U.S. Chemical Safety and
Hazard Investigation Board

Ethylene Release and Fire at Kuraray America, Inc. EVAL Plant

Pasadena, Texas | *Incident Date: May 19, 2018* | **No. 2018-03-I-TX**

Investigation Report

Published: December 16, 2022

SAFETY ISSUES:

- Emergency Pressure-Relief System Discharge Design
- Presence of Nonessential Workers During Startup and Upset Conditions
- Hazardous Location
- Recognized and Generally Accepted Good Engineering Practices
- Process Hazard Analysis Safeguards
- Process Hazard Analysis Recommendations
- Warning Signs
- Equipment Design
- Operating Procedures
- Operator Training
- Abnormal Operating Conditions
- Safety Interlock Disabling
- Alarm Management
- Process Alarm Response
- Safe Operating Limits
- Environmental Permit Limits
- Management System Self-Assessment Audits

U.S. Chemical Safety and Hazard Investigation Board

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Abbreviations

°F	degrees Fahrenheit
ACC	American Chemistry Council
ANSI	American National Standards Institute
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
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
EVAL	ethylene and vinyl alcohol copolymer
HIPS	high-integrity protection system
HRVOC	highly reactive volatile organic compound
ISA	International Society of Automation
ISOM	Isomerization
LOPC	loss of primary containment
MOC	Management of Change
NFPA	National Fire Protection Association
OSHA	U.S. Occupational Safety and Health Administration
PCV	pressure control valve
PHA	Process Hazard Analysis
PRD	pressure-relief device
psi	pounds per square inch (gauge pressure)
PSM	Process Safety Management (the OSHA PSM Standard)
PSSR	Pre-Startup Safety Review
RAGAGEP	Recognized and Generally Accepted Good Engineering Practices
RMP	Risk Management Plan
SDS	Safety Data Sheet
SPA	Safeguard Protection Analysis
VOC	volatile organic compound

Executive Summary

At 10:28 a.m. on Saturday, May 19, 2018, an ethylene release caught on fire, injuring 23 workers at the Kuraray America, Inc. (Kuraray) ethylene and vinyl alcohol copolymer (EVAL) plant in Pasadena, Texas.[a] At the time of the incident, 266 employees and contract workers were onsite.

The incident occurred during a chemical reactor system (EVAL Reactor 2) startup following a scheduled maintenance shutdown (turnaround). High-pressure conditions developed inside the reactor and activated the reactor's emergency pressure-relief system, discharging flammable ethylene vapor—through horizontally aimed piping—into the ambient air in an area where a number of contractors were working. These workers were performing various tasks that were not essential to the startup of the reactor, including welding, which likely ignited the ethylene vapor cloud, causing the fire. Kuraray reported that 2,347 pounds of ethylene were released in less than three minutes. When the pressure inside the reactor dropped sufficiently below the activation pressure, the spring-loaded emergency pressure-relief valve closed, extinguishing the fire.

Workers in the immediate area tried to escape from the ethylene release and fire. While fleeing, some workers were injured as they jumped from the second or third story of the plant structure and ran or otherwise exited from the area, tripping and falling or suffering sprains and other injuries along the way. Other workers were wearing fall protection equipment that physically attached them to structures in the area, which delayed their escape from the fire and increased the severity of their injuries.

Two injured workers were life-flighted from the Kuraray facility. One contract worker remained in critical condition for several days from life-threatening burns but survived. Emergency responders transported as many as 19 other injured workers to off-site medical facilities for treatment.

Cause

The U.S. Chemical Safety and Hazard Investigation Board (CSB) determined that the cause of the incident was Kuraray's long-standing emergency pressure-relief system design that discharged flammable ethylene vapor through horizontally aimed piping into the air, near workers. Had Kuraray's emergency pressure-relief system discharged vapor from the reactor to a **safe location,** the flammable ethylene gas should not have harmed any workers.

Kuraray's long chain of weakly implemented management system elements that made up its overall process safety management system also contributed to the incident. In addition to the management system elements that Kuraray used to manage the EVAL reactor's emergency pressure-relief system, other elements contributed by allowing high-pressure conditions to develop inside the chemical reactor system (EVAL Reactor 2). The combination of these ineffective management system elements culminated with the reactor's emergency pressure-relief system activating and discharging flammable

[a] Kuraray's EVAL Plant was covered by both the U.S. Occupational Safety and Health Administration (OSHA) Process Safety Management (PSM) Standard and the U.S. Environmental Protection Agency (EPA) Risk Management Plan (RMP) Rule.

ethylene vapor into the air, where it ignited near nonessential workers (that is, workers who were not essential to the startup of the chemical reactor).

Kuraray's safety management systems also fostered inconsistent practices for keeping nonessential personnel from being physically present within the unit during critical events and activities—such as unit startups or when upset process conditions develop—which contributed to the injuries suffered. Kuraray could have prevented these injuries by implementing a policy to exclude workers not involved in the startup. Furthermore, Kuraray could have taken protective actions during upset conditions to prevent worker injuries. For example, when the reactor's high-pressure alarm sounded (signaling upset conditions), Kuraray should have stopped work and evacuated the workers from the area.

Safety Issues

The CSB's investigation identified and evaluated the following safety issues:

1. **Emergency Pressure-Relief System Discharge Design**. This CSB investigation report details a chain of process safety management system failures that led to excessive pressure being generated within Kuraray's EVAL Reactor 2. Kuraray protected this reactor with a safety system that lowered this excess pressure by discharging flammable ethylene vapor into the air. Of all the factors that contributed to injuring the 23 workers, **none** was more significant than the design of the outlet piping from the reactor's emergency pressure-relief system, which caused the release to be aimed toward an area where workers were present. Had Kuraray designed this piping to discharge the flammable ethylene vapor to a safe location, this incident could have unfolded in precisely the same sequence—but without harming people. With well-designed outlet piping, the emergency pressure-relief system should have discharged the excess flammable ethylene vapor vertically upward, well above and safely away from workers.

   The CSB has historically advocated against discharging flammable vapor into the ambient air when a flare system can serve both to contain the flammable vapor and then combust (destroy, dispose, or burn) it safely. The CSB has stated that a flare system is an inherently safer option compared with dispersing flammable vapor into the atmosphere. Nevertheless, industry standards do provide users with guidance for directing flammable vapor vertically upward into the ambient air safely. Moreover, the American Petroleum Institute (API) Standard 521 addresses many concerns about releasing flammable vapor directly into the atmosphere and generally requires using inherently safer alternatives when the potential exists for a flammable vapor cloud explosion.

   Ensuring that emergency pressure-relief systems discharge to a safe location is not a new safety lesson nor a novel process safety concept. Past chemical disasters have caused great harm to people by discharging chemicals from emergency pressure-relief systems in an unsafe manner. These disasters include the Union Carbide disaster in Bhopal, India, in 1984 and the BASF tragedy in Cincinnati, Ohio, in 1990, both of which involved discharging chemicals from emergency pressure-relief systems in a manner that caused great harm to people. Notably, the BASF event resulted from not ensuring that a reactor's emergency pressure-relief system discharged flammable chemicals to a safe location.

The facts, conditions, and circumstances of the May 19, 2018, incident show that the emergency pressure-relief system for Kuraray's EVAL Reactor 2 did not discharge to a safe location. Had Kuraray applied the lessons provided by earlier chemical disasters, the company could have prevented the May 19, 2018, incident by ensuring the EVAL Reactor 2 emergency pressure-relief system discharged the flammable ethylene vapor to a safe location with no harm to people. (*See* Section 2.1)

2. **Presence of Nonessential Workers During Startup and Upset Conditions**. At the time of the incident, none of the contract workers near the EVAL Reactor 2 emergency pressure-relief system were essential to the startup, nor were they responding to the upset process conditions that led to the emergency release. When the flammable ethylene vapor discharged from the reactor's emergency pressure-relief system, many of these nonessential workers were in harm's way, and the welding work they were performing likely supplied the ignition source that created the fire. Although Kuraray had an unwritten safety practice to exclude nonessential personnel from a unit when reintroducing (pressuring or charging) ethylene into equipment after a turnaround, the company did not establish a formal exclusion zone to protect nonessential workers for the duration of the startup. In addition, neither Kuraray's operating procedures nor its operator training covered the known activities or conditions that should have prompted Kuraray's operations personnel to exclude nonessential workers from the unit. One way that Kuraray could have protected the nonessential workers was to ensure that they were immediately evacuated from the unit when the EVAL Reactor 2 High-High-Pressure alarm sounded—signaling upset conditions within the process. But Kuraray's process safety management systems did not consider the high-pressure conditions developing inside EVAL Reactor 2 as an upset condition that should halt the maintenance work and prompt an evacuation of nonessential workers. (*See* Section 2.2)

3. **Hazardous Location**.[a] In the context of the Kuraray incident, hazardous location describes the area with increased fire and explosion risk to workers resulting from the horizontal orientation of the reactor's emergency pressure-relief system outlet piping. With workers present, activating this safety system created a danger to their safety. The sequence of events that led to high pressure inside EVAL Reactor 2 on the day of the incident was only one of many scenarios that could activate the reactor's emergency pressure-relief system. Other known scenarios, which could arise at nearly any time, could have also built high pressure inside the reactor and triggered a similar flammable ethylene vapor release from the emergency pressure-relief system. These events included cooling failure, loss of refrigeration, power failure, or even a simple control valve malfunction. Because the reactor's emergency pressure-relief system did not discharge the flammable ethylene vapor to a safe location, a portion of the area adjacent to EVAL Reactor 2 presented a safety risk to workers and thus was a hazardous location. (*See* Section 2.3)

4. **Recognized and Generally Accepted Good Engineering Practices**. The phrase recognized and generally accepted good engineering practices (RAGAGEP) stems from the Occupational Safety and

[a] Hazardous location is a phrase typically used in the context of electrical equipment classification and the control of ignition sources. Hazardous location may also refer to the practice of setting up a safety boundary around certain chemical processing areas. For example, boundaries are sometimes set around areas that process, handle, or store chemicals such as strong acids or bases because of the increased chemical exposure risk. Before physically entering this type of hazardous location, workers may be required to upgrade their personal protective equipment, such as wearing goggles, a face shield, or a chemical suit.

Health Administration's (OSHA) Process Safety Management Standard. Under this regulation, OSHA requires employers to document that their equipment complies with RAGAGEP. Kuraray should have thoroughly evaluated whether its EVAL Reactor 2 emergency pressure-relief system met existing good engineering practices. The horizontally aimed discharge piping from this emergency pressure-relief system deviated from industry standards. Consequently, Kuraray should have performed an evaluation such as a dispersion and consequence analysis. In doing so, the safety risk to workers from a potential horizontal discharge of flammable vapor could have been identified, the outlet piping design problem could have been corrected, and the company could have prevented the May 19, 2018, incident. (*See* Section 2.4)

5. **Process Hazard Analysis Safeguards**. Federal process safety regulations (OSHA and EPA) require that companies like Kuraray periodically perform safety reviews, called process hazard analyses (PHAs), to identify, evaluate, and control process hazards. During these PHA reviews, companies identify their existing safeguards, including devices, systems, and actions that can stop a hazardous chain of events or lessen the consequence of a hazard. In 2015, Kuraray's PHA team identified three existing safeguards that should have controlled high-pressure conditions inside EVAL Reactor 2 without activating the emergency pressure-relief system. On the day of the incident, however, none of these safeguards were effective in preventing the EVAL Reactor 2 emergency pressure-relief system from activating. Because these safeguards were ineffective, high-pressure conditions inside the reactor reached the activation pressure of the emergency pressure-relief system, resulting in the discharge of flammable ethylene vapor toward workers. (*See* Section 2.5)

6. **Process Hazard Analysis Recommendations**. Safety recommendations stemming from a PHA must be resolved and documented. In 2015, Kuraray's PHA team developed a safety recommendation addressing worker safety concerns related to potential ethylene releases from emergency pressure-relief systems. Implementation of this safety recommendation could have led Kuraray to prevent the May 19, 2018, incident. Kuraray could have identified the safety risk to workers and corrected the reactor's emergency pressure-relief system design problem. But Kuraray declined to implement the safety recommendation, and consistent with the company's safety policy, its management team did not document its evaluation or reasoning for doing so. (*See* Section 2.6)

7. **Warning Signs**. Warning signs are indicators that something is wrong or may soon go wrong. In its investigation of the May 19, 2018, ethylene release and fire, the CSB found several pre-incident warning signs at Kuraray. For example, dangerous releases of flammable ethylene from emergency pressure-relief devices at the EVAL plant had previously occurred. In addition, Kuraray's own hazard review team had cautioned that ethylene vapor cloud explosions could occur when some of these safety systems discharged flammable ethylene vapor into the air. These events should have served as warnings about the serious design problem with some of Kuraray's emergency pressure-relief systems. Had Kuraray effectively recognized and acted on these earlier warnings, the company could have corrected its emergency pressure-relief systems to discharge to a safe location, preventing the May 19, 2018, incident. (*See* Section 2.7)

8. **Equipment Design**. An important adage in human performance safety guidance is "making it easy for people to do things right and hard for them to do things wrong" [1, p. 1]. Based on equipment design pressures, each of Kuraray's four EVAL reactors had an emergency pressure-relief system

designed to activate at a pressure of 1,150 pounds per square inch (psi), except for EVAL Reactor 2.[a] Kuraray designed the EVAL Reactor 2 emergency pressure-relief system to activate at 740 psi, which was 410 psi lower than the designed activation pressure of the other three reactors. Despite this significant difference in the design pressure for EVAL Reactor 2, Kuraray's control system did not provide workers with any special or unique warnings to help its board operators recognize that this reactor was different. When Kuraray's board operators saw high-pressure conditions inside EVAL Reactor 2, they did not treat it as an emergency. They did not remember that EVAL Reactor 2's safety system activated at a lower pressure than the other three EVAL reactors. (*See* Section 2.8)

9. **Operating Procedures**. Up-to-date written operating procedures that reflect current plant practices are necessary for the safe operation of a facility. Kuraray management supplied its operations team with nightly operating instructions that conflicted with the company's written operating procedures and resulted in unmanaged changes during the reactor startup. Kuraray's operators followed some nightly management instructions that deviated from the written operating procedures during the EVAL Reactor 2 startup, which contributed to the incident. For example, the nightly operating instructions that Kuraray management provided its board operators targeted a reactor pressure that was 100 psi higher than what the company's operating procedures called for, which narrowed the available gap between the targeted operating pressure and the emergency pressure-relief system's activation pressure. (*See* Section 2.9)

10. **Operator Training**. Training provides workers with the communication of knowledge and skills they need to perform tasks. In chemical manufacturing plants, training communicates important process knowledge, develops skills for performing operating procedures, and conveys other essential process operation tasks to the workers that carry out these tasks. Critical gaps in Kuraray's operator training contributed to the incident. For example, Kuraray's operator training program did not cover alarm setpoints or actions that operators should take in response to specific process alarms, such as high-pressure conditions inside an EVAL Reactor. (*See* Section 2.10)

11. **Abnormal Operating Conditions**. During the startup, ethylene vapor condensed and started flowing into EVAL Reactor 2, forming an inventory of liquid ethylene and creating a low-temperature condition. Kuraray's response to these abnormal operating conditions included heating the reactor's contents, causing some of the liquid ethylene to change to ethylene gas, which in turn generated high pressure inside the reactor and led to the incident. Kuraray's management system did not effectively handle abnormal operating conditions. By getting the right people involved when plant personnel first discovered the abnormal operating conditions, performing a hazard analysis, and developing written procedures to respond to the low-temperature conditions inside EVAL Reactor 2, the company could have prevented the May 19, 2018, incident. (*See* Section 2.11)

12. **Safety Interlock Disabling**. A safety interlock is a safeguard that takes automatic protective action at a predetermined limit to maintain safety. During the EVAL Reactor 2 startup, Kuraray operators disabled the reactor's abnormal condition safety interlock while troubleshooting a problem that stemmed from a misaligned valve (a closed manual valve that needed to be open). The EVAL Reactor 2 startup continued even though Kuraray had disabled this safeguard. As a result, when the

[a] Pressure values described in this report are gauge pressure, unless otherwise specified.

pressure inside EVAL Reactor 2 reached the high-pressure limit, the safety interlock did not activate. The automatic actions that should have been in place to reduce the pressure inside the reactor did not occur, allowing pressure to continue to climb. (*See* Section 2.12)

13. **Alarm Management**. Alarm management describes the systems that companies use to help optimize their operator alarms. In the context of a chemical manufacturing facility, an alarm is how the control system alerts an operator about a condition that needs a response. At the time of the incident, Kuraray had not completed its process alarm management efforts to improve the quality and reduce the frequency of alarms that the company tasked its board operators with responding to during upset or abnormal conditions. The control system sent about 160 alarms per hour to the board operators on the morning of the incident. This flood of alarms contributed to the incident by preventing board operators from effectively reviewing the process information and controlling the high-pressure conditions inside EVAL Reactor 2. (*See* Section 2.13)

14. **Process Alarm Response**. Kuraray's operating procedures did not include alarm information or operator guidance for responding to process alarms. The response that Kuraray's board operators took to active high-pressure alarms during the startup did not bring the reactor pressure back below the alarm limits. Although Kuraray equipped the EVAL Reactor system with an automated valve to direct vapor from the reactor to the flare under certain conditions, Kuraray physically and procedurally controlled when its board operators could open this valve. The company also did not provide its board operators with a procedure or training that directed when to open the valve that could send vapor from the reactor to the flare. Had Kuraray provided its board operators with clear operating procedures and effective training, the board operators may have prevented the incident by diverting ethylene gas into the flare system. By opening this valve, the board operators could have lowered the pressure inside the reactor enough to avoid activating the emergency pressure-relief system and discharging the flammable ethylene vapor into the air, near the workers. In addition, Kuraray could have lowered the pressure inside EVAL Reactor 2 and prevented the May 19, 2018, incident by using effective control system automation. At a predetermined high-pressure limit inside EVAL Reactor 2, Kuraray could have had its control system automatically open the valve and, by doing so, directed enough ethylene vapor to the flare to prevent the emergency pressure-relief system from activating. (*See* Section 2.14)

15. **Safe Operating Limits**. Federal process safety regulations require that companies like Kuraray establish safe upper and lower limits for process parameters such as temperatures, pressures, flows, or compositions. Kuraray's safe operating limits management system did not prevent high-pressure conditions from developing inside the reactor. Kuraray also set the safe operating limits for EVAL Reactor 2 too high—at the reactor's mechanical design conditions—to effectively prevent activating the EVAL Reactor 2 emergency pressure-relief system. Kuraray's safe operating limits did not consider the activation pressure of its emergency pressure-relief systems and the fact that these safety systems do not precisely activate at their design conditions. Kuraray could have prevented the May 19, 2018, incident by having a robust safe operating limits system with effective written procedures and operator training. With an effective safe operating limits system in place, Kuraray's board operators should have had the tools they needed to prevent this accident, including the predetermined steps they needed to take to lower and control the pressure inside the reactor. (*See* Section 2.15)

16. **Environmental Permit**. Kuraray had an environmental permit that limited the amount of volatile organic compounds (VOCs), including ethylene, that the company was allowed to send to its flare. As the pressure within the EVAL Reactor 2 steadily increased during the startup, Kuraray's board operators limited the flow of ethylene vapor to the flare to avoid exceeding these permit limits. In addition, Kuraray management restricted its board operators from using the automated valve, which could have directed even more ethylene vapor to the flare. The company did not have predetermined actions for its operators to take in response to the High- and High-High-Pressure alarms. Kuraray also set the EVAL Reactor 2 safe operating limits too high, and the board operators did not remember the reactor's mechanical design conditions. Kuraray's safety management system did not effectively prioritize keeping the reactor pressure below its alarm limits over the site's environmental permit constraint. Kuraray's ineffective safety management systems resulted in the company's desire to avoid exceeding the environmental permit limits for the company's flare system unduly influencing the board operators' response to the high-pressure conditions inside EVAL Reactor 2, which resulted in activating the reactor's emergency pressure-relief system and injuring 23 workers. (*See* Section 2.16)

17. **Safety Management System Self-Assessment Audits**. Federal process safety regulations require that companies like Kuraray periodically evaluate their process safety management systems to ensure these safety systems are effective. The investigation of the incident on May 19, 2018, revealed many weak process safety management systems at Kuraray. Although the problems with these management systems were identifiable and correctable, Kuraray's self-assessment audits did not achieve the level of detail required to address the process safety management system failures that contributed to the incident. (*See* Section 2.17)

Recommendations

New Recommendations

To Kuraray America, Inc.

2018-03-I-TX-R1

Develop and implement an emergency pressure-relief system design standard to ensure that each of these safety systems will discharge to a safe location. Include a requirement to periodically evaluate the site's emergency pressure-relief systems and make appropriate modifications to ensure that each of these systems discharge to a safe location such that material that could discharge from these safety systems will not harm people.

2018-03-I-TX-R2

Implement a site-wide system to evacuate nonessential personnel during upset conditions and exclude nonessential workers from being near equipment during transient operating modes, such as startup.

2018-03-I-TX-R3

Develop and implement a system requiring a periodic evaluation of the adequacy and effectiveness of any safeguard used to mitigate or otherwise lower the risk of process safety hazards. This safeguard protection analysis should be based on the requirements of Cal/OSHA's Process Safety Management for Petroleum Refineries regulations or an appropriate equivalent methodology.

2018-03-I-TX-R4

Develop and implement a policy detailing how to effectively address recommendations generated from company process safety management systems, including audits, incident investigations, management of change, and process hazard analysis that is consistent with existing OSHA guidance. Include a periodic training requirement for managers and other employees involved with evaluating and managing proposed recommendations to help ensure proposed safety improvements are effectively evaluated and appropriately implemented.

2018-03-I-TX-R5

Review the Center for Chemical Process Safety guidance on recognizing catastrophic incident warning signs and then develop and implement a program for the EVAL Plant that incorporates warning signs into its safety management system.

2018-03-I-TX-R6

Clarify the lower equipment design pressure of the EVAL Reactor 2 within the operator training systems, written procedures, and in the control system interface.

2018-03-I-TX-R7

Develop and implement a program to ensure that the company's EVAL Plant nightly operating instructions do not conflict with its written operating procedures. Ensure that employees use the management of change system when changes to the written operating procedures are desired. Additionally, develop and implement a written procedure and conduct training on how to perform the EVAL Reactor methanol flush operation.

2018-03-I-TX-R8

Strengthen the EVAL Plant's operator training program by 1) including the known activities, such as bringing ethylene back into the unit, upset conditions like the reactor's High-High-Pressure alarm, and providing guidance or otherwise clarifying when nonessential personnel should be excluded from being in the unit; 2) including alarm setpoints and actions that operators should take in response to specific process alarms, such as high pressure inside an EVAL Reactor; 3) including directions on when operators should use the emergency open valve; and 4) including safe operating limits, the consequence of deviating beyond the safe operating limits, and the predetermined steps operators need to take to return the process to a safe condition.

2018-03-I-TX-R9

Complete the alarm management efforts at the EVAL Plant and implement a continual program to meet or be lower than the alarm rate performance targets established in ISA 18.2.

2018-03-I-TX-R10

Improve the EVAL Plant's safety management system by 1) controlling when chilled liquid is circulated through the heat exchanger during startup; 2) enhancing recognition of liquid ethylene accumulation and response to low-temperature conditions inside an EVAL Reactor through alarms, written procedures, and operator training; 3) implementing a system to manage abnormal operating conditions effectively by, at a minimum, including appropriate technical representation, performing a hazard analysis of temporary or troubleshooting operations, and providing management oversight of any abnormal condition; 4) updating the written startup procedures to include guidance on the appropriate operator actions to take in response to process alarms; 5) using control system guidance to aid operator response to abnormal or upset conditions to keep the process within the safe operating limits; and 6) removing the physical and procedural controls used at the EVAL Plant to restrict board operators from accessing or using the emergency open valve, and updating the written procedures and operator training to provide guidance on when to open the emergency open valve.

2018-03-I-TX-R11

Modify the EVAL Plant's safe operating limits program to prevent operating under conditions that rely upon equipment design safety factors, such as the American Society of Mechanical Engineers (ASME) code material safety factors.

2018-03-I-TX-R12

Acquire the services of an independent third party to perform a comprehensive assessment of its EVAL Plant's process safety management systems. In addition to meeting the requirements outlined in Appendix B of this report, this comprehensive assessment should evaluate whether existing policies meet minimum federal process safety regulatory requirements and apply the Center for Chemical Process Safety model to verify both the suitability of these systems and their effective, consistent implementation.

1 Factual Information

1.1 Kuraray Overview

1.1.1 Corporate

Kuraray Co., Ltd. is a Japanese chemical company founded in 1926 as Kurashiki Kenshoku Co. Ltd. In 1972, Kuraray Co., Ltd. commercialized ethylene and vinyl alcohol (EVAL) copolymer production at its facility in Okayama, Japan, which the company trademarked as EVAL™ resin [2, 3]. EVAL™ functions as a gas barrier by blocking oxygen, making it useful for packaging foods and beverages [4]. EVAL is also used in plastic storage containers and automobile fuel tanks [5]. **Figure 1** provides additional information about the company's EVAL product. The top part of this image shows the EVAL™ molecular structure. A number of connected ethylene molecules (denoted by "m") are interspersed with a number of connected vinyl alcohol molecules (denoted by "n") [6]. The bottom portion of the image shows some product packaging applications that use EVAL™ [7].

Figure 1. Kuraray EVAL™ Ethylene and Vinyl Alcohol Copolymer. (Credit: Kuraray modified by CSB [8, 9])

Kuraray Co., Ltd. established EVAL Corporation of America in 1983 as a joint venture with Northern Petrochemical Company [10]. In 1986, Kuraray began manufacturing EVAL in the United States at its chemical production facility located in the Bayport Industrial District[a] (Bayport) near Pasadena, Texas [10]. Kuraray America, Inc. (Kuraray) was established in 1996 [11]. In 1999, Kuraray also began making EVAL in Antwerp, Belgium [3].

1.1.2 Site

The Kuraray EVAL Plant (EVAL Plant) in Texas had four EVAL production units (EVAL Unit). **Figure 2** shows a 2019 image of the Kuraray EVAL Plant in Pasadena, Texas, which is in Harris County. The gold star in the upper right quadrant shows the approximate location of the May 19, 2018, ethylene release and fire.

Figure 2. Kuraray EVAL Plant. (Credit: Google Earth)

The May 19, 2018, ethylene release and fire occurred in EVAL Unit 2. Kuraray built EVAL Units 1 and 2 in 1986 [10]. Kuraray started operating EVAL Unit 3 in December 1996 and EVAL Unit 4 in 2007.

[a] The Bayport Industrial District covers 12 square miles and accommodates over 70 specialty chemical companies with more than 15,000 employees [147].

1.2 Surrounding Area

Figure 3 shows the area surrounding the Kuraray EVAL Plant. The circles are set at one (blue), three (orange), and five (yellow) miles from EVAL Reactor 2.

Figure 3. Area Surrounding the Kuraray EVAL Plant. (Credit: Google Earth, annotated by CSB)

While the Kuraray EVAL Plant is surrounded primarily by industrial facilities, there are residences, a park, and a school in the area within one mile of the EVAL Plant (**Figure 4**).[a] **Figure 4** shows the two census blocks within approximately one mile of the Kuraray EVAL Plant that the CSB reviewed.

[a] Distances from Kuraray's EVAL Plant to these public areas were as follows: residences (2,500 feet), the park (3,400 feet), and the school (5,000 feet).

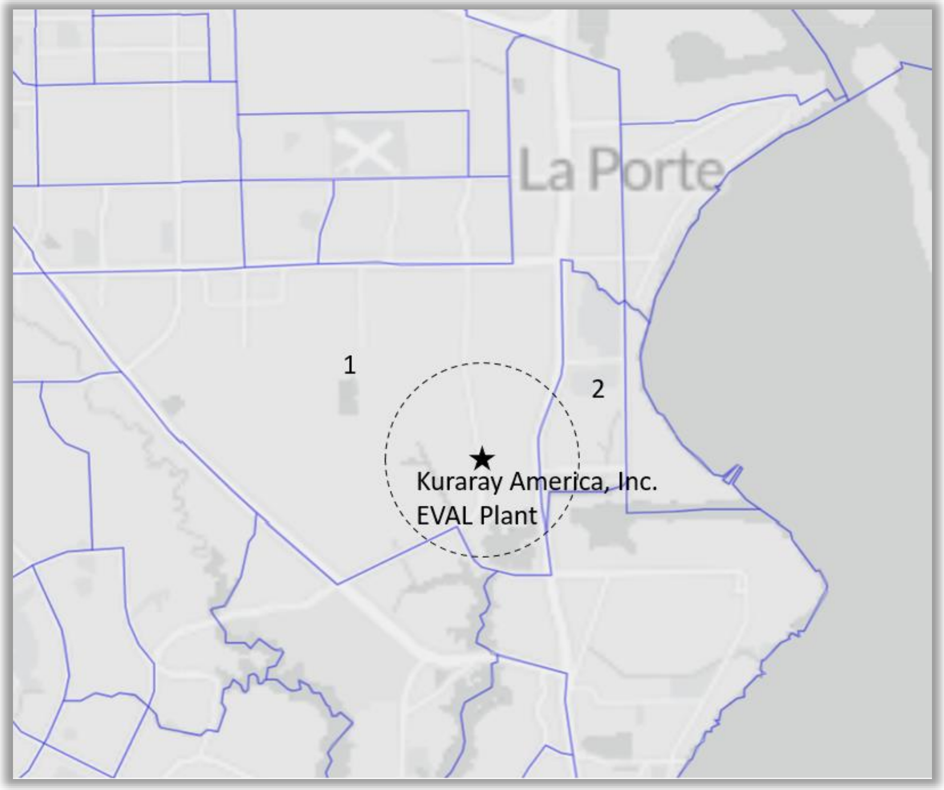

Figure 4. Census blocks near the EVAL Plant. (Credit: Census Reporter with annotations by CSB)

Table 1 summarizes the demographic data for these two census blocks[a]

[a] This information was compiled using 2020 Census data as presented by Census Reporter [151]. "Census Reporter is an independent project to make data from the American Community Survey easier to use. [It is] unaffiliated with the U.S. Census Bureau. A News Challenge grant from the Knight Foundation funded the initial build-out of the site. … Support for [Census Reporter's] 2020 Decennial Census features was provided by the Google News Initiative. … [T]he Medill School of Journalism at Northwestern University, home of the Knight Lab, [] provides in-kind support for some of Census Reporter's ongoing development. Most of [Census Reporter's] server hosting infrastructure is [] provided by the Oregon State University Open Source Lab [150]."

Table 1. Summarized Demographic Data.

Population	Race & Ethnicity (%)		Per Capita Income ($)	Poverty (%)	Number of Housing Units	Types of Housing Units (%)	
6,459	White	47	28,646	12	2,534	Single Unit	64
	Black	18				Multi-Unit	28
	Native	0				Mobile Home	8
	Asian	1				Boat, RV, Van, etc.	1
	Islander	0					
	Other	0					
	Two+	2					
	Hispanic	32					

Table 2 contains further demographic information for these census blocks. While not all individuals in the two census blocks reside within one mile of the Kuraray EVAL Plant, in general, the population in the area is predominantly non-white, with 12 percent of the population below the poverty level.

Table 2. Tabulation of Demographic Data.

