late March 2025, the coke trap of Furnace 1 was opened and inspected during a March-April ethane cracking unit outage. Coke was visible almost up to the manway (**Figure 5**). Shell decided in early April 2025 that the coke traps of all seven furnaces needed to be cleaned, as more coke accumulation could pose operational challenges. None of the coke traps in any of the furnaces had ever been cleaned prior to this time. The coke traps of Furnaces 1, 2, 4, and 7 were successfully cleaned for the first time during the ethane cracking unit outage. Furnace 5 was the next coke trap to be cleaned.

2.2 FURNACE ISOLATION

On May 30, 2025, Furnace 5, the incident furnace, was shut down to clean its coke trap for the first time since it began operating. During the night shift on May 31, 2025, Shell completed the energy isolation of Furnace 5. At this time, Furnaces 1, 2, 3, and 4 were in ethane cracking mode. The next day, Furnace 6 was shut down. Furnace 7 was placed in hot steam standby mode (HSSB) on June 4, the day of the incident (**Section 1.3**).

Both the furnace-side and tower-side MOVs for Furnace 5 were closed as part of the energy isolation plan for the coke trap cleaning. The isolation was obtained by closing both MOVs, isolating the steam to the cavity between the double gates of each MOV, and opening a bleed valve between the two MOVs to ensure any cracked gas would not flow back to the furnace (**Section 1.4**). **Figure 12** shows a simplified process flow diagram of the MOVs and the energy isolation for Furnace 5 during the coke trap cleaning.

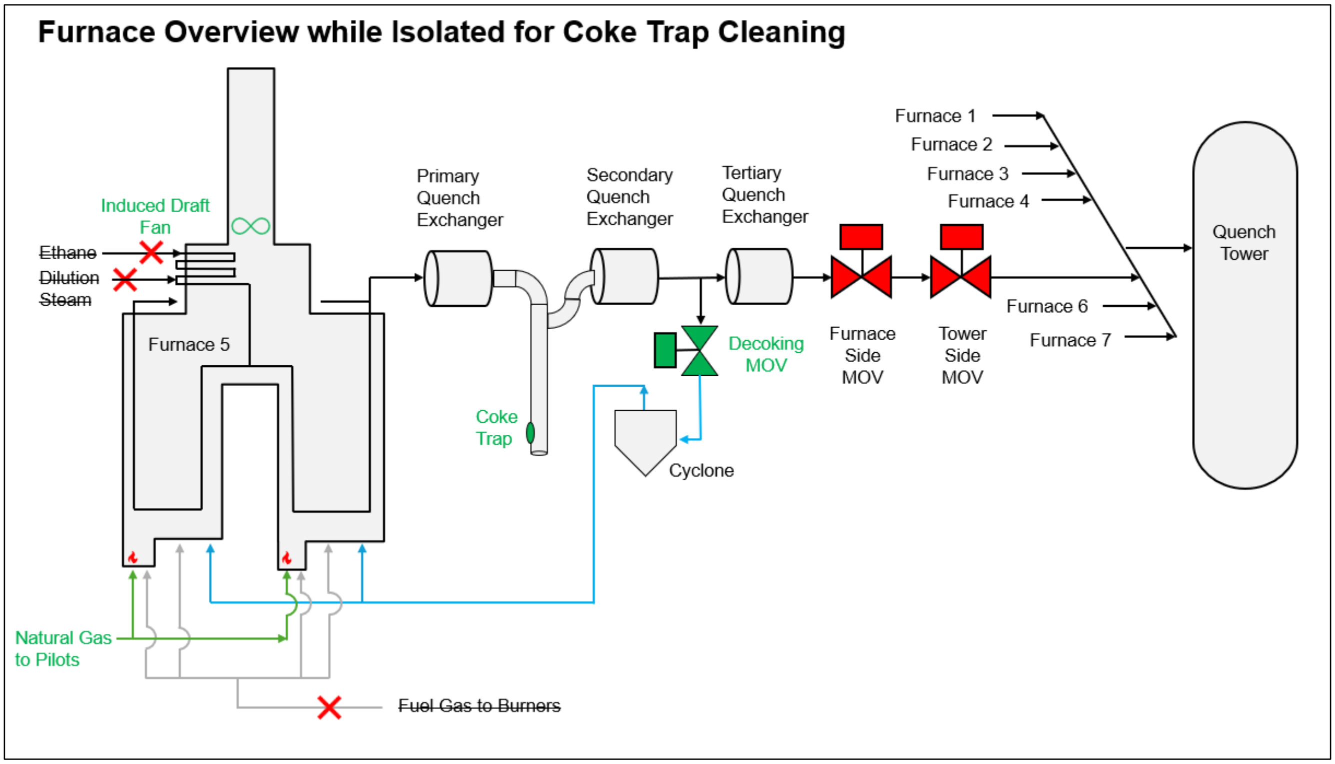


Figure 12. Simplified process flow diagram of Furnace 5 while isolated for non-entry maintenance to clean the coke trap. Red valves represent closed MOVs and green valves represent open MOVs. (Credit: CSB)

Because cleaning the coke trap would not require anyone to enter the furnace, Shell did not isolate the furnace for entry. With the furnace-side MOV closed to isolate the furnace from the quench tower, the decoking MOV was open.[a]

Shell wanted to avoid repeating a prior experience with furnace refractory damage and left the furnace pilots on to keep the temperature above the atmospheric dew point and prevent condensation.[b,c] Additionally, Shell expected the flammable cracked gas to be isolated from the furnace throughout the coke trap cleaning and the return to ethane cracking mode.

While the furnace was in pilot-only mode, a group of alarms, including those for high furnace firebox pressure, high carbon monoxide concentration, and high methane concentration in the furnace, were automatically suppressed.[d] These alarms were suppressed by design to help manage alarm floods and nuisance alarms.

[a] Because the decoking MOV works in tandem with the furnace-side MOV, one is closed when the other is open.

[b] Refractories are used to contain heat and protect processing equipment from intense temperatures. In industry, they are used to line all types of boilers and furnaces [52]. *See* What Are Refractories? | The Refractories Institute (TRI).

[c] A prior ethane cracking furnace refractory damage incident occurred when the refractory brick floor of a furnace came in contact with water during hydrotest activities on the night shift of October 18, 2021.

[d] Alarm suppression silenced the alarm volume. A grey bell icon next to the pressure and concentration values indicated to the console operator that the alarms were suppressed.

Over the next three days, the Furnace 5 coke trap was cleaned. The Furnace 5 coke trap cleaning was concluded on June 3, and at approximately 1:40 p.m. on June 3, power was restored to both the furnace-side and tower-side MOVs on Furnace 5 to begin returning the furnace to ethane cracking mode.

2.3 Furnace Return to Operation

On June 4, 2025, Shell's Operations department continued activities to bring Furnace 5 back to service and removed the energy isolation from the coke trap cleanout. Shell's Operations department planned to transition Furnace 5 from an isolated, pilot-only mode to HSSB. Shell's furnace start-up procedure did not apply to transitioning out of pilot-only mode, so there were no specific steps for operators to follow, even though the pilots were already lit.

During a morning meeting, the Operations Production Specialist (known as a P-Spec at Shell) assigned the task of opening the tower-side valve to the PACO engineer (**Figure 13**). However, the PACO engineer had never performed this process before. There also was no discussion about Shell's Operations department or the PACO engineer issuing a safety instrumented system (SIS) bypass form to command the tower-side MOV open.[a]

Unit Area	24 Hr Plan
Furnaces	Total feed [redacted]th Furnace 1 Feed in [redacted] t/h Furnace 2 Feed in [redacted] t/h Furnace 3 Feed in [redacted] t/h Furnace 4 Feed in [redacted] t/h Furnace 5 coke trap clean out complete, Open [redacted] MOV-513, bring furnace up to HSSB Furnace 6 EIF hung for coke trap clean out, shoot trap with temp gun, report to PSPEC, burner cleaning, ID fan Firmware upgrade and battery change out Furnace 7 Feed in [redacted] t/h

Support Needed - Hot Side [P-Spec]
Open [redacted] MOV-513 PACO

Figure 13. Excerpts from the June 4, 2025, morning meeting notes (Credit: Shell, redacted by CSB).

2.4 Creation of an Unintended Flow Path

By 12:00 p.m. on June 4, 2025, Shell's Operations department was ready to open the tower-side valve so that the Furnace 5 start-up could continue. The PACO engineer asked an instrument technician to unlock the SIS. At 2:04 p.m., the SIS was unlocked, and the PACO engineer was able to control the MOVs.

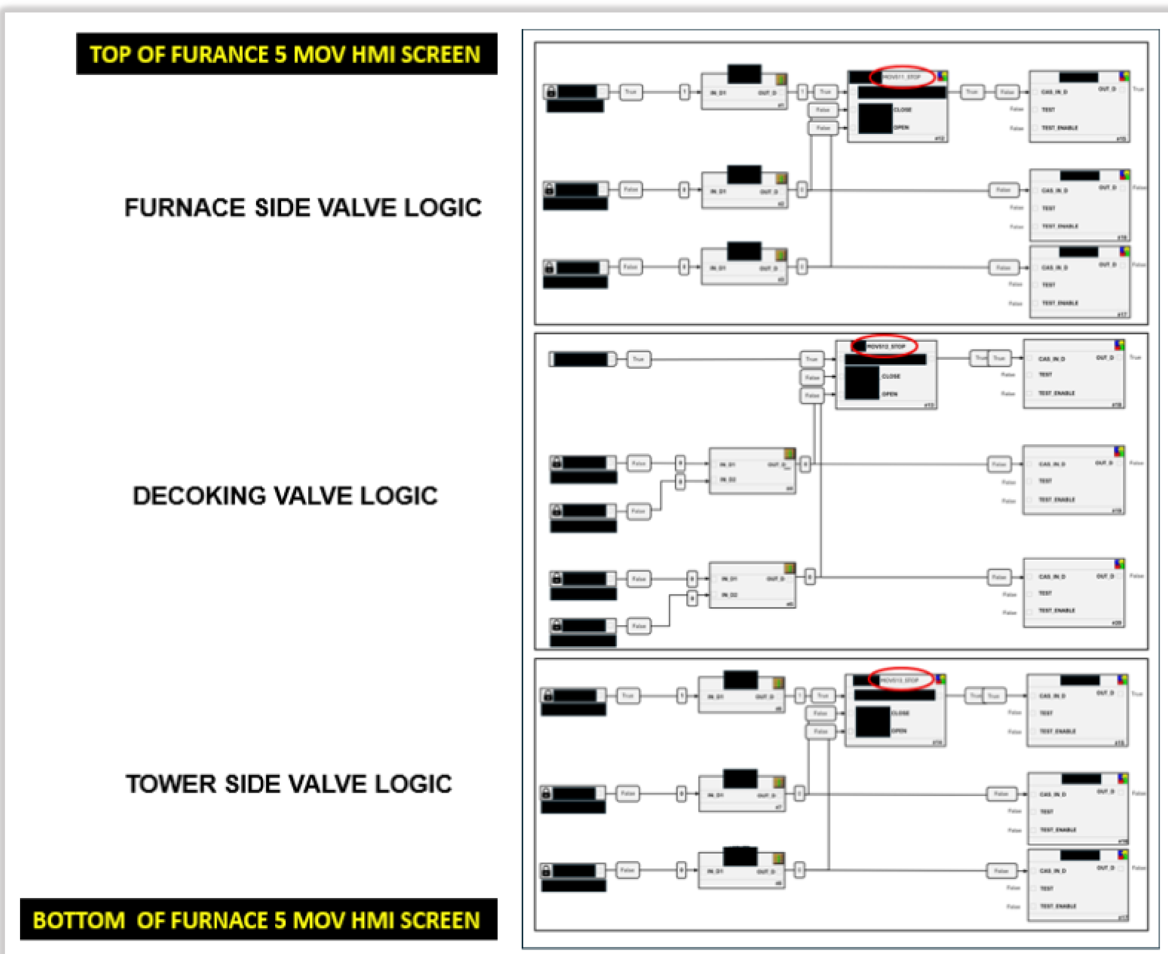
To complete the assigned task, the PACO engineer used a Shell-approved, written job aid to command the tower-side valve to open. The job aid required the use of a human-machine interface (HMI) screen to manipulate the logic in order to issue an open command to the tower-side valve (**Figure 14**). This HMI is used by a PACO

[a] A Safety Instrumented System (SIS) is a separate and independent combination of sensors, logic solvers, final elements, and support systems that are designed and managed to achieve a specified safety integrity level. A SIS may implement one or more Safety Instrumented Functions (SIFs), which take the process to a safe state when predetermined conditions are violated [71, 69].

engineer when overriding the SIS and is not used by operators during day-to-day operation of the ethane cracking unit.