Block Number	Population	Median Age	Race and Ethnicity (%)		Per Capita Income ($)	Poverty (%)	Number of Housing Units	Types of Structures (%)	
1	3,948	31.7	40.0	White	23,895	15.3	1,553	64	Single Unit
			21.0	Black				35	Multi-Unit
			0.0	Native				1	Mobile Home
			0.0	Asian				1	Boat, RV, van, etc.
			0.0	Islander					
			0.0	Other					
			2.0	Two+					
			37.0	Hispanic					
2	2,511	40.3	58.0	White	36,116	7.0	981	63	Single Unit
			14.0	Black				17	Multi-Unit
			0.0	Native				18	Mobile Home
			2.0	Asian				1	Boat, RV, van, etc.
			0.0	Islander					
			0.0	Other					
			2.0	Two+					
			24.0	Hispanic					

1.3 Kuraray Personnel

Kuraray employed about 130 people at its EVAL Plant [12]. Operations employees normally worked on one of four rotating 12-hour shifts. During the turnaround, the operations staff was doubled up, with half working a 12-hour day shift and the other half working a 12-hour night shift. As a result, at the time of the incident, there were 19 operators at the facility. Two of these operators were working as board operators inside the control room. Board Operator 1 had 18 years of experience at the EVAL Plant, and Board Operator 2 had 12 years of experience at the EVAL Plant. In addition to the 19 operators, Kuraray had several operations supervisors at the EVAL Plant on the day of the incident. Supervisor 1 had 27 years of experience at the EVAL Plant.

1.4 Ethylene

In its 2007 book, *Petroleum Technology*, Wiley Critical Content experts identified ethylene as "the largest-volume petrochemical produced worldwide" [13, p. 727]. These experts also noted that ethylene is almost exclusively used as a "building block" to make other chemicals [13, p. 727]. According to the American Chemistry Council (ACC), ethylene is not used directly by or sold to consumers [14]. Instead, commercial ethylene is used as a feedstock in the production of industrial chemicals [14].

Ethylene contains one double bond in its molecular structure, making it more reactive than the single bonds found in most components of crude oil and natural gas [15, p. 92]. This reactivity makes ethylene useful in the production of other chemicals [15, p. 92].

The Safety Data Sheet (SDS) for ethylene provided to the CSB by Kuraray following the incident shows that a primary hazard of ethylene is its flammability. The National Fire Protection Association (NFPA) diamond for ethylene shows that its flammability hazard is a 4, the most severe NFPA hazard rating [16, 17] (**Figure 5**).

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 5. The NFPA Diamond for Ethylene [17]. (Credit: CAMEO[a] Chemicals)

[a] Computer-Aided Management of Emergency Operations (CAMEO) is a system of software applications used to plan for and respond to chemical emergencies [152].

Ethylene is a colorless gas with flammability (explosive) limits reported as low as 2.7 and as high as 36 (volume percent) [18].[a] The relative vapor density of ethylene is 0.98 (air is equal to 1.0) [18].

Ethylene is among many other chemicals that the U.S. Environmental Protection Agency (EPA) has identified as volatile organic compounds (VOCs) [19]. VOCs have carbon and participate in atmospheric photochemical (sunlight) reactions [20]. In some parts of Texas, including Harris County, ethylene is considered a highly reactive volatile organic compound (HRVOC) because it disproportionately contributes to ground-level ozone formation [21].

1.5 Process Description

The May 19, 2018, incident at Kuraray occurred when high-pressure conditions developed within a reactor system during startup following a maintenance turnaround. **Figure 6** shows a simplified schematic of Kuraray's reactor system (EVAL Reactor) used to make ethylene and vinyl alcohol copolymer (EVAL). The equipment shown in **Figure 6** is limited to the items most relevant to the May 19, 2018, EVAL Reactor startup incident.

[a] "Vapor-air mixtures will ignite and burn only over a well-specified range of compositions. The mixture will not burn when the composition is lower than the lower flammable limit (LFL); the mixture is too lean for combustion. The mixture is also not combustible when the composition is too rich; that is, when it is above the upper flammable limit (UFL). A mixture is flammable only when the composition is between the LFL and the UFL. Commonly used units are volume percent fuel (percentage of fuel plus air). Lower explosion limit (LEL) and upper explosion limit (UEL) are used interchangeably with LFL and UFL" [149, p. 228].

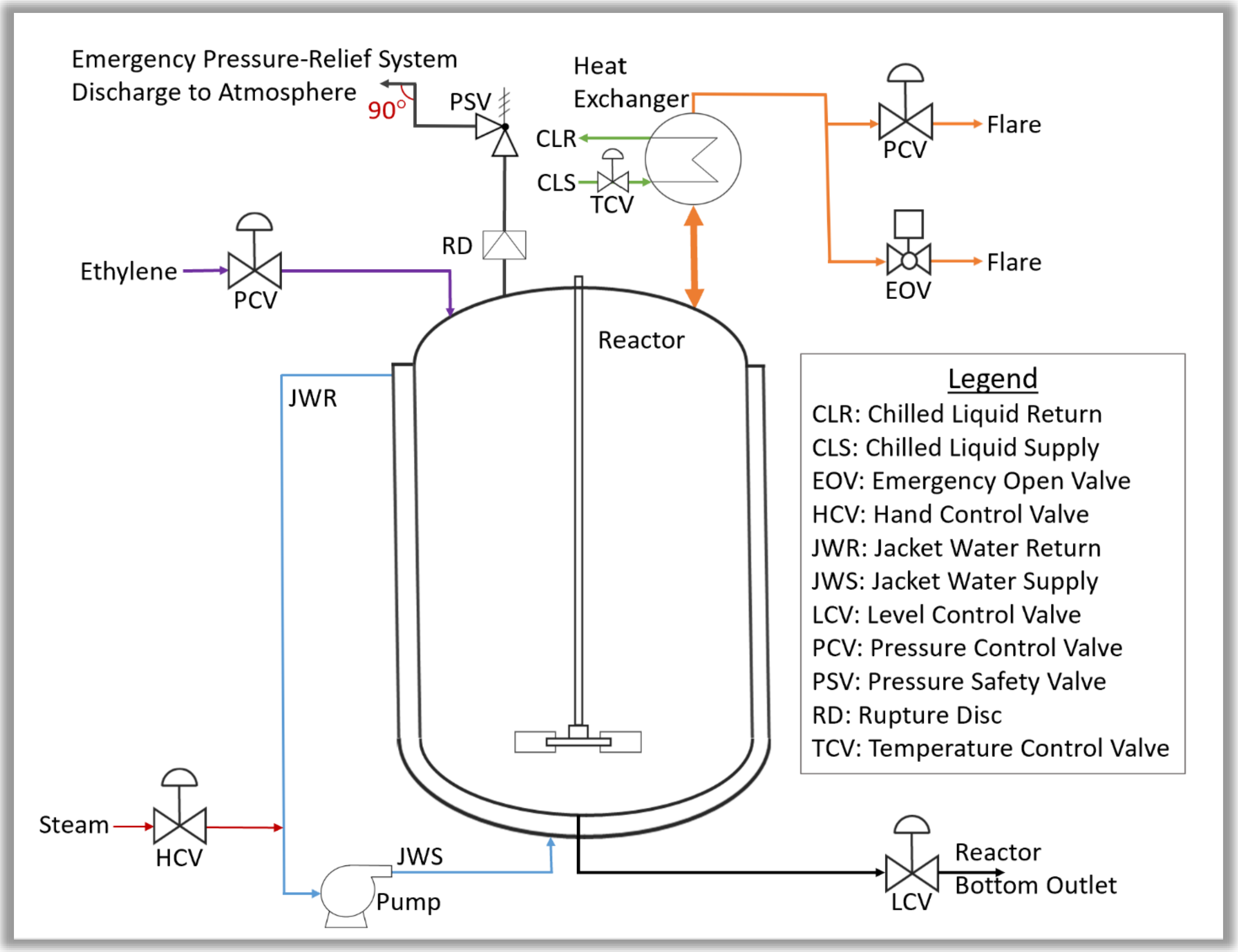

Figure 6. EVAL Reactor. (Credit: CSB)

The EVAL Reactor included a pressure vessel with a mixer[a] mounted inside. Kuraray equipped the reactor with a heat transfer jacket that allowed a portion of the reactor surface to be cooled or heated. Kuraray used a pump to circulate water through the heat transfer jacket. Board operators could increase the circulating jacket water temperature by opening a hand control valve to add steam. Board operators could also adjust the liquid level inside the reactor using the level control valve.

Kuraray directed vapor from the top of the reactor through a heat exchanger that used a chilled liquid[b] system for cooling. A temperature control valve adjusted the flow of chilled liquid through the heat exchanger.[c] To control the pressure inside the reactor, Kuraray used two pressure control valves. The first pressure control valve lowered the pressure inside the reactor by removing reactor vapor from the

[a] The mixer shown in **Figure 6** is intentionally different from Kuraray's actual design to avoid unnecessarily depicting detailed proprietary design information.

[b] The CSB Factual Investigative Update for the Kuraray incident referred to this chilled liquid as "brine," consistent with how plant personnel used the term [23].

[c] The actual equipment included more than one heat exchanger and temperature control valve (**Figure 10**). Among other things, this explains why Kuraray workers refer to "valves" when discussing the temperature control valve.

heat exchanger's outlet and sending this vapor to the flare. The second pressure control valve raised the reactor pressure by adding ethylene vapor to the reactor.[a]

Kuraray controlled the EVAL Reactor pressure by adding more ethylene to increase the pressure or flowing more reactor vapor to the flare to decrease the pressure. Other parameters, including jacket water flow and temperature, and chilled liquid flow and temperature, also affected the pressure inside the EVAL Reactor. Kuraray equipped the EVAL Reactor system with an emergency open valve to increase the amount of vapor sent to the flare during certain conditions. For scenarios in which these pressure control systems could not maintain control of the EVAL Reactor pressure, Kuraray equipped the EVAL Reactor with an emergency pressure-relief system[b] intended to prevent the reactor from rupturing under high-pressure conditions. This emergency pressure-relief system included both a rupture disc and an emergency pressure-relief valve in series (**Figure 7**).[c] The post-incident photo in **Figure 7** shows the location and piping configuration of the emergency pressure-relief system for EVAL Reactor 2—the reactor system involved in the incident.[d]

[a] With two pressure control systems on the reactor, Kuraray typically targeted the pressure control to the flare to operate about 30 psi higher than the pressure control used for supplying ethylene to the reactor. This offset between the two control systems was done to help ensure that the ethylene pressure control valve would be fully closed before the pressure control valve to the flare would open.

[b] A recent industry training video provided a general description of how emergency pressure-relief systems are used to protect equipment. This video also provided a description of some of the important design considerations for these systems, such as ensuring that emergency pressure-relief systems discharge to a safe location [134].

[c] The phrase *emergency pressure-relief system* used in this report is intended to describe the entirety of this safety system, including the inlet piping, rupture disc, piping between the rupture disc and the emergency pressure-relief valve, the emergency pressure-relief valve, and the outlet or discharge piping from the emergency pressure-relief valve to its disposal location. For EVAL Reactor 2, the disposal location was the ambient air, also referred to as the atmosphere. Although this report uses the term emergency pressure-relief valve, the terms *pressure relief valve*, *safety relief valve*, *pressure safety valve*, or *relief valve* can be used interchangeably. For a specific application, however, readers should know that these other names can reflect different operating characteristics and using precise terminology for a specific application may be appropriate. The emergency pressure-relief valve Kuraray installed to protect EVAL Reactor 2 was a Farris 2600 Series. Farris described this safety device as a pressure relief valve, which is "a pressure relief device designed to re-close and prevent the further flow of fluid after normal conditions have been restored" [148, p. 9].

[d] The CSB investigator who captured the image shown in **Figure 7** was standing on the ground. The camera was angled upward and was facing the west-southwest (WSW) direction.

Figure 7. EVAL Reactor 2 Emergency Pressure-Relief System. (Credit: CSB)

The emergency pressure-relief system for EVAL Reactor 2 was designed to discharge reactor vapor to the ambient air (atmosphere) about 40 feet above the ground. Annotating the horizontal 90-degree angle on this piping (**Figure 6**, **Figure 7**, and **Figure 8**) illustrates that Kuraray did not install the outlet piping from the emergency pressure-relief system vertically upward (180-degree angle). As will be further discussed, this piping design detail directed flammable ethylene vapor through the horizontally aimed piping and toward an area where many workers were performing maintenance activities that included welding operations.

Figure 8. EVAL Reactor 2 Emergency Pressure-Relief System Outlet Piping. (Credit: CSB)

The pressure control system that supplied ethylene to EVAL Reactor 2 also provided a High-Pressure alarm at 620 pounds per square inch (psi) and a High-High-Pressure alarm at 640 psi.[a] Activating the High-High-Pressure alarm also triggered a High-High-Pressure safety interlock that, among other actions, isolated the feeds (such as ethylene) to the reactor and fully opened the chilled liquid temperature control valve to the heat exchanger. This High-High-Pressure safety interlock, however, did not automatically open the emergency open valve to send vapor from the reactor to the flare.

Kuraray operated four different EVAL Reactors at its Pasadena, Texas facility. Three of these reactors had an emergency pressure-relief system designed to activate at a pressure of 1,150 psi, but the activation pressure for EVAL Reactor 2 was much lower. **Table 3** shows the High-High-Pressure alarm limits and the emergency pressure-relief system activation pressure for the four EVAL Reactors.

[a] Pressure values described in this report are gauge pressure, unless otherwise specified.

Table 3. EVAL Reactor Emergency Pressure-Relief System Design and Alarm Conditions.[a]

EVAL Reactor Number	Emergency Pressure-Relief System Activation Pressure (psi)	High-High-Pressure Alarm Ethylene PCV (psi)
1	1,150	890
2	740	640
3	1,150	—
4	1,150	—

Kuraray did not provide the CSB with alarm information for EVAL Reactors 3 or 4.

Each EVAL Reactor could make a variety of different product grades. Kuraray had target operating conditions for each product grade. As a result, the normal operating pressure was a function of product grade, and there was no "normal" operating pressure for each EVAL Reactor.

The emergency pressure-relief system for EVAL Reactor 2 had an activation pressure of 740 psi—410 psi lower than that of the other three EVAL Reactors. The lower activation pressure of the emergency pressure-relief system for EVAL Reactor 2 resulted from this reactor having a lower mechanical design pressure than the other three reactors. Because of this lower design pressure, Kuraray could not manufacture some EVAL product grades in EVAL Reactor 2.

1.6 Incident Description

A detailed timeline of events is provided in Appendix A.

1.6.1 Pre-Incident Information

Kuraray shut down its EVAL Plant on April 6, 2018, for a maintenance turnaround and to install various equipment upgrades. One of these equipment upgrades included the commissioning of a new chilled liquid refrigeration compressor to replace an existing ammonia-based system with one using hydrofluorocarbon. On May 14, 2018, five days before the incident, personnel finished commissioning this new refrigeration equipment. With the new refrigeration system in operation, chilled liquid at a temperature as low as 4°F (degrees Fahrenheit) circulated through the EVAL Reactor 2 heat exchanger.

When Kuraray brought an EVAL Reactor back online following a turnaround, the nightly operating instructions and operating procedures directed operations personnel to complete several steps before initiating the normal chemical reaction to produce EVAL. These steps included:

- replacing oxygen in the reactor with nitrogen;

[a] This report is simplifying the EVAL Unit and EVAL Reactor numbering from that used in the CSB Factual Investigative Update for this incident [23]. The numbering system of 1100, 1200, 1300, and 1400 has been simplified to 1, 2, 3, and 4, respectively.

- replacing nitrogen in the reactor with ethylene;
- flushing methanol through the reactor to remove residual water;
- incrementally raising the reactor system pressure with ethylene vapor to check for leaks; and
- achieving the target reactor system operating pressure with ethylene.

1.6.2 The Incident

On May 18, 2018, the day before the incident, Kuraray operations personnel introduced methanol and ethylene into EVAL Reactor 2, and they began increasing the system pressure by feeding more ethylene to the reactor to check for leaks. At about 11:25 p.m., just over 11 hours before the incident occurred, the ethylene, along with the low temperature from the chilled liquid circulating through the heat exchanger, created reactor system pressure conditions that could condense some of the ethylene gas into a liquid. The temperature inside EVAL Reactor 2 then began to decrease as liquid ethylene entered the reactor. **Figure 9** shows a timeline of the key events leading up to the incident. The green area shows events that took place while the pressure inside the reactor was less than 500 psi. The yellow section covers events that took place when the reactor pressure was between 500 and 700 psi, and the red portion shows events that took place with pressure inside EVAL Reactor 2 above 700 psi.

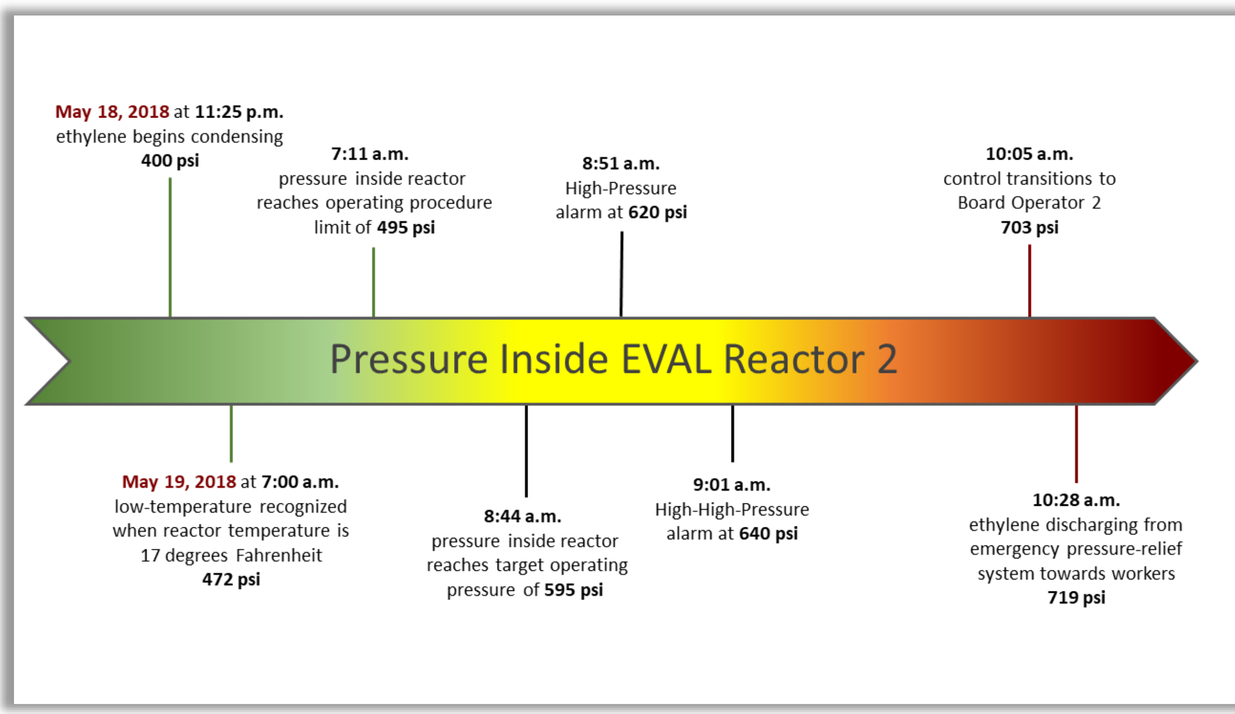

Figure 9. Timeline of Key Events. (Credit: CSB)

After the day shift took over at about 5:30 a.m. on the morning of May 19, 2018, Kuraray divided the operational tasks inside the control room between two board operators.[a] Board Operator 1 focused on operational activities for EVAL Units 1 and 2, while Board Operator 2 focused on EVAL Units 3 and 4.

At approximately 7:00 a.m., Supervisor 1 checked on the process status by reviewing some of the displays at one of the computer control system workstations. During this review, Supervisor 1 recognized the low reactor temperature inside EVAL Reactor 2 and instructed Board Operator 1 to stop circulating chilled liquid through the heat exchanger by closing the temperature control valve (**Figure 10**). **Figure 10** shows an excerpt from **Figure 6** that highlights the chilled liquid temperature control valve (blue dashed-line rectangle).

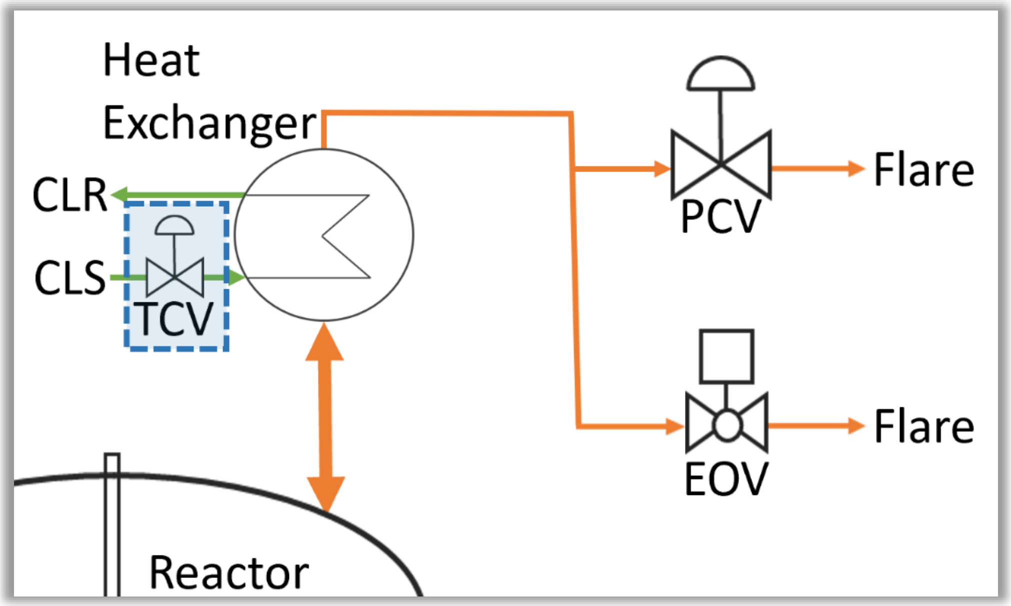

Figure 10. Temperature Control Valve. (Credit: CSB)

Supervisor 1 explained:

> [I was just] kind of seeing where things are at for myself and kind of get an idea. And I looked at [EVAL Reactor 2] and [I saw the chilled liquid] valves open. I [saw] it was 17 degrees F [Fahrenheit]. I knew that probably means liquid ethylene. I walked [over] to the board man and told the board man, "Close those valves." I said, "Don't let them be open."
>
> I just said, "Close the valves." I knew it would probably just warm back up on its own, no issue. I've seen that once from an interlock engagement and we just closed them back off. It is kind of … when you see it the first

[a] Kuraray's control room had a computer control system with workstations for three board operators. Each of the stations had access to the same information, meaning that any of the EVAL Reactors could be monitored or controlled from any of these workstations.

> time, gets your attention. But [when I saw this before], we just closed the valves, and it just came back on its own with no issue.

The low-temperature conditions inside EVAL Reactor 2 did not appear to create any notable safety concerns among the Kuraray operations personnel working on the startup, as Kuraray operations personnel took no special steps before continuing with startup tasks. Although some liquid ethylene had accumulated inside the reactor, Kuraray operations personnel did not have any discussions or call for a meeting with engineering or other technical staff to help decide what actions to take.

To help warm the reactor toward the target operating temperature, at 7:08 a.m. Board Operator 1 opened the control valve that added steam to increase the temperature of the water circulating through the reactor's heat transfer jacket (**Figure 11**). **Figure 11** shows an excerpt from **Figure 6** that highlights the hand control valve (blue dashed-line rectangle) that Kuraray operators periodically used to increase the temperature of the reactor jacket water by injecting steam into the circulating water. By raising the jacket water temperature, however, the injected steam was also raising the pressure inside the reactor because some liquid ethylene vaporized.

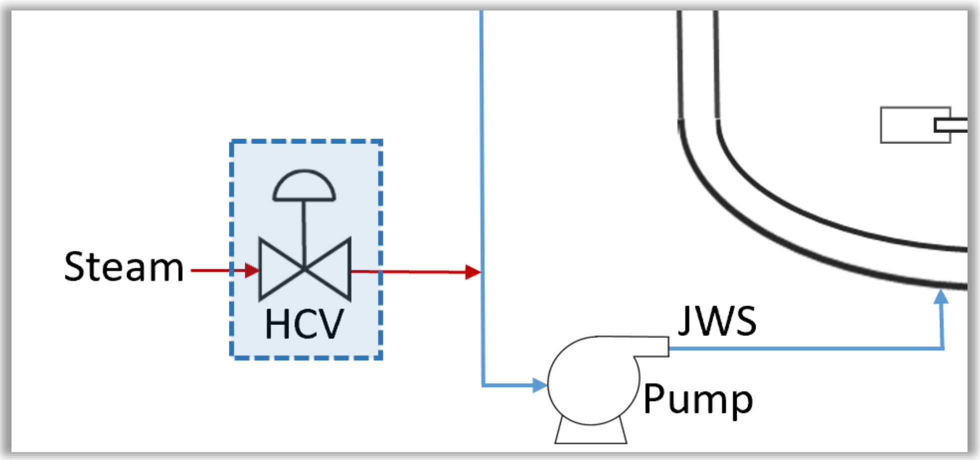

Figure 11. Steam Injection. (Credit: CSB)

At 7:11 a.m., the pressure inside EVAL Reactor 2 reached 495 psi. Although the operating procedures called for limiting the pressure inside the reactor to 495 psi, Kuraray's board operators were following the operating instructions that Kuraray management had provided in the form of nightly operating instructions. This operating instruction targeted increasing the pressure to 595 psi, 100 psi above the limit specified in the operating procedure.

By about 8:44 a.m., the pressure inside EVAL Reactor 2 reached the target pressure of 595 psi, but the pressure continued to increase beyond the target pressure. At 8:51 a.m., the pressure inside EVAL Reactor 2 reached 620 psi, activating the High-Pressure alarm. Ten minutes later, at 9:01 a.m., the reactor's High-High-Pressure alarm went off at 640 psi. Each of these high-pressure alarms was acknowledged by one of the Kuraray board operators, likely Board Operator 1.[a] As the pressure inside the reactor continually increased, Board Operator 1 periodically tried to lower the pressure by opening the pressure control valve (**Figure 12**) to send some vapor from the reactor to the flare. **Figure 12** shows an excerpt from **Figure 6** that highlights the pressure control valve (blue dashed-line rectangle) that Kuraray operators periodically used to direct vapor from the reactor to the flare to reduce the pressure inside the reactor.

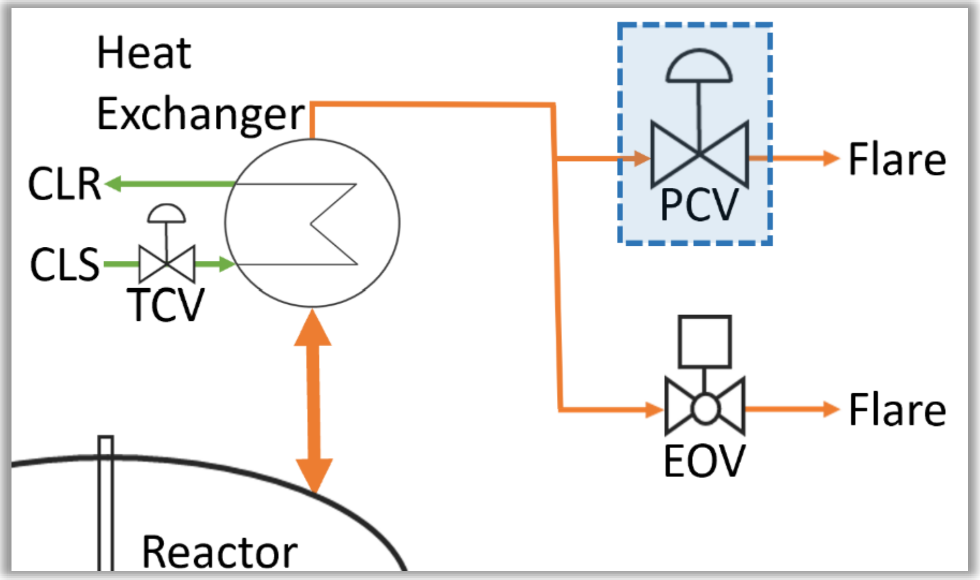

Figure 12. Pressure Control Valve to Flare. (Credit: CSB)

To avoid exceeding an environmental permit emissions limit on non-combusted volatile organic compounds (VOCs) exiting the flare, Board Operator 1 limited how much he opened the pressure control valve. To reduce the pressure inside the reactor while keeping the VOCs below the environmental emission limit, he adjusted the vapor flow from the reactor to the flare. In explaining how he controlled the reactor pressure to CSB investigators, Board Operator 1 stated:

> Usually, we look at the reactor pressure, and we use [the pressure control valve] to control the reactor pressure on there.

[a] The pressure inside EVAL Reactor 2 remained above the High- and High-High-Pressure alarm settings until after the emergency pressure-relief valve opened. Kuraray's control system configuration had each alarm sound on every control panel. As a result, when Kuraray operators acknowledged any alarm, the control system also silenced (acknowledged), all the active control system alarms. Because of this control system design, it is not possible to know which Kuraray employee acknowledged the high-pressure alarms.

> There was a high-pressure reactor [alarm] that I [saw] at the time. That's why I opened [the pressure control valve] up 30, 35 [percent].[a]
>
> I opened it up. You know, at the same time, you know, [I] was trying to watch the VOCs on the flare [because] we have a certain limit for the VOCs on the flare.
>
> There's a fine [if we exceed] a certain limit for VOCs on the flare.
>
> [The environmental limit is] … basically an average of what ethylenes we're leaving to the flare, and it calculates so much in an hour's time. So, you know, I was trying to watch that.

Later in the morning, Board Operator 1 began focusing his attention on starting up a distillation column downstream of EVAL Reactor 2. During this time, while Board Operator 1 primarily focused on the distillation column startup, other operations also were routinely needing his attention. Among other things, these operations included:

- the continual pressure increases within EVAL Reactor 2; and
- acknowledging numerous control system alarms related to a compressor startup.

Board Operator 1 explained the heavy workload, saying:

> And, you know, … I had a lot of other stuff going on with [the distillation column] startup. Then … the VOCs and then … acknowledging the back-panel alarm from the compressor trying to be started up also.

At 10:05 a.m., as Board Operator 1 was focused on the distillation column startup, Supervisor 1 asked Board Operator 2 to take over the operation of EVAL Reactor 2 to initiate the next step in the startup process—flushing a batch of methanol and vinyl acetate through the reactor (flush batch).[b] Board Operator 1 handed his copy of the procedure to Board Operator 2.

Kuraray used a checklist procedure that operators filled out as they flushed the reactor with methanol and vinyl acetate—the flush batch. To complete the flush batch, board operators used the control system to make needed calculations as they performed the procedure.

When Board Operator 2 took over the EVAL Reactor 2 startup, the pressure inside the reactor was 703 psi. Still, the control room workers were focused on the next step in the startup—beginning the flush batch. Board Operator 2 was not aware of how close the reactor system's pressure was to the activation

[a] Although Board Operator 1 described limiting the pressure control valve opening from 30 to 35 percent open (**Figure 12**), Kuraray's process control data showed that operators opened the valve more—as much as 100 percent—to help lower the reactor pressure. After the incident, Kuraray clarified in its operating procedure that during an "emergency," venting equipment for safety has the highest priority, and operators should disregard the environmental VOC emission limits. Kuraray also changed its controls to open the emergency open valve automatically (**Figure 13**), directing vapor from the reactor to the flare when a reactor's high-pressure alarm activates.

[b] Kuraray's board operators received training and periodically operated each of the four EVAL Units.

pressure design (740 psi) of the emergency pressure-relief system. Board Operator 2 explained the transition to CSB investigators. He stated:

> When I … took over the reactor from [Board Operator 1], … I didn't do anything with the pressure or anything. I merely got it to start a flush batch for [Board Operator 1] to get that started.

To work through the procedure for flushing the reactor with methanol and vinyl acetate, Board Operator 2 briefly left the control room to retrieve his reading glasses. Board Operator 2 explained to CSB investigators how the events unfolded:

> So, I walk over there to [Board Operator 1] on his side of the board and [get the procedure]. So, I go sit back down at my console, and I'm sitting there reading over the [procedure] and having a little trouble reading it. So, I needed to get my reading glasses. So, I get up, and I tell the guys, I said, "Hey, I'm going to go grab my reading glasses. I'll be right back." So, I walk out there and get them and come back inside. Put them on. I'm sitting there reading the [procedure]. You know, just looking over the first part, which is what I need to do to put the flush batch in. Which is calculate my methanol and [vinyl acetate]. Get my methanol ratio put in right on that [computer control system].

At that time, 266 employees and contract workers were onsite [22]. Kuraray control system records show that the operators' efforts to start the methanol and vinyl acetate flush began at 10:10 a.m. Board Operator 2 continued describing the events that preceded the incident. He explained in detail:

> [… I] turn over to the [computer screen] graphic and I pull up … we have a batch meter where we put in our … our methanol ratio and then our … how much [vinyl acetate] we're going to put in for the batch and how much methanol we're going to put in the batch. So, I put those numbers in, and … [at] the same time I'm fixing up, I'm calling a technician to go upstairs and line up my [vinyl acetate] and methanol. We leave all that stuff blocked in until we need it again. You know, just in case something were to leak by or something. So, call him up there, and he's standing by to line it up, and I get him to line up the [vinyl acetate] and methanol.
>
> So, we got the [vinyl acetate and] methanol flow [for the flush batch], and right before I go to start the batch on the reactor, I see the … I happened to look over and see the pressure on the reactor. And it's … at that time it was about 710 pounds. My immediate first reaction when I saw that was to open up [the pressure control valve to the flare].[a] If we get high pressure in the reactor, we open it up, and it helps relieve the pressure.

[a] Kuraray's control system records show that Board Operator 2 opened the pressure control valve to the flare from 30 to 35 percent open at 10:15 a.m.

> Now it's … when you open this valve, it's not going to drop it [the pressure inside the reactor] quick. There's an orifice in the line, and … that prevents us from putting too much ethylene in the flare at one time. So, I opened that … opened that pressure control valve up to 35 [percent]. At the same time, … we were trying to start up a compressor. We were doing ethylene purges on a compressor. When we do that, we purge the process side of this compressor. We purge it with ethylene to remove all the nitrogen and oxygen out of it to get it ready for startup. When we do that, … we pressure everything up and then go out to the flare with it.
>
> At the same time, we were doing all that … we watch … on our flare we watch flare VOCs. And we have to stay under a certain permit limit, or we'll have an environmental deal. So, … when I opened that [pressure control valve] on the reactor … I only went to 35 [percent open] because I was thinking of the VOCs downstream at the flare.

The activation pressure of the emergency pressure-relief system was identical for each of the EVAL Reactors except EVAL Reactor 2. Reactors 1, 3, and 4 all have emergency pressure-relief systems designed to activate at 1,150 psi. EVAL Reactor 2, however, relieves at a much lower pressure—740 psi. This difference stems from EVAL Reactor 2 having a lower design pressure than the other three EVAL Reactors. Board Operator 2 told CSB investigators that he was not aware of how close the reactor's operating pressure was to activating the emergency pressure-relief system. At 10:28 a.m., about thirteen minutes after Board Operator 2 first noted the high pressure inside EVAL Reactor 2, the emergency pressure-relief system opened and discharged high-pressure ethylene near many of the contractors working in the area.

In explaining what happened to CSB investigators, Board Operator 2 stated:

> [… I] was unsure of what the relief valve setting was on [EVAL Reactor 2]. So, when I opened [the pressure control valve] to 35 [percent] instead of 100 [percent], I was thinking of the flare downstream. […] I was trying not to breach the flare VOCs to put us in an environmental situation.
>
> I did not have time to look at the [pressure] trend. By the time I opened that valve to the 35 [percent], it was, [lifting the emergency pressure-relief valve] was almost like it […] was instantaneous. Maybe … about a minute after.
>
> Had I known exactly what [pressure] that [emergency pressure-relief system] was going to relieve at, I could have opened up the [emergency open valve] and relieved it a lot faster (**Figure 13**).

Board Operator 1 also forgot that EVAL Reactor 2 had a lower design pressure, stating: "I was not aware we were even close [to the pressure where] the reactor pressure relief valve [might lift]." **Figure 13** shows an excerpt from **Figure 6** that highlights the emergency open valve (blue dashed-line rectangle) that Kuraray operators could have used to direct vapor from the reactor to the flare to reduce the pressure inside the reactor further.

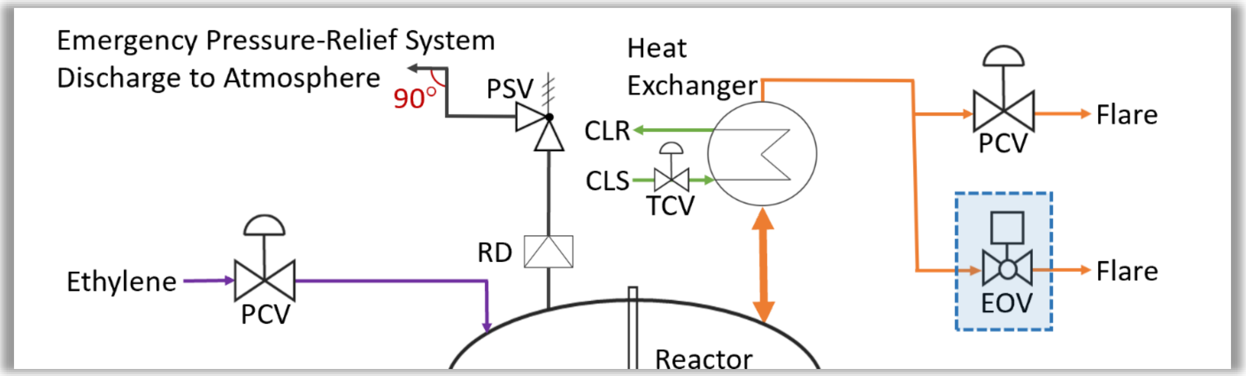

Figure 13. Emergency Open Valve to Flare. (Credit: CSB)

Board Operator 2 continued explaining the incident. He stated:

> I was thinking the [emergency pressure-relief system] setting at that time was the same as the high-pressure drum, which runs around 1,100 pounds. A little over 1,100 pounds.
>
> And then operators out in the unit started getting on the radio. You know, "There's a fire! There's a fire!" And then the … [supervisor] … went outside and I believe as soon … immediately as soon as he went out, he knew what it was so he told us … told us to open the [emergency open valve] on the reactor. So, my first response is I went and opened the [emergency open valve] on the reactor.

Figure 14 shows images of the ethylene fire at Kuraray after the initial cloud of ethylene vapor was consumed. The left photo shows the developed fire from a local road, and the right image shows a screen capture from a video of the fire.

Figure 14. Ethylene Fire. (Credit: left image, Houston Chronicle; right image, Tiffany Craig, KHOU TV, courtesy of Edward Ross)

Outside the control room, many workers were in the vicinity of EVAL Reactor 2, performing various tasks that included pump demolition, hydrotesting, welding, insulating, and scaffolding. None of these workers were essential to the startup. These workers had no warning that the emergency pressure-relief system was about to discharge a high-pressure stream of ethylene vapor toward them. One worker explained to CSB investigators that he was speaking with his supervisor when the emergency pressure-relief system on EVAL Reactor 2 opened:

> [W]hen we felt the vibrations on the ground. I told him there [are] no earthquakes in Texas. Something's wrong. Let's get everybody out of the unit. So, at … at that time when [the ethylene vapor release] started, we … I went in to start […] telling everybody to get … get out. And that's when it lit off.
>
> I'd say [it was] from 15, maybe to 25 seconds [between the vibration from the release and when the ethylene fire erupted].[a]

[a] Witness accounts of the event vary on a number of aspects, including the timing between the ethylene release and the ignition of the ethylene.

The images in **Figure 15** show the approximate area and direction of the ethylene release from the EVAL Reactor 2 emergency pressure-relief system (yellow oval in the right image). The gold star shows the likely location of the ignition source—an operating welding machine on the bed of a pickup truck.[a]

Figure 15. Ethylene Release.[b] (Credit: left image, CSB; right image, Google Earth annotated by CSB)

Another worker who was near the reactor recounted his experience with CSB investigators. He said:

> I know I was standing [near the reactor], and […] I don't remember hearing a pop or anything like that. I remember hearing a real loud rumble, and I turned to look over my left shoulder. I was standing there […], and I looked over my left shoulder, and I just saw a wall of fire. I saw everybody else run, so I took off running.

Figure 16 shows the location of the likely ignition source—an operating welding machine on the bed of the pickup truck facing forward, located below the horizontally aimed ethylene discharging from the EVAL Reactor 2 emergency pressure-relief system.

[a] The Harris County Fire Marshal's Office identified the ignition source as "located in or around the operating welder [welding machine] located in the back of the Dodge pickup" [129, p. 13]. The pickup truck was parked next to the reactor structure, under the outlet piping from the EVAL Reactor 2 emergency pressure-relief system. In addition, the Harris County Fire Marshal's report on the Kuraray incident shows 24 worker injuries with 19 of these workers being transported for medical treatment.

[b] Each image in **Figure 15** is shown looking east. The left image was captured by a CSB investigator standing on the ground, north and west of EVAL Reactor 2, with the camera facing east. The right picture is a satellite or aerial image from west of the facility looking down and to the east.

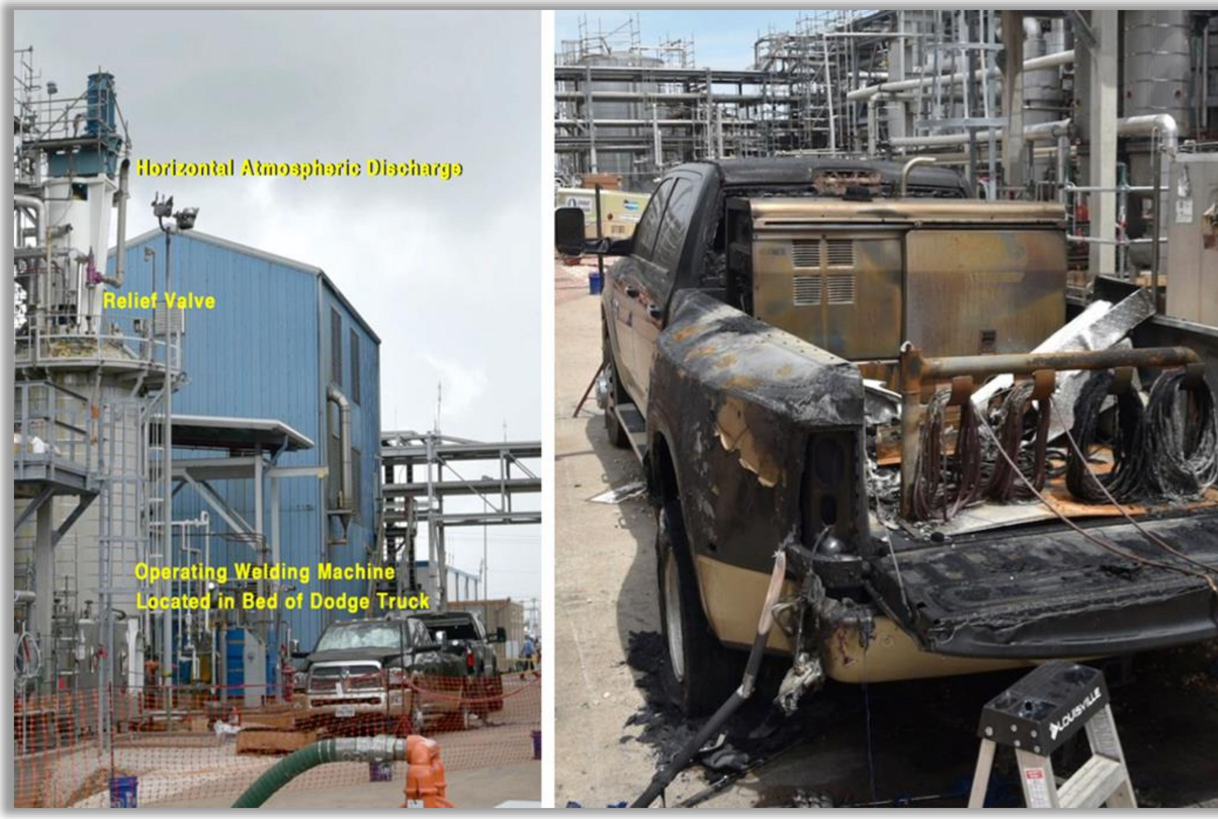

Figure 16. Likely Ignition Source. (Credit: CSB [23])

Workers in the immediate vicinity of the ethylene release and fire urgently tried to evacuate from the area. In doing so, some workers were injured as they jumped from the second or third story of the plant structure and ran or otherwise exited the area, tripping and falling or suffering sprains along the way.

One of the supervisors explained to CSB investigators that while some workers were able to escape immediately, other workers were burned because they were wearing equipment for fall protection and were physically tied off and connected to the plant structure, delaying their escape. One worker jumped but forgot that he was wearing fall protection equipment and was left hanging from the structure. While he was not directly in the flame, he sustained burns from the fire's radiant heat.

Emergency responders transported as many as 21 injured workers to off-site medical facilities for treatment [22].[a] Two workers were life-flighted from the Kuraray facility. One of these workers remained in critical condition for several days from life-threatening burns but survived.

The fire burned for about three minutes until enough ethylene vapor had been released to reduce the pressure inside EVAL Reactor 2, allowing the spring-loaded emergency pressure-relief valve to close, stopping the flow of flammable vapor, and extinguishing the fire. Kuraray reported releasing 2,347 pounds of ethylene through the EVAL Reactor 2 emergency pressure-relief system [12].

[a] In its 2019 RMP, Kuraray reported that the incident injured a total of 23 workers [12].

1.7 Discharging Emergency Pressure-Relief Systems to a Safe Location[a]

The emergency pressure-relief valve that Kuraray had installed to protect EVAL Reactor 2 was a 2600 Series safety device manufactured by Farris [24]. The Farris installation and maintenance instructions for this device included a safety warning to help ensure that the discharge was directed to a safe location [25, p. 4]. Farris warned its users to ensure that:

> The exhaust from the main valve outlet or any other ports that could exhaust, should be vented to a safe location to eliminate the potential for serious injury or damage during relief operation [25, p. 4].

Kuraray provided its employees with a list of scenarios that qualify as the top level of process safety events. Notably, Kuraray's list of most serious events (**Figure 17**) included discharging emergency pressure-relief systems to an unsafe location. **Figure 17** shows an excerpt from Kuraray's Incident Investigation and Reporting policy showing that the company considered discharging an emergency pressure-relief system (pressure relief device or PRD) to an unsafe location to be among the most serious incident consequences. In this "Tier" system, Tier 1 is the most serious, and Tier 4 is the least serious process safety consequence [26, p. 12].

[a] On March 4, 2020, Georges Melhem of ioMosaic provided a webinar with the American Institute of Chemical Engineers (AIChE) titled "What is a Safe Discharge Location" [138]. Readers wanting to understand the approach Dr. Melhem proposed to assess whether a particular emergency pressure-relief system discharges to a safe location are encouraged to view this free webinar. While this CSB report focuses on discharging flammable vapor into the air, the webinar also discusses toxics, asphyxiants, and even materials such as steam that can present thermal burn hazards to workers.

kuraray

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Incident Investigation and Reporting

A Tier 1 Process Safety Event is an unplanned or uncontrolled release of any material, including non-toxic and non-flammable materials (e.g. steam, hot condensate, nitrogen, compressed CO_2 or compressed air), from a process that results in one or more of the consequences listed below:

1. A "days away from work" injury and/or fatality or hospital admission, by either employee, contractor, or third party.
2. An officially declared community evacuation or community shelter-in-place;
3. A fire or explosion resulting in greater than or equal to $25,000 of direct cost to the Company;
4. A pressure relief device (PRD) discharge to atmosphere whether directly or via a downstream destructive device that results in one or more of the following four consequences:
   i. liquid carryover;
   ii. discharge to a potentially unsafe location;
   iii. an on-site shelter-in-place;
   iv. public protective measures (e.g. road closure);
   v. and a PRD discharge quantity greater than the threshold quantities, or
5. A release of material greater than the threshold quantities described in Table 1 in any one-hour period.

Figure 17. Serious Process Safety Incident Criteria. (Credit: Kuraray, annotated by CSB)

Kuraray's incident "Tier" system is based on American Petroleum Institute (API) Recommended Practice API RP 754, *Process Safety Performance Indicators For The Refining And Petrochemical Industries*, which stated that "Tiers 1 and 2 are suitable for nationwide public reporting and Tiers 3 and 4 are intended for internal use at individual facilities" [26, p. 1]. **Figure 18** shows how API uses a pyramid to describe the four "Tiers" of process safety event consequences. Tier 1 consists of the most consequential events, which API described as loss of primary containment (LOPC) events of greater consequence [26, p. 12]. The May 19, 2018, incident at Kuraray was a Tier 1 process safety event. API considers that Tiers 3 and 4 tend to be leading indicators that are predictive of higher consequence events, while Tiers 1 and 2 tend to describe serious process safety events that have already occurred (lagging indicators) [26, p. 12].

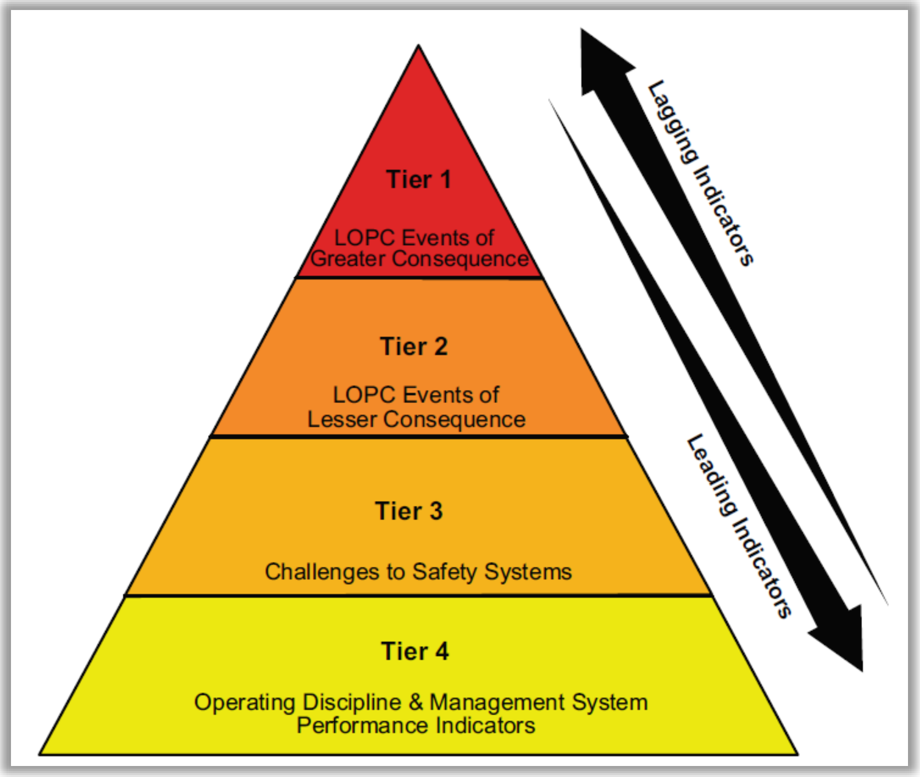


Figure 18. Process Safety Indicator Pyramid. (Credit: API RP 754 [26])

1.8 Other Kuraray Emergency Pressure-Relief Systems

Although the CSB investigation focused on the EVAL Reactor 2 emergency pressure-relief system, publicly available images suggest that Kuraray also designed other emergency pressure-relief systems that discharged through horizontally aimed piping. The CSB obtained **Figure 19** using the Google Maps "Street View" feature. The image shows several piping systems designed to discharge into the air through horizontally aimed piping, including the emergency pressure-relief system for one of the other three EVAL Reactors (farthest right yellow oval with yellow arrow). The outlet piping from this EVAL Reactor appears designed to release reactor vapors containing flammable ethylene through horizontally aimed piping toward a public road.

Figure 19. Horizontally Aimed Discharge Piping. (Credit: Google Maps annotated by CSB)

In discussing this other EVAL Reactor's emergency pressure-relief system, one Kuraray supervisor stated that it could discharge flammable ethylene toward Choate Road, a public road that runs outside the southern perimeter of the plant.[a] He said:

> [That other EVAL Reactor emergency pressure-relief system] also angles towards the street. Yeah, we have a road over there. It aimed toward our road, and if anything did come out and kept traveling, the next road is that public street.

In addition, one Kuraray employee suggested that similar horizontally aimed discharge piping may exist at Kuraray's EVAL facilities in Japan and Belgium. He said:

[a] Choate Road is about 90 feet south of EVAL Reactor 1 and about 40 feet south of the plant's fence line.

> […] Kuraray Japan doesn't have a process safety mandate, or even any documents. So, if you look across all three [EVAL] plants, […], there's no process safety standard that says, "This is the way an [EVAL] reactor vent system should be designed," right? 1980s technology has been copied and pasted five, six, seven times.

1.9 Emergency Pressure-Relief System Validation Project

In 2011, seven years before the May 19, 2018, incident, Kuraray began engineering work to ensure that it had proper designs for the site's emergency pressure-relief systems. This project systematically reviewed the design of Kuraray's emergency pressure-relief systems. Among other things, this project's objectives included evaluating the adequacy of the existing design for "current plant configuration and operating conditions." Kuraray hired an engineering firm to perform these services.

During the initial phases of this project, however, the engineering firm identified safety concerns with the design of some existing emergency pressure-relief systems. Among these concerns, the firm found that for some of Kuraray's systems, liquid ethylene could be released into the air, creating the potential for a vapor cloud explosion.[a] In 2013, the engineering firm proposed a preliminary design to address these safety concerns. The proposed design called for "combining all the safety vents (in ethylene and reaction service) that currently discharge into the air to be contained in blowdown tanks." The proposed design planned for "these [blowdown tanks to provide] the volume needed to contain reliefs and at the same time offering the settling time for the liquid ethylene and other volatiles to vaporize and reach to the flare." The emergency pressure-relief system from EVAL Reactor 2 was included in the scope of this proposed design.

In other words, according to the engineering firm, to prevent a future vapor cloud explosion, Kuraray needed to change some of its emergency pressure-relief systems capable of discharging liquid ethylene near workers. Ethylene from these relevant atmospheric-discharging emergency pressure-relief systems could be collected in equipment that would contain the liquid ethylene. After capturing the liquid ethylene, the proposed system would warm it up and vaporize it. The proposed design directed these ethylene vapors from the containment system to a flare to burn the hydrocarbon vapor safely. Demonstrating the complexity and amount of equipment involved, the firm's proposed design had a cost estimate approaching $10 million.

The engineering firm's proposal included a basic design with a cost estimate that targeted 30 percent accuracy. If Kuraray had pursued this project to the next phase (detailed engineering), the company still had to perform a significant amount of engineering work to implement this proposal. Detailed engineering plans included new piping and instrumentation diagrams, rigorous equipment pressure drop calculations, equipment specifications, risk analysis, process hazard analysis (PHA), piping layouts, civil and structural designs, construction permits, process control designs, operability study, reviewing materials of construction, and developing a more accurate cost estimate.

[a] The engineering firm's evaluation of the EVAL Reactor 2 emergency pressure-relief system did not find a scenario that could release liquid ethylene.

1.10 Laws, Codes, and Guidelines

Kuraray's emergency pressure-relief system design packages included a general list of laws, codes, and guidelines that may apply to each system. **Figure 20** shows the list of laws, codes, and guidelines that Kuraray typically included with each emergency pressure-relief system design package. Kuraray used this list in the design package for the EVAL Reactor 2 emergency pressure-relief system.[a]

LAWS, CODES AND GUIDELINES

<u>**Laws, Codes and Guidelines**</u>

* The following laws, codes and guidelines are considered whenever applicable to the emergency relief system design.

- OSHA (Occupational Safety and Health Administration)
- NFPA 30 (Flammable and Combustible Liquids Code)
- ASME Section VIII (Pressure Vessels)
- ASME Section I (Power Boilers)
- ASME RTP-1e (Reinforced Thermoset Plastic Corrosion Resistant Equipment)
- ANSI / ASHRAE 15 (Safety Code for Mechanical Refrigeration)
- ANSI (Piping Codes)
- API Guidelines (API RP 520 and API RP 521)
- API Standard 620 / 650 / 2000 (Venting Atmospheric and Low-Pressure Storage Tanks)

Figure 20. Laws, Codes, and Guidelines for the EVAL Reactor 2 Emergency Pressure-Relief System. (Credit: Kuraray)

1.11 2015 Process Hazard Analysis

Kuraray's process hazard analysis (PHA) program used a risk ranking approach to assess the risk associated with each hazard scenario. The risk was a function of the consequence of the scenario and how likely the scenario was. Each evaluated PHA scenario was assigned a risk ranking category that Kuraray described as <u>Unacceptable</u>, <u>Undesirable</u>, or <u>Tolerable</u>, with <u>Unacceptable</u> representing the highest risk ranking.

Kuraray's 2015 PHA team evaluated low-temperature conditions that might develop in EVAL Reactor 2 as an operability concern, but the team documented no safety concern or hazard from such conditions.

Kuraray's PHA team found that potential ethylene releases from some of the site's emergency pressure-relief systems (including EVAL Reactor 2) could result in a flash fire or a vapor cloud explosion with

[a] The design package for the EVAL Reactor 2 emergency pressure-relief system was approved on March 23, 2012.

worker fatalities. For EVAL Reactor 2, Kuraray's PHA team documented this scenario as an Undesirable risk.

When evaluating vapor cloud explosion risks from scenarios that could release ethylene into the air from the EVAL Reactor 2 emergency pressure-relief system, Kuraray's 2015 PHA team concluded that at least three different safeguards could act to reduce the risk of this hazard. These safeguards included:

- high-pressure alarms with an operator opening the emergency open valve;
- reactor abnormal condition (High-High-Pressure) safety interlock; and
- a high-pressure switch that could trigger closing valves to isolate reactor feeds.

Kuraray's 2015 PHA team recommended upgrading and automating the emergency open valve that directs reactor vapor to the flare (**Figure 13**). At a pressure above the EVAL Reactor 2 High-High-Pressure alarm, the recommendation called for the control system to take over and fully open the emergency open valve to reduce the pressure inside the reactor. Although the original action item Kuraray developed to implement this recommendation called for making this change in time for the post-turnaround startup in the spring of 2018, the action item was postponed to 2019. As a result, during the EVAL Reactor 2 startup on May 19, 2018, the emergency open valve still required manual activation, and the control system did not automatically open this valve.

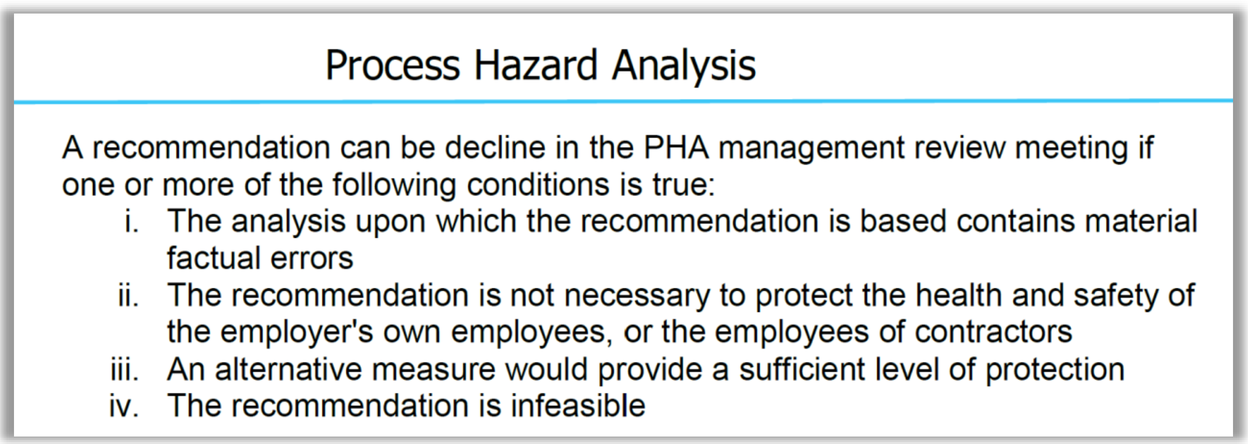
The PHA team also recommended that Kuraray perform a study to evaluate potential ethylene releases from emergency pressure-relief systems and their impact on personnel. Kuraray management did not accept the PHA team's recommendation, however, and Kuraray never performed the proposed study.

The reasons for not implementing this recommendation are not clear, but one Kuraray employee who took part in the PHA management review meeting provided some insight. In describing his perception of why Kuraray management declined, or otherwise did not adopt, some PHA recommendations, the employee said:

> I think there were something over 90 total [PHA recommendations], and my management would say, "Huh, we've never seen this before," and maybe not acknowledge that there is a risk because I don't think Japan [corporate] recognizes there's a risk.
>
> So, … I just wanted to communicate that […] might be a reason for the … it's not really ignorance, it's more just not acceptance of the risks that are presented, because many of those managers have been at Kuraray for 20, 30 years, and have only worked at Kuraray, right? So, they don't know the industry standards.

> It's kind of the opposite of maybe what happened at Texas City [March 23, 2005, BP incident], where you had a different plant manager coming in every … two or three years, right? It's kind of the opposite.[a]
>
> So, … if you have questions about why some of these recommendations weren't completed or were completed or what the priority was, […] I was in the management review meetings for this. It was postponed probably three or four times over the course of three to four months. […] It was a long time [between the PHA and the management review meeting], but in that management meeting […], smaller items occupied too much time, and I think they cannibalized the more important items.

Kuraray's internal PHA policy allowed site management to decline PHA recommendations if certain conditions were true. **Figure 21** shows an excerpt from Kuraray's internal PHA policy that describes the criteria management should evaluate and apply before declining a PHA team's recommendation. These conditions generally match published U.S. Occupational Safety and Health Administration (OSHA) guidance (*See* Section 2.6) [27, pp. 105-106], with one notable exception. While OSHA's guidance calls for the employer to document that one or more of these conditions are true, Kuraray's PHA policy did not require its management to document its reasons for declining PHA recommendations.