The PACO engineer was attempting to issue an open command to the tower-side valve but the SIS was not responding so they asked a nearby process control engineer for assistance. That process control engineer, who had commanded open valves before, immediately noticed that the SIS was in “read-only” mode and informed the PACO engineer that the SIS would need to be in “debug” mode to accept the open command.[a] The job aid’s instructions were ambiguous on when to unlock the SIS and enter the debug mode.

The furnace-side MOV was located at the top of the HMI screen that displayed the three Furnace 5 MOVs, with the tower-side MOV located at the bottom of the screen and the decoking MOV located between the two, as shown in **Figure 14**. The HMI screen for the MOVs in the SIS required a user to scroll down to navigate from the furnace-side MOV to the tower-side MOV. The MOV SIS logic blocks were identified by descriptions that differed only in the last digit for each valve: 511 for the furnace-side MOV, 512 for the decoking MOV, and 513 for the tower-side MOV.



[a] Debug mode is an engineering diagnostic mode that allows a user to override any programmed logic that operates process equipment. Entering debug mode requires removing SIS protections, which should be a controlled, non-routine, and infrequent activity.

Figure 14. Human-machine interface (HMI) screen of the three Furnace 5 MOVs. The valve numbers, which differ by the only the last digit, are circled in red. (Credit: CSB)

When the PACO engineer entered "debug" mode, the HMI screen for the MOVs in the SIS refreshed and automatically started back at the top. As a result, while the PACO engineer previously had been looking at the tower-side MOV logic, which was at the bottom of the screen, the PACO engineer's attention was now instead focused on the furnace-side MOV logic at the top of the screen. In other words, the upper third of the SIS screen shown in **Figure 14** was now visible to the PACO engineer, rather than the lower third. Instead of looking at the tower-side MOV at the bottom of the screen, the PACO engineer was now looking at the similar logic furnace-side MOV at the top of the screen.

At 2:14 p.m., the PACO engineer inadvertently sent a command for the furnace-side MOV to open, instead of sending the command to the tower-side MOV. When the furnace-side MOV began opening, an alarm was activated to indicate that the MOV was in an unexpected state. However, the descriptor text displayed for the furnace-side MOV alarm was identical to that for the tower-side MOV alarm, again except for the last digit of the valve number. The alarm was acknowledged by the console operator. Because the console operator was aware that the PACO engineer planned to open the tower-side valve, the console operator assumed incorrectly that the alarm was for the tower-side valve and did not pursue corrective actions.[a]

Approximately two minutes later, the PACO engineer noticed that the tower-side MOV was not moving. Because the PACO engineer believed (incorrectly) that the furnace-side MOV was already in the open position prior to issuing the open command, the PACO engineer concluded that the open command did not cause the MOV valve to change position and accordingly removed the command from the SIS logic. About 1 minute later, the PACO engineer scrolled back to the bottom of the HMI screen and sent a command to open the tower-side MOV, as initially planned.

At around 2:20 p.m., the ethylene control room console operator noticed that the furnace-side MOV was open and the tower-side MOV was opening. The ethane cracking unit console operator immediately went to the engineering workstation and told the PACO engineer to close the tower-side valve, which by this point was 78 percent open and continuing to open. This series of events is depicted in **Figure 15**.

[a] Shell determined that if the console operator had used the approved corrective action for the alarm, a field operator would have been sent to investigate the state of the furnace-side MOV. This could have placed a responding field operator near the explosion, which could have resulted in the field operator being seriously or even fatally injured.

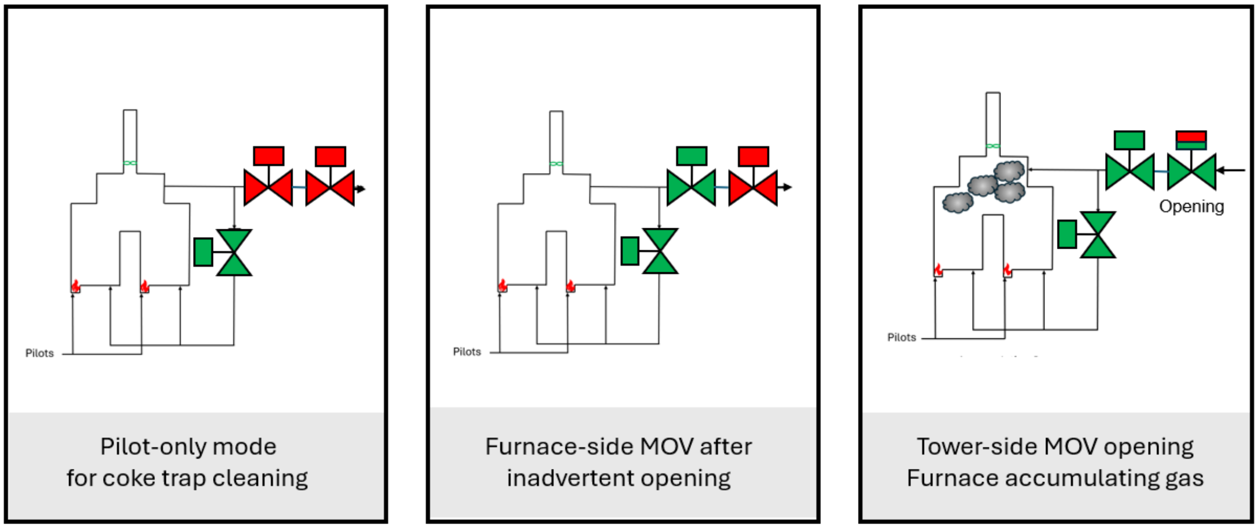


Figure 15. The sequence of creating the unintended flow path to the furnace. Red valves represent closed MOVs, and green valves represent open MOVs. (Credit: CSB)

Once the furnace-side valve was open and with the tower-side valve in the process of opening, an unintended flow path was created. The path allowed cracked gas from the higher-pressure header to backflow into the lower-pressure Furnace 5 firebox (**Figure 16**).

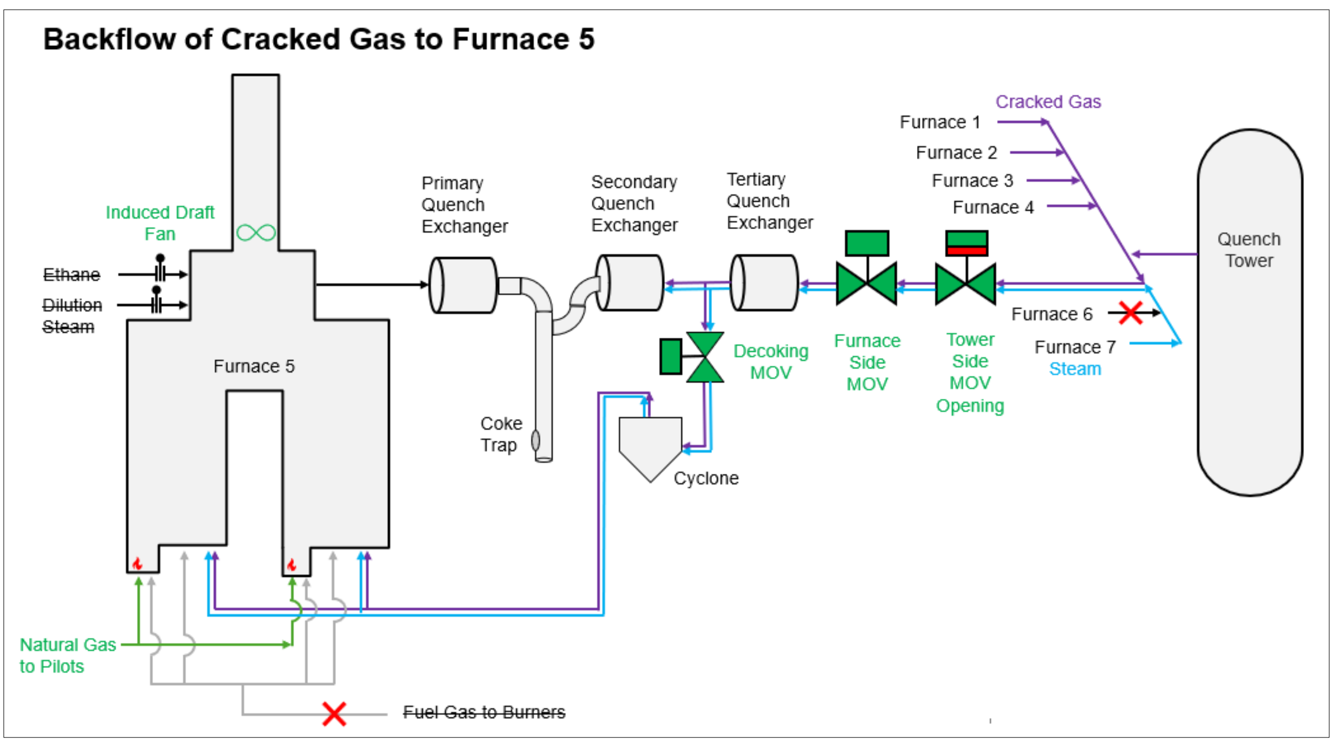


Figure 16. Unintended flow path of cracked gas to Furnace 5. Red valves represent closed MOVs, and green valves represent open MOVs. (Credit: CSB)

2.5 Gas Accumulation and Ignition

It takes approximately four minutes for one of Shell's MOVs to travel from fully closed to fully open. Consequently, the cracked gas and steam in the header from the other furnaces continued to backflow into the Furnace 5 firebox for approximately 2.5 minutes.

During this time, the Furnace 5 Induced Draft (ID) fan on the furnace stack was operating in speed control mode, and the rate of backflowing ethylene into the firebox exceeded the fan's exhaust rate, causing the furnace to accumulate flammable cracked gas. A console operator had placed the ID fan in speed control around 9:20 a.m. on June 3, 2025, after the fan's motor control firmware was updated during the coke trap cleaning. It was common operating practice to manually ramp up the ID fan to higher speeds using a speed controller as the furnace was being placed in service, and then transition the fan to a pressure controller.

With a structural limit of 0.01 psig, the furnace walls initially contained and confined the accumulating gas in the firebox. However, the furnace was not designed to contain an internal explosion. By 2:20 p.m. on June 4, 2025 -- roughly just 6 minutes after the PACO engineer had sent the inadvertent open command to the furnace-side MOV -- an estimated 641 pounds of cracked gas had accumulated in the Furnace 5 firebox, came in contact with the lit pilots, and ignited, resulting in an explosion that blew out of the furnace's walls, resulting in a loss of containment of the cracked gas and combustion products, and a subsequent fire (**Figure 17**).

Figure 17. Furnace 5 after the explosion. (Credit: KDKA-TV)

The Shell site Emergency Response Team at the facility responded and began firefighting efforts, which continued until 4:00 p.m. Fire-fighting water runoff was captured by a collection system and sent to Shell's wastewater treatment plant.

2.6 Consequences

The explosion resulted in a release of hazardous chemicals and substantial property damage.[a] Visible emissions were observed from the Furnace 5 stack for approximately 5 minutes and from the lower section of the furnace for a total of 9 minutes. Shell estimated that 515 pounds of non-combusted cracked gas and approximately 4,600 pounds of combustion products from combusted cracked gas were released by this incident.

[a] Release means any emitting, emptying, discharging, or escaping into the environment of any toxic chemical [65].

Although there were no injuries, Shell evacuated 15 employees in the ethane cracking unit (ECU) area due to the fire [31, p. 2]. A contractor became trapped in the ECU elevator next to Furnace 5 and was rescued. Additionally, multiple other Shell employees were in the area around Furnaces 4, 5, and 6.[a]

Following the incident, Furnaces 4 and 6 were taken offline to allow for assessment, while the other furnaces remained in ethane-cracking mode. After comprehensive inspections, both Furnaces 4 and 6 were deemed safe for operation and subsequently brought back online. Furnace 6 resumed normal operations on June 18, 2025, followed by Furnace 4 on June 20, 2025, after about two weeks without operating.

Shell estimated that the explosion resulted in property damage of $95 million. Furnace 5 was restarted on January 22, 2026, after a six-month reconstruction.

2.6.1 OSHA Enforcement Actions

On December 1, 2025, OSHA issued three citations to Shell stemming from the June 4, 2025, incident, with a proposed penalty of $26,480 [32]. The citations were closed on January 2, 2026.[b] Details on the OSHA citations can be found in **Appendix C** of this report**.**

[a] No exclusion zone was established around Furnace 5, as Shell did not consider the transition from pilot-only mode to HSSB a start-up activity or an abnormal situation.

[b] *See* Inspection Detail | Occupational Safety and Health Administration osha.gov.

3 SAFETY ISSUES

Although there were many factors that contributed to the incident, the CSB's investigation focused on the following two primary safety issues:

- Reliance on Administrative Controls
- Human-Machine Interface

3.1 RELIANCE ON ADMINISTRATIVE CONTROLS

The hierarchy of controls is a method of organizing safeguards into ranked categories based on their effectiveness at preventing incidents or protecting workers from hazards [33, 34]. Typically, controls are organized into five categories, with the top being the most effective and the bottom being the least effective. In order of effectiveness, the controls are: eliminating the hazards, utilizing the other inherently safer design principles, engineering controls, administrative controls, and personal protective equipment [33, 34]. A compilation of the National Institute for Occupational Safety and Health (NIOSH), OSHA, and the Center for Chemical Process Safety (CCPS) concepts regarding the relative effectiveness of each control in the hierarchy of controls is shown in **Figure 18**.

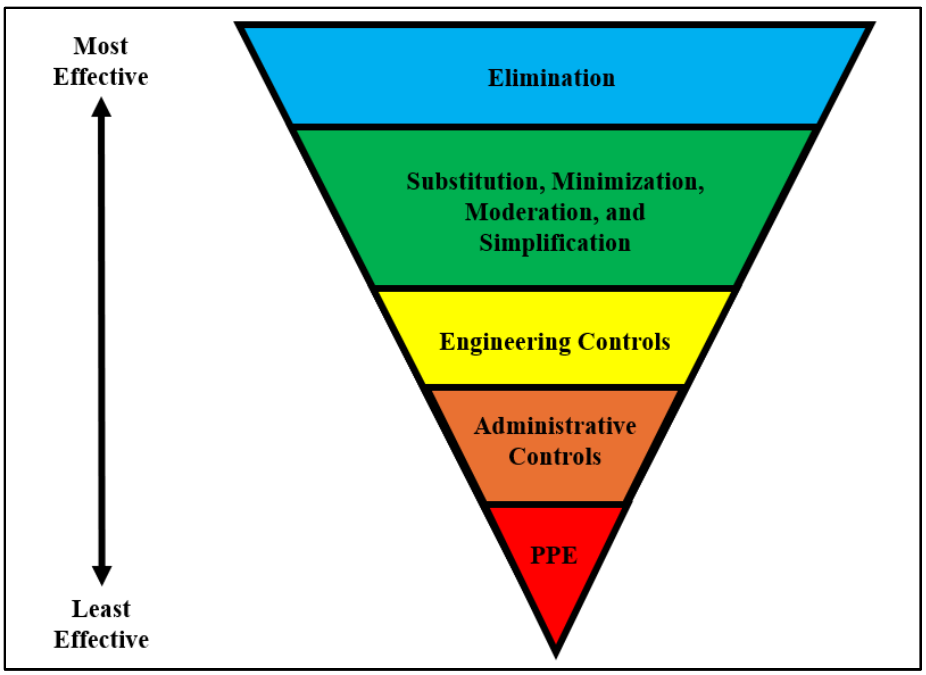


Figure 18. The hierarchy of controls. (Credit: CSB, modified from CCPS [35], NIOSH [33], and OSHA [34])

Inherently safer design minimizes or eliminates hazards by using process conditions or materials that are less hazardous. These concepts can be incorporated into processes and equipment designs through elimination, substitution,[a] minimization,[b] moderation,[c] and simplification [35, p. 18].[d]

The next category on the hierarchy of controls is engineering controls; these are controls that are designed into the processes and process equipment to keep a process within safe operating limits, shut down the process after an upset, or reduce human exposure to the effects of an upset [35, p. 13, 36]. Engineering controls require minimal human interaction to prevent or mitigate hazards [33, 34].

Administrative controls, such as those relied upon by Shell in this incident, use policies and procedures (e.g., responding to alarms) that rely on humans to recognize, diagnose, and react correctly to detect, prevent, or mitigate a hazard [35, p. 30, 36]. To be effective, administrative controls must be robust, where the company provides adequate training and drills, qualifies employees on the policies and procedures, and regularly validates the effectiveness of the controls [37, pp. 7-8].

Per the hierarchy of controls philosophy, it is always preferable to select the most effective type of control(s) when analyzing hazards, and sometimes the most protection comes from a combination of multiple control types [33, 34]. Because administrative controls and personal protective equipment (PPE) rely on human behavior, they should not be relied on as the only implemented controls, and if they are, only unless a company trains and qualifies workers on the controls and validates the controls' effectiveness.

[a] Substitution is defined as "[replacing] a chemical/material with a benign or less hazardous substance; or replace a process or processing technology with one that is benign or is less hazardous [35, p. 18].

[b] Minimization is defined as "using or having smaller quantities of hazardous substances [35, p. 18]."

[c] Moderation is defined as "[using] less hazardous or energetic processing or storage conditions, a less hazardous form of a material, or facilities that minimize the impact of a release of hazardous material or energy [35, p. 18]."

[d] Simplification is defined as "design [of] facilities which eliminate unnecessary complexity and make operating errors less likely, and which are forgiving of errors that are made [35, p. 18]."

3.1.1 POLICIES, PROCEDURES, AND ALARMS

The Shell investigation team identified 11 policies, procedures, and alarms that the facility relied on and believed could have prevented or mitigated the incident had they not failed. The controls are summarized in **Table 2**.

Table 2. Policies, procedures, and alarms (Credit: Shell, modified by CSB)

Administrative Control	What was the control?	How did Shell intend the control to act?	How did the control fail?
Policy	Either the furnace-side or the tower-side MOV is closed when coming out of a Lock Out/Tag Out for energy isolation.[1]	A PACO engineer would open the tower-side MOV, while the furnace-side MOV would remain closed until the furnace was restarted. Once restarted, the pressure in the furnace would be greater than the pressure in the quench tower, preventing backflow once the furnace-side MOV was opened.	While the PACO engineer intended to open the tower-side MOV, the open command was inadvertently sent to the furnace-side MOV. Reasoning the furnace-side MOV was already open, the PACO engineer commanded open the tower-side MOV resulting in both MOVs being open at the same time creating the flow path of flammable cracked gas to the furnace pilots.
Policy	Control of ignition sources	Ignition sources would be removed when performing work on equipment that contains flammable materials. Although the isolation was effective for the coke trap cleaning, the decision to leave the pilots on provided an ignition source for the flammable vapors.	When the isolation was inadvertently removed, the cracked gas in the header backflowed into the furnace, contacted the lit pilots, and ignited.
Operator Response to Alarm	Firebox pressure transmitter high alarm	When the alarm activates, the corrective action would require the induced draft fan to be put in pressure control mode, venting the flammable vapors to the atmosphere. If the high-pressure alarm remained active for 15 minutes, the furnace would be manually shut down by the team lead.	The high-pressure alarm was suppressed due to the furnace operating in pilot-only mode
Operator Response to Alarm	Firebox gas detector for methane and carbon monoxide high alarms	As cracked gas began to backflow into the furnace, the alarm would have alerted operators to the backflow of flammable gas into the furnace. Operators could have detected the backflow sooner and began troubleshooting.	The carbon monoxide gas alarm would have activated approximately 90 seconds prior to ignition. The carbon monoxide alarm was suppressed while the furnace was in pilot-only mode. Additionally, even though the methane alarm was also suppressed, it never reached its high alarm setpoint.

[1] Lock Out/Tag Out refers to the placement of a lock and isolation tag on an isolating device, indicating that the isolating device and its system shall not be operated or removed until the lock and isolation tags are removed [58, p. 3].

Administrative Control	What was the control?	How did Shell intend the control to act?	How did the control fail?
Operator Response to Alarm	Critical "fail-to-trip" alarm for the furnace-side MOV.	This alarm would notify the console operator that the furnace-side MOV was in an unexpected state, allowing the operator to troubleshoot earlier and potentially activate the Emergency Shutdown switch.	The text of the alarm description for the furnace-side (MOV-511) and tower-side MOV (MOV-513) is identical, except for the last digit of the numerical tag identifier. Therefore, when the alarm activated approximately five minutes prior to the ignition and explosion, the ethylene control room console operator simply acknowledged the alarm and assumed that it was associated with opening the tower-side MOV. No corrective actions were taken.
Procedure	A start-up procedure for Shell's Operations department to transition from HSSB to ethane cracking mode.	Operators would follow a procedure that they were trained and qualified on to control the MOVs from the field panel. This would allow the field operator to monitor and control the opening of the MOVs in the correct sequence, without involving the PACO engineer.	The start-up procedure begins after the isolation has been removed. Steps in the start-up procedure had already been deviated from because the furnace pilots remained lit during the isolation and coke trap cleaning, which requires the PACO engineer to operate the MOVs from the room with the engineering workstation.
Procedure	The field operator executes and observes the furnace-side, tower-side, and decoking MOV movements.	The furnace-side, tower-side, and the decoking MOV would be manipulated by a field operator using a local field control panel. This would allow the field operator to control MOV movements and observe the MOVs' physical positions.	The furnace design team assumed that the tower-side MOV would be closed for isolation and that the furnace-side MOV would be open or vice versa when changing between decoking and ethane cracking mode. When maintenance was required on a furnace, operators closed both MOVs to isolate the equipment. When transitioning from an isolated state, the MOVs would be reopened, which could only be done by a PACO engineer. This resulted in the furnace-side and tower-side MOVs being commanded from the engineering room rather than the field, leaving no field operator to witness the MOV positions.
Procedure	Written job aid for the PACO engineer.	The job aid would be used to issue an open command by the PACO engineer. Following the job aid would result in the correct MOV opening.	The PACO engineer used the job aid to issue an open command to the tower-side MOV. The steps in the job aid to select the mode of the SIS and issue the open command were found to be out of sequence, which caused the open command not to be accepted by the tower-side MOV. When the PACO engineer entered the correct mode to issue the command, the HMI screen refreshed instantly. This refresh resulted in the open command being issued to the furnace-side MOV, which was at the top of the screen.

Administrative Control	What was the control?	How did Shell intend the control to act?	How did the control fail?
Policy	SIS temporary operation of controls	An SIS bypass form would be completed each time the SIS is overridden, bypassed, or impaired if not proceduralized. The engineer or operators would develop a mitigation plan and specifically identify which equipment tags to monitor when the form is filled out.	Employees at Shell believed that the SIS bypass form was only required when Shell's Operations department would open the MOV and did not fill out the form and establish the required plan to mitigate an incident. However, Shell's policy does not exempt a PACO engineer from filling out a bypass form.
Procedure	Emergency Shutdown (ESD) switch[2]	The ESD switch is intended to be activated by an operator in the event of a furnace tube rupture. This switch closes the furnace- and tower-side MOVs.	The ESD switch was not used because the console operator asked the PACO engineer to close the tower-side MOV after noticing the furnace-side MOV had been mistakenly opened.
Policy	Managing personnel and establishing exclusion zones	The Site Managing Personnel Policy requires an announcement of an exclusion zone during start-up and in abnormal situations, removing non-essential personnel from the area.	Transitioning into and out of a maintenance activity is not considered a shutdown, start-up, or abnormal situation. As a result, no exclusion zone was initiated. There was a craftsman in the furnace elevator, as well as multiple employees in the area of Furnaces 4, 5, and 6 at the time of the explosion.

[2] Shell determined that use of the ESD switch would not have changed the outcome. Had the console operator activated the ESD switch, the tower-side MOV would have taken longer to close than if the PACO engineer had closed it using a closed command from the SIS.

The controls identified by Shell were all policies, procedures, or operator responses to alarms, all of which rely on human compliance. As such, the CSB concludes that all the controls Shell had in place to prevent backflow to the firebox when an isolation valve was open during the decoking process, at the time of the incident, were administrative controls.

Reliance on Administrative Controls

Within a complex system, the introduction of a single error is almost never the only cause of a catastrophe [38, pp. 475-477]. Rather, "multiple defenses" typically must fail for the error to lead to an accident [38, p. 481, 39].

The CSB concludes that all 11 controls that Shell identified failed because employees had not been adequately trained prior to this incident and lacked awareness of them or the ability to comply with them. The 11 controls that Shell relied on were not as effective as other, more robust, controls could have been. Had inherently safer design, engineering controls, or more robust administrative controls been in place, the June 4, 2025, incident could have been prevented.

Control of Ignition Sources

As discussed in **Sections 2.2** and **2.3**, Shell left the pilots on during the coke trap cleaning task. Although the furnace isolation was effective during the coke trap cleaning, the decision to leave the pilots on provided a ready ignition source for the cracked gas once the reverse flow path was inadvertently created. The lit pilots acted as the ignition source for the incident, which led to the explosion and fire.

KEY LESSON

Hazardous energy and potential ignition sources, such as lit pilots, should be controlled during maintenance activities.