Process Hazard Analysis

A recommendation can be decline in the PHA management review meeting if one or more of the following conditions is true:

i. The analysis upon which the recommendation is based contains material factual errors
ii. The recommendation is not necessary to protect the health and safety of the employer's own employees, or the employees of contractors
iii. An alternative measure would provide a sufficient level of protection
iv. The recommendation is infeasible

Figure 21. Conditions for Kuraray Management to Decline a PHA Recommendation. (Credit: Kuraray)

1.12 Previous Incidents

During an interview with a senior-level Kuraray manager, CSB investigators asked if there had been any previous releases from emergency pressure-relief systems that created flammable ethylene vapor clouds. The Kuraray manager explained that there had been a significant incident in the late 1980s, shortly after the plant was first operating:

[a] *The Report of the BP U.S. Refineries Independent Safety Review Panel* (Baker Panel) report noted the high turnover in leadership at the BP Texas City refinery [139, p. 43]. Between 2000 and 2005, the refinery had eight different plant managers [139, p. 34]. And between 2001 and 2003, the refinery had five different plant managers [139, p. 43].

> Yes, [there was a previous incident].
>
> Not recently. I can't give you the circumstances. I can't even give you a year. But I can remember, maybe in the late '80s, we had a relief valve go off on the third stage of the compressor.
>
> And it went to atmosphere, and I was in the control room, and we saw the [flammable gas] meters go off. … Not that any of them reached 100 percent, but they reached, you know, the 20 percent alarm points. For like the [flammable gas] meters at the sump and the tank farm, so it was a pretty good … [distance from the release point].
>
> But [the vapor cloud] didn't ignite.

More recently, Kuraray records show that on March 22, 2015, another emergency pressure-relief system discharged high-pressure ethylene horizontally into the air. As with the incident from the 1980s, the ethylene vapor cloud did not ignite. Kuraray's 2015 PHA team reviewed this incident. As a result, the Kuraray PHA team included the potential for ethylene discharging from an emergency pressure-relief system resulting in a vapor cloud explosion with multiple fatalities as a potential hazard in the 2015 PHA. One member of the 2015 PHA team recalled the incident to CSB investigators. He explained:

> We had an incident in 2015, a couple of months before the PHA, where we released ethylene to the atmosphere from [another emergency pressure-relief system].[a]
>
> The operator left the incoming [pressure control valve] in manual and did not see the alarms, and the vessel went 200 pounds above [its maximum allowable working pressure].
>
> So that was … the big item in our minds when we went through the PHA …

Kuraray's 2015 PHA also included a section describing the hazardous characteristics of chemicals used in the process, including ethylene. Notably, the PHA discussion of ethylene hazards included a warning against venting ethylene into the air. **Figure 22** shows an excerpt from Kuraray's 2015 PHA that warns against venting ethylene into the air (atmosphere) because of its flammability hazard.

[a] The emergency pressure-relief system involved in this 2015 ethylene release was not protecting a reactor system.

Substance	Hazardous Characteristics
Ethylene	Extremely flammable. Extremely cold material; can cause burns similar to frostbite. Inhalation causes chemical asphyxiation. Inhalation causes headaches, dizziness, drowsiness, and nausea, and may lead to unconsciousness. Keep away from sources of ignition (e.g., heat and open flames). Use with adequate ventilation. Do not vent into atmosphere or enclosure unless area is sufficiently ventilated to reduce vapor concentrations below flammable limit.

Figure 22. Hazardous Characteristics of Ethylene. (Credit: Kuraray [emphasis added by CSB])

1.13 Operating Instructions and Operating Procedures

Before midnight on May 17, 2018, Kuraray temporarily cleared nonessential personnel from the unit while operators finished replacing the nitrogen in EVAL Reactor 2 with ethylene. With the concentrated ethylene now inside the reactor, only one step remained in the startup procedure that Kuraray's operations personnel were completing: increasing the reactor pressure to 150 psi with a temperature of 86°F. After this last step, Kuraray operators should begin the flush batch.

In addition to operating procedures, Kuraray management supplied nightly operating instructions. The nightly operating instructions from earlier that evening (May 17, 2018) included directions for starting methanol flushes to EVAL Reactor 2. Although not covered by a written procedure, Kuraray performed methanol flushes to remove any liquid water left in the reactor after the maintenance turnaround. On May 18, 2018, Kuraray operators added methanol to EVAL Reactor 2 from 1:50 a.m. to 4:13 a.m. During this time, the liquid level in the reactor rose to about 2 percent.

The nightly operating instructions also directed operators to add ethylene to the reactor to reach the target pressure of 595 psi. At every 100 psi, the nightly operating instructions required operators to check for leaks by spraying a soap solution on piping and vessel connections. By applying this leak detection technique, any ethylene leaks should appear as soap bubbles.[a] At 3:00 p.m. on May 18, 2018, operators began adding ethylene to increase the pressure inside EVAL Reactor 2. Increasing the pressure inside the reactor above 150 psi at this point in the startup was one of several deviations from Kuraray's written operating procedures, which called for starting the flush batch before or at the same time as increasing the reactor pressure. Because of a valve misalignment (a closed manual valve that needed to be open), Kuraray operations personnel could not establish flow from the EVAL Reactor 2 bottom outlet to downstream equipment to remove the methanol flush. The valve misalignment also prevented Kuraray operations personnel from starting the flush batch until May 19, 2018, at 10:05 a.m., 23 minutes before the incident.

When Kuraray's board operators were adding ethylene to increase the pressure inside EVAL Reactor 2, the operating procedures called for limiting the pressure to 565 psi. Once the board operators began heating the reactor's jacket water while simultaneously increasing the reactor pressure by adding ethylene, the operating procedures were more restrictive. Under simultaneous heating and pressuring

[a] This video shows how using a soap solution can help locate gas leaks [135].

conditions, the operating procedures limited the pressure inside the reactor to a maximum of 495 psi at a temperature of no more than 137°F.

1.14 Ethylene Vapor Condenses During Startup

On May 14, 2018, Kuraray began circulating chilled liquid through EVAL Reactor 2's heat exchanger to commission its new refrigeration system. During an EVAL Reactor startup, circulating chilled liquid through the heat exchanger was not necessary until the desired chemical reaction was underway and generating heat. On May 18, 2018, as Kuraray operations personnel worked to achieve the operating pressure specified by the nightly operating instructions (595 psi), chilled liquid at a temperature of about 4°F circulated through the heat exchanger. Because chilled liquid was circulating through the heat exchanger, when the EVAL Reactor 2 pressure exceeded 400 psi (11:25 p.m.), some of the ethylene condensed, and cold liquid ethylene began flowing from the heat exchanger into the reactor.

1.15 Low Reactor Temperature

At 7:00 a.m. on the morning of May 19, 2018, when Supervisor 1 saw the low temperature inside EVAL Reactor 2 (17°F), he instructed Board Operator 1 to stop circulating chilled liquid through the heat exchanger by closing the temperature control valve (**Figure 10**). The supervisor had seen this situation before, and the low reactor temperature did not present a safety concern, in his opinion. When speaking to CSB investigators about the low-temperature condition in EVAL Reactor 2, he said:

> I just said, "Close the valves." I knew it would probably just warm back up on its own, no issue. I've seen that once from an interlock engagement and we just closed them back off. It is kind of … when you see it the first time, gets your attention. But [when I saw this before], we just closed the valves, and it just came back on its own with no issue.

When Kuraray operations personnel began the startup of EVAL Reactor 2, commissioning activities related to the new refrigeration system had already opened the chilled liquid valves, allowing chilled liquid to circulate through the heat exchanger. This was an abnormal condition because Kuraray did not normally circulate chilled liquid through the heat exchanger until much later during the startup sequence. Because Kuraray's safety management systems did not identify the early circulation of chilled liquid as a concern, however, the operating procedures did not instruct anyone to verify that this system was not cooling the heat exchanger for EVAL Reactor 2 during startup. As a result, a low inventory of liquid ethylene was in the reactor.

1.16 Pressure Exceeds Procedural Limit

At 7:08 a.m. on May 19, 2018, Board Operator 1 opened the control valve that added steam to the reactor's jacket water supply. After this point, Kuraray was both heating the reactor and adding ethylene to increase the pressure inside the reactor. At 7:11 a.m., the pressure inside EVAL Reactor 2 reached 495 psi. The operating procedure did not call for heating the reactor contents until adding the flush batch to the reactor. Because the flush batch had not been started, Kuraray was not even on step 1 of the flush batch procedure. The operating procedure did not call for pressuring or heating the reactor contents until step 15.

1.17 Methanol Flush Removal

During the reactor startup on May 19, 2018, Kuraray operators were troubleshooting to determine why they could not get the methanol flush inside EVAL Reactor 2 to flow from the reactor to downstream equipment. During this troubleshooting, Board Operator 1 manually activated the EVAL Reactor 2 High-High-Pressure safety interlock.

After manually activating the interlock during the troubleshooting, Board Operator 1 turned the reactor High-High-Pressure safety interlock to the “off” position. As the startup continued, this interlock remained off. With this interlock off, the chilled liquid temperature control valve would not automatically open when the pressure inside the EVAL Reactor 2 reached the High-High-Pressure alarm and safety interlock condition of 640 psi. Kuraray operations personnel disabled this safety interlock, and the EVAL Reactor 2 startup continued without this safeguard.

Troubleshooting efforts continued, and the operators found a misaligned valve (a closed manual valve that needed to be open) that prevented them from transferring the methanol and water in EVAL Reactor 2 to downstream equipment. After one of the Kuraray operators opened the misaligned valve, liquid from EVAL Reactor 2 began flowing to downstream equipment.

1.18 Kuraray Alarm Management

Kuraray’s control room had a computer control system with workstations for three board operators.[a] Each of the stations had access to the same information, meaning that any of the EVAL Reactors could be monitored or controlled from any of these workstations. This design allowed alarms triggered by the computer control system to notify operators audibly and through visual displays on the alarm summary page at each control station.

When the computer control system detected an alarm condition, the system changed the visual display information from green to another color (depending on the alarm priority). The text for that parameter would also be flashing. When one of the board operators acknowledged the computer control system alarm, the blinking stopped, and the audible alarm noise was silenced. Kuraray designed its control system to “mass acknowledge the alarms.” Acknowledging an alarm stopped the flashing for every instrument in an alarm condition and cleared the alarm for all instruments that had returned to a normal state. Only when the control system detected that the process parameter had gone back to a normal level (below the alarm condition) did the visual display reset the text color back to green.

In April 2018, Kuraray’s process control team met to review and discuss the site alarm management program. A slide deck from this meeting shows that in 2017 the team focused on the following:

[a] The Abnormal Situation Management (ASM®) Consortium published *Operator Interface Requirements: Going Beyond the Obvious to Achieve Excellence*, a guideline for designing effective control system displays for board operators [133].

- Analyzing the existing alarm conditions;
- Establishing an alarm philosophy;[a] and
- Performing alarm rationalization.[b]

The Kuraray process control team's slide deck shows that its 2018 goals included implementing alarm management and achieving conformance with ISA 18.2. The slide deck also described how Kuraray, like many other companies, evolved to have too many process alarms. Before computerized control systems, the company had a physical panel board with a hardwired alarm annunciator panel. The cost and physical space needed for each alarm made it necessary to justify each alarm. Operators often preferred the physical alarm panel because they could review all active alarms with a single glance at the board. With the transition to computer control systems, alarms were inexpensive to configure, and designers configured most control system parameters with alarms.

Figure 23 is a slide from Kuraray's alarm management slide deck showing how the physical limitations of the old alarm system helped to ensure that only the most important parameters were equipped with an alarm.

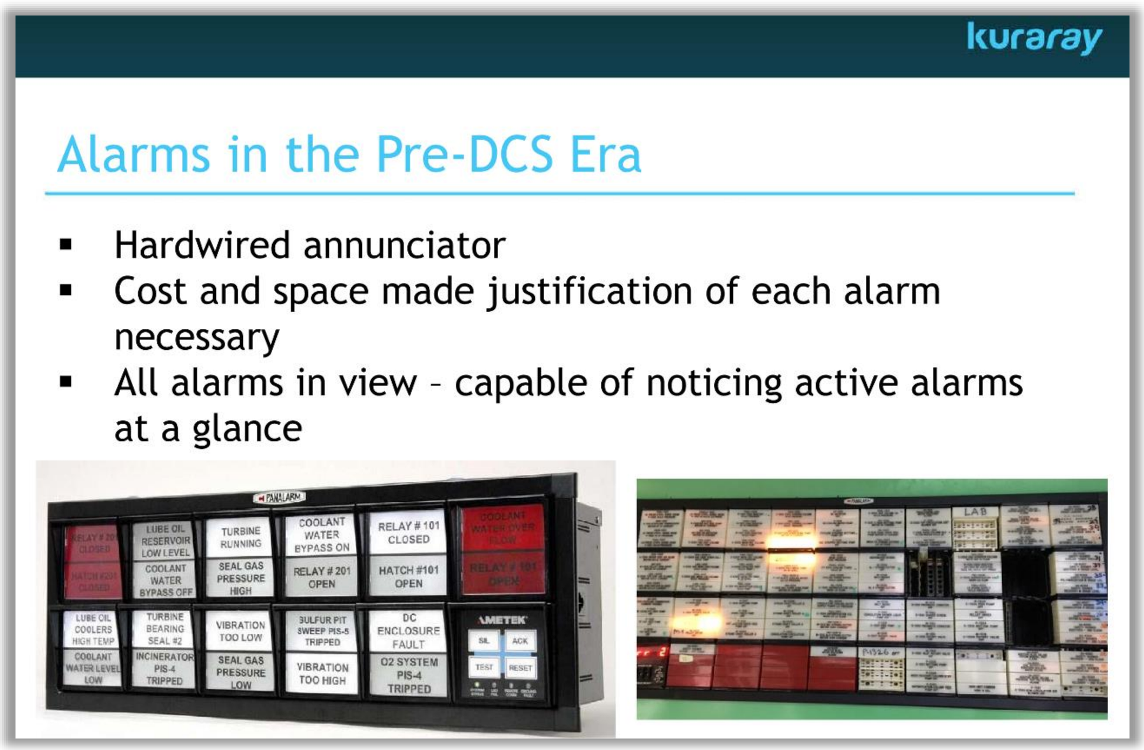


Figure 23. Alarm Annunciator Panel. (Credit: Kuraray)

[a] An alarm philosophy is a "document that establishes the basic definitions, principles, and processes to design, implement, and maintain an alarm system" [106, p. 17].

[b] Alarm rationalization is a "process to review potential alarms using the principles of the alarm philosophy, to select alarms for design, and to document the rationale for each alarm" [106, p. 23].

The Kuraray team's analysis of existing alarm conditions found that during a nearly one-month period in November 2016, the control system activated more than 265,000 alarms with an average alarm rate of 395 alarms per hour. The team also reduced the number of configured alarms by 64 percent. Kuraray had self-identified future priorities for its alarm management team, including the need for developing adaptive alarming[a] during transient operations (including startup and shutdown) and providing a clear, predetermined action for operators to take when responding to an alarm.[b]

1.19 Pressure Inside EVAL Reactor 2

Figure 24 shows the pressure inside EVAL Reactor 2 in psi (psi) leading up to the incident on May 19, 2018. Kuraray operators stopped adding ethylene to the reactor at 8:46 a.m. when the pressure inside EVAL Reactor 2 was 606 psi. At 9:01 a.m., the High-High-Pressure alarm sounded when the pressure inside the reactor was 640 psi. Although actions taken by Kuraray's board operators slowed the rate at which the pressure inside the reactor was increasing, the pressure continued rising until the emergency pressure-relief system activated at 10:28 a.m.

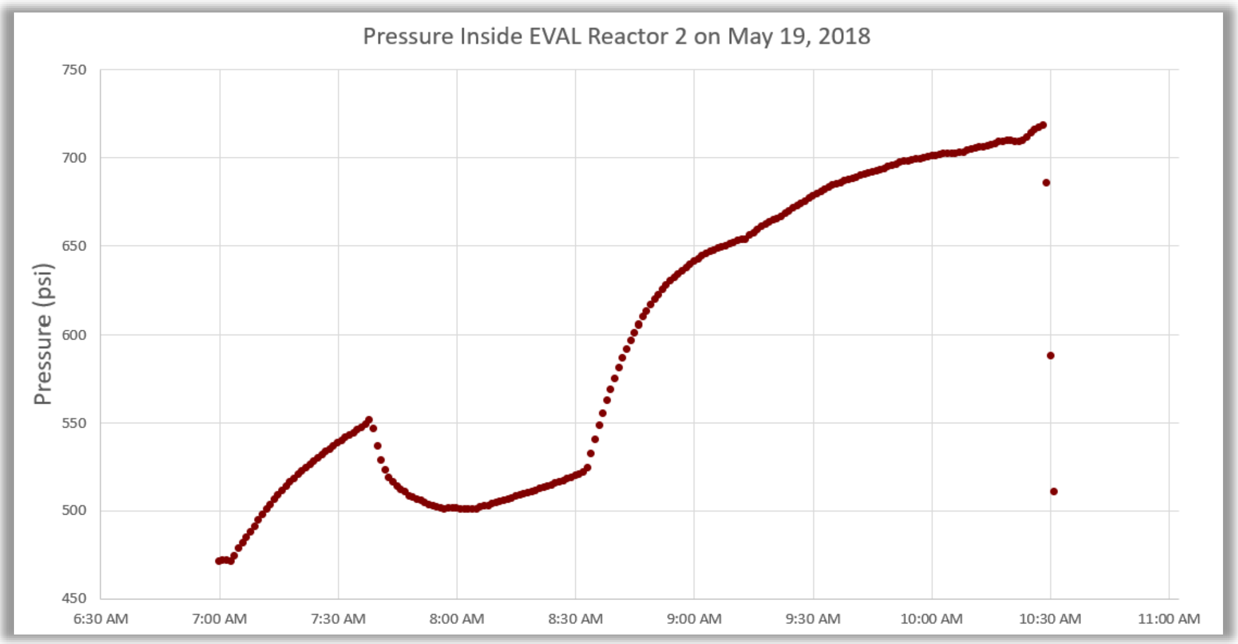


Figure 24. EVAL Reactor 2 Pressure.[c] (Credit: CSB)

1.20 Operating Procedure Guidance on Alarms

When running, the normal operating pressure for EVAL Reactor 2 was 595 psi, about 80 percent of 740 psi—the activation pressure of the emergency pressure-relief system. In addition, Kuraray designed the

[a] An adaptive alarm is an "alarm for which the setpoint is changed by an algorithm ([for example], calculated based on production rate)" [106, p. 15].

[b] Kuraray did not have a corporate standard on alarm management.

[c] The graph in **Figure 24** shows individual one-minute data points from 7:00 a.m. through 10:31 a.m.

system to have high-pressure alarms at 620 and 640 psi—84 and 86 percent of the emergency pressure-relief system activation pressure, respectively.

Kuraray's operating procedures did not include alarm information or operator guidance on responding to process alarms. Increasing the flow of vapor from the reactor to the flare could help to reduce the pressure inside the reactor. After the High-High-Pressure alarm was activated, Kuraray's board operators made 14 adjustments to the flow of ethylene vapor from the reactor to the flare. But the pressure kept increasing (**Figure 12**). The pressure inside EVAL Reactor 2 was above the High-High-Pressure alarm condition for 87 minutes. The pressure never dropped below the alarm limit until after the incident.

1.21 Use of Emergency Open Valve

The use of the emergency open valve was managed by both procedural and physical controls. The operating procedure stated, "**Do not open [the emergency open valve] without supervisor approval.**" In addition, the emergency open valve was activated using a physical switch on a panel board and was not part of the computer control system. Kuraray management installed a protective cap over the switch and locked the cap closed with a plastic hasp to control when board operators could use the emergency open valve. As one worker described to CSB investigators, "Those [devices], you definitely need approval to … switch." To open the valve, Kuraray required its board operators to fill out a form, get a supervisor's approval, and remove the plastic hasp to access the switch.

Kuraray's 2015 PHA identified high pressure inside EVAL Reactor 2 as having the potential to "lift the relief valve [activate the emergency pressure-relief system] and vent ethylene to the atmosphere which results in a vapor cloud which finds an ignition source, explodes and causes multiple fatalities." Kuraray's 2015 PHA team recommended upgrading and automating the emergency open valve that directs reactor vapor to the flare to help prevent this scenario. At a pressure above the EVAL Reactor 2 High-High-Pressure alarm threshold, the recommendation called for having the control system automatically take over and fully open the emergency open valve to reduce the pressure inside the reactor. Although the original action item Kuraray developed to implement this recommendation called for making this change in time for the post-turnaround startup in the spring of 2018, Kuraray postponed upgrading this safety system to 2019.

1.22 Safe Operating Limits

Kuraray had a safety policy addressing the company's requirements for operating procedures. This policy required operating procedures to contain various items, including operating limits, the consequences of deviating from operating limits, and the steps required to avoid or correct deviations from these limits.

Kuraray documented its safe operating limits, the consequences of deviating beyond these limits, and the corrective actions to take in a spreadsheet that included hundreds of limits throughout the entire facility.[a] Kuraray's operating procedures for EVAL Reactor 2, including the procedures for startup and normal

[a] Kuraray's Plant Process Equipment / Safe Operating limits spreadsheet was provided to the CSB in response to the CSB's request for safe upper and lower operating limits for the subject process.

operation, did not list, describe, or otherwise refer to these safe operating limits. For a Kuraray board operator to recall a specific safe operating limit, they needed to look it up in the spreadsheet. In describing how this worked to CSB investigators, one board operator explained, “I believe I would have to go into the [shared drive name] and search for that, each individual column. … I’ve found it to be difficult.” Another Kuraray employee tried to explain the overall confusion surrounding Kuraray’s operating limits. He explained:

> … [W]e don’t have accurate operating limits that are documented. And the operator’s not aware of these operating limits. So not only are they not accurate, they’re not accessible. And where they’re located over here doesn’t necessarily match the alarm that’s on the [computer control system] here, which they should.

Although Kuraray had an established set of documented safe operating limits, the company also had an undocumented set of safe operating limits that its operators may not have known about. The documented limits for EVAL Reactor 2 were reflected in the spreadsheet. Kuraray asserted to the CSB that its various control system alarm limits served as undocumented safe operating limits. Although not written in procedures or covered in training materials provided to the CSB, Kuraray asserted that the EVAL Reactor 2 safe operating limits went beyond the single condition of 740 psi and 203°F and also included the High- and High-High-Pressure alarm conditions of 620 and 640 psi. To minimize reader confusion around documented and undocumented safe operating limits, the remainder of this report will focus on the documented safe operating limits with which Kuraray’s operators were familiar at the time of the incident.

1.22.1 EVAL Reactor 2 Safe Operating Limit

Kuraray established safe operating limits for its equipment, including EVAL Reactor 2. Kuraray set the safe operating limit for EVAL Reactor 2 at 740 psi and 203°F—the reactor’s mechanical design conditions.[a]

1.22.2 Consequence of Deviation

Kuraray’s spreadsheet of safe operating limits showed that the potential consequence of exceeding EVAL Reactor 2’s safe operating limits was accurately predicted and consistent with the May 19, 2018, incident. Kuraray identified that developing high pressure inside the reactor would result in a discharge of flammable ethylene (reactor vapor) through the emergency pressure-relief system into the air, resulting in a fire or explosion when this vapor cloud found an ignition source.

[a] Although not written in procedures or covered in training materials provided to the CSB, Kuraray asserts that its safe operating limits went beyond the single condition of 740 psi and 203°F, but also included the High- and High-High-Pressure alarm conditions of 620 and 640 psi. There were no low temperature limits for EVAL Reactor 2.

1.22.3 Predetermined Steps to Avoid or Correct Deviations

Kuraray documentation shows that to prevent such a catastrophic consequence from high-pressure conditions inside the EVAL 2 Reactor, its operators should:

- Stop feeds to the reactor, such as ethylene flow into the reactor; and
- Increase reactor cooling by:
  - Increasing the flow of chilled liquid through the heat exchanger;
  - Increasing water flow through the heat transfer jacket;
  - Keeping other feeds and outlet streams flowing;[a] and
  - Sending reactor vapor to the flare through both the pressure control valve and the emergency open valve.

One of the Kuraray board operators explained to CSB investigators that deciding when to use the emergency open valve was left up to each individual operator based on their judgment and experience. When investigators asked how Kuraray trained him to know when to open the emergency open valve, the board operator said:

> I've never received that specific instruction. … I don't want to say it's a judgment call … but … at a certain point, if the [pressure control valve to the flare] isn't working, that's your last resort before the [emergency pressure-relief system activates]. … I've never been told, hey, if it gets to 705 [psi], flip the [emergency open valve], you know. There's not like a dead set number at this point flip the [emergency open valve]. It's just always, I guess, you kind of have to judge and say, okay, if our pressure is this or we've caught it, or we haven't caught it, you know, whatever. But no, I've never been given any specific instruction at what point to flip the [emergency open valve].

1.22.4 Safe Operating Limits Procedure

Kuraray's operating procedure on safe operating limits stated:

> Efforts to reduce pressures or temperatures should begin when normal conditions have been exceeded and every effort should be made to avoid reaching these upper limits.

The safe operating limits procedure included the following:

> Most vessels at [Kuraray] are built to ASME specifications which include a 3X safety factor. Most materials of construction are 304 [stainless steel]

[a] Because EVAL Reactor 2 was in startup, the step of keeping other feeds and outlet streams flowing did not apply.

> or better. Most design temperatures are established by requirements and not by actual limitations. 304 [stainless steel] has no significant loss of material strength up to 300 [degrees Fahrenheit]. **Therefore in an emergency or other unusual conditions the limits as listed in the attachment** [the safe operating limits spreadsheet] **may be exceeded with management review and supervision**. Management will review or calculate the allowable conditions under such circumstances and issue specific written instructions and approval for the situation, normally through the Management of Change (MOC) system (emphasis added).

1.23 Operator Training

Kuraray provided the CSB with its EVAL Training Manual. These materials show that Kuraray trained its operators on detailed process descriptions that included an explanation of the available controls and the general presence of alarms. Kuraray's operator training materials included a discussion of the EVAL Reactor 2 design pressure and highlighted that its design pressure was lower than the design pressure of the other three EVAL Reactors.

1.24 Environmental Permit Limit for VOCs to the Flare

As part of its efforts to follow the site's environmental permit, Kuraray had a flow meter and an analyzer to evaluate the materials flowing to its flare. A key focus involved monitoring the volatile organic compounds (VOCs), including ethylene. Kuraray's control system used a flare system flow meter and analyzer to provide an hourly average of VOCs directed to the flare. The control system provided Kuraray's board operators with alarms and operator messaging that helped them keep the VOCs below the environmental permit limits.

1.25 Nonessential Personnel

At the time of the incident, a number of nonessential workers were in the vicinity of EVAL Reactor 2, performing various tasks that included pump demolition, hydrotesting, welding, insulating, and scaffolding.

In fact, some contract workers at Kuraray on the day of the incident were surprised to learn that a startup was taking place and that Kuraray allowed them to continue working near the unit. As workers said:

> Because of the BP [Texas City] incident, many, many plants throughout Texas and the Gulf Coast, because of that incident, anytime any plant … And I'm thinking everybody should follow this. Anytime you introduce anything back into a unit, that personnel should not be around there whatsoever. And … that all stems from the BP incident.
>
> A lot of people are either sent home or sent to the lunchroom, whatever the case may be. … [T]hat's how a lot of plants do it now because of the incident at BP.

> [I]f I'm made aware that the unit is being brought up, … I'm not going to allow our employees to go in there. And I know I am 100 percent sure that my management team would have supported me or would have done the same thing if they would have known.
>
> Normally, when they're bringing up a unit, they don't even want you in the unit. So, we wouldn't have gone in the unit.

In explaining Kuraray's usual practice for keeping nonessential workers out of the unit, a Kuraray supervisor said:

> … [I]t depends what piece of equipment we're discussing, and what it is. Normally, when we initially bring a new feed stream into the unit, we do it when people, other people than operators, are not on the unit … the initial charge. After the initial charge is in the unit, and we have not seen any leaks or anything of that nature, we deem it safe for the people to come back on the unit, and [they] go to work.

A Kuraray operator also explained that nonessential personnel are kept out of the unit during the first introduction of chemicals, such as ethylene:

> … [S]ay for instance, when we first brought ethylene into the unit, we evacuated all the contractors, and we brought … safely brought the ethylene into the unit, checked for leaks, and we canceled all hot works. We did everything. Because you're bringing in [high-pressure] ethylene in [piping]. So, it's … you definitely want to make sure you evacuate the area for that.
>
> If we don't find any leaks, or we walk around with [a flammable gas detector], if we don't find any detection on anything, then we get with the contractors. If they're doing hot work permits, we re-sniff the areas for [hazardous vapor] and all that kind of stuff. And if the area … is deemed safe for work, … we update their permits and let them get back to work.

Kuraray's pre-startup safety review (PSSR) policy did not require a PSSR before starting an existing unit or require that nonessential personnel be removed from the area before startup after a turnaround.[a]

1.26 Self-Assessment Audit

Kuraray completed its most recent regulatory compliance self-assessment audit in November 2015. Among other issues, the audit was intended to evaluate the "completeness and effectiveness of the existing and planned" process safety management systems and develop recommendations to address each area requiring "enhancement" to support PSM implementation. Kuraray's audit team consisted of five

[a] Kuraray's Pre-Startup Safety Review (PSSR) policy required a PSSR for new facilities or for modified facilities if the change was accompanied by a Management of Change (MOC).

highly experienced company employees with a total of 124 years of industry experience and an average of 25 years of industry experience.

Kuraray's self-assessment audit developed 64 proposed recommendations in 11 of the 14 PSM elements. **Table 4** shows the results from the audit of Kuraray's process safety management program, including the PSM element, the number of audit team recommendations, and the number of these recommendations that Kuraray management accepted.

Table 4. Kuraray's 2015 Compliance Audit.

Process Safety Management Element	Number of Proposed Recommendations	Number of Accepted Recommendations
Process Safety Information	4	2
Process Hazard Analysis	20	9
Operating Procedures	4	2
Employee Participation	–	–
Training	4	3
Contractors	4	–
Pre-Startup Safety Review	–	–
Mechanical Integrity	10	5
Hot Work	4	4
Management of Change	5	5
Incident Investigation	4	3
Emergency Planning and Response	4	3
Compliance Audits	–	–
Trade Secrets	1	1
Total	64	37

During Kuraray's management review, only 37 of the 64 proposed recommendations were accepted and assigned corrective actions and due dates to track completion (58 percent). Kuraray management did not accept the other 27 proposed recommendations (42 percent).

1.27 Process Safety Regulations

Kuraray records show that its EVAL Plant was covered by both OSHA's PSM Standard and the EPA's RMP Rule [12]. In addition, as a member of the American Chemistry Council (ACC) [28], Kuraray applied the Responsible Care® Process Safety Code of Management Practices to its Pasadena facility operations [29]. According to the ACC, the Process Safety Code "[is intended] to complement regulatory requirements," including both the OSHA PSM Standard and the EPA RMP Rule [29, p. 1].

1.27.1 OSHA Process Safety Management Standard

Kuraray considered its EVAL Plant covered by the OSHA PSM Standard[a] because of the chemical quantities used or stored.[b] Kuraray records show that EVAL Unit 2 was likely covered by the PSM Standard because it contained more than 10,000 pounds of flammable chemicals.

1.27.2 OSHA Citations

OSHA launched an inspection of the EVAL Plant following the May 19, 2018, incident. OSHA's accident investigation summary of the incident stated:

> At 10:15 a.m. on May 19, 2018, employees were completing welding projects with a pickup truck near a reactor. The reactor was charged with ethylene and heated. Expansion of ethylene increased the pressure in [the] reactor, exceeding the setpoint of the relief valve. The relief valve opened and vented ethylene to [the] atmosphere where it was then ignited by the welding projects going on nearby. The flash fire resulted in 21 employees being hospitalized for burns, bruises, and cuts. Another 150 employees were injured but were not hospitalized [30].