Shell's decision to leave the pilots on differed from the existing site Furnace Isolation Plan, which called for isolating and stopping the flow of natural gas to the furnace pilots, and did not adhere to the Safe Isolation Policy deviation process, which would have required an additional review of the decision. Leaving the pilots on also deviated from Shell's procedure for cold furnace startup.[a] Shell did not follow its procedure deviation review process to continue the start-up, as the furnace was transitioning out of a modified lockout.

Linde, as the licensor and engineering contractor, had provided documentation to Shell in accordance with its scope of work and responsibilities, including an "Operating Manual - Cracking Furnaces" with guidance on cleaning the coke trap.[b] The manual stated:

> The expected coke amount [of] an annual emptying of the coke traps should be considered. For emptying, the furnace has to be in a complete shutdown, isolated and cooled down.

The manual included a Normal Shutdown section that outlined the procedure for transitioning the furnace from cracking operation to shut down, including deactivation of the pilot burner system and isolation of the furnace. This included identifying locations of blinds and required spacers for Shell.

The CSB concludes that Shell's decision to keep the pilots lit during the coke trap cleaning made it impossible for its workers to comply with Shell's existing furnace cold start-up procedure and Shell's policy to control hazardous energy, both of which were administrative controls. Additionally, Shell did not provide an approved, alternative procedure for starting up the furnace from pilot-only mode. Because Shell did not comply with its own policies, the existing policies and procedures were ineffective at preventing the explosion and fire.

[a] According to Shell's furnace start-up procedure, the first pilot is not lit until late in the procedure at step 98.

[b] NFPA 86, *Standard for Ovens and Furnaces* 2023, is intended to minimize fire and explosion hazards of ovens and furnaces used for commercial and industrial processing of materials. NFPA states that it "shall be the responsibility of the furnace manufacturer to provide instructions for inspection, testing, and maintenance," while it "shall be the responsibility of the user to establish, schedule, and enforce the frequency and extent of the inspection, testing, and maintenance program, as well as the corrective actions taken" [56, p. 25].

Operator Response to an Alarm

Additionally, Shell's furnace firebox high-pressure alarm, carbon monoxide detection alarm, and methane detection alarm were all suppressed by design at the time of the incident.[a] Shell determined that these and other alarms were not needed when the furnace was shut down and had logic automatically turn them off so they would not be nuisance alarms during the shutdown period. Suppressing these alarms during the Furnace 5 start-up delayed the console operator from being alerted to and taking corrective actions for the accumulation of flammable gas in the firebox.

The CSB concludes that Shell identified and automatically suppressed safety-critical alarms while a furnace was down for maintenance, preventing operators from identifying that the furnace was filling with flammable cracked gas and taking corrective actions that could have prevented the explosion.

KEY LESSON

Facilities should not suppress safety-critical alarms without analyzing the hazards involved with silencing them in each plant mode of operation, such as start-up, normal operation, and shutdown [48, p. 33].

When the furnace-side valve was opened, an alarm indicating that the MOV was in an unexpected state was sent to the console operator. The text of the unexpected state alarm description for the furnace-side valve and the tower-side valve is identical, except for the last digit of the MOV's identification number. The console operator was aware of the PACO engineer's task and dismissed the alarm after assuming it was associated with the PACO engineer's activities. The console operator assumed the unexpected state alarm was on the tower-side valve, since they had discussed commanding it open.

The CSB concludes that the nearly identical alarm descriptors for the motor-operated valves made the reliance on an operator's response to the alarm indicating that a motor-operated valve was in an unexpected state an ineffective control to prevent an explosion. The console operator and process control engineer had discussed opening the tower-side valve, and the console operator assumed that the alarm was associated with that task.

Shell and Linde also designed the plant with the intent that the MOVs be controlled by a field operator who could observe valve positions. Additionally, Shell maintained a policy requiring the MOVs to be observed as they move. However, the local field control panel was not set up to remove the double isolation. Moreover, the tower-side valve was typically commanded open from an engineering workstation adjacent to the control room by a PACO engineer. Having a trained and qualified field operator perform the tasks using the local field control panel could have prevented the furnace-side MOV from being completely open before the tower-side MOV was opened.

The CSB concludes that Shell's policy that field operators open and close the motor-operated valves was an ineffective control to prevent an explosion because only a process control engineer could open the tower-side motor-operated valve by manipulating the safety instrumented system logic instead of a trained operator who would have knowledge that the furnace-side valve should have been closed.

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[a] In a suppressed-by-design alarm state, an alarm is suppressed based on operating conditions or plant mode of operation and not annunciated. An alarm in the suppressed-by-design state is under the control of logic that determines whether the alarm is relevant [48, pp. 24, 33].

Job Aids

The PACO engineer that Shell assigned to open the MOV had never performed the task before. The engineer was assigned the task during the daily production meeting and had to refer to a written job aid for opening the valve. After the incident, the steps in the job aid to select the mode of the SIS and issue the open command were found to be out of sequence. The SIS not being in the correct mode prevented the PACO engineer from opening the tower-side valve, and led to the MOV control screen refreshing when the correct mode was engaged, allowing the PACO engineer to inadvertently issue an open command to the furnace-side MOV.

The PACO engineer was monitoring a nearby operations console with a simplified process graphic and noticed that the tower-side valve was not opening. Realizing the furnace-side valve was now at the top of the SIS screen, the PACO engineer scrolled down the HMI and sent an open command to the tower-side valve without closing the furnace-side valve, believing (incorrectly) that the in-line furnace-side valve must have already been open before the open command was sent. The PACO engineer had limited process knowledge and was unable to appreciate the process hazards of commanding open the tower-side valve with the furnace-side valve open. This action allowed both MOVs to be open simultaneously, which violated Shell's policy to open only one MOV when removing the furnace isolation.

The CCPS Process Safety Monograph, *Human Factors Primer for Front Line Leaders*, focuses on the everyday decisions made by plant operations and maintenance front line leaders in their planning and conducting work. The monograph explains that:

> Job aids are any kind of instructional information designed to help people perform tasks consistently, safely, and effectively. The contributing factors of many major accidents have included problems with job aids that were unavailable, out-of-date, confusing, too complicated, lacking important information about the process or hazards, or status of maintenance tasks etc.
>
> Job aids should be created with a team that includes people experienced in performing the tasks and with good knowledge of the facility. Effective job aids also have a feedback mechanism. The intent of the job aid is to support operational discipline. Periodic reviews should be conducted to check that the job aids are being used correctly and are effective [40, p. 12].

The CSB concludes that Shell's written job aid was an ineffective administrative control because it did not list the correct sequence of steps to open a motor-operated valve. The process control engineer had to change modes in the safety instrumented system during the task due to the out-of-sequence steps, which forced the valve logic screen to refresh. Upon refreshing, the logic screen returned to the top and displayed the furnace-side valve, which was inadvertently opened. Additionally, the problematic job aid was ineffective in ensuring that only one valve was opened during the furnace start-up.

Safety Instrumented Systems Bypassing

Shell also had a policy requiring that an SIS bypass form be completed any time the SIS would be overridden if no procedure existed for the task. However, Shell told the CSB that it only required the SIS bypass form if Shell's Operations department opened the MOV, but not the PACO engineer. Upon review of this policy, the CSB did not find where this provision was stated. An excerpt of the SIS bypass form is shown in **Figure 19**.

Mitigation Plan	Prewritten Mitigation Procedure (URL for Procedure and Procedure Title for Description)	Is there a prewritten SIF override or mitigation procedure?	What is the mitigation plan if no procedure already exists? Clearly list what variables and tag names will be monitored as part of the mitigation plan. For ALL SIF and SCE Overrides, utilize the HAZOP register to ensure all major threat lines are covered.
		YES | NO	

Impairment Mitigation Continued	Define the safe operating window for each tag listed above, if applicable.	Name of Developer for this Safety Impairment Mitigations - type name, change status to propose, and save form	Approval Date/Time
			Date: Time:

Figure 19. Excerpt from Shell's SIS bypass form. (Credit: Shell)

This section of the form in **Figure 19** highlights how Shell requires a mitigation plan when overriding SIS protections. Specifically shown in the figure is a section that asks the overrider to "clearly list what variables and tag names will be monitored…". Had the PACO engineer been expected to complete a SIS bypass form, a well-developed mitigation plan could have identified the methane concentration sensor's tag as a safeguard, enabling monitoring and detection of gas accumulation in the furnace.

Shell had successfully used a process control engineering resource to command the opening of a tower-side MOV 19 times prior to the June 4, 2025, incident. In the CCPS series of Safe Work Practices, the *Safe Work Practice - Temporary Instrumentation and Controls Bypass* publication highlights the following to consider before bypassing instrumentation and controls logic:

> There may not be a direct pathway from the bypassing of a device to an incident. In some instances, even if it is bypassed, an event may not occur. How are you preventing normalization of deviation associated with this phenomenon (i.e., it has not happened before so it will not happen now)?
>
> Be aware that bypassing without consequences could lead to a false sense of security with operating and maintenance personnel [41, p. 3].

In addition to maintaining an active bypass audit program, the CCPS safe work practice also provides the following strategies and effective practices for companies to manage and mitigate hazards with bypassing:

> Ensure that the equipment to be worked on is correctly identified and labeled so that only the intended device will be bypassed.
>
> Ensure the operations and maintenance [engineering] personnel understand how the equipment and process control system works so that they do not inadvertently bypass or impair a safeguard.
>
> Communication is essential between the control room, the operating personnel and the people conducting the work [41, pp. 6-7].

The CSB concludes that Shell should have completed a safety instrumented system bypass form as the process control engineer was not exempted from the policy. Had the bypass form been completed, a mitigation plan would have been developed, and specific equipment tags would have been identified to watch while the motor-operated valve was forced open. The CSB further concludes that Shell's safety instrumented system bypass form policy was an ineffective administrative control because employees did not know what it required or how to comply with it.

3.1.2 Hazard Identification and Risk Analysis

In its 2023 revalidation of the ethane cracking unit process hazard analysis (PHA), Shell identified the explosion hazard in an offline furnace from misdirected/reverse flow when the furnace-side MOV failed to close while the tower-side MOV was open as an incident that could result in multiple fatalities (**Figure 20**).

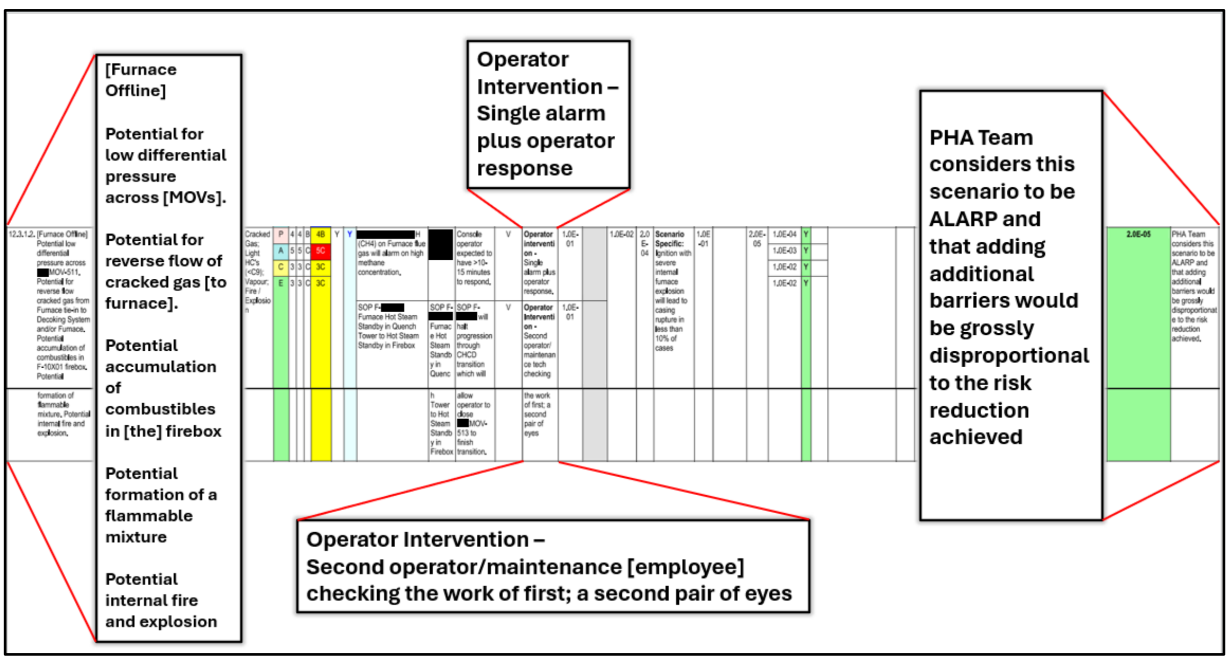


Figure 20. Excerpt from Shell's 2023 ethane cracking unit PHA revalidation. The excerpt identifies an explosion hazard caused by misdirected/reverse flow across the MOVs. (Credit: Shell, modified by CSB)

Shell identified two controls to prevent an explosion: operator response to a furnace high methane concentration alarm and a start-up procedure. Both are administrative controls. Neither of these controls was in effect the day of the incident, as the alarm was suppressed and the procedure evaluated by the PHA was not in use. Shell's PHA revalidation team believed that the two administrative controls were sufficient and that adding engineering controls would be "grossly disproportional to the risk reduction" they would provide.

The Shell PHA revalidation team also identified a separate cause of reverse flow of cracked gas during a furnace shutdown. The team determined that cracked gas could flow through a tubing bypass around a differential pressure transmitter between the quench tower and the furnace. The team recommended that management eliminate this risk of reverse flow. However, this recommendation was not accepted because Shell management determined the risk associated with reverse flow was tolerable.

KEY LESSON

Administrative controls should not be solely relied on to prevent fire and explosion scenarios, especially those identified as potentially fatal events.

In its book, *Guidelines for Revalidating a Process Hazard Analysis*, the CCPS provides a PHA Quality and Completeness Checklist for evaluating a PHA against quality and completeness criteria established by company and regulatory requirements [42, pp. 175-180]. The following checklist question in the CCPS book provides an example of the discussion that a PHA revalidation team should have when justifying the exclusive use of administrative controls for a potential explosion scenario:

> Did the PHA rely solely on safe work procedures or other administrative controls (e.g., operating procedures, lockout/tagout procedures, work permits, management of change [MOC]) to eliminate or reduce the severity of loss scenarios that could be serious if administrative controls are ignored or violated?

The CSB concludes that Shell actively chose to rely solely on administrative controls to prevent a potentially fatal explosion in its process hazard analysis revalidation.

The CSB recommends that Shell review the Shell Polymers Monaca Ethane Cracking Unit process hazard analysis to identify deviations addressed solely with administrative controls. Implement an inherently safer design or an engineered control for any scenario identified that could result in a fatality, serious injury, or substantial property damage.

3.1.3 Engineered Controls

Shell licensed the furnace and quench tower designs and technologies from Linde for its ethane cracking unit.[a,b] In its original design, Linde incorporated two interlocks[c] into Shell's local field control panel.

The first engineered control was a sequenced key interlock, which requires keys to be used in a certain order to open valves. Utilizing the keys with the local field control panel could have prevented the inadvertent valve opening because the SIS would not have been overridden, and the specific key sequence should have prevented the incorrect valve from opening.

The second engineered control would have automatically closed the furnace-side valve upon detecting the low pressure associated with backflow to the furnace. This engineering control was designed to be a safety integrity level (SIL) 2 interlock.[d]

However, although the local field control panel was able to operate both the tower-side and furnace-side MOVs, it was not programmed so the double isolation could be removed during the plant commissioning and startup. As such, Linde's engineered controls were not implemented when the furnace was in its double-isolated state.

Shell did not make its local field control panel capable of removing the double isolation prior to the explosion. Reprogramming the local field control panel had been identified as a potential future project and was on a list with many other improvement opportunities at the facility. Other projects were considered higher priority, however, and were funded, while Shell continued to task a PACO engineer to bypass the SIS and manipulate MOVs during furnace maintenance activities that required isolation.

The CSB concludes that Linde provided an engineered control to reduce the risk of cracked gas backflowing into a furnace. However, Shell did not set up the furnace's local field control panel to remove the double isolation from the furnace, thereby disabling Linde's engineered control when the furnace was in a double-isolated state.

The CSB recommends that Shell, based on licensor input and good industry practices, such as ANSI/ISA-61511-2-2018 / IEC 61511-2:2016, *Functional Safety – Safety Instrumented Systems for the Process Industry Sector – Part 2: Guidelines for the application of IEC 61511-1:2016* and *Part 3: Guidance for the Determination of the Required Safety Integrity Levels*, implement and maintain an engineered control to prevent backflow of cracked gas into a furnace during all modes of furnace operation.

[a] *See* Selas-Linde | The furnace experts [62].

[b] *See* Linde Petrochemical Processing [61].

[c] An interlock is a protective response that is initiated by an out-of-limit process condition, an instrument that will not allow one part of a process to function unless another part is functioning, or a device, such as a switch, that prevents a piece of equipment from operating when a hazard exists [72].

[d] A safety integrity level is a discrete level (one out of a possible four) for specifying the probability of a safety instrumented system satisfactorily performing the required safety instrumented functions under all of the stated conditions within a stated period of time. Safety integrity level 4 has the highest level of safety integrity and safety integrity level 1 has the lowest [59, p. 22, 63, p. 224].

3.1.4 POST-INCIDENT CHANGES

After the incident, Shell revised the Basic Process Control System (BPCS)[a] and SIS logic to enable Shell's Operations department to open and close the furnace-side, decoking, and tower-side MOVs from the local field control panel for Furnace 5. Additionally, Shell implemented new SIS logic that keeps the Furnace 5 tower-side MOV closed if a field operator mistakenly opens the furnace-side MOV. These control changes eliminated the need to involve a PACO engineer to manipulate any of the furnace MOV valves.

Shell also issued and provided training on an operating procedure for "Recovery from Double Isolation Maintenance," which provides written, step-by-step instructions and information for opening or closing either the furnace-side or tower-side MOV.

3.2 HUMAN-MACHINE INTERFACE

In chemical process facilities, HMIs serve as a vital communication channel between plant personnel and chemical processes, directly influencing process safety, product quality, and overall efficiency [43]. A well-designed HMI provides plant personnel with clear, context-specific information under both normal and abnormal conditions. This allows them to monitor and execute tasks effectively while minimizing errors. Conversely, a poor HMI hampers plant personnel response, introduces misunderstandings, and can lead to unintended consequences. In 1990, the late Professor (and safety expert) James Reason explained:

> [...] rather than being the main instigators of these disasters, those at the human-machine interface were the inheritors of system defects created by poor design, conflicting goals, defective organization and bad management decisions. Their part, in effect, was simply that of creating the conditions under which these latent failures could reveal themselves [38].

Therefore, it is essential that facilities have HMIs that support sound decision-making and reduce the likelihood of human error.

The development of industrial HMIs has traditionally been guided by standards from organizations such as the International Society of Automation (ISA) [43]. The ISA-101 series of standards and technical reports (TRs) provides a framework for designing, implementing, and managing HMIs to enhance safety, usability, and operational efficiency in industrial systems [44]. They include an American National Standards Institute (ANSI) standard, ANSI/ISA-101.01-2015, *Human-machine interfaces for Process Automation Systems*, along with two TRs: ISA-TR101.01-2022, *HMI Philosophy*, *and* ISA-TR101.02-2019, *HMI Usability and Performance*.

[a] A Basic Process Control System (BPCS) is "[a] system that responds to input signals from the process and its associated equipment, other programmable systems, and/or from an operator, and generates output signals causing the process and its associated equipment to operate in the desired manner and within normal production limits" [68].

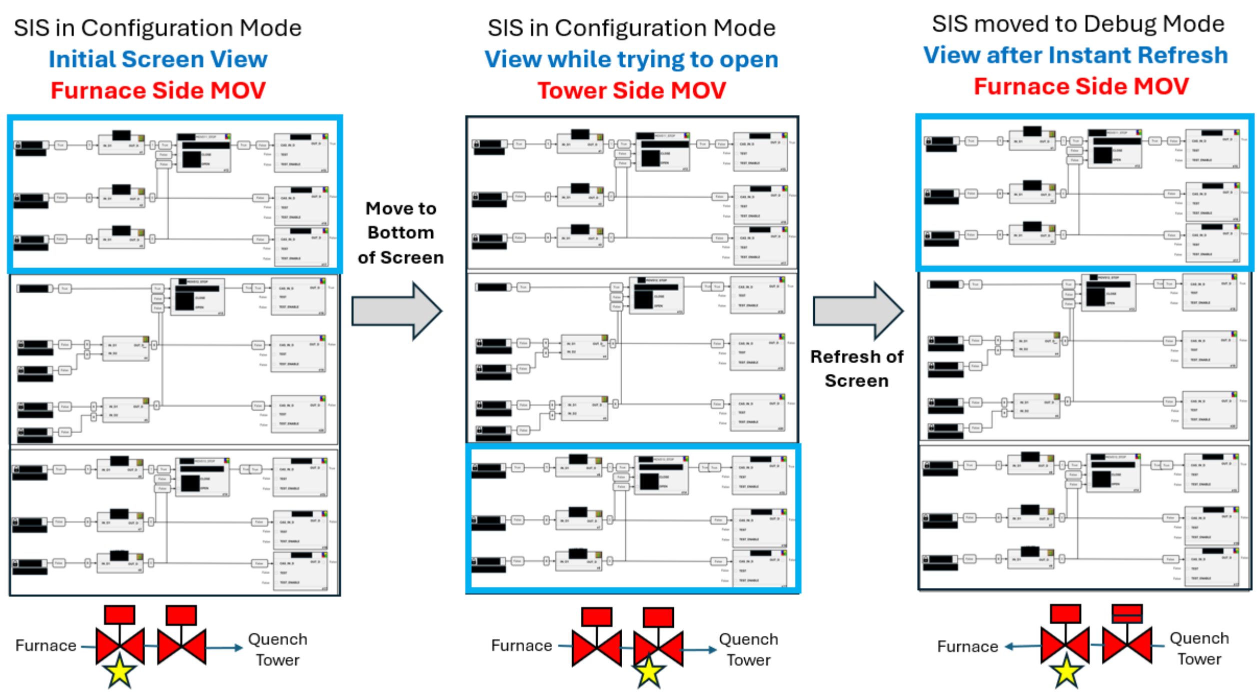
The ISA-101 standard and its TRs equip organizations with a framework for creating robust, user-friendly, and performance-driven HMIs. By adopting these standards, facilities can reduce operator error, improve situational awareness, and boost safety and compliance [44].[a]

3.2.1 Furnace Motor-Operated Valves HMI

Shell hired a process automation contractor to provide a control system HMI design specification for the new ethane cracking plant. The first version of the design specification was produced in 2016 and a second version was issued in 2017.

HMI displays often group data by physical equipment [45]. At Shell, the three MOVs at the outlet of the furnace were combined into a single screen of SIS logic arranged from top to bottom with the furnace-side MOV at the top, the decoking MOV in the middle, and the tower-side MOV at the bottom, and required scrolling to view the different valves (**Figure 14**). However, the approach of having the same type of physical equipment on the same screen can increase the risk of overlooking abnormal events [46].

Figure 21 shows how having the same type of equipment with similar descriptors on the same screen can increase the risk of selecting the wrong MOV. With nearly identical visual logic block layouts for the three MOVs on the same screen, the PACO engineer had no clear indication that they had issued an open command to a the wrong MOV after the screen refreshed, which created an inadvertent flow path for the cracked gas.



[a] A report on a serious injury incident at Georgia Pacific's Monticello, Mississippi facility involving an HMI can be found in CSB's Incident Reports - Volume 3 [55, pp. 59-60], located at Incident Reports - Volume 3.