OSHA issued 13 citations to Kuraray with a proposed penalty of $70,779 [31]. Kuraray contested the citations, and a settlement agreement was reached on February 21, 2020, that withdrew six citations and lowered the penalty to $65,138 [32].[c] Among other things, the settlement agreement included an assurance by Kuraray that each condition described in the citations had been corrected. Each of the final citations involved some aspect of OSHA's PSM Standard [30]. Details of these citations can be found on the OSHA website [30]. The citations included the following:

- Kuraray's process hazard analysis did not effectively identify, evaluate, and control process hazards. This included not evaluating workers being in the emergency pressure-relief system's exhaust zone while EVAL Reactor 2 operated in upset conditions—when the pressure inside the reactor approached the activation pressure of the emergency pressure-relief system.

- Kuraray did not effectively train workers on the safe operating limits for EVAL Reactor 2.

- Kuraray did not establish effective, safe work practices, such as removing nonessential personnel from the area when upset conditions (high-pressure) were taking place in EVAL Reactor 2.

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[a] *See* 29 C.F.R. § 1910.119.

[b] The PSM Standard covers chemicals that have been deemed hazardous either because of their chemical composition and quantity (listed in Appendix A) or because of their flammability characteristics (flash point below 100°F). *See* 29 C.F.R. § 1910.119.

[c] As part of this settlement agreement, Kuraray did not admit to any violations of the "Occupational Safety and Health Act or regulations or standards promulgated there under" [32]. In addition, the Secretary of Labor did not agree to waive its "interpretation of the standard, compliance with the standard, nor its application to this employer" [32].

- The company did not inform contract workers of the potential fire and explosion hazards related to the EVAL Reactor 2 startup conditions or process upsets.
- Kuraray's management of change procedures did not effectively address changes made during the EVAL Reactor 2 startup, including the bypassing of the EVAL Reactor 2 abnormal condition safety interlock.
- Kuraray did not include certain contract employee representatives in the investigation of the EVAL Reactor 2 incident.

The citations that were withdrawn included [30, 32]:

- Kuraray did not ensure that its emergency pressure-relief systems follow recognized and generally accepted good engineering practices (RAGAGEP) by discharging to a safe location.
- Kuraray's management decided not to implement recommendations from its PHA that called for the company "to eliminate atmospheric relief valves relieving to unsafe locations" [30, p. 8]. Instead, OSHA agreed to narrow its citation to Kuraray's lack of a written schedule for completing interim measures or final resolution of PHA corrective actions.

1.27.3 EPA Risk Management Program

Kuraray considered that the quantity of ethylene in its process prompted coverage by the EPA's RMP Rule.[a] The Kuraray EVAL Plant submitted its most recent RMP to the EPA in 2019 [12]. Kuraray reported that the incident on May 19, 2018, injured 23 workers after releasing 2,347 pounds of ethylene that caught on fire [12].[b]

1.28 Weather

The weather at 10:50 a.m. (the nearest data to the time of the incident) was partly cloudy, with winds from the south at 17 miles per hour and an ambient air temperature of 88°F. The relative humidity was 58 percent, and the dew point was 72°F. The barometric pressure was 29.90 inches of mercury. Visibility was 10 miles. The wind gust was zero miles per hour, and no rainfall was recorded. These weather data come from the Ellington Field weather station, which is roughly eight miles from the Kuraray facility [33].

Kuraray reported that the weather conditions at the time of the incident included an ambient air temperature of 85°F, with winds from the south-southeast at 15 miles per hour [12].

[a] 40 C.F.R. §§ 68.150-68.195.

[b] Kuraray's summary of the incident stated, "EVAL has had one accident involving ethylene and resulted in a fire and injuries to employees or contractors. There were no injuries, exposure or impact to the public. There have been changes made to facility equipment and process controls, improved training, operating procedures, and emergency response as a result of the accident" [12].

1.29 Post-Incident Actions

1.29.1 Emergency Pressure-Relief System

After the May 19, 2018, incident, Kuraray modified the EVAL Reactor 2 emergency pressure-relief system design to help ensure that this system discharges to a safe location. To accomplish this, Kuraray changed the outlet piping so that it terminated at least 50 feet horizontally away from and 10 feet vertically above any existing equipment. Kuraray provided the CSB with documents for the modified EVAL Reactor 2 emergency pressure-relief system. The documents show that the emergency pressure-relief system now follows existing industry guidance and will discharge through piping aimed vertically upward. Kuraray also elevated the discharge point so that it now terminates about 90 feet above the ground.

Figure 25 shows how Kuraray modified the emergency pressure-relief system discharge piping after the incident. The redesigned discharge piping will now direct flammable ethylene vapor vertically into the air at a location that Kuraray determined to be a safe location, including performing a dispersion analysis of the system.

Figure 25. Post-incident Emergency Pressure-Relief System Modifications.
(Credit: Google Maps annotated by CSB)

1.29.2 Plant-Wide Emergency Alarm

After the incident, Kuraray changed its practices to protect personnel during certain upset conditions. For example, during the startup of an EVAL Reactor, Kuraray now instructs its operators to activate the plant-wide emergency alarm if the reactor pressure exceeds the high-pressure alarm value by a specified threshold. Although these thresholds are not constant values and are specific to the equipment involved, the computer control system displays a visual operator guidance message to activate (sound) the plant alarm.

1.29.3 Emergency Open Valve

After the incident, Kuraray changed its controls to open the emergency open valve (**Figure 13**) automatically to direct vapor from the reactor to the flare when a reactor's High-High-Pressure alarm activates. In addition, Kuraray updated the EVAL Reactor 2 operating procedure to clarify that VOC emission limits should be disregarded during an emergency because keeping the pressure within safe limits has the "highest priority."

1.29.4 Safe Operating Limits

Kuraray established a new set of safe operating limits for EVAL Reactor 2. The new limits include:

- upper control limit;
- upper operating limit;
- upper safe operating limit;
- upper do not exceed limit; and
- upper design limit.

Safety interlock actions take place at the upper operating limit. Between the "upper operating limit" and the "upper safe operating limit," the board operator receives a guided message from the control system to activate (sound) the plant alarm system. Finally, the "upper do not exceed limit" was set at 90 percent of the emergency pressure-relief system activation pressure to help ensure all predetermined actions are taken and reduce the likelihood of activating the emergency pressure-relief system.

1.29.5 Nonessential Personnel

Documentation Kuraray provided to the CSB shows that after the incident, the company changed its practices to protect nonessential personnel. For example, Kuraray now requires a 50-foot exclusion zone around each EVAL Reactor during startup. Kuraray workers use red barrier tape to identify this exclusion zone, and the company allows only the shift supervisor or their designee to enter the exclusion zone.

2 Incident Analysis

This incident occurred when high-pressure conditions developed inside EVAL Reactor 2, activating the emergency pressure-relief system and discharging flammable ethylene toward workers. The ethylene vapor ignited, creating a fire that injured 23 workers.

This section discusses the following safety issues the CSB identified in its investigation:

1. **Emergency Pressure-Relief System Discharge Design**. This CSB investigation report details a chain of process safety management system failures that led to excessive pressure being generated within Kuraray's EVAL Reactor 2. Kuraray protected this reactor with a safety system that lowered this excess pressure by discharging flammable ethylene vapor into the air. Of all the factors that contributed to injuring the 23 workers, **none** was more significant than the design of the outlet piping from the reactor's emergency pressure-relief system, which caused the release to be aimed toward an area where workers were present. Had Kuraray designed this piping to discharge the flammable ethylene vapor to a safe location, this incident could have unfolded in precisely the same sequence—but without harming people. With well-designed outlet piping, the emergency pressure-relief system should have discharged the excess flammable ethylene vapor vertically upward, well above and safely away from workers.

   The CSB has historically advocated against discharging flammable vapor into the ambient air when a flare system can serve both to contain the flammable vapor and then combust (destroy, dispose, or burn) it safely. The CSB has stated that a flare system is an inherently safer option compared with dispersing flammable vapor into the atmosphere. Nevertheless, industry standards do provide users with guidance for directing flammable vapor vertically upward into the ambient air safely. Moreover, the American Petroleum Institute (API) Standard 521 addresses many concerns about releasing flammable vapor directly into the atmosphere and generally requires using inherently safer alternatives when the potential exists for a flammable vapor cloud explosion.

   Ensuring that emergency pressure-relief systems discharge to a safe location is not a new safety lesson nor a novel process safety concept. Past chemical disasters have caused great harm to people by discharging chemicals from emergency pressure-relief systems in an unsafe manner. These disasters include the Union Carbide disaster in Bhopal, India, in 1984 and the BASF tragedy in Cincinnati, Ohio, in 1990, both of which involved discharging chemicals from emergency pressure-relief systems in a manner that caused great harm to people. Notably, the BASF event resulted from not ensuring that a reactor's emergency pressure-relief system discharged flammable chemicals to a safe location.

   The facts, conditions, and circumstances of the May 19, 2018, incident show that the emergency pressure-relief system for Kuraray's EVAL Reactor 2 did not discharge to a safe location. Had Kuraray applied the lessons provided by earlier chemical disasters, the company could have prevented the May 19, 2018, incident by ensuring the EVAL Reactor 2 emergency pressure-relief system discharged the flammable ethylene vapor to a safe location with no harm to people. (*See* Section 2.1)

2. **Presence of Nonessential Workers During Startup and Upset Conditions**. At the time of the incident, none of the contract workers near the EVAL Reactor 2 emergency pressure-relief system were essential to the startup, nor were they responding to the upset process conditions that led to the emergency release. When the flammable ethylene vapor discharged from the reactor's emergency pressure-relief system, many of these nonessential workers were in harm's way, and the welding work they were performing likely supplied the ignition source that created the fire. Although Kuraray had an unwritten safety practice to exclude nonessential personnel from a unit when reintroducing (pressuring or charging) ethylene into equipment after a turnaround, the company did not establish a formal exclusion zone to protect nonessential workers for the duration of the startup. In addition, neither Kuraray's operating procedures nor its operator training covered the known activities or conditions that should have prompted Kuraray's operations personnel to exclude nonessential workers from the unit. One way that Kuraray could have protected the nonessential workers was to ensure that they were immediately evacuated from the unit when the EVAL Reactor 2 High-High-Pressure alarm sounded—signaling upset conditions within the process. But Kuraray's process safety management systems did not consider the high-pressure conditions developing inside EVAL Reactor 2 as an upset condition that should halt the maintenance work and prompt an evacuation of nonessential workers. (*See* Section 2.2)

3. **Hazardous Location**. In the context of the Kuraray incident, hazardous location describes the area with increased fire and explosion risk to workers resulting from the horizontal orientation of the reactor's emergency pressure-relief system outlet piping. With workers present, activating this safety system created a danger to their safety. The sequence of events that led to high pressure inside EVAL Reactor 2 on the day of the incident was only one of many scenarios that could activate the reactor's emergency pressure-relief system. Other known scenarios, which could arise at nearly any time, could have also built high pressure inside the reactor and triggered a similar flammable ethylene vapor release from the emergency pressure-relief system. These events included cooling failure, loss of refrigeration, power failure, or even a simple control valve malfunction. Because the reactor's emergency pressure-relief system did not discharge the flammable ethylene vapor to a safe location, a portion of the area adjacent to EVAL Reactor 2 presented a safety risk to workers and thus was a hazardous location. (*See* Section 2.3)

4. **Recognized and Generally Accepted Good Engineering Practices**. The phrase recognized and generally accepted good engineering practices (RAGAGEP) stems from the Occupational Safety and Health Administration's (OSHA) Process Safety Management Standard. Under this regulation, OSHA requires employers to document that their equipment complies with RAGAGEP. Kuraray should have thoroughly evaluated whether its EVAL Reactor 2 emergency pressure-relief system met existing good engineering practices. The horizontally aimed discharge piping from this emergency pressure-relief system deviated from industry standards. Consequently, Kuraray should have performed an evaluation such as a dispersion and consequence analysis. In doing so, the safety risk to workers from a potential horizontal discharge of flammable vapor could have been identified, the outlet piping design problem could

have been corrected, and the company could have prevented the May 19, 2018, incident. (*See* Section 2.4)

5. **Process Hazard Analysis Safeguards**. Federal process safety regulations (OSHA and EPA) require that companies like Kuraray periodically perform safety reviews, called process hazard analyses (PHAs), to identify, evaluate, and control process hazards. During these PHA reviews, companies identify their existing safeguards, including devices, systems, and actions that can stop a hazardous chain of events or lessen the consequence of a hazard. In 2015, Kuraray's PHA team identified three existing safeguards that should have controlled high-pressure conditions inside EVAL Reactor 2 without activating the emergency pressure-relief system. On the day of the incident, however, none of these safeguards were effective in preventing the EVAL Reactor 2 emergency pressure-relief system from activating. Because these safeguards were ineffective, high-pressure conditions inside the reactor reached the activation pressure of the emergency pressure-relief system, resulting in the discharge of flammable ethylene vapor toward workers. (*See* Section 2.5)

6. **Process Hazard Analysis Recommendations**. Safety recommendations stemming from a PHA must be resolved and documented. In 2015, Kuraray's PHA team developed a safety recommendation addressing worker safety concerns related to potential ethylene releases from emergency pressure-relief systems. Implementation of this safety recommendation could have led Kuraray to prevent the May 19, 2018, incident. Kuraray could have identified the safety risk to workers and corrected the reactor's emergency pressure-relief system design problem. But Kuraray declined to implement the safety recommendation, and consistent with the company's safety policy, its management team did not document its evaluation or reasoning for doing so. (*See* Section 2.6)

7. **Warning Signs**. Warning signs are indicators that something is wrong or may soon go wrong. In its investigation of the May 19, 2018, ethylene release and fire, the CSB found several pre-incident warning signs at Kuraray. For example, dangerous releases of flammable ethylene from emergency pressure-relief devices at the EVAL plant had previously occurred. In addition, Kuraray's own hazard review team had cautioned that ethylene vapor cloud explosions could occur when some of these safety systems discharged flammable ethylene vapor into the air. These events should have served as warnings about the serious design problem with some of Kuraray's emergency pressure-relief systems. Had Kuraray effectively recognized and acted on these earlier warnings, the company could have corrected its emergency pressure-relief systems to discharge to a safe location, preventing the May 19, 2018, incident. (*See* Section 2.7)

8. **Equipment Design**. An important adage in human performance safety guidance is "making it easy for people to do things right and hard for them to do things wrong" [1, p. 1]. Based on equipment design pressures, each of Kuraray's four EVAL reactors had an emergency pressure-relief system designed to activate at a pressure of 1,150 pounds per square inch (psi), except for EVAL Reactor 2. Kuraray designed the EVAL Reactor 2 emergency pressure-relief system to activate at 740 psi, which was 410 psi lower than the designed activation pressure of the other three reactors. Despite this significant difference in the design pressure for EVAL Reactor 2, Kuraray's control system did not provide workers with any special or unique warnings to help its

board operators recognize that this reactor was different. When Kuraray's board operators saw high-pressure conditions inside EVAL Reactor 2, they did not treat it as an emergency. They did not remember that EVAL Reactor 2's safety system activated at a lower pressure than the other three EVAL reactors. (*See* Section 2.8)

9. **Operating Procedures**. Up-to-date written operating procedures that reflect current plant practices are necessary for the safe operation of a facility. Kuraray management supplied its operations team with nightly operating instructions that conflicted with the company's written operating procedures and resulted in unmanaged changes during the reactor startup. Kuraray's operators followed some nightly management instructions that deviated from the written operating procedures during the EVAL Reactor 2 startup, which contributed to the incident. For example, the nightly operating instructions that Kuraray management provided its board operators targeted a reactor pressure that was 100 psi higher than what the company's operating procedures called for, which narrowed the available gap between the targeted operating pressure and the emergency pressure-relief system's activation pressure. (*See* Section 2.9)

10. **Operator Training**. Training provides workers with the communication of knowledge and skills they need to perform tasks. In chemical manufacturing plants, training communicates important process knowledge, develops skills for performing operating procedures, and conveys other essential process operation tasks to the workers that carry out these tasks. Critical gaps in Kuraray's operator training contributed to the incident. For example, Kuraray's operator training program did not cover alarm setpoints or actions that operators should take in response to specific process alarms, such as high-pressure conditions inside an EVAL Reactor. (*See* Section 2.10)

11. **Abnormal Operating Conditions**. During the startup, ethylene vapor condensed and started flowing into EVAL Reactor 2, forming an inventory of liquid ethylene and creating a low-temperature condition. Kuraray's response to these abnormal operating conditions included heating the reactor's contents, causing some of the liquid ethylene to change to ethylene gas, which in turn generated high pressure inside the reactor and led to the incident. Kuraray's management system did not effectively handle abnormal operating conditions. By getting the right people involved when plant personnel first discovered the abnormal operating conditions, performing a hazard analysis, and developing written procedures to respond to the low-temperature conditions inside EVAL Reactor 2, the company could have prevented the May 19, 2018, incident. (*See* Section 2.11)

12. **Safety Interlock Disabling**. A safety interlock is a safeguard that takes automatic protective action at a predetermined limit to maintain safety. During the EVAL Reactor 2 startup, Kuraray operators disabled the reactor's abnormal condition safety interlock while troubleshooting a problem that stemmed from a misaligned valve (a closed manual valve that needed to be open). The EVAL Reactor 2 startup continued even though Kuraray had disabled this safeguard. As a result, when the pressure inside EVAL Reactor 2 reached the high-pressure limit, the safety interlock did not activate. The automatic actions that should have been in place to reduce the pressure inside the reactor did not occur, allowing pressure to continue to climb. (*See* Section 2.12)

13. **Alarm Management**. Alarm management describes the systems that companies use to help optimize their operator alarms. In the context of a chemical manufacturing facility, an alarm is how the control system alerts an operator about a condition that needs a response. At the time of the incident, Kuraray had not completed its process alarm management efforts to improve the quality and reduce the frequency of alarms that the company tasked its board operators with responding to during upset or abnormal conditions. The control system sent about 160 alarms per hour to the board operators on the morning of the incident. This flood of alarms contributed to the incident by preventing board operators from effectively reviewing the process information and controlling the high-pressure conditions inside EVAL Reactor 2. (*See* Section 2.13)

14. **Process Alarm Response**. Kuraray's operating procedures did not include alarm information or operator guidance for responding to process alarms. The response that Kuraray's board operators took to active high-pressure alarms during the startup did not bring the reactor pressure back below the alarm limits. Although Kuraray equipped the EVAL Reactor system with an automated valve to direct vapor from the reactor to the flare under certain conditions, Kuraray physically and procedurally controlled when its board operators could open this valve. The company also did not provide its board operators with a procedure or training that directed when to open the valve that could send vapor from the reactor to the flare. Had Kuraray provided its board operators with clear operating procedures and effective training, the board operators may have prevented the incident by diverting ethylene gas into the flare system. By opening this valve, the board operators could have lowered the pressure inside the reactor enough to avoid activating the emergency pressure-relief system and discharging the flammable ethylene vapor into the air, near the workers. In addition, Kuraray could have lowered the pressure inside EVAL Reactor 2 and prevented the May 19, 2018, incident by using effective control system automation. At a predetermined high-pressure limit inside EVAL Reactor 2, Kuraray could have had its control system automatically open the valve and, by doing so, directed enough ethylene vapor to the flare to prevent the emergency pressure-relief system from activating. (*See* Section 2.14)

15. **Safe Operating Limits**. Federal process safety regulations require that companies like Kuraray establish safe upper and lower limits for process parameters such as temperatures, pressures, flows, or compositions. Kuraray's safe operating limits management system did not prevent high-pressure conditions from developing inside the reactor. Kuraray also set the safe operating limits for EVAL Reactor 2 too high—at the reactor's mechanical design conditions—to effectively prevent activating the EVAL Reactor 2 emergency pressure-relief system. Kuraray's safe operating limits did not consider the activation pressure of its emergency pressure-relief systems and the fact that these safety systems do not precisely activate at their design conditions. Kuraray could have prevented the May 19, 2018, incident by having a robust safe operating limits system with effective written procedures and operator training. With an effective safe operating limits system in place, Kuraray's board operators should have had the tools they needed to prevent this accident, including the predetermined steps they needed to take to lower and control the pressure inside the reactor. (*See* Section 2.15)

16. **Environmental Permit**. Kuraray had an environmental permit that limited the amount of volatile organic compounds (VOCs), including ethylene, that the company was allowed to send to

its flare. As the pressure within the EVAL Reactor 2 steadily increased during the startup, Kuraray's board operators limited the flow of ethylene vapor to the flare to avoid exceeding these permit limits. In addition, Kuraray management restricted its board operators from using the automated valve, which could have directed even more ethylene vapor to the flare. The company did not have predetermined actions for its operators to take in response to the High- and High-High-Pressure alarms. Kuraray also set the EVAL Reactor 2 safe operating limits too high, and the board operators did not remember the reactor's mechanical design conditions. Kuraray's safety management system did not effectively prioritize keeping the reactor pressure below its alarm limits over the site's environmental permit constraint. Kuraray's ineffective safety management systems resulted in the company's desire to avoid exceeding the environmental permit limits for the company's flare system unduly influencing the board operators' response to the high-pressure conditions inside EVAL Reactor 2, which resulted in activating the reactor's emergency pressure-relief system and injuring 23 workers. (*See* Section 2.16)

17. **Safety Management System Self-Assessment Audits**. Federal process safety regulations require that companies like Kuraray periodically evaluate their process safety management systems to ensure these safety systems are effective. The investigation of the incident on May 19, 2018, revealed many weak process safety management systems at Kuraray. Although the problems with these management systems were identifiable and correctable, Kuraray's self-assessment audits did not achieve the level of detail required to address the process safety management system failures that contributed to the incident. (*See* Section 2.17)

See Appendix C for the accident map (AcciMap), which provides a graphical analysis of this incident.

2.1 Emergency Pressure-Relief System Discharge Design

Like the safety valve on household water heaters [34], emergency pressure-relief systems protect equipment at chemical manufacturing facilities. It is not uncommon to have many potential scenarios that could cause high pressure inside industrial equipment, and emergency pressure-relief system design should address these scenarios. This safety equipment not only needs to protect the equipment, but its design must also protect workers. Ensuring that workers are aware of when reactor operating pressure approaches a design limit is essential, but other high-pressure scenarios could take place during a reactor startup or during normal operations where operators might not have time to take action, and the emergency pressure-relief system would still activate to protect the equipment. Consequently, to protect people, emergency pressure-relief systems must discharge to a safe location.

An emergency pressure-relief system is a layer of protection that is often considered the last line of defense to prevent equipment rupture due to a high-pressure situation [35, p. 178]. When processes are operating correctly, system pressure stays under control and within the equipment's design limits. Undesired scenarios could cause these design limits to be exceeded. When these scenarios occur, the emergency pressure-relief system must lower the system pressure by transferring some material to a lower pressure, safe location [36, p. 336]. Otherwise, a catastrophic equipment rupture could occur, harming people or propelling equipment fragments that could impact other critical equipment, escalating the incident's consequences.

As a general emergency pressure-relief system design philosophy, API Standard 521 (API 521) cautions that "in no instance should the safety of a plant or its personnel be compromised" [37, p. 14, 38, p. 14]. Indeed, to protect people, emergency pressure-relief systems must discharge to a safe location. The primary breakdown at Kuraray was that the outlet piping from the EVAL Reactor 2 emergency pressure-relief system did not discharge the flammable ethylene vapor to a safe location.

The CSB concludes that among the many process safety management system failures that led to injuring the 23 workers at Kuraray, none was more significant than the design of the EVAL Reactor 2 emergency pressure-relief system's outlet piping. When the emergency pressure-relief system activated, this piping design directed flammable ethylene vapor through horizontally aimed piping toward an area where many workers were performing maintenance activities, including welding operations.

The CSB has historically advocated against discharging flammable vapor into the ambient air when a flare system can serve both to contain the flammable vapor and then combust (destroy, dispose, or burn) it safely. The CSB has stated that a flare system is an inherently safer option compared with dispersing flammable vapor into the atmosphere [39, p. 119]. Nevertheless, industry standards do provide users with guidance for directing flammable vapor vertically upward into the ambient air safely. API 521 addresses the CSB's concerns about releases directly into the atmosphere and generally requires using inherently safer alternatives when the potential exists for a flammable vapor cloud explosion [40, p. 2].

Had Kuraray's emergency pressure-relief system discharged the flammable ethylene vapor to a safe location, following industry good practice guidance such as that provided by API Standard 521 (API 521), the flammable ethylene vapor should not have harmed any workers. By following API 521 guidance, the emergency pressure-relief system outlet piping could have been extended and directed vertically upward such that the flammable ethylene vapor could safely discharge from a sufficient elevation that could not impact or otherwise injure workers who might be nearby.

The CSB concludes that with well-designed outlet piping, the flammable ethylene vapor could have safely discharged vertically upward, likely limiting the incident consequences to activating the EVAL Reactor 2 emergency pressure-relief system and releasing ethylene into the environment.

2.1.1 Discharging to a Safe Location

In his 1993 book *Lessons From Disaster: How Organizations Have No Memory and Accidents Recur*, process safety expert Trevor Kletz stated:

> It might seem to an outsider that industrial accidents occur because we do not know how to prevent them. In fact, they occur because we do not use the knowledge that is available [41, p. 1].

Analyzing past disasters is important to show how we can learn from accidents and apply safety lessons to help prevent similar chemical disasters in the future [42, p. 1]. Ensuring that emergency pressure-relief systems discharge to a safe location is not a new safety lesson nor a novel process safety concept. Like many others, this safety lesson should have been learned from previous chemical disasters.

On February 24, 1992, OSHA issued its final PSM rule at 29 C.F.R. Part 1910 [43, pp. 6355-6417]. The preamble to the final rule stated:

> Releases of toxic, reactive or flammable liquids and gases in processes involving highly hazardous chemicals have been reported for many years. Incidents continue to occur in a variety of industries which use a variety of highly hazardous chemicals which may be toxic, reactive, flammable, or explosive or exhibit a combination of these attributes [43, p. 6356].
>
> Regardless of the industry that uses these highly hazardous chemicals, there exists a potential for an accidental release if a highly hazardous chemical is not properly controlled. This in turn presents the potential for a devastating incident. Recent major incidents include the ***1984 Bhopal incident resulting in more than 2,000 deaths***; the October 1989 Phillips 66 Chemical Plant incident resulting in 24 deaths and 132 injuries; the July 1990 Arco Chemical incident resulting in 17 deaths; ***the July 1990 BASF incident resulting in 2 deaths and 41 injuries***; and the May 1991 IMC incident resulting in 8 deaths and 128 injuries [43, p. 6356] (emphasis added).

Of the five chemical disasters that OSHA cited, two of these events (Bhopal and BASF) involved discharging chemicals from emergency pressure-relief systems in a manner that caused great harm to people.

Bhopal, which is considered the worst industrial accident ever, involved the discharge of methyl isocyanate, a toxic chemical, from an emergency pressure-relief system that activated due to a runaway reaction that generated high-pressure conditions inside a storage tank [42, p. 110, 44, p. 537].[a] Hundreds of thousands of people were exposed to the dense lethal cloud that erupted from the storage tank's emergency pressure-relief system and drifted over the city of Bhopal. Within days of the toxic chemical release, an estimated 3,800 people were fatally injured, and tens of thousands were injured. Thousands more people later died from illnesses attributed to exposure to the toxic gas [45, 42, 44].

The July 1990 BASF incident also is helpful to revisit in light of the May 19, 2018, incident at Kuraray because a critical safety lesson from the BASF disaster was that emergency pressure-relief systems must discharge flammable chemicals to a safe location.

On July 19, 1990, a release of flammable chemicals exploded, and a fire erupted, fatally injuring two workers and injuring 41 other workers at a BASF chemical manufacturing facility in Cincinnati, Ohio [46, pp. 407-408, 47]. The blast also injured some residents and damaged more than 300 nearby homes [48, 49, 50]. In a news release summarizing more than $1 million in proposed penalties, OSHA stated that the explosion and fire followed a sequence of events where high-pressure conditions developed inside a reactor during a cleaning operation. Among other things, OSHA found that BASF ***failed to ensure that the reactor's emergency pressure-relief system discharged to a safe location***. According to OSHA, when the emergency pressure-relief system was activated, it discharged a mixture of flammable chemicals into the plant, where it found an ignition source triggering a vapor cloud explosion [46, pp. 407-408, 47].

The CSB concludes that had Kuraray applied the lessons provided by previous chemical disasters, including the Union Carbide disaster in Bhopal, India, in 1984 and the BASF tragedy in Cincinnati, Ohio, in 1990 (which involved discharging chemicals from emergency pressure-relief systems in a manner that caused great harm to people), the company could have prevented the May 19, 2018, incident by ensuring the EVAL Reactor 2 emergency pressure-relief system discharged the flammable ethylene vapor to a safe location, with no harm to people.

In his 1990 book, *Critical Aspects of Safety and Loss Prevention*, Trevor Kletz cautioned readers to consider what will happen when emergency pressure-relief systems function as designed, emphasizing these safety systems must discharge to a safe location. Kletz forewarned:

[a] On December 2, 1984, water inadvertently entered a storage tank containing more than 80,000 pounds of methyl isocyanate (MIC) at the Union Carbide India Limited (Union Carbide) pesticide plant in Bhopal, India. The MIC reacted with the water, creating high-pressure conditions within the tank, which activated the tank's emergency pressure-relief system and discharged MIC vapor into the atmosphere, resulting in a massive toxic gas release [45, 42, 44].

> Relief valves are designed to lift and so when they do they should not create a hazard by discharging material over people or plant ... [51, p. 146].

In his 1994 book, *What Went Wrong*, which studied case histories of process disasters, Trevor Kletz warned readers to avoid discharging material from emergency pressure-relief systems into the air. Kletz cautioned:

> If, despite my advice, you let relief devices discharge to atmosphere, make sure that if the discharge ignites, the flame will not impinge on other equipment and **no one will be in the line of fire** [52, p. 181] (emphasis added).[a]

Ensuring no harm to people by confirming these safety systems discharge to a safe location is a basic emergency pressure-relief system design principle. The CSB concludes that the facts, conditions, and circumstances of the May 19, 2018, incident show that the emergency pressure-relief system for Kuraray's EVAL Reactor 2 did not discharge to a safe location.

Consistent with defining a safe location as one that ensures no harm to people, API stated that an unsafe location is one that may harm people. API defined an unsafe (hazardous) location for discharging flammable vapor from emergency pressure-relief systems in its industry guidance document, *Process Safety Performance Indicators for the Refining and Petrochemical Industries*, API RP 754. According to API RP 754, an unsafe location is:

> An atmospheric PRD [pressure-relief device or emergency pressure-relief system] or upset emission discharge or a downstream destructive device [for example, flare, scrubber] discharge that results in a potential hazard to personnel, whether present or not, due to the formation of flammable mixtures at ground level or on elevated work structures, presence of toxic or corrosive materials at ground level or on elevated work structures, or thermal radiation effects at ground level or on elevated work structures from ignition of relief streams at the point of emission as specified in API 521 Section 5.8.4.4 [38, p. 135, 26, p. 10].