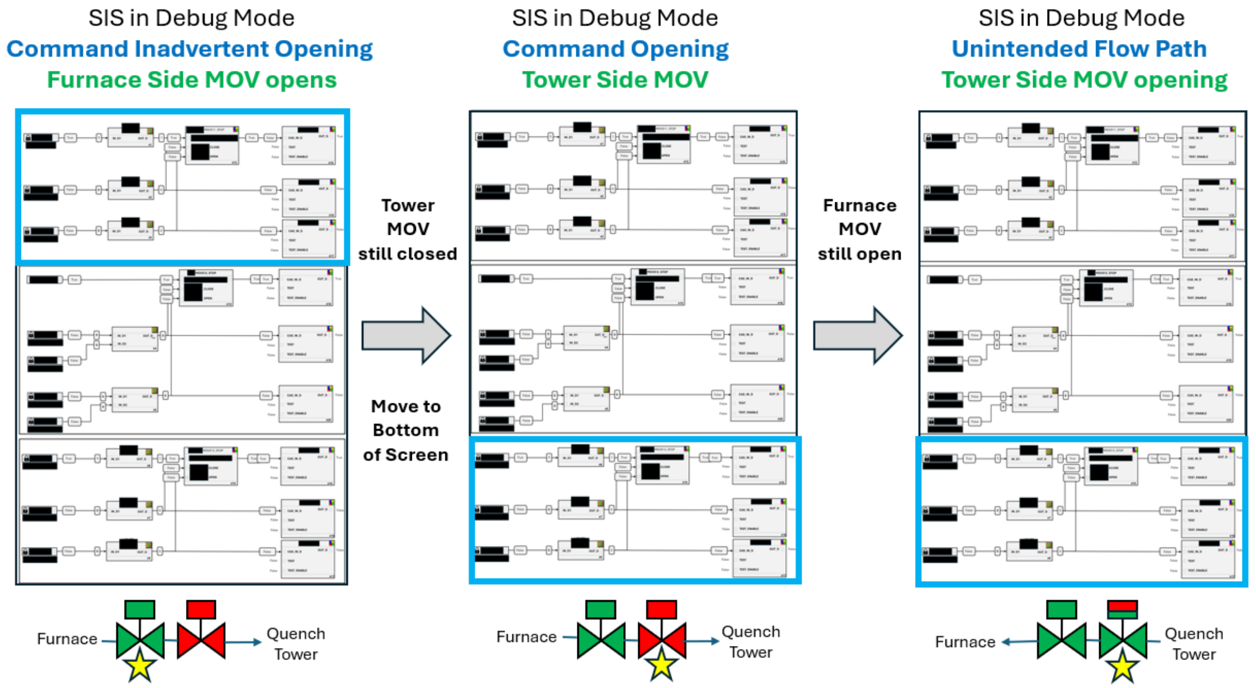


Figure 21. Sequence of events creating the unintended flow path to the furnace. The blue square indicates the approximate field of vision of the PACO engineer of the SIS display. The gold star indicates the MOV being commanded by the PACO engineer using the SIS logic. (Credit: CSB)

The CSB concludes that Shell's safety instrumented system logic screen human-machine interface for the furnace motor-operated valves contributed to the incident because it was not designed to reduce the likelihood that a process control engineer could select the incorrect motor-operated valve.

Density of Displayed Information[a]

Shell's "Detailed Design Specification for HMI" included general graphic conventions to be followed while creating HMIs for the new BPCS and SIS systems. Shell's guidance document specified that the facility should, wherever possible, (1) combine control logic groups from the same area/units into one [SIS Logic] graphic and (2) divide control logic cause and effects over multiple graphics based on the complexity and size of the cause and effects.

ISA guidance states that information presented to a user should be based on the display's function or purpose, tempered by human perception limits. If an initial HMI logic display presents too much information on a single screen, requiring scrolling from top to bottom, it may be excessive for a single screen and warrant a redesign. Redesign options include splitting the display into multiple, smaller displays or consolidating data into a single display with a lower overall screen density. Information presented to the user should be based on the results of the function and task analyses.

[a] The density of displayed information of an interface describes how many things one sees in a given space. A visually dense HMI puts a lot of information on the screen. A visually sparse HMI puts less information on the screen. The overall user interface density is the value a user gets from the interface divided by the time and space the interface occupies [64].

The CSB found no complexity or size restrictions in the Shell HMI Detailed Design Specification that would separate MOV 511, 512, and 513 across multiple graphics.

The CSB concludes that Shell did not provide adequate guidance for complexity and size requirements in its detailed design specification for the safety instrumented system logic human-machine interfaces. Had guidance for the density of display information in the safety instrumented system logic diagrams been provided, Shell could have separated the three safety instrumented system furnace motor-operated valves into different logic diagrams, eliminating the need to scroll between the valves to command them open or closed.

Task Analysis

To have an effective HMI to safely open an MOV at the outlet of an ethane cracking furnace, a task analysis should be conducted to understand anticipated user actions and ensure safety. ISA guidance calls for tasks to be evaluated at various stages, including normal operations, startup, shutdown, detection of abnormal situations, recovery from abnormal situations, and emergency shutdown/isolation.

For a new facility project like the Shell ethane cracker, ISA guidance states that the initial steps in developing a task analysis should include examining manufacturers' equipment manuals and evaluating practices at similar facilities, such as Shell's other ethane cracking plants. ISA suggests that facilities develop a task list of possible operator actions to consider, including: (i) physical equipment operations, such as operating a control valve or an on-off valve; (ii) logic block operations, such as a proportional-integral-derivative (PID) controller or a manual control station; and (iii) resetting interlock conditions. A task analysis should be revisited as often as necessary because the process is likely to have changed over time compared with any existing documentation, such as the job aid used by Shell on the day of the incident to open and close the furnace MOVs.

Shell's Human Factors Checklist for the 2023 PHA Revalidation also did not consider the operation of the MOVs from "Recovery from Double Isolation Maintenance" even though a PACO engineer had commanded the opening of a quench tower-side MOV over a dozen times (**Figure 22**).

2. CONTROL ROOM WORK ENVIRONMENT	1. Is the layout of the consoles logical, consistent and effective?	Yes
	2. Can process variables be adequately controlled with the existing equipment?	Yes

Figure 22. A section of Shell's Human Factors Checklist used in the 2023 ECU PHA Revalidation. The checklist indicates that the PHA Team did not document opening and closing the MOVs from the engineering workstation as a human factors issue. (Credit: Shell)

Command Entry

ANSI/ISA-101.01-2015 provides guidance on successful command entry. During the incident, an unsafe control action occurred when the PACO engineer provided an open command to the tower-side MOV after inadvertently opening the furnace-side MOV. The standard states that "commands that result in direct action to the process should require multiple input actions from the operator and not be possible from a single inadvertent input action […] users should have a method for canceling a command change during the change process or have a means for recovering quickly to prior configuration or both [47, p. 49] ."

Error Avoidance Methods

A facility's HMI philosophy should clearly indicate the error avoidance methods employed. Consideration should be given to error-avoidance techniques and confirmation steps for potentially hazardous operations, such as opening an MOV while other ethylene cracking furnaces are producing cracked gas, when a furnace's pilots are lit, or when abnormal conditions occur, such as a furnace's induced fan operating in speed control instead of the normal pressure control. It may be useful to reject entries outside of an approved range. Error avoidance methods should not hamper an operator's ability to make changes rapidly.

In such conditions, it would be appropriate to reject an SIS command entry to open the furnace-side valve before the tower-side valve is commanded open to prevent the creation of an unintended flow path and the accumulation of flammable gas in a furnace with the pilots lit. Events such as the explosion in Furnace 5 are the result of inadequate control and a lack of enforcement of safety constraints in system design and operations.

The CSB concludes that, without a task analysis, the safety instrumented logic human-machine interface used at Shell to command the Furnace 5 valves open and closed was not evaluated for the density of displayed information, adequate command entry methods, or the need for error avoidance methods to select the correct motor-operated valve to prevent a furnace explosion.

KEY LESSON

To help avoid unintended actions, an HMI should provide feedback indicating the selected action and allow the action to be canceled before it is executed. The close proximity and similarity of input options within a display area may lead users to select the wrong ones. Users should be able to cancel or modify an action if they determine that its execution would be undesirable [49, p. 291].

Labeling

Shell's HMI Design Specification provided guidance that descriptions in SIS logic graphics should be as comprehensive as possible and were limited to 40 characters. The document provided guidance for SIS logic graphics, including an example graphic for three pieces of cracked gas equipment, "A", "B", and "C" as shown in **Figure 23**.

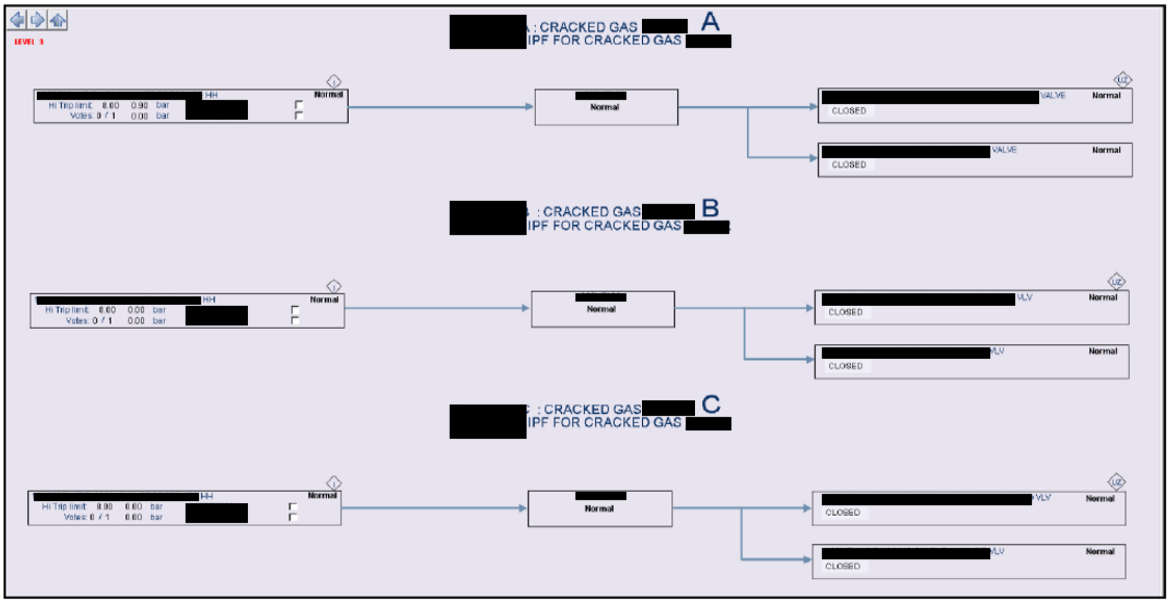


Figure 23. Example SIS graphic from the Detailed Design Specification for HMI at Shell Polymers Monaca showing the use of text labels to identify three pieces of cracked gas equipment as “CRACKED GAS [redacted] A”, “CRACKED GAS [redacted] B”, “CRACKED GAS [redacted] C”. (Credit: Shell, redacted by CSB)

The CSB found that Shell did not provide a description, such as “Furnace-Side MOV”, “Tower-Side MOV”, or “Decoking MOV”, that is “as comprehensive as possible” as the labels shown in the example graphic (**Figure 23**).

The CSB concludes that the absence of recommended labels for the three MOV’s on the SIS logic screen contributed to the incident by making it difficult for the process control engineer to notice that the logic screen had refreshed and moved the active zone from the bottom to the top of the screen, leading to the incorrect motor-operated valve being opened.

3.2.2 Post-Incident Changes

Shell eliminated the job aid after the incident and no longer uses the HMI with the SIS MOV logic to command the furnace MOVs open or closed. The job aid, developed during the facility's commissioning, is no longer needed because the practice of a PACO engineer sending commands directly to a furnace MOV has been discontinued.[a] Training was provided to all PACO engineers and operations personnel so that employees will know that the site PACO engineers are no longer required to command the opening or closing of the MOV valves, which would now be open and closed using the local field control panel.

[a] The commissioning of a facility involves the activities needed to transition from final construction to an operating facility. Commissioning involves not only the plant equipment but also the operating and maintenance personnel, as well as the facility documentation and written procedures [57].

4 Conclusions

4.1 Findings

Administrative Controls

1. All the controls Shell had in place to prevent backflow to the firebox when an isolation valve was open during the decoking process, at the time of the incident, were administrative controls.
2. All 11 controls that Shell identified failed because employees had not been adequately trained prior to this incident and lacked awareness of them or the ability to comply with them. The 11 controls that Shell relied on were not as effective as other, more robust, controls could have been. Had inherently safer design, engineering controls, or more robust administrative controls been in place, the June 4, 2025, incident could have been prevented.
3. Shell's decision to keep the pilots lit during the coke trap cleaning made it impossible for its workers to comply with Shell's existing furnace cold start-up procedure and Shell's policy to control hazardous energy, both of which were administrative controls. Additionally, Shell did not provide an approved, alternative procedure for starting up the furnace from pilot-only mode. Because Shell did not comply with its own policies, the existing policies and procedures were ineffective at preventing the explosion and fire.
4. Shell identified and automatically suppressed safety-critical alarms while a furnace was down for maintenance, preventing operators from identifying that the furnace was filling with flammable cracked gas and taking corrective actions that could have prevented the explosion.
5. The nearly identical alarm descriptors for the motor-operated valves made the reliance on an operator's response to the alarm indicating that a motor-operated valve was in an unexpected state an ineffective control to prevent an explosion. The console operator and process control engineer had discussed opening the tower-side valve, and the console operator assumed that the alarm was associated with that task.
6. Shell's policy that field operators open and close the motor-operated valves was an ineffective control to prevent an explosion because only a process control engineer could open the tower-side motor-operated valve by manipulating the safety instrumented system logic instead of a trained operator who would have knowledge that the furnace-side valve should have been closed.
7. Shell's written job aid was an ineffective administrative control because it did not list the correct sequence of steps to open a motor-operated valve. The process control engineer had to change modes in the safety instrumented system during the task due to the out-of-sequence steps, which forced the valve logic screen to refresh. Upon refreshing, the logic screen returned to the top and displayed the furnace-side valve, which was inadvertently opened. Additionally, the problematic job aid was ineffective in ensuring that only one valve was opened during the furnace start-up.

8. Shell should have completed a safety instrumented system bypass form as the process control engineer was not exempted from the policy. Had the bypass form been completed, a mitigation plan would have been developed, and specific equipment tags would have been identified to watch while the motor-operated valve was forced open.

9. Shell's safety instrumented system bypass form policy was an ineffective administrative control because employees did not know what it required or how to comply with it.

10. Shell actively chose to rely solely on administrative controls to prevent a potentially fatal explosion in its process hazard analysis revalidation.

11. Linde provided an engineered control to reduce the risk of cracked gas backflowing into a furnace. However, Shell did not set up the furnace's local field control panel to remove the double isolation from the furnace, thereby disabling Linde's engineered control when the furnace was in a double-isolated state.

Human-machine interface

1. Shell's safety instrumented system logic screen human-machine interface for the furnace motor-operated valves contributed to the incident because it was not designed to reduce the likelihood that a process control engineer could select the incorrect motor-operated valve.

2. Shell did not provide adequate guidance for complexity and size requirements in its detailed design specification for the safety instrumented system logic human-machine interfaces. Had guidance for the density of display information in the safety instrumented system logic diagrams been provided, Shell could have separated the three safety instrumented system furnace motor-operated valves into different logic diagrams, eliminating the need to scroll between the valves to command them open or closed.

3. Without a task analysis, the safety instrumented logic human-machine interface used at Shell to command the Furnace 5 valves open and closed was not evaluated for the density of displayed information, adequate command entry methods, or the need for error avoidance methods to select the correct motor-operated valve to prevent a furnace explosion.

4. The absence of recommended labels for the three MOV's on the safety instrumented system logic screen contributed to the incident by making it difficult for the process control engineer to notice that the logic screen had refreshed and moved the active zone from the bottom to the top of the screen, leading to the incorrect motor-operated valve being opened.

4.2 Cause

The CSB determined that the cause of the incident was the inadvertent simultaneous opening of both motor-operated valves that were being used to isolate the furnace. Opening both valves created a path for cracked gas to backflow and accumulate in the furnace's firebox, where an existing flame ignited the flammable vapors, resulting in the explosion. Contributing to the incident was assigning a PACO engineer with limited process knowledge to manipulate the valves, as well as Shell's use of ineffective administrative controls to prevent the backflow hazard and subsequent explosion. Also contributing to the incident was the safety instrumented system logic human-machine interface Shell used at the time of the incident to open the motor-operated valves, which combined all three valves on a single diagram without clear labels to distinguish them.

5 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:

5.1 Shell Polymers Monaca[a]

2025-05-I-PA-R1

Review the Shell Polymers Monaca Ethane Cracking Unit process hazard analysis to identify process deviations that are addressed solely with administrative controls. Implement an inherently safer design or an engineered control for any scenario identified that could result in a fatality, serious injury, or substantial property damage.

2025-05-I-PA-R2

Based on licensor input and good industry practices, such as ANSI/ISA-61511-2-2018 / IEC 61511-2:2016, *Functional Safety – Safety Instrumented Systems for the Process Industry Sector – Part 2: Guidelines for the application of IEC 61511-1:2016* and *Part 3: Guidance for the Determination of the Required Safety Integrity Levels*, implement and maintain an engineered control to prevent backflow of cracked gas into a furnace during all modes of furnace operation.

[a] As discussed in **Section 3.1.4** herein, after the incident, Shell implemented new controls that enable operations staff to open and close the furnace-side, decoking, and tower-side MOVs on Furnace 5 from a local field control panel, eliminating the need for a PACO engineer to manipulate any of the furnace MOV valves. Shell also implemented new SIS logic that keeps the Furnace 5 tower-side MOV closed if a field operator mistakenly opens the furnace-side MOV. Additionally, Shell issued -- and provided training on -- a new operating procedure that provides written step-by-step instructions and information for opening or closing either the furnace-side or tower-side MOV. Because of Shell's corrective actions, the CSB is not making any recommendations to Shell regarding these issues. However, the CSB urges Shell to ensure that the new controls are fully implemented and consistently adhered to for all the furnaces at the facility. Further, although the CSB is not making a recommendation to Shell regarding maintenance of the furnace coke traps, the CSB urges Shell to ensure that the furnace coke traps are cleaned on a periodic basis and in accordance with guidance provided by Linde.

6 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. Hazardous energy and potential ignition sources, such as lit pilots, should be controlled during maintenance activities.
2. Facilities should not suppress safety-critical alarms without analyzing the hazards involved with silencing them in each plant mode of operation, such as start-up, normal operation, and shutdown [48, p. 33].
3. Administrative controls should not be solely relied on to prevent fire and explosion scenarios, especially those identified as potentially fatal events.
4. To avoid unintended actions, an HMI should provide feedback indicating the selected action and allow the action to be canceled before it is executed. The close proximity and similarity of input options within a display area may lead users to select the wrong ones. Users should be able to cancel or modify an action if they determine that its execution would be undesirable [49, p. 291].

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Appendix A: Timeline

A1. October 2, 2022 – October 3, 2022

The Furnace 5 tower-side MOV was closed for the start-up of the new ethane cracking unit.

A2. November 15, 2022

The new Shell Polymers Monaca facility started production.

A3. May 6, 2023 – July 2, 2023

The Furnace 5 tower-side MOV was closed for Furnace 5 induced draft fan work.

A4. August 10, 2023 – September 1, 2023

The Furnace 5 tower-side MOV was closed for a Furnace 5 piping weld repair.

A5. November 8, 2024

The Furnace 5 tower-side MOV was closed for preventive maintenance.[a]

A6. Late March 2025

The Furnace 1 coke trap was opened and inspected. Coke was visible almost up to the manway **(Figure 5**).

A7. April 2025 – May 2025

Shell decided that the coke traps of all the furnaces would need to be cleaned. During a Shell Polymers Monaca site outage, the coke traps of Furnaces 1, 2, 3, and 7 were cleaned for the first time.

A8. May 30, 2025

The Furnace 5 coke trap was to be cleaned for the first time. The furnace-side and tower-side MOVs were closed, and Furnace 5 was set to pilot-only mode.

[a] Preventive maintenance seeks to reduce the frequency and severity of unplanned shutdowns by establishing a fixed schedule of routine inspection and repairs [70].

A9. May 31, 2025

Night shift completed the energy isolation of Furnace 5.[a]

A10. May 31, 2025 – June 3, 2025

The coke trap of Furnace 5 was cleaned without incident.

A11. June 1, 2025

Furnace 6 was shut down. It had been in ethane cracking mode.

A12. June 3, 2025

A12.1 9:20 a.m.

The Furnace 5 ID fan was changed from pressure control to speed control and set to approximately 163 revolutions per minute (RPM).

A12.2 1:40 p.m.

Power was restored to both the furnace-side and tower-side MOVs on Furnace 5.

A13. June 4, 2025

Furnace 7 was placed in HSSB mode. It had been in ethane cracking mode.

A13.1 8:00 a.m.

During the morning meeting to discuss transitioning Furnace 5 from pilot-only mode to HSSB, the PACO engineer was assigned the task of opening the tower-side MOV (**Figure 13**).

A13.2 12:19 p.m.

The PACO engineer requested assistance from an instrument and electrical technician to unlock the SIS.

[a] Energy isolation or the control of hazardous energy by Lock-out and Tag-out is a critical part of a strong all-around safety program [67].

A13.3 2:04 P.M.

The SIS was unlocked so that the PACO engineer could open the furnace-side MOV.

A13.4 2:13:47 P.M.

The PACO engineer enabled configuration mode on the SIS.

A13.5 2:14:28 P.M.

The Furnace 5 furnace-side MOV was commanded open by the PACO engineer in the SIS.

A13.6 2:16:46 P.M.

The PACO engineer realized that they had inadvertently issued an open command to the Furnace 5 furnace-side MOV and removed it.

A13.7 2:17:50 P.M.

The Furnace 5 tower-side MOV was commanded open by the PACO engineer in the SIS.

A13.8 2:20 P.M.

The ethane cracking unit console operator noticed that the Furnace 5 furnace-side MOV was open and that the Furnace 5 tower-side MOV was traveling open and immediately instructed the PACO engineer to close the tower-side MOV.

A13.9 2:20:39 P.M.

The Furnace 5 tower-side MOV was commanded to close by the PACO engineer via the SIS.

A13.10 2:20:45 P.M.

Cracked gas accumulated in the Furnace 5 firebox. The gas was ignited by a lit pilot, causing an explosion and subsequent fire.

A13.11 2:23:26 P.M.

The last visible flame was seen coming from the Furnace 5 firebox.

A13.12 2:23:30 P.M.

The tower-side valve on Furnace 5 was fully closed and seated, isolating the flammable cracked gas source from the Furnace 5 firebox.

APPENDIX B: DESCRIPTION OF SURROUNDING AREA

CUBIT Radius Report 1, 3, and 5 miles around 300 Frankfort Road, Monaca, PA 15061

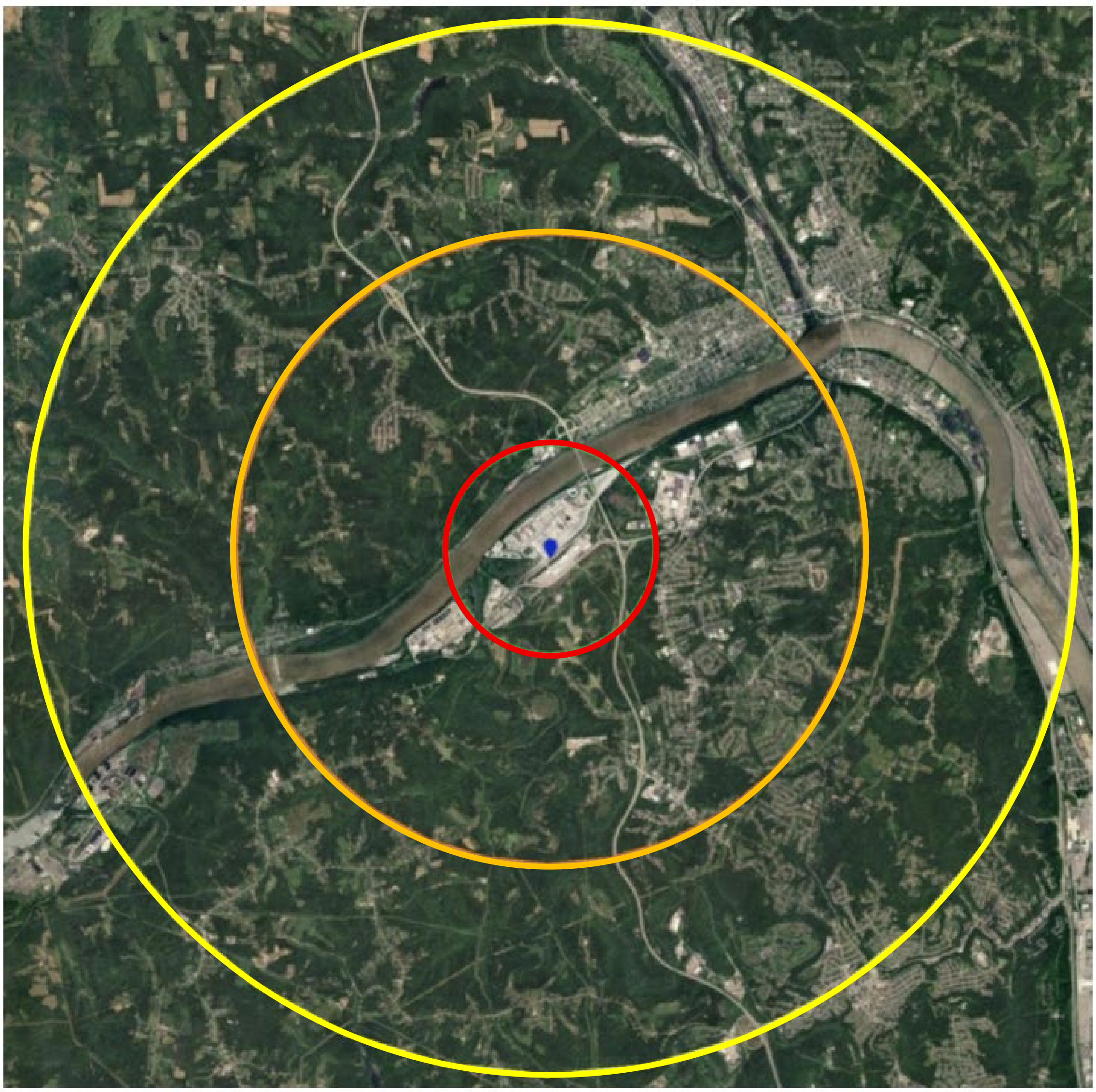
RADIUS REPORT FOR

1, 3, and 5 miles around
300 Frankfort Road, Monaca, PA 15061

PREPARED FOR: U.S. Chemical Safety and Hazard Investigation Board
DATE: March 05, 2026