[a] In this safety video, Energy Safety Canada explains that line of fire is one of its 10 lifesaving rules. It defines line of fire as keeping yourself (and others) out of harm's way by positioning yourself to avoid moving objects, vehicles, dropped objects, and pressure releases [142]. Another safety video further reviews line of fire safety and explains that "line of fire injuries occur when the path of a moving object or hazardous energy intersects with an individual's body" [140].

> NOTE The term "unsafe location" is used in the description of one of the four potential Tier 1[a] or Tier 2[b] consequences associated with an engineered pressure relief or an upset emission from a permitted or regulated source. The assumption is the discharge from the engineered pressure relief whether directly to atmosphere or via a downstream destructive device or the emission from a permitted or regulated source are engineered for safe dispersion of the release [26, p. 10].

The facts, conditions, and circumstances of the May 19, 2018, Kuraray incident show that the EVAL Reactor 2 emergency pressure-relief system discharge location met the API 754 criteria for an unsafe location.

In 1994, OSHA published *Process Safety Management (PSM) of Highly Hazardous Chemicals Compliance Guidelines and Enforcement Procedures* [27]. In the guidelines, OSHA addressed the need for safety assessment through a series of safety-related questions, including whether emergency pressure-relief systems will discharge to a safe location.

> Do observations of a representative sample of process-related equipment indicate that **obvious hazards** have been identified, evaluated, or controlled? … For example, … pressure relief valves and rupture disks are properly designed and discharge to a **safe area** [27, p. 38] (emphasis added).

The October 1984 issue of the *Loss Prevention Bulletin* included an article discussing the safe disposal of discharges from emergency pressure-relief devices. The article, *The Safe Disposal of Relief Discharges*, stated:

> The need for a relief device, be it a safety valve or a rupture disc may be clear and obvious; indeed, it is often legally determined. However, defining the relief criteria, calculating and specifying the relief valve and then providing and erecting it are not the only problems. It is also necessary to ensure that the process of discharge, which is often of a violent nature, **can cause no harm to people** and adjacent equipment and

---

[a] According to API RP 754, "a Tier 1 [process safety event] is a [loss of primary containment] with the greatest consequence as defined by this RP. A Tier 1 [process safety event] is an unplanned or uncontrolled release of any material, including non-toxic and non-flammable materials ([for example] steam, hot water, nitrogen, compressed CO2 [carbon dioxide] or compressed air), from a process that results in one or more of the consequences listed [in API 754]" [26, p. 13]. Tier 1 consequences include "Discharge to a potentially unsafe location" from "[a]n engineered pressure-relief ([for example pressure-relief device, safety instrumented system], or manually initiated emergency depressure) discharge, of a quantity greater than or equal to the threshold quantities in Table 1 in any 1-hour period, to atmosphere whether directly or via a downstream destructive device that results in one or more of the following four consequences. The threshold quantity determination is made at the discharge of the engineered PRD, while the consequence is determined when the material reaches atmosphere whether directly or via a downstream destructive device" [26, p. 13].

[b] According to API RP 754, a Tier 2 process safety event is "an unplanned or uncontrolled release of any material, including non-toxic and non-flammable materials ([for example] steam, hot water, nitrogen, compressed CO2 [carbon dioxide], or compressed air), from a process that results in one or more of the consequences listed [in API 754] and is not reported as a Tier 1 [process safety event]" [26, p. 19]. The list of Tier 2 consequences included "Discharge to a potentially unsafe location" [26, p. 19].

> that the materials discharged are dispersed, destroyed or collected and disposed of safely [53, p. 15] (emphasis added).

The American Society of Mechanical Engineers (ASME) design code, which is used to build many of the vessels in the chemical industry, including EVAL Reactor 2, requires that outlet piping from emergency pressure-relief systems "shall lead to a safe place of discharge" [54, p. 103, 55, p. 47, 56, p. 96].

Other publicly available examples of good practice safety guidance that follow this basic design principle include the following:

- "Pressure relief vent piping systems shall be constructed and arranged to direct the flow of gas to a safe location … [57, 58]."
- "Vents, pressure relief, and rupture disk discharge points should be located to vent to a **safe location**. Locate these discharge points such that they do not create a hazard for operators or maintenance personnel on walkways or platforms. Location of these vents should be a safe distance from building [heating, ventilation, and air conditioning] intakes. Consequence modeling may be utilized to determine the distance from the vent that a hazardous concentration may exist [59, p. 114] (emphasis added)."
- "Pressure relief device discharges shall be arranged such that they are not a hazard to personnel or other equipment and, when necessary, lead to a **safe location** for disposal of fluids being relieved [60, p. 21] (emphasis added)."
- "For full effectiveness, the pressure relief system must be included in the overall process design, and must be adequately sized to permit discharge of vessel contents at a safe pressure and to a **safe location** [61, pp. 1351-1352] (emphasis added)."
- "Emergency relief systems consist basically of one or more emergency relief devices, relieving either directly to the atmosphere "in a **safe location**" or by way of a relief header to a means of treating or handling the discharge, which can range from a stack to a combination of treatment devices in series [62, p. 171] (emphasis added)."
- "The discharge point for relief devices should also be a consideration in designing relief protection. The nature of the discharge and the point of the discharge may present significant hazards [63, p. 338]."
- "In the circumstance where the [pressure-relief device] is activated, the diverted reaction effluent (gas, liquid, or hybrid mixture) must be routed to a **safe location**; this location may be a flare for burning, a chemical scrubber, or even the atmosphere [64, p. 7] (emphasis added)."
- "Systems designed to completely or partially depressurize the process. These take the form of [safety relief valves] or valves which automatically open at a predetermined setpoint to vent piping or vessels to a **safe location** [65, p. 295] (emphasis added)."

- "For most processes, the last lines of defense are pressure relief systems. When designed properly, such systems are capable of preventing vessel and piping failures, and direct the relief effluent to a **safe location** [66, p. 2] (emphasis added)."
- "The **safe** discharge **location** must be identified for each individual relief device [67, p. 8] (emphasis added)."
- "[A pressure-relief valve is] a generic term which might refer to relief valves, safety valves, and pilot operated valves. The purpose of a [pressure-relief valve] is to automatically open and to relieve the excess system pressure by sending the process gasses or fluids to a **safe location** when its pressure setting is reached [68, p. xlii] (emphasis added)."
- "API [Standard] 521 recognizes that disposal to atmosphere can be safe and has been demonstrated. However, in accordance with [Section] 5.8.1 careful attention is required to ensure that atmospheric disposal of relief streams is safe [69, p. 4]."
- "The basic purpose of a vent or vent line is to ensure that gases escaping from a pressure-relief valve are directed to a **safe location** where they will not cause any harm [70, p. 161] (emphasis added)."
- "Relief valve exhaust must be directed or piped to a **safe location** [71, p. 958] (emphasis added)."
- "The simplest process vent system is one that consists of one vent device with minimal piping discharging directly to atmosphere at the nearest **safe location** [72, p. 1] (emphasis added)."
- "When discharging directly to the atmosphere, discharge shall not impinge on other piping or equipment and shall be directed away from platforms and other areas used by personnel [73, p. 47]."
- "The valve discharge and discharge pipe shall be checked for possible hazards to personnel [74, p. 45]."
- "Verify the discharge of the device is piped to a **safe point** of discharge [75, p. 3] (emphasis added)."
- "Discharge piping should be piped to a **safe area** to prevent discharge of high pressure fluids from causing harm to personnel or equipment [76] (emphasis added)."
- "[Emergency pressure-relief and effluent handling] systems should be designed to protect equipment from overpressure and to either contain or safely control hazardous materials discharged during an emergency [77, p. 1]."

In a March 2006 safety publication, the Center for Chemical Process Safety (CCPS) described a historical problem with some emergency pressure-relief system outlet piping designs discharging process fluids to a convenient location rather than to a safe location. The CCPS stated:

> Any material which could be released from process equipment, including pressure relief valves or rupture disks, must discharge to a safe location. Relief devices often discharge to a 'convenient' location – and that may not be the same as a 'safe' location [78]!

The safety publication highlighted the importance of discharging to a safe location by showing a picture (**Figure 26**) of elevated emergency pressure-relief system outlet piping directed toward the ground.

Figure 26. March 2006 *Process Safety Beacon*. (Credit: CCPS [78])

When describing the potential hazard of this piping design, the CCPS stated:

> The discharge from the relief valves in picture #3 is directed downward, toward an area where people could be working. As in the first picture, anyone working in this area when a relief valve opens could be injured [78].
>
> Relief valves and rupture disks are part of an emergency pressure relief **system**. Its design must not only prevent equipment overpressure, it must also make certain that material discharged does not lead to personnel injury. The system needs to ensure that there is no fire, explosion, or toxic material exposure hazard from the material released through a relief valve or rupture disk [78] (emphasis in original).
>
> Any material which could be released from process equipment, including pressure relief valves or rupture disks, must discharge to a **safe location** [78] (emphasis added).

In relevant corporate safety guidance, Kuraray itself supported the safety philosophy that emergency pressure-relief systems must discharge to a safe location. Specifically, in its policy on incident investigations, Kuraray provided its employees with a list of scenarios that qualify as the most serious level of process safety events. Notably, Kuraray's list of most serious scenarios included discharging emergency pressure-relief systems to an unsafe location (*See* **Figure 17**).

The CSB concludes that there are many publications that provide industry safety guidance making it clear that emergency pressure-relief systems must discharge to a safe location to prevent harm to people. The CSB further concludes that although Kuraray's corporate safety guidance recognized the potential severity of discharging emergency pressure-relief systems to an unsafe location, the company did not address this hazard for its EVAL Reactor 2 emergency pressure-relief system.

2.1.2 Industry Safety Standards Rely on Vertical Discharge

Although there is an abundance of industry good practice safety guidance discussing the need to discharge emergency pressure-relief systems to a safe location, no guidance suggests that it is appropriate to discharge flammable hydrocarbon vapors into the air through horizontally aimed piping.

API 521, *Pressure-Relieving and Depressuring Systems*, specifies requirements for emergency pressure-relief systems, including examining the causes of overpressure, determining relief rates, and "selecting and designing disposal systems, including such component parts as piping, vessels, flares, and vent stacks" [37, p. 1, 38, p. 1].

Published industry studies have shown that flammable gases can be discharged into the air safely by following the design guidelines in API 521. Among other considerations, emergency pressure-relief system outlet piping should direct a release of flammable vapor **vertically** upward to satisfy these design guidelines [79, p. 12].

An entire section of API 521 is devoted to safely discharging vapors (including flammable hydrocarbons) from emergency pressure-relief systems into the air [37, pp. 144-152, 38, pp. 125-141]. Several portions of this section are relevant to evaluating the Kuraray incident because they provide insight as to what the industry considers necessary to ensure that emergency pressure-relief systems discharge flammable hydrocarbon vapor to a safe location:

> In many situations, [pressure-relief device] vapor streams can be safely discharged directly to the atmosphere if environmental regulations permit such discharges. This has been demonstrated by many years of safe operation with atmospheric releases from properly installed vapor [pressure-relief devices]. Technical work sponsored by API[a] has also shown that within the normal operational range of conventional [pressure-relief devices], well-defined flammable zones can generally be predicted

[a] "V. O. Hoehne, R. G. Luce, and L. W. Miga, "The Effect of Velocity, Temperature, and Gas Molecular Weight on Flammability Limits in Wind-Blown Jets of Hydrocarbon Gases," report to the American Petroleum Institute, Battelle Memorial Institute, Columbus Ohio, 1970, and Proceedings—Refining Department, Volume 50, 1970, pp. 1057–1081" [37, p. 237].

> for vapor releases. With proper recognition of the appropriate design parameters, vapor releases to the atmosphere can provide for the highest degree of safety. Where feasible, this arrangement offers significant advantages over alternative methods of disposal because of its inherent simplicity, dependability and economy. The decision to discharge hydrocarbons or other flammable or hazardous vapors to the atmosphere requires careful attention to ensure that disposal can be accomplished without creating a potential hazard or causing other problems, such as the formation of flammable mixtures at grade level or on elevated structures, exposure of personnel to toxic vapors or corrosive chemicals, ignition of relief streams at the point of emission, excessive noise levels, and air pollution [37, p. 144, 38, p. 125].
>
> The studies demonstrate the adequacy of the general industry practice of locating [pressure-relief valve] stacks that discharge to the atmosphere at least [15 meters (50 feet)] horizontally from any structures or equipment running to a higher elevation than the discharge point. In most cases, this is adequate to prevent flammable vapors from reaching the higher structures. With these jet momentum releases, there should also be no concern about large clouds of flammable vapors or flammable conditions existing at levels below the release level of the stack. These studies have generally verified long-standing experience relative to the safety of vapor releases **vertically** to the atmosphere from atmospheric [pressure-relief valve] discharge stacks [37, p. 147, 38, p. 127] (emphasis added).
>
> When hydrocarbon-relief streams comprised entirely of vapors are discharged to the atmosphere, mixtures in the flammable range unavoidably occur downstream of the outlet as the vapor mixes with air. Under most circumstances in which individual [pressure-relief valves] discharge **vertically** upward through their own stacks, this flammable zone is confined to a rather limited definable pattern at elevations above the level of release [37, p. 145, 38, p. 126] (emphasis added).
>
> Based on these dispersion data, it can be concluded that where discharge velocities causing turbulent mixing are achieved, the hazard of flammable concentrations below the level of the discharge point is negligible. Fixed distances may be used for designs based upon experience, which precludes the need to perform dispersion analyses. This confirms the many years of experience with vapor releases from [pressure-relief valves] discharging directly to the atmosphere without accumulating flammable concentrations [37, p. 146, 38, p. 127].

For installation details related to piping, API 521 directs the user to API Standard 520 (API 520), *Sizing, Selection, and Installation of Pressure-Relieving Devices,* Part II—Installation. API 520 provides figures to describe how users should design piping for discharging emergency pressure-relief systems. As shown in **Figure 27**, for atmospheric discharge, API 520 demonstrates that the piping should be aimed vertically upward [80, p. 8, 81, p. 9]. API 520 used the image in **Figure 27**, showing outlet piping aimed vertically upward, to inform users of the general design requirements for emergency pressure-relief system outlet piping.

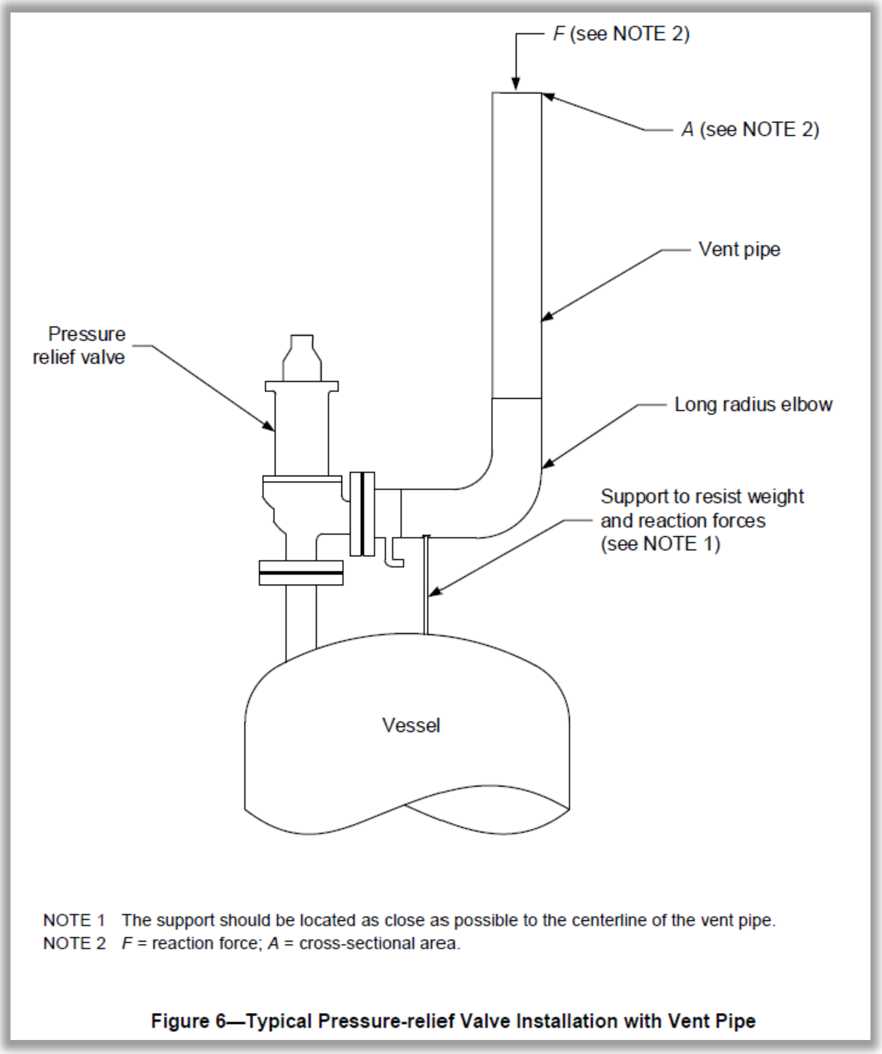

Figure 27. Vertical Outlet Piping. (Credit: API [80, p. 8, 81, p. 9])

2.1.3 Horizontally Aimed Discharge of Flammable Vapor

The CSB identified one published study that evaluated a horizontal release of flammable crude oil vapor, where the horizontal release did not discharge the flammable vapor to a safe location. The authors of the study stated:

> In the cases with subsonic horizontal gas exit velocities, the rate of air entrainment is too slow to prevent the flammable plume from reaching grade. [API 521] correctly identifies this situation as one which may result in flammable vapors at grade [79, p. 15].

Kuraray informed the CSB that the company's pressure-relief system experts stated that horizontally aimed discharges of flammable vapor from emergency pressure-relief systems are not specifically prohibited by industry standards, such as API 521. The CSB consulted with API 521 subject matter experts and was told that API 521 does not prohibit discharging flammable vapor from emergency pressure-relief systems through horizontally aimed piping. The API 521 experts said that a horizontal discharge might even be desirable in some cases, such as when the discharge of flammable vapor from an emergency pressure-relief system might intersect with the potential flight path of a helicopter taking off or landing on an offshore oil rig.

Since API 521 does not include guidance on safely discharging flammable vapor from emergency pressure-relief systems through horizontally aimed piping, such a design may require companies to develop their own safety standard to ensure that a sufficiently robust analysis is performed to show that the horizontal discharge is directed to a safe location—ensuring no harm to people.

The CSB concludes that API 521, *Pressure-Relieving and Depressuring Systems,* does not provide users with guidance for safely discharging flammable vapor into the air from horizontally aimed emergency pressure-relief system piping. Therefore, API 521 cannot serve as the sole safety design basis for an emergency pressure-relief system that horizontally discharges flammable vapor into the ambient air.

2.1.4 Emergency Pressure-Relief System Validation Project

In 2011, seven years before the May 19, 2018, incident, Kuraray began engineering work to ensure that it had proper designs for the site's emergency pressure-relief systems. Among other concerns, the Kuraray project team concluded that Kuraray needed to change some of its emergency pressure-relief systems capable of discharging liquid ethylene near workers (*See* Section 1.9). Notably, the project's scope did not include a dispersion study of flammable hydrocarbon vapor releases into the air, and Kuraray's project records did not include a safety evaluation of the discharge from emergency pressure-relief systems.

Implementing the engineering firm's proposed changes could have prevented the May 19, 2018, incident since the ethylene vapor released from the EVAL Reactor 2 emergency pressure-relief system would have been contained in equipment and directed to a flare instead of into the air toward workers. Although Kuraray implemented some of the engineering firm's recommendations, Kuraray did not implement the engineering firm's proposal to capture the ethylene emergency pressure-relief system vents and route them to a flare. Project documents provided to the CSB do not explain why Kuraray did not implement the engineering firm's proposal. While one Kuraray employee clearly recalled that the company did not implement the proposal "due to cost," a key Kuraray manager did not recall the safety concern. Rather, he thought the proposal stemmed from his desire to reduce environmental emissions.

Kuraray never corrected the hazardous EVAL Reactor 2 emergency pressure-relief piping, in part because Kuraray never implemented the overarching proposal to capture discharges from its emergency pressure-relief systems and route them to a flare and also because the engineering firm's scope of work did not appear to have included evaluating whether each emergency pressure-relief system discharged to a safe location.

The CSB concludes that Kuraray could have prevented the May 19, 2018, incident by implementing its engineering firm's proposal to direct ethylene from emergency pressure-relief systems to a flare. The engineering firm's proposal called for containing the flammable ethylene from the emergency pressure-relief system within piping that directed the vapor to a flare for safe disposal instead of discharging the flammable ethylene vapor into the air (through horizontally aimed piping) near workers.

2.1.5 2015 Process Hazard Analysis

Another opportunity for Kuraray to prevent the incident on May 19, 2018, incident followed the company's most recent PHA conducted in 2015. Kuraray's PHA team found that potential ethylene releases from some of the site's emergency pressure-relief systems (including EVAL Reactor 2) could result in a flash fire or a vapor cloud explosion. The PHA team recommended that Kuraray perform a study to evaluate these potential ethylene releases from emergency pressure-relief systems and their impact on personnel. Kuraray management did not accept the PHA team's recommendation, however, and Kuraray never performed the proposed study.

The CSB concludes that Kuraray did not adopt safety recommendations that its 2015 Process Hazard Analysis (PHA) team proposed after finding that atmospheric ethylene releases from some emergency pressure-relief systems, including the EVAL Reactor 2 emergency pressure-relief system, could harm workers by creating a flash fire or vapor cloud explosion.

2.1.6 API Safety Guidance to Prevent Vapor Cloud Explosions

Kuraray management's failure to address its PHA team's recommendation (which asked the company to further evaluate how atmospheric releases of ethylene might adversely affect the safety of workers) was a significant contributing cause to the May 19, 2018, incident. To better understand the causal connection between this management decision and the incident, it is helpful to understand how API 521 addresses scenarios in which releases from certain emergency pressure-relief systems into the air can create the potential for a vapor cloud explosion.

As part of its investigation of the 2005 BP Texas City refinery explosion and fire that resulted in 15 fatalities, the CSB evaluated the 1997 edition of API Recommended Practice 521 (API RP 521), *Guide for Pressure-Relieving and Depressuring Systems*, which was the generally accepted industry good practice guidance for pressure-relieving and disposal systems at the time, to determine its effectiveness in addressing hazards posed by blowdown drums with integral stacks open to the air. The CSB identified several gaps in the guidance and noted in its investigation report on the incident that API RP 521, among other things, did not address the potential overpressure hazard of vessel liquid overfill or the hazard of a large liquid release to a disposal drum that vents directly into the air. The guidance also did not advise on the safe siting of a vent stack or flare. API RP 521 did not address the concept that a flare system is an inherently safer design than an atmospheric vent stack because it safely combusts flammable hydrocarbons before they are vented into the air, where they could become a serious fire or vapor cloud explosion hazard. Considering the issues discovered after reviewing API RP 521, the CSB issued Recommendation No. 2005-4-I-TX-R4 to API on October 31, 2005, to revise API RP 521:

> Revise API Recommended Practice 521, Guide for Pressure Relieving and Depressuring Systems to ensure that the guidance:
>
> - Identifies overfilling vessels as a potential hazard for evaluation in selecting and designing pressure relief and disposal systems;
> - Addresses the need to adequately size disposal drums for credible worst-case liquid relief scenarios, based on accurate relief valve and disposal collection piping studies;
> - Warns against the use of atmospheric blowdown drums and stacks attached to collection piping systems that receive flammable discharges from multiple relief valves and urges the use of appropriate inherently safer alternatives such as a flare system [40, p. 1].

Following the CSB's recommendation, API strengthened API 521 from a recommended practice to a standard. API also issued updated versions of this industry standard in 2007 and again in 2014. These revisions included specifying what users must do to avoid or prevent a vapor cloud explosion scenario from certain emergency pressure-relief systems that discharge into the air. For these unacceptable scenarios, API 521 stated:

> If there is a vapor cloud explosion hazard associated with one or more relief cases or discharges, then one of the following **shall** be used:
>
> - disposal by a flare …;
> - discharging into a lower-pressure system …;
> - application of HIPS [High-Integrity Protective Systems] …; and
> - eliminating the relevant relief cases (redesign of equipment, etc.) [37, p. 155, 38, p. 135] (emphasis added).

As a result of the improvements that API made to API 521, in April 2016, the CSB voted to change the status of the recommendation to Closed—Acceptable Action [40]. The CSB stated, "Revisions made to the text [in API 521] address concerns about releases directly to atmosphere and generally require using inherently safer alternatives when the potential exists for a flammable vapor cloud explosion" [40, p. 2].

The CSB concludes that Kuraray could have prevented the May 19, 2018, incident by applying one of the four safer strategies that API 521 specified to prevent vapor cloud explosions—redesigning equipment to avoid the scenario, flaring, containing the flammable material in a lower-pressure system, or applying high-integrity protective systems.

2.1.7 Kleen Energy Incident

In addition to the Kuraray incident, the 2010 Kleen Energy incident provides another vivid example of the danger involved when flammable gas is not discharged to a safe location. On Sunday, February 7, 2010, Kleen Energy, a natural gas-fueled power plant under construction in Middletown, Connecticut, experienced a catastrophic natural gas explosion that fatally injured six workers and injured at least 50 other workers [82, p. 1].

The incident occurred during the planned cleaning of fuel gas piping, part of the commissioning and startup phase of the Kleen Energy project. At the time of the incident, workers were conducting a "gas blow," whereby natural gas was forced through the piping at high pressure and volume to remove debris [82, pp. 2-3]. **Figure 28** shows the horizontally aimed discharge of natural gas during a gas blow at Kleen Energy. Like the outlet piping from the EVAL Reactor 2 emergency pressure-relief system, the gas blow piping did not discharge flammable gas to a safe location. At the exit of the horizontally aimed piping, the cleaning operation intentionally discharged the natural gas (and debris) into the air [82, p. 11].

Figure 28. Horizontal Natural Gas Blow at Kleen Energy. (Credit: CSB [83])

Figure 29 shows a portion of the Kleen Energy facility that was heavily damaged when flammable gas (used to clean piping) was discharged into the air horizontally, ignited, and exploded. This release of natural gas into the air was similar to an atmospheric discharge from an emergency pressure-relief system.

Figure 29. Explosion Damage at Kleen Energy. (Credit: CSB [84])

Figure 30 shows the vertical discharge of natural gas during a gas blow at Kleen Energy on January 30, 2010, one week before the incident [82, p. 5].[a] The brown color is from the piping debris. The natural gas that propelled the debris out of the piping was colorless. Workers conducted multiple gas blows to clean the piping. With each successive gas blow, the amount of debris and the color of the release decreased. Although most of the gas blows at Kleen Energy discharged natural gas and debris vertically upward (**Figure 30**), the gas blow that resulted in the explosion on February 7, 2010, was a horizontally aimed discharge (**Figure 28**) [82, p. 2].

[a] Although the gas blow show in **Figure 30** did not ignite, the release discharge point may not have been sufficiently elevated to be considered as discharging to a safe location.

Figure 30. Vertical Natural Gas Blow at Kleen Energy.[a] (Credit: CSB [83])

At the time of the explosion, workers were blowing natural gas into the air from open-ended piping between two large structures known as heat recovery steam generators [82, p. 2]. This location, though outdoors, was congested by the surrounding power generation equipment. **Figure 31** is an image from Deadly Practices, a CSB safety video, showing how the horizontally aimed discharge of flammable gas in a congested area led to the explosion at Kleen Energy.

[a] Although the gas blow show in **Figure 30** did not ignite, the release discharge point may not have been sufficiently elevated to be considered as discharging to a safe location.

Like the outlet piping from the EVAL Reactor 2 emergency pressure-relief system, the gas blow piping was installed in a horizontal orientation and did not discharge the flammable gas to a safe location. At Kleen Energy, both the congested area and the vent pipe's horizontal orientation likely adversely affected the dispersion of the natural gas [82, p. 2].

Figure 31. Animation of Horizontally Aimed Gas Blow. (Credit: CSB [83])

In 2011, as a result of a CSB recommendation, the State of Connecticut banned the practice of performing gas blows to clean fuel gas piping at power plants [85]. CSB Recommendation 2010-01-I-CT-UR16 to the Governor and Legislature of the State of Connecticut stated, "Enact legislation applicable to power plants in the state that prohibits the use of flammable gas that is released to the atmosphere to clean fuel gas piping." On September 14, 2011, the Board unanimously voted to approve closing this recommendation with the status of Closed—Acceptable Action.

2.1.8 Other Kuraray Emergency Pressure-Relief Systems

Although the CSB investigation focused on the EVAL Reactor 2 emergency pressure-relief system, publicly available images suggest that Kuraray also designed other emergency pressure-relief systems with outlet piping that discharged through horizontally aimed piping (*See* Section 1.8).

The CSB concludes that Kuraray's use of emergency pressure-relief systems with horizontally aimed outlet piping may be a systemic problem. The emergency pressure-relief system for EVAL Reactor 1 was designed to discharge flammable ethylene vapor horizontally toward a public road, which could place members of the public in harm's way. In addition, the CSB learned that the corporation might have used this dangerous design in all its EVAL facilities.

As described in Section 1.29.1, Kuraray changed its EVAL Reactor 2 emergency pressure-relief system design after the incident. Among other changes, Kuraray modified the outlet piping to discharge vertically upward, following existing industry guidance. Kuraray also increased the elevation of this piping and performed a dispersion analysis to show that should this system activate and discharge flammable ethylene into the air (in the future), such a release should not harm any workers.

The CSB recommends that Kuraray develop and implement an emergency pressure-relief system design standard to ensure that each of these safety systems will discharge to a safe location. Include a requirement to periodically evaluate the site's emergency pressure-relief systems and make appropriate modifications to ensure that each of these systems discharge to a safe location such that material that could discharge from these safety systems will not harm people. (*See* Recommendation 2018-03-I-TX-R1).

2.2 Evacuate Nonessential Workers During Startup and Upset Conditions

In its book, *Guidelines for Siting and Layout of Facilities*, the Center for Chemical Process Safety (CCPS) presented a series of case histories illustrating situations in which companies did not perform their risk management tasks well [86, p. 265].[a] The first case history that the CCPS reviewed was the March 23, 2005, BP Texas City refinery incident [86, p. 268].

In discussing the lessons from the BP Texas City refinery incident about the presence of nonessential personnel, the CCPS concluded:

> … [T]he severity of the [BP Texas City] incident was increased by the presence of many people congregated in and around temporary trailers, which were inappropriately sited too close to a potential hazard. To help reduce risks to personnel working near hazardous areas, consider:
>
> - All hazards in the surrounding area when siting temporary buildings …;
> - Siting temporary buildings in remote locations …; and
> - The need to create an exclusion zone around process units under startup conditions. Incidents are more likely to occur under transient operations such as a startup. All non-essential personnel and vehicles should be removed from adjacent areas for the duration of the startup [86, p. 270].

[a] Kuraray is a CCPS member company [137].

The last of the CCPS bullet points should be explored in light of the Kuraray incident.[a] Some companies have adopted this recommended approach to help reduce the potential severity of incidents during transient operations, such as a unit startup. In their post-incident statements to CSB investigators, several workers commented that they were surprised to learn that Kuraray was starting up EVAL Reactor 2. Following the March 2005 disaster at the BP refinery in Texas City, these contract workers often traveled from site to site for different companies, and they had grown accustomed to either their own management or the local site management withdrawing or restricting nonessential personnel from units during a startup.