Shell Polymers Monaca at 300 Frankfort Road

MAP



CUBIT Radius Report 1, 3, and 5 miles around 300 Frankfort Road, Monaca, PA 15061

DEMOGRAPHICS

Population

	1 mile	3 miles	5 miles
Population	787	18,940	53,890
Population Density (people per sq mi)	295	712	721

Source: U.S. Census Bureau, 2024 American Community Survey, Tables B01003

Income

	1 mile		3 miles		5 miles	
Median Household Income (in 2024 inflation adjusted dollars)	$62,989		$85,738		$74,455	
Average Household Income (in 2024 inflation adjusted dollars)	$86,624		$107,547		$97,632	
Families in Poverty	6	3%	181	3%	885	6%
Households	377		8,183		23,474	
Less than $25,000	34	9%	900	11%	3,352	14%
$25,000 to $49,999	129	34%	1,608	20%	4,510	19%
$50,000 to $74,999	55	15%	1,147	14%	3,961	17%
$75,000 to $99,999	36	10%	1,017	12%	3,014	13%
$100,000 to $199,999	95	25%	2,506	31%	6,400	27%
Over $200,000	28	7%	1,006	12%	2,237	10%

Source: U.S. Census Bureau, 2024 American Community Survey, Tables B19001, B19013, B19025, B17010

Age

	1 mile		3 miles		5 miles	
Median Age	50		44		44	
Population	787		18,940		53,890	
Ages 9 & under	50	6%	1,898	10%	5,696	11%
Ages 10 to 19	82	10%	2,589	14%	6,360	12%
Ages 20 to 29	76	10%	1,712	9%	5,416	10%
Ages 30 to 39	77	10%	2,133	11%	6,364	12%
Ages 40 to 49	103	13%	2,630	14%	7,111	13%
Ages 50 to 59	153	19%	2,490	13%	7,234	13%
Ages 60 to 69	133	17%	2,344	12%	7,328	14%
Ages 70 & over	113	14%	3,145	17%	8,382	16%

Source: U.S. Census Bureau, 2024 American Community Survey, Tables B01001

CUBIT Radius Report 1, 3, and 5 miles around 300 Frankfort Road, Monaca, PA 15061

Race & Ethnicity

	1 mile		3 miles		5 miles	
Population	787		18,940		53,890	
White	697	89%	17,564	93%	48,142	89%
Black	35	4%	488	3%	2,236	4%
American Indian	0	0%	8	0%	26	0%
Asian	2	0%	57	0%	210	0%
Pacific Islander	0	0%	0	0%	0	0%
Other race	1	0%	37	0%	58	0%
Two or more races	27	3%	436	2%	2,033	4%
Hispanic or Latino	26	3%	349	2%	1,185	2%

Source: U.S. Census Bureau, 2024 American Community Survey, Tables B03002

Educational Attainment

	1 mile		3 miles		5 miles	
Population Aged 25 & Over	634		13,835		39,465	
No high school diploma	15	2%	356	3%	1,820	5%
High school graduate or equal	279	44%	4,134	30%	13,225	34%
Some college	135	21%	2,570	19%	6,855	17%
Associate's degree	62	10%	1,667	12%	5,082	13%
Bachelor's degree	107	17%	3,530	26%	8,478	21%
Advanced degree	36	6%	1,577	11%	4,004	10%

Source: U.S. Census Bureau, 2024 American Community Survey, Tables B15002

Employment Status

	1 mile		3 miles		5 miles	
Population Aged 16 & Over	683		15,478		44,106	
In labor force	400	59%	9,819	63%	27,890	63%
Civilian labor force	400	59%	9,810	63%	27,839	63%
Employed	378	55%	9,264	60%	26,355	60%
Unemployed	22	3%	545	4%	1,484	3%
In armed forces	0	0%	10	0%	51	0%
Not in labor force	283	41%	5,658	37%	16,215	37%

Source: U.S. Census Bureau, 2024 American Community Survey, Tables B23025

CUBIT Radius Report 1, 3, and 5 miles around 300 Frankfort Road, Monaca, PA 15061

Households

	1 mile		3 miles		5 miles	
Households	377		8,183		23,474	
Family households	221	59%	5,206	64%	14,652	62%
Married couples	181	48%	4,379	54%	11,459	49%
With kids under 18	47	12%	1,747	21%	4,014	17%
Other family types	40	11%	827	10%	3,193	14%
Single dad households with kids	4	1%	115	1%	510	2%
Single mom households with kids	10	3%	196	2%	1,048	4%
Non-family households	156	41%	2,977	36%	8,822	38%

Source: U.S. Census Bureau, 2024 American Community Survey, Tables B11001, B11003

Homes

	1 mile		3 miles		5 miles	
Homes	417		8,700		25,506	
Occupied Homes	377		8,183		23,474	
Owner occupied units	214	57%	5,992	73%	16,633	71%
Renter occupied units	162	43%	2,191	27%	6,841	29%

Source: U.S. Census Bureau, 2024 American Community Survey, Tables B25024, B25003

Housing Unit Value

	1 mile		3 miles		5 miles	
Median Home Value	$210,992		$247,097		$215,895	
Owner Occupied Homes	214		5,992		16,633	
Under $100,000	29	14%	428	7%	2,196	13%
$100,000 to $199,999	69	32%	1,300	22%	5,238	31%
$200,000 to $299,999	71	33%	2,477	41%	5,054	30%
$300,000 to $399,999	19	9%	968	16%	2,135	13%
$400,000 to $499,999	7	3%	428	7%	1,142	7%
$500,000 to $749,999	11	5%	288	5%	665	4%
$750,000 to $999,999	9	4%	73	1%	131	1%
$1,000,000 to $1,499,999	1	0%	21	0%	40	0%
$1,500,000 to $1,999,999	0	0%	1	0%	2	0%
Over $2,000,000	0	0%	9	0%	30	0%

Source: U.S. Census Bureau, 2024 American Community Survey, Tables B25075

CUBIT **Radius Report** 1, 3, and 5 miles around 300 Frankfort Road, Monaca, PA 15061

Detailed Age

	1 mile		3 miles		5 miles	
Population	787		18,940		53,890	
Male:	409	52%	9,183	48%	25,949	48%
Under 5 years	11	1%	448	2%	1,205	2%
5 to 9 years	6	1%	373	2%	1,466	3%
10 to 14 years	18	2%	715	4%	1,673	3%
15 to 17 years	23	3%	391	2%	998	2%
18 and 19 years	3	0%	347	2%	673	1%
20 years	0	0%	79	0%	163	0%
21 years	5	1%	43	0%	150	0%
22 to 24 years	2	0%	181	1%	753	1%
25 to 29 years	34	4%	620	3%	1,636	3%
30 to 34 years	12	2%	348	2%	1,379	3%
35 to 39 years	30	4%	664	4%	1,710	3%
40 to 44 years	15	2%	671	4%	2,148	4%
45 to 49 years	44	6%	722	4%	1,581	3%
50 to 54 years	39	5%	683	4%	1,853	3%
55 to 59 years	39	5%	558	3%	1,706	3%
60 and 61 years	4	1%	259	1%	953	2%
62 to 64 years	5	1%	196	1%	812	2%
65 and 66 years	9	1%	246	1%	649	1%
67 to 69 years	59	7%	405	2%	954	2%
70 to 74 years	15	2%	532	3%	1,487	3%
75 to 79 years	13	2%	385	2%	1,055	2%
80 to 84 years	17	2%	194	1%	491	1%
85 years and over	4	1%	124	1%	457	1%
Female:	379	48%	9,758	52%	27,941	52%
Under 5 years	15	2%	459	2%	1,293	2%
5 to 9 years	18	2%	618	3%	1,732	3%
10 to 14 years	22	3%	562	3%	1,592	3%
15 to 17 years	14	2%	394	2%	1,039	2%
18 and 19 years	1	0%	180	1%	388	1%
20 years	8	1%	54	0%	96	0%
21 years	3	0%	125	1%	439	1%
22 to 24 years	3	0%	137	1%	768	1%
25 to 29 years	21	3%	474	3%	1,411	3%
30 to 34 years	23	3%	564	3%	1,540	3%
35 to 39 years	11	1%	558	3%	1,734	3%
40 to 44 years	37	5%	720	4%	1,867	3%
45 to 49 years	7	1%	516	3%	1,515	3%
50 to 54 years	25	3%	603	3%	1,841	3%
55 to 59 years	50	6%	646	3%	1,834	3%
60 and 61 years	11	1%	227	1%	858	2%
62 to 64 years	11	1%	435	2%	1,391	3%
65 and 66 years	19	2%	252	1%	669	1%
67 to 69 years	16	2%	325	2%	1,043	2%
70 to 74 years	19	2%	861	5%	1,904	4%
75 to 79 years	11	1%	313	2%	1,079	2%
80 to 84 years	26	3%	458	2%	1,006	2%
85 years and over	7	1%	278	1%	902	2%

Source: U.S. Census Bureau, 2024 American Community Survey, Tables B01001, B01003. The numbers in the above table may not total up due to rounding.

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ADDITIONAL INFORMATION

Units in Structure

	1 mile		3 miles		5 miles	
Summary Table						
Total housing units:	**417**		**8,699**		**25,506**	
Single unit	339	81%	7,018	81%	20,197	79%
Multi-unit	74	18%	1,614	19%	5,029	20%
Mobile home	3	1%	65	1%	274	1%
Boat, RV, van, etc.	1	0%	4	0%	4	0%

Detailed Table						
Total housing units:	**417**		**8,699**		**25,506**	
1, detached	271	65%	6,484	75%	18,963	74%
1, attached	68	16%	534	6%	1,234	5%
2 units	20	5%	201	2%	926	4%
3 or 4 units	31	7%	610	7%	1,404	6%
5 to 9 units	10	2%	192	2%	747	3%
10 to 19 units	6	1%	249	3%	682	3%
20 to 49 units	6	1%	228	3%	767	3%
50 or more units	1	0%	134	2%	503	2%
Mobile home	3	1%	65	1%	274	1%
Boat, RV, van, etc.	1	0%	4	0%	4	0%

Source: U.S. Census Bureau, 2024 American Community Survey, Tables B25024

APPENDIX C: OSHA CITATIONS

OSHA issued the following citations on December 1, 2025, to Shell:

1. 29 C.F.R § 1910.119 (e)(3)(i): The Process Hazard Analysis (PHA) did not address the hazards of the process: a) In the Ethane Cracking Unit (ECU), on or about June 4, 2025 – The PHA did not cover the hazards of the process during decoking operations and the subsequent startup to return to normal cracking operations. Failure to address the hazards of the process allowed MOV-511 and MOV-513 to be inadvertently opened at the same time allowing cracked gas to enter the Furnace #5 firebox from the cracked gas header resulting in an explosion and fire.[a]

2. 29 C.F.R. § 1910.119(e)(3)(vi): The PHA did not address human factors: a) In the ECU, on or about June 4, 2025 - The employer's PHA did not consider or adequately address human factors for non-routine operations such as what happens if a critical step is performed wrong when MOV-511 and MOV-513 are returned to normal operation after being isolated for furnace maintenance. Failure to address human factors in the PHA allowed MOV-511 and MOV-513 to be inadvertently opened at the same time, allowing cracked gas to enter the Furnace #5 firebox from the cracked gas header, resulting in an explosion and fire.

3. 29 C.F.R. § 1910.119 (f)(1)(i)(C): The employer did not develop and implement written operating procedures that provide clear instructions for safely conducting temporary operations: a) In the ECU, on or about June 4, 2025 - The employer did not develop and implement written operating procedures that provide clear instructions for safely conducting temporary operations such as returning motor-operated valves (MOVs) to normal operation after being isolated for furnace maintenance. Failure to develop and implement clear instructions allowed MOV-511 and MOV-513 to be inadvertently opened at the same time allowing cracked gas to enter the Furnace #5 firebox from the cracked gas header resulting in an explosion and fire.

[a] MOV-511 is the furnace-side MOV, and MOV-513 is the tower-side MOV. The decoking MOV also had to be open to allow cracked gas to accumulate in Furnace 5. *See* **Figure 12** and **Figure 16**.

U.S. Chemical Safety and Hazard Investigation Board

Members of the U.S. Chemical Safety and Hazard Investigation Board:

Steve Owens
Chairperson

Sylvia E. Johnson, Ph.D.
Member