At the time of the Kuraray incident, many workers were in the vicinity of EVAL Reactor 2, performing various tasks that included pump demolition, hydrotesting, welding, insulating, and scaffolding. These tasks were not essential to the EVAL Reactor 2 startup. The CSB concludes that at the time of the incident, none of the contract workers located near the EVAL Reactor 2 emergency pressure-relief system were performing tasks associated with operating the reactor, responding to the abnormal reactor conditions, or were otherwise essential to the startup.

The CSB also concludes that neither Kuraray's operating procedures nor its operator training covered the known activities or conditions that should have prompted Kuraray's operations personnel to exclude nonessential personnel from the unit. These events include bringing ethylene back into the unit or during upset conditions, such as high-pressure conditions that trigger a reactor High-High-Pressure alarm.

While Kuraray had an unwritten operational practice of excluding nonessential personnel from a unit while ethylene was first introduced, the site practice did not include a formal exclusion zone for the startup's duration. When the EVAL Reactor 2 High-High-Pressure alarm sounded—showing upset conditions in the unit—no one evacuated the nonessential personnel working in the unit.

The CSB concludes that Kuraray had an unwritten safety practice to exclude nonessential personnel from a unit when reintroducing (pressuring or charging) ethylene into equipment after a turnaround, but the company lacked a formal exclusion zone to protect nonessential workers for the duration of the startup.

The CSB concludes that Kuraray's safety management systems did not consider the high-pressure conditions developing inside EVAL Reactor 2 as an upset condition that should halt the maintenance work being performed and prompt the evacuation of nonessential personnel.

The CSB further concludes that when the flammable ethylene vapor was discharged from the reactor's emergency pressure-relief system, many nonessential workers were in harm's way, and the welding work they were performing likely supplied the ignition source that created the fire.

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[a] The CSB investigation report on the March 23, 2005, BP Texas City disaster found that BP's pre-startup safety review (PSSR) procedure required a PSSR before starting up a unit after a turnaround. BP's PSSR policy went beyond the minimum OSHA PSSR requirements. The PSSR policy included a provision to ensure that nonessential personnel were removed from the unit and neighboring units before startup. Still, BP did not perform any of the company's PSSR procedural steps before starting the ISOM unit, and nonessential personnel remained [39, p. 47]. None of the 15 fatally injured workers were essential to the isomerization (ISOM) unit's startup [39, p. 68]. Kuraray's PSSR policy did not require a PSSR before starting a unit or include a provision to remove nonessential personnel before startup after a turnaround.

As described in Sections 1.29.2 and 1.29.5, Kuraray modified its practices to protect nonessential personnel after the incident. During the startup of an EVAL Reactor, Kuraray now uses the control system to display a visual operator guidance message instructing its operators to activate (sound) the plant-wide emergency alarm if the reactor pressure exceeds the high-pressure alarm value by a specified threshold. In addition, Kuraray now requires a 50-foot exclusion zone around each EVAL Reactor during startup.

As a result of the settlement agreement between OSHA and Kuraray (*See* Section 1.27.2), OSHA required Kuraray to evacuate nonessential workers from the area during EVAL Reactor 2 High-High Pressure alarm conditions.[a] The OSHA enforcement effort did not extend to the other areas of the Kuraray facility, nor did it require Kuraray to implement a site-wide system to establish an exclusion zone during transient operating phases, such as startup.

The CSB recommends that Kuraray implement a site-wide system to evacuate nonessential personnel during upset conditions and exclude nonessential workers from being near equipment during transient operating modes, such as startup (*See* 2018-03-I-TX-R2).

2.3 Hazardous Location

With the EVAL Plant having several emergency pressure-relief systems with the potential to discharge flammable ethylene to unsafe locations, workers at Kuraray were routinely exposed to elevated risk. For example, the EVAL Reactor 2 emergency pressure-relief system could activate and discharge flammable ethylene near workers from any of several scenarios that could arise at nearly any time. Beyond the specific events that led to the high-pressure conditions on May 19, 2018, Kuraray had documented a number of scenarios that could generate high pressure inside EVAL Reactor 2. These events included cooling failure, loss of refrigeration, power failure, or even a simple malfunction of the control valve supplying ethylene to the reactor (**Figure 6**).

The CSB concludes that the safety of workers near the EVAL Reactor 2 emergency pressure-relief system was routinely at risk. Known scenarios that could generate high pressure inside the reactor could arise at any time, including cooling failure, loss of refrigeration, power failure, or even a simple malfunction of the control valve supplying ethylene to the reactor. With workers present, activating this safety system created a danger to their safety.

The CSB also concludes that because the emergency pressure-relief system did not discharge ethylene to a safe location, a portion of the area adjacent to EVAL Reactor 2 was a hazardous location for workers.

Kuraray made changes to the EVAL Reactor 2 emergency pressure-relief system design after the incident. These changes should help ensure that the area adjacent to EVAL Reactor 2 is not a hazardous location for workers.

[a] The CSB is not issuing new Recommendations that overlap with the OSHA's enforcement efforts that are documented in the settlement agreement between Kuraray and OSHA.

2.4 Recognized and Generally Accepted Good Engineering Practices

For two of the 14 OSHA PSM elements (Process Safety Information and Mechanical Integrity), OSHA requires companies to document how equipment, such as an emergency pressure-relief system, conforms with recognized and generally accepted good engineering practices (RAGAGEP).[a] Of these two PSM elements, the Process Safety Information aspect of RAGAGEP was the most relevant to the May 19, 2018, incident at the Kuraray EVAL Plant.

According to OSHA, Process Safety Information must be both complete and accurate. Companies must document the information they used to develop the equipment design. OSHA explained this requirement by saying:

> In other words, what were the codes and standards relied on to establish good engineering practice [87, p. 5]?

The information available to the CSB suggests that at the time of the May 19, 2018, incident, the design of the emergency pressure-relief system for EVAL Reactor 2 was unchanged from when Kuraray installed this system in 1986. OSHA addresses what employers need to do when good engineering practice has changed after equipment has been installed or when a design does not conform with industry codes or industry standards:

> For existing equipment designed and constructed in accordance with codes, standards, or practices that are no longer in general use, the employer shall determine and document that the equipment is designed, maintained, inspected, tested, and operating in a **safe manner** (emphasis added).[b]
>
> For existing equipment designed and constructed many years ago in accordance with the codes and standards available at that time and no longer in general use today, the employer must document which codes and standards were used and that the design and construction along with the testing, inspection and operation are still suitable for the intended use. Where the process technology requires a design which **departs from the applicable codes and standards**, the employer **must document that the design and construction is suitable** for the intended purpose [87, p. 5] (emphasis added).

With regard to Process Safety Information, OSHA requires employers to document the design and design basis of their emergency pressure-relief systems.[c] Furthermore, employers need to select and show what

[a] *See* 29 C.F.R. § 1910.119. Before the OSHA PSM Standard was issued, industry good practice guidance was available to companies on how to use good engineering practices to achieve safe facilities. One such example was the *Guidelines for Technical Management of Chemical Process Safety* published by the CCPS in 1989 [128].

[b] *See* 29 C.F.R. § 1910.119 (d)(3)(iii).

[c] *See* 29 C.F.R. § 1910.119 (d)(3)(i)(D).

design codes and standards they apply to equipment and how this equipment conforms with the chosen RAGAGEP [88, pp. 7-11].[a]

The engineering firm that developed the 2012 design package for Kuraray's emergency pressure-relief systems, however, did not identify the codes or standards that specifically applied to the design of each emergency pressure-relief system or explain how each system conformed with RAGAGEP. Rather, Kuraray's emergency pressure-relief system design packages just listed several laws, codes, and guidelines that may or may not apply to each system. **Figure 20** shows the list of laws, codes, and guidelines the engineering firm typically included with each emergency pressure-relief system design package. Kuraray used this list in the design package for the EVAL Reactor 2 emergency pressure-relief system.[b] Based on this information, the design basis included API 521 as well as API 520, and the ASME pressure vessel code.

Although the EVAL Reactor 2 emergency pressure-relief system discharged horizontally, the design was based on industry codes that require discharge to a safe location and industry standards that rely on vertical discharge to help ensure safety when discharging flammable vapor into the air. These industry standards do not provide users with guidance for safely discharging flammable vapor into the air from horizontally aimed emergency pressure-relief system piping. The EVAL Reactor 2 design and design basis documentation, however, did not include any evaluation showing that the emergency pressure-relief system would discharge to a safe location. Such an evaluation could include a dispersion and consequence analysis showing no expected adverse safety and health effects (that is, no harm to workers). While the design information did include a sketch showing that this emergency pressure-relief system discharged through horizontally aimed piping, nothing suggested that an evaluation had been performed to ensure that discharging flammable ethylene through this piping would not harm workers.

The CSB concludes that Kuraray did not demonstrate how its EVAL Reactor 2 emergency pressure-relief system conformed with recognized and generally accepted good engineering practices (RAGAGEP) or that this safety equipment was designed and operated in a safe manner.

The outlet piping from the EVAL Reactor 2 emergency pressure-relief system was oriented such that the release discharged flammable ethylene horizontally, parallel to the ground, toward an area where nonessential workers were performing their assigned tasks. The CSB concludes that Kuraray did not perform an evaluation, such as a dispersion analysis, to ensure that releasing ethylene vapor from the EVAL Reactor 2 emergency pressure-relief system through its horizontally aimed piping would discharge the flammable ethylene to a safe location.

The CSB also concludes that had Kuraray evaluated the safety of horizontally discharging high-pressure ethylene into the air when developing its Process Safety Information for the EVAL Reactor 2 emergency pressure-relief system, the safety risk to workers could have been identified, the outlet piping design problem could have been corrected, and the company could have prevented the May 19, 2018, incident.

[a] *See* 29 C.F.R. § 1910.119.

[b] Several of the laws, codes, and guidelines identified, such as the ASME (American Society of Mechanical Engineers) Section I (Power Boilers), seem irrelevant for the design of the EVAL Reactor 2 emergency pressure-relief system.

As described in Section 1.29.1, Kuraray modified its EVAL Reactor 2 emergency pressure-relief system design after the incident. Among other changes, Kuraray modified the outlet piping to discharge vertically upward, following existing industry guidance. Kuraray also increased the elevation of this piping and performed a dispersion analysis to show that should this system activate and discharge flammable ethylene into the air (in the future), such a release should not harm any workers.

2.5 PHA Safeguards

On August 6, 2012, the Chevron refinery in Richmond, California, experienced a catastrophic pipe failure in a crude unit, causing the release of flammable hydrocarbon process fluid, which partially vaporized into a large cloud. The vapor cloud engulfed 19 Chevron employees who narrowly escaped, avoiding serious injury. About 15,000 people from the surrounding area sought medical treatment in the weeks following the incident. The CSB's investigation found that the pipe failure was caused by sulfidation corrosion, a damage mechanism that causes piping walls to thin over time [89, p. 3].

Additionally, the CSB investigation found that the process hazard analysis conducted on the piping that failed at the Chevron refinery did not identify corrosion as a potential cause of a leak or rupture. The CSB also found that Chevron did not require the use of a recognized methodology for objectively determining the effectiveness of safeguards in place to prevent hazardous consequences. Instead, Chevron relied upon the judgment and experiences of the members of its PHA team [89, pp. 31-32].

Following the August 6, 2012, fire at the Chevron refinery in Richmond, California, both Cal/OSHA and Contra Costa County strengthened their process safety regulations by requiring certain facilities to periodically perform a safeguard protection analysis (SPA) [90, 91].

In its Process Safety Management for Petroleum Refineries regulations, Cal/OSHA now requires companies to perform a safeguard protection analysis for each PHA scenario that identifies the potential for a major incident.[a] This analysis must determine the effectiveness of "existing individual safeguards, the combined effectiveness of all existing safeguards for each failure scenario in the PHA, the individual and combined effectiveness of safeguards recommended in the PHA, and the individual and combined effectiveness of additional or alternative safeguards that may be needed" [92, p. 8].[b]

The safeguard protection analysis must "use a quantitative or semi-quantitative method, such as Layer of Protection Analysis,[c] or an equally effective method to identify the most protective safeguards. The risk reduction obtainable by each safeguard shall be based on site-specific failure rate data, or in the absence of such data, industry failure rate data for each device, system or human factor" [92, p. 9].

[a] Cal/OSHA defines a major incident as, "An event within or affecting a process that causes a fire, explosion or release of a highly hazardous material and has the potential to result in death or serious physical harm" [92].

[b] Contra Costa County strengthened its Industrial Safety Ordinance to also require companies to perform a safeguard protection analysis [91].

[c] A Layer of Protection Analysis (LOPA) is a well-recognized hazard analysis methodology that is intended to determine if a sufficient number of safeguards or layers of protection exist to protect against a particular hazard or accident scenario [143, 144, p. 13].

As discussed in Section 1.11, Kuraray's 2015 PHA team identified three safeguards that could control high-pressure conditions inside EVAL Reactor 2 and avoid activating the emergency pressure-relief system. These safeguards included:

- high-pressure alarms with an operator opening the emergency open valve;
- reactor abnormal condition (High-High-Pressure) safety interlock; and
- a high-pressure switch that could trigger closing valves to isolate reactor feeds.

As the pressure inside EVAL Reactor 2 continued to increase, none of these safeguards were effective at controlling the pressure inside the reactor without activating the emergency pressure-relief system and discharging flammable ethylene into the air.

The first safeguard required the board operator to open the emergency open valve to lower the reactor pressure by sending vapor from the reactor to the flare. Although three operations personnel looked at the control system on the morning of the incident, the design of the alarm system, along with the startup environment, did not result in effective actions being taken to reduce the reactor pressure as the PHA team had envisioned. Because Kuraray restricted the use of this safeguard (*See* Section 2.14.2), the board operator did not open the emergency open valve until after the incident.

A second safeguard, the reactor's abnormal condition (High-High-Pressure) safety interlock, which used automatic controls to protect the reactor from high-pressure conditions, was not effective because it was disabled during the startup (*See* Section 1.17).

The third safeguard, the high-pressure switch, also was not effective because the board operator had already closed the valves to stop the feeds from entering the reactor, and the continually increasing pressure inside EVAL Reactor 2 was not caused by ethylene flowing into the reactor. Rather, the inventory of liquid ethylene being warmed inside the reactor was generating ethylene vapor and driving the increasing pressure inside the reactor system (*See* Appendix A at 8:46 a.m.).

The CSB concludes that on the day of the incident, none of the safeguards that Kuraray concluded should control the pressure inside the reactor without activating the EVAL Reactor 2 emergency pressure-relief system were effective. Because these safeguards were ineffective, high-pressure conditions inside the reactor reached the activation pressure of the emergency pressure-relief system, and the flammable ethylene was discharged toward workers.

The CSB recommends that Kuraray develop and implement a system requiring a periodic evaluation of the adequacy and effectiveness of any safeguard used to mitigate or otherwise lower the risk of process safety hazards. This safeguard protection analysis should be based on the requirements of Cal/OSHA's Process Safety Management for Petroleum Refineries regulations or an appropriate equivalent methodology. (*See* Recommendation 2018-03-I-TX-R3).

2.6 PHA Recommendations

As discussed in Section 1.11, Kuraray's 2015 PHA team recommended that Kuraray perform a study to evaluate potential ethylene releases from emergency pressure-relief systems and their safety impact on personnel. Kuraray management did not accept the PHA team's recommendation, however, and Kuraray never performed the proposed study.

Kuraray's PHA policy did not require its management to document its reasons for declining PHA recommendations. Because Kuraray did not document its decisions or plans, it was not clear what Kuraray's management intended to do with this PHA recommendation.

The CSB concludes that Kuraray did not implement or effectively manage the disposition of the recommendation made by its 2015 PHA team to evaluate the potential safety impact on workers from ethylene that could be discharged into the air from emergency pressure-relief systems.

OSHA's guidance on addressing PHA team recommendations allows companies to "justifiably decline to adopt a recommendation," but the guidance requires companies to document "in writing and based upon adequate evidence" that at least one of the following conditions was true:

1. The analysis upon which the recommendation is based contains material factual errors;
2. The recommendation is not necessary to protect the health and safety of the employer's own employees or the employees of contractors;
3. An alternative measure would provide a sufficient level of protection; or
4. The recommendation is infeasible [27, p. 106].

The CSB concludes that had Kuraray effectively evaluated its 2015 PHA team's recommendations to address the worker safety concerns related to potential ethylene releases from emergency pressure-relief systems before declining these safety recommendations, it is likely that the company could have identified the safety risk to workers, corrected the design problem with the EVAL Reactor 2 emergency pressure-relief system discharge location, and prevented the May 19, 2018, incident.

The CSB recommends that Kuraray develop and implement a policy detailing how to effectively address recommendations generated from company process safety management systems, including audits, incident investigations, management of change, and process hazard analysis that is consistent with existing OSHA guidance. Include a periodic training requirement for managers and other employees involved with evaluating and managing proposed recommendations to help ensure proposed safety improvements are effectively evaluated and appropriately implemented. (*See* Recommendation 2018-03-I-TX-R4).

2.7 Warning Signs

> "It is tragic the number of times people are harmed in accidents where earlier warning signs had been overlooked [93, p. 120]."

In 2012, the CCPS published *Recognizing Catastrophic Incident Warning Signs in the Process Industries*, a book focused on recognizing "indicators that something is wrong or about to go wrong" and taking action to prevent a major incident [94, pp. 1-3]. In the book's Introduction, CCPS states:

> Warning signs are indicators that something is wrong or about to go wrong. When we recognize and act on these indicators, a loss may be prevented. Of course, this will only happen when we know what to look for and are willing to take the initiative to do something about it. A review of significant incidents in the process industries suggests that most if not all incidents were preceded by warning signs. Some of these signs were clearly visible but not acted upon because their significance was not understood. Other warning signs were less obvious, but observant personnel may have detected them [94, p. 1].

In its investigation of the May 19, 2018, ethylene release and fire, the CSB found pre-incident warning signs at Kuraray. Dangerous releases of flammable ethylene from emergency pressure-relief devices at the EVAL Plant had previously occurred. In addition, Kuraray's own hazard review team had cautioned that ethylene vapor cloud explosions could occur when some of these safety systems discharged flammable ethylene vapor into the air. These events should have served as warnings about the serious design problem with some of Kuraray's emergency pressure-relief systems. Had Kuraray effectively recognized and acted on these earlier warnings, the company could have corrected its emergency pressure-relief systems by ensuring that each of them would be discharged to a safe location, and the incident on May 19, 2018, could have been prevented.

Warning signs available to Kuraray included:

- A release of hydrocarbon vapor from an emergency pressure-relief system in the 1980s formed a flammable vapor cloud but did not ignite;
- A release of high-pressure ethylene from an emergency pressure-relief system on March 22, 2015, where the flammable ethylene vapor cloud did not ignite;
- Kuraray information on ethylene hazards warned against venting (discharging) ethylene into the air because of its flammability hazard;
- During the emergency pressure-relief system validation project, the engineering firm found some systems that could discharge ethylene into the air and cause a future vapor cloud explosion, and in 2013 the firm proposed that Kuraray collect and send the ethylene discharges

from these systems to a flare for safe disposal, but Kuraray did not implement this proposal; and

- Kuraray's 2015 PHA team found that potential ethylene releases from some of the site's emergency pressure relief systems could cause a flash fire or vapor cloud explosion with worker fatalities. The PHA team recommended that Kuraray perform a study to evaluate potential ethylene releases from these emergency pressure-relief systems and their safety impact on workers, but the site's management did not accept the recommendation, and Kuraray did not conduct the study.

Over the site's history, Kuraray had at least two previous incidents where emergency pressure-relief systems discharged flammable ethylene into the air. In each event, the ethylene vapor was near the ground—but did not ignite. One release was in the 1980s, and a more recent incident occurred in 2015. Each of these incidents revealed an emergency pressure-relief system that did not discharge to a safe location. Kuraray also had warnings from its 2015 PHA team and the engineering firm it hired in 2011 to examine these safety systems. Both groups warned that some of Kuraray's emergency pressure-relief systems had the potential to cause great harm to people.

The CSB concludes that Kuraray had earlier warnings about the serious design problem with some of its emergency pressure-relief systems. By acting on these earlier warnings, Kuraray could have prevented the May 19, 2018, incident.

To reduce the risk of a catastrophic incident, the CCPS stated that recognizing and responding to warning signs is an important first step. The CCPS presented a call to action in advocating that companies embrace the use of warning signs as predictors of increased danger and include warning signs within their process safety management systems. Among other things, the CCPS recommended that companies:

- Perform an initial survey of warning signs;
- Build warning sign analysis into the safety management system;
- Use the new system and track related action items;
- Evaluate effectiveness in the next safety management system assessment; and
- Maintain vigilance against recurring warning signs [94, pp. 175-179].

The CSB recommends that Kuraray review the Center for Chemical Process Safety guidance on recognizing catastrophic incident warning signs and then develop and implement a program for the EVAL Plant that incorporates warning signs into its safety management system. (*See* Recommendation 2018-03-I-TX-R5).

2.8 Equipment Design

At 10:05 a.m. on May 19, 2018, when Supervisor 1 asked Board Operator 2 to take over the startup of EVAL Reactor 2 and perform the flush batch, none of the three workers—Supervisor 1, Board Operator 1, or Board Operator 2—appeared to be concerned about the high pressure in the reactor or aware of how close the reactor pressure was to the activation pressure of its emergency pressure-relief system.

Inside the reactor, however, the pressure was high, and the High-High-Pressure alarm had been on for more than an hour (since 9:01 a.m.). Emergency pressure-relief equipment is manufactured to activate within a certain acceptable tolerance. This safety equipment should be expected to activate near the design pressure but could activate within a few percentage points—above or below this pressure. As a result of this tolerance, the maximum operating pressure inside equipment is typically designated to be less than 90 percent of the activation pressure of the emergency pressure-relief system [95, p. 69]. Kuraray set the normal operating pressure for EVAL Reactor 2 at 595 psi, about 80 percent of 740 psi—the activation pressure of the emergency pressure-relief system. In addition, Kuraray designed the system to have high-pressure alarms at 620 and 640 psi—84 and 86 percent of the emergency pressure-relief system activation pressure, respectively.[a]

The lower design pressure of Kuraray's EVAL Reactor 2 contributed to activating the reactor's emergency pressure-relief system and discharging flammable ethylene into the air. Kuraray used four different EVAL Reactors. Three of these reactors had an emergency pressure-relief system designed to activate at a pressure of 1,150 psi, but the activation pressure of the EVAL Reactor 2 was lower. Kuraray designed the EVAL Reactor 2 emergency pressure-relief system to activate at 740 psi, which was 410 psi lower than the designed activation pressure of the other three reactors. The lower activation pressure of the emergency pressure-relief system for EVAL Reactor 2 resulted from this reactor having a lower mechanical design pressure than the other three reactors. During the startup on May 19, 2018, Kuraray's board operators did not remember that EVAL Reactor 2 had a lower design pressure than the other three EVAL Reactors. Although the pressure in EVAL Reactor 2 was high during the startup, Kuraray operations personnel were surprised when the emergency pressure-relief system was activated because they believed the pressure inside the reactor was well below the emergency pressure-relief system's activation pressure.

Despite this significant difference between the EVAL Reactor 2 design pressure and the design pressure of the other three reactors, however, Kuraray did not design its control system to provide its workers with any special or unique warnings to help them recall that EVAL Reactor 2 was different. In addition, Kuraray's startup procedures did not discuss the reactor design pressures, nor did they highlight that EVAL Reactor 2 had a lower design pressure than the other three reactors.[b]

The CSB previously discussed how system design affects human performance in its investigation report on the November 2016 ExxonMobil Baton Rouge refinery isobutane release and fire [96, pp. 12-19]. Like the system design at the ExxonMobil refinery, Kuraray's control system design neglected an

[a] As part of the company's alarm management efforts, Kuraray disabled a third EVAL Reactor 2 high-pressure alarm set at 690 psi.

[b] Kuraray's operator training materials did include a discussion of the EVAL Reactor 2 design pressure and highlighted that its design pressure was lower than the design pressure of the other three EVAL Reactors.

important adage that API provided in safety guidance for improving human performance: “making it easy for people to do things right and hard for them to do things wrong” [1, p. 1].

Renowned safety expert Trevor Kletz is credited with bringing attention to inherent safety and helping to make it a broadly accepted fundamental process safety concept [93, p. 73, 97, 98]. In his efforts to advance inherent safety, Kletz also advocated for making plants more user-friendly “so that error by operators or maintenance workers or equipment failure does not have a serious effect on safety, output or efficiency” [99, p. 3]. Among other attributes, “friendly plants contain small or zero inventories of hazardous materials, are simple, with few opportunities for error, easy to control and hard to assemble incorrectly” [99, p. 3].

In its 2012 book, *Guidelines for Engineering Design for Process Safety*, the CCPS explained that inherently safer design is a design philosophy that, among other things, seeks to eliminate or reduce hazards associated with materials or operations. The CCPS stated that one of the major strategies of inherently safer design, called “simplify,” involves designing plants that do not have unnecessary complexity, which makes operating errors less likely or more forgiving [63, p. 129].

Kuraray could have taken a number of approaches to help prevent this incident or to lower the potential consequences from activating the EVAL Reactor 2 emergency pressure-relief system. One approach would have been to simplify the plant by building all four reactors with the same internal design pressure. Simplifying the plant design would have prevented the need for the operators to remember that one of the four EVAL reactor systems (in this case, EVAL Reactor 2) had a significantly lower design pressure than the others. In addition, when high-pressure conditions existed within the reactor, the control system could have automatically opened the emergency open valve (**Figure 13**) to direct vapor from the reactor to the flare to lower the pressure inside the reactor and help prevent activation of the emergency pressure-relief system. Furthermore, Kuraray could have used its automatic computer control system to sound an outside alarm (within the unit) to evacuate people in the vicinity of any equipment approaching its design limits. Other less robust techniques could also have been applied, such as displaying the EVAL Reactor 2 emergency pressure-relief system’s activation pressure on the control system graphic or improving the safe operating limits system and using the control system to clearly direct the board operators to take predetermined measures to lower the pressure inside the reactor.

The lower design pressure of EVAL Reactor 2 contributed to activating the reactor’s emergency pressure-relief system and discharging flammable ethylene into the air. The events that unfolded showed the system design issues that stemmed from having a lower design pressure for just one of the four EVAL reactor systems. When Kuraray’s board operators saw high-pressure conditions inside EVAL Reactor 2, they did not treat it as an emergency. They did not remember that EVAL Reactor 2 had a lower design pressure than the other EVAL reactors. Simplifying the plant design would have prevented the need for the operators to remember that one of the four EVAL reactor systems (in this case, EVAL Reactor 2) had a significantly lower design pressure than the others.

The CSB concludes that the design pressure differences between Kuraray’s four EVAL Reactors contributed to the incident. EVAL Reactor 2’s design pressure was 740 psi, which was 410 psi lower than the design pressure of the other three reactors.

The CSB recommends that Kuraray clarify the lower equipment design pressure of the EVAL Reactor 2 within the operator training systems, written procedures, and in the control system interface. (*See* Recommendation 2018-03-I-TX-R6).

2.9 Operating Procedures

In its 1995 book, *Guidelines for Process Safety Documentation*, the CCPS stated that up-to-date written operating procedures that reflect current plant practices are necessary for the safe operation of a facility [100, p. 195].

Under its PSM Standard, OSHA requires employers to "develop and implement written operating procedures … that provide clear instructions for safely conducting activities involved in each covered process" [101, p. 12]. Furthermore, OSHA specifically identifies the need to have written procedures to address startups following a turnaround and requires employers to certify (annually) that these procedures are current and accurate [101, pp. 12-13].[a]

In addition to having written operating procedures, Kuraray management supplied nightly operating instructions.

The nightly operating instructions that Kuraray management provided its operators on the evening of May 17, 2018, directed its operators to perform methanol flushes to EVAL Reactor 2. Although not covered by a written procedure, Kuraray performed methanol flushes to remove any liquid water left in the reactor after the maintenance turnaround. During the methanol flush removal, a misaligned valve (a closed manual valve that needed to be open) prevented transferring the methanol and water in EVAL Reactor 2 to downstream equipment. This valve misalignment led to bypassing the EVAL Reactor 2 abnormal condition safety interlock.

The CSB concludes that although Kuraray performed a methanol flush of its EVAL Reactors after some maintenance activities, the company did not have a written procedure or train its operators to perform the methanol flush. A misstep during the methanol flush led Kuraray to disable an important safety interlock, which remained disabled as the startup proceeded.

The CSB recommends that Kuraray develop and implement a written procedure and conduct training on how to perform the EVAL Reactor methanol flush operation. (*See* Recommendation 2018-03-I-TX-R7).

The practice of following nightly operating instructions that deviated from written operating procedures was not an isolated practice. Leading up to the incident, at least three Kuraray board operators on two different shifts followed nightly operating instructions that deviated from the company's written startup procedures for EVAL Reactor 2.

By following Kuraray's nightly operating instructions, the company deviated from its operating procedures during the EVAL Reactor 2 startup. These deviations included:

[a] EPA has a similar requirement for written operating procedures under 40 C.F.R. § 68.52.

- No startup procedure covered the methanol flush used to remove any liquid water remaining inside EVAL Reactor 2;
- Kuraray increased the pressure inside EVAL Reactor 2 by adding ethylene before starting the flush batch procedure; and
- The nightly operating instructions conflicted with the operating procedures. The nightly operating instructions targeted higher pressure (595 psi) inside EVAL Reactor 2 than the operating procedures described. The operating procedures limited the pressure inside EVAL Reactor 2 to:
    - 565 psi when adding ethylene to increase the pressure inside the reactor;[a] or
    - 495 psi at a maximum temperature of 137°F when heating the reactor contents while adding ethylene to increase the pressure inside the reactor.

The CSB concludes that nightly operating instructions supplied by Kuraray management conflicted with the company's written operating procedures, resulting in unmanaged changes to the reactor startup that contributed to the May 19, 2018, incident.

The CSB recommends that Kuraray develop and implement a program to ensure that the company's EVAL Plant nightly operating instructions do not conflict with its written operating procedures. Kuraray also should ensure that employees use the management of change system when changes to the written operating procedures are desired. (*See* Recommendation 2018-03-I-TX-R7).

2.10 Operator Training

In its 1995 book, *Guidelines for Process Safety Documentation*, the CCPS stated that training provides the communication of knowledge and skills to workers:

> In the chemical and hydrocarbon processing industries, the training function includes passing on process knowledge, skills in performing operating and emergency procedures, and many other aspects of process operation and maintenance to those who actually perform the tasks [100, p. 203].

The CCPS also stated that the "primary goal of training is to ensure" that operators and other workers are aware of important process safety management concepts, including:

- hazards present in the process;
- the significance of worker actions relative to process safety;

[a] Kuraray did not have a temperature limit associated with the 565 pounds per square inch pressure limit that applied when pressuring the reactor with ethylene during the startup. The 137°F temperature limit only applied when the reactor contents were being heated with the jacket water while ethylene was simultaneously added to raise the pressure inside the reactor.

- how to operate and keep the process within safe operating limits; and
- how to handle potential emergencies [100, p. 203].

The CSB concludes that several operational causes of the May 19, 2018, incident were not listed, described, explained, or otherwise covered by Kuraray's operator training manual. These included:

- The known activities, such as bringing ethylene back into the unit, upset conditions like the reactor's High-High-Pressure alarm, and explaining when nonessential personnel should be excluded from being in the unit;
- Alarm setpoints and actions that operators should take in response to specific process alarms, such as high pressure inside an EVAL Reactor;
- Directions on when operators should use the emergency open valve; and
- Safe operating limits, the consequence of deviating beyond the safe operating limits, or the predetermined steps operators need to take to return the process to a safe condition.

The CSB recommends that Kuraray strengthen the EVAL Plant's operator training program by including:

- The known activities, such as bringing ethylene back into the unit, upset conditions like the reactor's High-High-Pressure alarm, and providing guidance or otherwise clarifying when nonessential personnel should be excluded from being in the unit;
- Alarm setpoints and actions that operators should take in response to specific process alarms, such as high pressure inside an EVAL Reactor;
- Directions on when operators should use the emergency open valve; and
- Safe operating limits, the consequence of deviating beyond the safe operating limits, and the predetermined steps operators need to take to return the process to a safe condition (*See* 2018-03-I-TX-R8).

2.11 Abnormal Operating Conditions

2.11.1 Liquid Ethylene Enters the Reactor

On May 18, 2018, as Kuraray operations personnel worked to achieve the operating pressure specified by the nightly operating instructions (595 psi), chilled liquid at a temperature of about 4°F circulated through the heat exchanger. Because chilled liquid was circulating through the heat exchanger, when the EVAL Reactor 2 pressure exceeded 400 psi (11:25 p.m.), some of the ethylene condensed, and cold liquid ethylene began flowing from the heat exchanger into the reactor. Although it was unnecessary to use the chilled liquid system during the early phases of the EVAL Reactor 2 startup, nothing in Kuraray's operating procedures or training directed operators to verify that chilled liquid was not circulating through the heat exchanger or otherwise prohibited using the chilled liquid.

The CSB concludes that Kuraray's safety management systems did not control the circulation of chilled liquid through the heat exchanger during startup, leading to an abnormal operating condition—liquid ethylene accumulation inside the reactor. When the EVAL Reactor 2 pressure exceeded 400 psi as chilled liquid circulated through the heat exchanger at about 4°F, ethylene vapor began condensing to liquid ethylene. This liquid ethylene began flowing into EVAL Reactor 2.

The CSB recommends that Kuraray improve the EVAL Plant's safety management system by controlling when chilled liquid is circulated through the heat exchanger during startup. (*See* Part 1 of Recommendation 2018-03-I-TX-R10).

2.11.2 Low Reactor Temperature

When Kuraray operations personnel began the startup of EVAL Reactor 2, commissioning activities related to the new refrigeration system had already opened the chilled liquid valves, allowing chilled liquid to circulate through the heat exchanger. This was an abnormal condition because Kuraray did not normally circulate chilled liquid through the heat exchanger until much later during the startup sequence. But Kuraray's safety management systems did not identify the early circulation of chilled liquid as a concern, and the operating procedures did not instruct anyone to verify that this system was not cooling the heat exchanger for EVAL Reactor 2 during startup. As a result, a low inventory of liquid ethylene was in the reactor, which created a low-temperature condition.

Kuraray operations personnel did not recognize the abnormal low-temperature condition for eight hours when Supervisor 1 found it as he reviewed the status of the operation using the control system. There were no low-temperature alarms or safe operating limits to alert workers of this abnormal condition.[a] Neither the operating procedures nor training materials suggested that low temperatures inside the reactor presented a safety concern. Supervisor 1 was not concerned because he had experienced low-temperature conditions inside an EVAL Reactor and had successfully managed them without an incident. Further, Kuraray's process hazard analysis did not find a safety hazard associated with low-temperature conditions inside an EVAL Reactor. Moreover, Kuraray lacked a procedure addressing what to do in this abnormal situation—a cold reactor holding a low inventory of liquid ethylene. Because nothing in Kuraray's safety management systems called for stopping the process, the startup continued.

The CSB concludes that Kuraray's safety management systems enabled the reactor startup to continue despite the presence of an abnormal operating condition—the low temperature of the liquid inside the reactor. Kuraray lacked a procedure or other guidance explaining what actions its operators should take to correct the reactor's low-temperature condition. Although intended to hold ethylene vapor, the reactor now contained some cold liquid ethylene. Despite the abnormally low temperature, because nothing in Kuraray's safety management systems called for stopping the process, the startup continued.

[a] As part of the company's alarm management efforts, Kuraray disabled its EVAL Reactor 2 low-temperature alarms. Before alarm management, EVAL Reactor 2 had a Low-Temperature alarm set at 25°F and a Low-Low-Temperature alarm set at 20°F.

The CSB recommends that Kuraray improve the EVAL Plant's safety management system by enhancing recognition of liquid ethylene accumulation and response to low-temperature conditions inside an EVAL Reactor through alarms, written procedures, and operator training. (*See* Part 2 of Recommendation 2018-03-I-TX-R10).

2.11.3 High Reactor Pressure

At 7:08 a.m. on May 19, 2018, Kuraray began heating the reactor while simultaneously adding ethylene to raise the reactor's pressure. At 7:11 a.m., the pressure inside EVAL Reactor 2 reached 495 psi. Nightly operating instructions directed Kuraray's operators to add ethylene to the reactor to reach the target pressure of 595 psi.

Kuraray's operating procedures called for limiting the pressure inside EVAL Reactor 2 to 565 psi as long as simultaneous heating and pressuring operations were not taking place. Once Kuraray began heating the reactor's jacket water while adding ethylene to increase the pressure, the operating procedures called for limiting the pressure inside EVAL Reactor 2 to 495 psi with a maximum reactor temperature of 137°F. The operating procedure clarified that Kuraray limited the pressure inside the reactor to 495 psi "to prevent exceeding [595 psi], which could require venting excess pressure to the flare."

Had Kuraray followed its written operating procedures instead of the nightly operating instructions, its operations personnel should have stopped increasing the pressure inside the reactor until after transferring the flush batch into EVAL Reactor 2. Because Kuraray's operators were following nightly operating instructions instead of the written startup procedures, however, they were raising the pressure to 595 psi, which was 100 psi above the maximum pressure allowed by the written operating procedures under simultaneous heating and pressuring conditions.

The nightly operating instructions that Kuraray management provided its board operators called for raising the pressure inside EVAL Reactor 2 by 100 psi beyond the maximum pressure allowed by the written operating procedures under simultaneous heating and pressuring conditions. Kuraray did not follow its written operating procedure, which would have limited the reactor's pressure to 495 psi while heating the reactor's contents and simultaneously adding ethylene.

The CSB concludes that as operators responded to the low-temperature condition inside EVAL Reactor 2, Kuraray's safety management systems allowed its nightly operating instructions to conflict with established written operating procedures, leading to another abnormal operating condition—high pressure within the reactor.

The CSB addressed Kuraray's safety gap of issuing nightly operating instructions that conflict with the company's existing operating procedures above in Section 2.9.

The CSB recommends that Kuraray develop and implement a program to ensure that the company's EVAL Plant nightly operating instructions do not conflict with its written operating procedures. Kuraray also should ensure that employees use the management of change system when changes to the written operating procedures are desired. (*See* Recommendation 2018-03-I-TX-R7).

2.11.4 Response to Abnormal Conditions

In its 2011 book *Conduct of Operations and Operational Discipline*, the CCPS described a better approach to addressing abnormal conditions. When faced with an abnormal situation, the CCPS recommends keeping (or putting) the process in a safe configuration and seeking the involvement of wider expertise to help ensure safety [102, p. XXV].

Less than four years before the Kuraray incident, another major process safety incident occurred just a few miles from the Kuraray site. On November 15, 2014, four employees were fatally injured at the DuPont facility in La Porte, Texas, when the operations response to abnormal conditions during startup culminated with releasing—and exposing these workers to—a highly toxic chemical [103]. The CSB investigation found common themes between the Kuraray and DuPont incidents, including:

- An abnormal condition was identified as workers were starting up the process;
- The abnormal condition was viewed as an operational concern and not a safety hazard;
- Written procedures did not address the abnormal condition;
- Operator training did not address the abnormal condition;
- No program for effectively handling abnormal conditions existed;
- Written procedures were not developed to help operators respond to the abnormal condition;
- No hazard analysis or safety evaluation was performed; and
- The operations response to the abnormal condition revealed long-standing equipment design flaws,[a] resulting in a major process safety incident.[b]

If Kuraray had a program for effectively handling abnormal conditions that included getting the right people involved, performing a hazard analysis, and developing written procedures to respond to the low-temperature conditions inside EVAL Reactor 2, the company could have prevented the May 19, 2018, incident. It is likely that a formal safety review would have recognized the need to heat the reactor contents slowly and placed tighter limits on the allowable pressure inside EVAL Reactor 2. At a minimum, such a review should have found that the nightly operating instructions deviated from the written operating procedures. Under simultaneous heating and pressuring conditions during startup, Kuraray's written operating procedures limited the pressure inside the reactor to a maximum of 495 psi at a maximum temperature of 137°F. Kuraray could have prevented the incident by following its written startup procedure.

[a] At DuPont, the operations response revealed the hazard of trapping toxic liquid methyl mercaptan in the piping intended for waste gas disposal, while the operations response at Kuraray revealed the hazard of horizontally discharging flammable ethylene from emergency pressure-relief systems into the ambient air toward workers.

[b] During its investigation of the November 15, 2014, incident at DuPont the CSB also found that some emergency pressure-relief systems did not discharge to a safe location. Among other things, the CSB recommended that DuPont evaluate its emergency pressure-relief system discharge locations to ensure public and worker health and safety to the greatest extent feasible [146, pp. 7-8].

The CSB concludes that Kuraray did not have a program to manage abnormal operating conditions. The company could have prevented the May 19, 2018, incident by getting the right people involved, performing a hazard analysis, and developing a written plan to guide the response to the abnormally low-temperature conditions inside the reactor.

The CSB further concludes that a formal safety review should have recognized the need to heat the reactor contents slowly and placed tighter limits on the allowable pressure inside EVAL Reactor 2. At a minimum, such a review should have found that the nightly operating instructions had deviated from the written operating procedures. Kuraray could have prevented the incident by adhering to the operating pressure and temperature targets specified in its written startup procedure.

The CSB recommends that Kuraray improve the EVAL Plant's safety management system by implementing a system to manage abnormal operating conditions effectively by, at a minimum, including appropriate technical representation, performing a hazard analysis of temporary or troubleshooting operations, and providing management oversight of any abnormal condition. (*See* Part 3 of Recommendation 2018-03-I-TX-R10).

2.12 Safety Interlock Disabling

In its 2007 book, *Human Factors Methods for Improving Performance in the Process Industries*, the CCPS explained that plant operators or mechanics sometimes need to disable safety systems, including safety interlock systems, deliberately. The CCPS stated that intentionally defeating a safety interlock system may occur to "perform maintenance, troubleshoot, tune a process, achieve higher production, alleviate an intermittent fault, or for convenience" [104, pp. 185-187]. Once disabled, a number of things could result in the safety system functionality not being restored. The CCPS stated, "Such disablement or bypasses may be intended as temporary but owing to forgetfulness, shift changes, or other reasons, restoration may not occur" [104, p. 187]. The CCPS provided several guidelines to address these human factors related to the disabling of safety systems, including:

- Have a procedure for safety system bypassing, and ensure it is followed;
- Establish and enforce criteria for disabling safety systems;
- Require an appropriate level of technical and management approval to bypass or disable safety systems;
- Set time limits for bypassed safety systems;
- Provide a means to display a list of all currently disabled safety systems; and
- Ensure safety system restoration by using a permit-to-work system [104, pp. 187-188].

In his 1994 book, *What Went Wrong – Case Histories of Process Plant Disasters*, Trevor Kletz stated, "Many accidents have occurred because operators made trips [safety interlocks] inoperative" [52, p. 237].

For example, bypassing a safety interlock led to the April 23, 2004, explosion and fire at the Formosa Plastics Corporation facility in Illiopolis, Illinois, that fatally injured five workers and severely injured three other workers. In its investigation report, the CSB concluded that bypassing the safety interlock for the bottom valve of a reactor allowed the valve to be opened while this reactor was full, heated, and pressurized. The opened valve inadvertently released highly flammable vinyl chloride monomer within the building that housed manufacturing equipment, including this reactor. The vinyl chloride monomer vapor cloud ignited and exploded [105].

During the EVAL Reactor 2 startup at Kuraray, a misaligned valve (a closed manual valve that needed to be open) delayed transferring the methanol flush from the reactor to downstream equipment. While Kuraray operators were troubleshooting this issue, they disabled the reactor's abnormal condition safety interlock. Among other things, this High-High-Pressure safety interlock for the EVAL Reactor fully opened the chilled liquid temperature control valve (**Figure 10**) to reduce the reactor pressure by circulating chilled liquid through the heat exchanger when the pressure inside the reactor reached the High-High-Pressure alarm condition. The EVAL Reactor 2 startup continued even though Kuraray disabled this safeguard. As a result, when the pressure inside EVAL Reactor 2 reached the High-High-Pressure condition, the safety interlock did not activate, and the automatic actions to reduce the pressure inside the reactor did not occur.

The CSB concludes that Kuraray did not have an effective system to manage the disabling of safety interlocks and ensure that these critical systems were available before continuing startup activities.

One of the citations retained under the settlement agreement between OSHA and Kuraray was related to Kuraray's disabling of the High-High-Pressure safety interlock during the startup [32, p. 5]. According to the settlement agreement, OSHA cited Kuraray under the PSM management of change element (29 C.F.R. § 1910.119(l)(1)) because Kuraray did not use its interlock bypass procedure to manage change when bypassing this safety interlock. As part of the settlement agreement, Kuraray told OSHA that the company corrected the safety problems described in the citation [32, p. 6].[a]

2.13 Alarm Management

Alarm management describes the systems that companies use to help optimize their operator alarms. In the context of a chemical manufacturing facility, an alarm is how the control system alerts an operator about a condition that needs a response. The International Society of Automation (ISA) defined alarm management as the "collection of processes and practices for determining, documenting, designing, operating, monitoring, and maintaining alarm systems" [106, p. 17].

Poor alarm management practices have contributed to major accidents [107, p. 425]. For example, The Report of the President's Commission on the 1979 Three Mile Island nuclear power incident found that more than 100 alarms sounded in the first few minutes of the accident. The commission found that because so many of these alarms were unimportant signals, the operators could not concentrate on the more important alarms [108, p. 11].

[a] The CSB is not issuing new Recommendations that overlap with the OSHA's enforcement efforts that are documented in the settlement agreement between Kuraray and OSHA.

Alarm management was also causal to the September 25, 1998, explosion and fire at the Esso Australia Resources Ltd. gas plant at Longford [109, pp. 208-209]. Among other consequences, this incident fatally injured two workers and injured eight other workers [109, p. 11]. In the 2010 book, *Failure to Learn*, the author stated, "the accident sequence at Longford got under way because control room operators were confronted with so many alarms that they could not respond to them effectively" [110, p. 115].

At a Texaco refinery in 1994, two operators had to respond to 275 alarms in less than 11 minutes, leading up to an explosion [111, pp. 27-28]. Investigators found that during the incident, "alarms were being presented to operators at the rate of one every two to three seconds" and "at times … operators were doing nothing but acknowledging alarms" [111, pp. 27-28]. Among other safety improvements, the report on the Texaco refinery explosion recommended that alarms should be "limited to the number that an operator can effectively monitor" [111, p. 36]. The condition of overwhelming operators with alarms has become known as an ***alarm flood***.

2.13.1 CCPS Guidance

In the 2017 edition of its book, *Guidelines for Safe Automation of Chemical Processes*, the CCPS explained why alarm flood is an important process safety topic. By overwhelming the operator with alarms, alarm flooding adversely affects operator performance and has contributed to major incidents. The CCPS stated:

> **Alarm flood**—The presentation of more alarms in a given period of time than an operator can effectively respond to. During an alarm flood, multiple alarms present themselves in a short time, usually initiated by a single event (typically >10 alarms in ten minutes following an upset event). Alarm flooding is one of the most dangerous problems with alarm systems and potentially the most complex to solve. It has been identified as the root cause to significant plant incidents such as Texaco Pembroke (1994) and Three Mile Island Nuclear plant (1979). These alarm floods overwhelm the operator, which make it difficult to process the alarms, determine the cause and priority of the event, and to respond to new alarms due to the developing event or resulting cascade events [112, 107, p. 427].

2.13.2 ISA Standard

In 2009, the ISA published standard ANSI/ISA-18.2-2009, *Management of Alarm Systems for the Process Industries*. The ISA updated this standard in 2016 with ANSI/ISA-18.2-2016, *Management of Alarm Systems for the Process Industries* (ISA 18.2) [106]. A 2010 paper clarified that the connection between industry alarm management practices and major accidents was a driving factor in the development of ISA 18.2 [113, p. 1]. Also, a technical article written by Yokogawa, the manufacturer of Kuraray's control system, stated that "Following this approach [ISA 18.2] will result in an optimal alarm management system that prevents minor alarms and upsets from escalating into serious incidents" [114, p. 3].

ISA 18.2 defines an alarm as an "audible and/or visible means of indicating to the operator an equipment malfunction, process deviation, or abnormal condition requiring a timely response" [106, p. 16].

ISA 18.2 defines *alarm flood* as the "condition during which the alarm rate is greater than the operator can effectively manage ([for example], more than ten alarms per 10 minutes)" [106, p. 16].

Among other things, ISA 18.2 provided metrics to indicate "the overall health of the alarm system" [106, p. 75]. **Figure 32** shows the recommended targets that ISA 18.2 provided for the average alarm rate handled by a single console operator [106, p. 75, 114, p. 3].

Practical limits to human capabilities

Very likely to be acceptable	Maximum manageable
~150 alarms per day	~300 alarms per day
~6 alarms per hour (average)	~12 alarms per hour (average)
~1 alarm per 10 minutes (average)	~2 alarms per 10 minutes (average)

Figure 32. Average Alarm Rates. (Credit: Control Engineering, Marcus Tennant [114, p. 3])

These recommended targets include *average alarm rates* that "are based upon the ability of an operator and the time necessary to detect an alarm, diagnose the situation, respond with corrective action(s), and monitor the condition to verify the abnormal condition has been corrected" [106, p. 75]. An article on the ISA website discussing the effectiveness of alarm systems suggests that an alarm rate of more than 12 alarms per hour might indicate a stressful condition on the operator and may represent a situation where companies should not expect a successful response to an alarm condition [115].

2.13.3 Pre-Incident Alarms

As discussed in the timeline, in the 3 hours and 28 minutes leading up to the incident, Kuraray's process control system inundated board operators with 552 alarms. Two operators were faced with handling these 552 alarms. Even if distributed equally, which was unlikely the case, the alarm load per board operator per hour was about 80. This rate of alarms exceeded the maximum manageable frequency shown in **Figure 32**.

The high number of alarms likely harmed the ability of Kuraray's board operators to respond to the high-pressure conditions developing inside EVAL Reactor 2. Although Kuraray management was implementing an alarm management program to improve the quality and reduce the frequency of alarms its board operators were tasked with responding to, these efforts were not completed before the May 19, 2018, incident.

The CSB concludes that Kuraray's control system flooded the board operators with alarms, which contributed to the incident by hindering the operators' ability to effectively review the process information and control the high-pressure conditions that developed within the reactor.

The CSB recommends that Kuraray complete the alarm management efforts at the EVAL Plant and implement a continual program to meet or be lower than the alarm rate performance targets established in ISA 18.2 (*See* Recommendation 2018-03-I-TX-R9).

2.14 Process Alarm Response

Kuraray's operating procedures policy required its operating procedures to include, among other things, "safety systems and their functions." Kuraray did not clarify whether its operating procedures should include process alarms and the expected operator response to alarms. In Appendix C to §1910.119, *Compliance Guidelines and Recommendations for Process Safety Management (Nonmandatory)*, OSHA stated, "operating procedures addressing operating parameters will contain operating instructions about pressure limits, temperature ranges, flow rates, what to do when an upset condition occurs, what alarms and instruments are pertinent if an upset condition occurs, and other subjects" [116].

Figure 24 shows that when the board operator manually activated the High-High-Pressure safety interlock at 7:37 a.m., the chilled liquid circulating through the heat exchanger effectively lowered the pressure inside EVAL Reactor 2. When the board operator closed the chilled liquid valves to stop circulating chilled liquid through the heat exchanger at 8:31 a.m., the reactor's pressure began rapidly increasing.

At 8:46 a.m., the pressure inside EVAL Reactor 2 was 606 psi, and Board Operator 1 closed the ethylene pressure control valve to stop adding ethylene to EVAL Reactor 2 (**Figure 6**). After the ethylene supply was isolated, the pressure within EVAL Reactor 2 continued to increase because the jacket water system was used to heat the reactor's contents, and not enough vapor was sent from the reactor to the flare. As the pressure inside the reactor continued increasing, the control system activated the High- and High-High-Pressure alarms at 8:51 a.m. and 9:01 a.m., respectively. When these alarms sounded, the board operators acknowledged the alarms, and Board Operator 1 further opened the pressure control valve to increase the flow of vapor from the reactor to the flare. Although Kuraray's board operators made adjustments that slowed the rate at which the pressure inside the reactor increased, the pressure inside EVAL Reactor 2 continued increasing and never dropped below the high-pressure alarm conditions (**Figure 24**). At 10:28 a.m., the emergency pressure-relief system was activated. Although the emergency pressure-relief system protected the reactor from high-pressure conditions, the discharged ethylene ignited and harmed workers.

The CSB concludes that Kuraray's startup procedures lacked guidance or actions for the board operators to take in response to process alarms, which contributed to the incident. When the reactor's High- and High-High-Pressure alarms were activated, board operators only directed a small portion of ethylene inside the reactor to the flare through the pressure control valve. In addition, the board operator continued heating the jacket water, further increasing pressure inside the reactor. Despite the active process alarms, the operators' response to these high-pressure alarms did not bring the reactor pressure below the alarm limits.

The CSB recommends that Kuraray improve the EVAL Plant's safety management system by updating the written startup procedures to include guidance on the appropriate operator actions to take in response to process alarms. (*See* Part 4 of Recommendation 2018-03-I-TX-R10).

2.14.1 Operator Guidance Through Alarm System Messaging

Kuraray's control system could provide guidance to its board operators. For example, when the VOCs to the flare were high, the control system displayed a visual operating guideline message stating, "High Flare VOC Emissions Reduce, Reduce Purging." Kuraray used this instruction to direct operators to reduce ethylene flow to the flare to prevent exceeding its environmental permit limit. Although Kuraray used the control system to provide operator guidance for issues related to its environmental permit, Kuraray did not use the control system to provide guidance when the pressure inside EVAL Reactor 2 was high or as the pressure continued climbing well beyond the high-pressure alarm limits.

The CSB concludes that effective alarm system messaging could have helped Kuraray's board operators to better respond to the high-pressure conditions that developed inside the reactor, which could have prevented the activation of the reactor's emergency pressure-relief system.

The CSB recommends that Kuraray improve the EVAL Plant's safety management system by using control system guidance to aid operator response to abnormal or upset conditions to keep the process within the safe operating limits. (*See* Part 5 of Recommendation 2018-03-I-TX-R10).

2.14.2 Emergency Open Valve

As shown in **Figure 13**, in addition to a pressure control valve, Kuraray also had an emergency open valve that the board operators could use to direct additional vapor from the reactor to the flare to help lower the pressure inside the reactor. Although the pressure inside EVAL Reactor 2 continued rising above the High- and High-High-Pressure alarm conditions, neither Kuraray board operator used the emergency open valve to direct vapor from the reactor into the flare system until after the emergency pressure-relief system had activated.

Using the emergency open valve was tightly controlled by Kuraray. The operating procedure stated, "**Do not open [the emergency open valve] without supervisor approval.**" In addition, the emergency open valve was activated using a physical switch on a panel board and was not part of the computer control system. Kuraray management installed a protective cap over the switch and locked the cap closed with a plastic hasp to control when its board operators used the emergency open valve. As one worker described to CSB investigators, "Those [devices], you definitely need approval to … switch." To open the valve, Kuraray required its board operators to fill out a form, get a supervisor's approval, and remove the plastic hasp to access the switch. Even with the continually increasing pressure inside EVAL Reactor 2, neither board operator sought permission to open the emergency open valve before the emergency pressure-relief system was activated. Kuraray was both physically and procedurally controlling when its board operators could open the emergency open valve. In addition, Kuraray did not provide its board operators with a procedure or training directing them on when to open the emergency open valve.

The restrictions and lack of guidance preventing Kuraray's board operators from using the emergency open valve included:

- The EVAL Reactor 2 startup procedure required the board operator to get permission from a supervisor before using the emergency open valve;

- To control its use, Kuraray physically locked the switch that board operators needed to access to open the emergency open valve; and
- Neither the written startup procedure nor operator training instructed the board operator when they should use the emergency open valve.

The CSB concludes that the physical and procedural controls that Kuraray put in place to govern the use of the emergency open valve contributed to the incident by restricting the board operators from accessing or otherwise using the emergency open valve. The CSB also concludes that the lack of a procedure or training directing when operators should use the emergency open valve also contributed to the incident.

The CSB recommends that Kuraray improve the EVAL Plant's safety management system by removing the physical and procedural controls used at the EVAL Plant to restrict board operators from accessing or using the emergency open valve, and updating the written procedures and operator training to provide guidance on when to open the emergency open valve. (*See* Part 6 of Recommendation 2018-03-I-TX-R10).

Kuraray's 2015 PHA team had recommended automating the emergency open valve that directs reactor vapor to the flare to help prevent the type of scenario that unfolded on May 19, 2018. At a pressure above the EVAL Reactor 2 High-High-Pressure alarm, the PHA recommendation called for having the control system automatically take over and fully open the emergency open valve to reduce the pressure inside the reactor. The CSB concludes that because Kuraray postponed the implementation of its PHA recommendation to control the opening of its emergency open valve automatically, this safeguard was not available during the EVAL Reactor 2 startup on May 19, 2018.

When Kuraray postponed its plan for upgrading and automating the emergency open valve to 2019, the company continued relying on its board operators to function as a safeguard to maintain control of the pressure inside the reactor during the startup on May 19, 2018. When the High- and High-High-Pressure alarms sounded, however, neither board operator opened the emergency open valve to lower the reactor pressure by sending vapor from the reactor to the flare. Kuraray restricted the use of the emergency open valve, and this valve was not opened until after the incident.

Kuraray relied on this safeguard despite the physical and procedural controls the company imposed on its board operators that restricted them from using the emergency open valve and despite not providing the board operators with a procedure or training directing them on when to open the emergency open valve.

The CSB concludes that Kuraray could have lowered the pressure inside EVAL Reactor 2 and prevented the incident on May 19, 2018, by using effective control system automation. At a predetermined high-pressure condition inside EVAL Reactor 2, Kuraray could have had its control system automatically open the emergency open valve and directed enough ethylene vapor to the flare to prevent the emergency pressure-relief system from activating.

After the incident, Kuraray changed its controls to open the emergency open valve (**Figure 13**) automatically to direct vapor from the reactor to the flare when a reactor's High-High-Pressure alarm activates.

The CSB also concludes that Kuraray should have provided its board operators with clear operating procedures and effective training without physically or procedurally restricting their access to the emergency open valve's panel board switch. By doing so, Kuraray's board operators could have prevented the incident by opening the emergency open valve to prevent the high-pressure conditions from activating the emergency pressure-relief system and discharging the flammable ethylene vapor into the air.

2.15 Safe Operating Limits

The OSHA PSM Standard addresses the need to identify ***safe operating limits*** as part of the Process Safety Information. OSHA identified categories of Process Safety Information that include:

- Hazards of the Chemicals Used in the Process;
- Technology of the Process; and
- Equipment in the Process [87, pp. 2-5].

As part of the technology of the process, employers need to identify process limits that help establish when a process has deviated from normal operating conditions into upset conditions [87, p. 3]. These "safe upper and lower limits" should include items such as "temperatures, pressures, flows or compositions."[a] In addition to identifying these process limits, employers also need to identify the potential consequences if the process deviates beyond these limits [87, p. 3].

2.15.1 CCPS Approach

The CCPS defined *safe operating limits* as the "limits established for critical process parameters, such as temperature, pressure, level, flow, or concentration, based on a combination of equipment design limits and the dynamics of the process" [117].

Although OSHA requires employers to identify safe operating limits, the agency does not explain how employers should do this. In its 2012 book, *Guidelines for Engineering Design for Process Safety*, the CCPS helped fill this gap.[b] In its approach to identifying safe operating limits, the CCPS used operating zones. **Figure 33** shows the illustration that the CCPS used to help explain the relationship between normal operating conditions and safe operating limits [63, p. 136].

[a] *See* 29 C.F.R. § 1910.119 (d)(2)(i)(D).

[b] In 2018, the Celanese company published a paper describing a robust safe operating limits program that purportedly contributed to its success in reducing loss of primary containment incidents [136]. Companies might consider reviewing the details of the program that Celanese has shared.

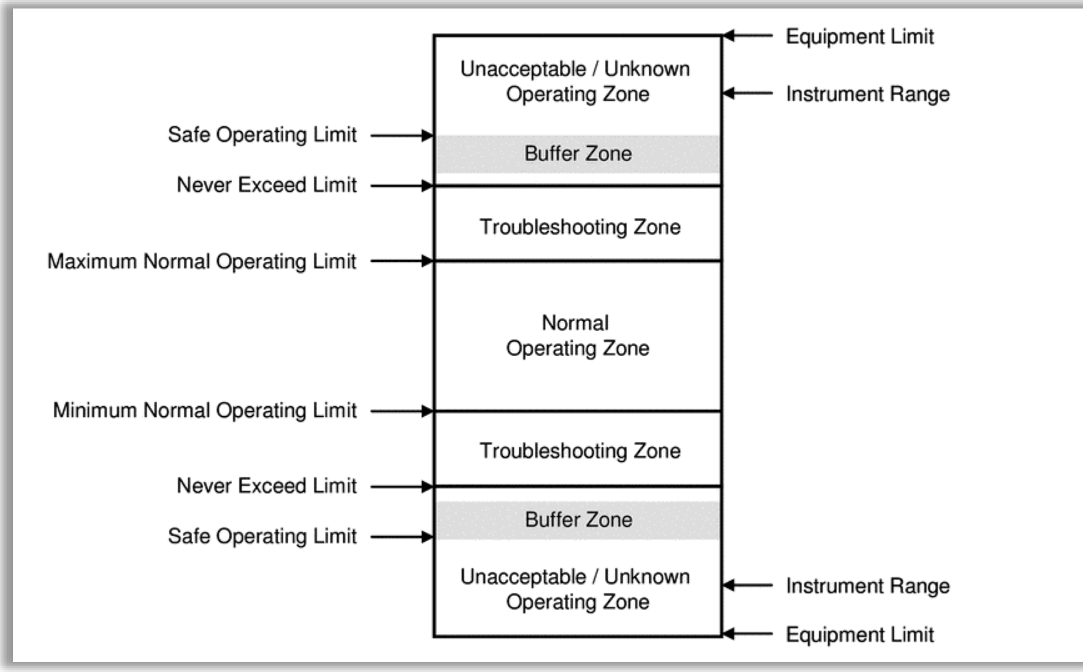

Figure 33. Zones of Operation [63, p. 136]. (Credit: CCPS)

The CCPS model shows that outside the normal operating conditions is a troubleshooting zone that provides time for operators to make adjustments and return to the normal operating zone. Beyond the troubleshooting zone is the buffer zone to help ensure that the process does not reach the unacceptable / unknown operating zone. The CCPS stated that the process should not be intentionally operated in the buffer zone. The safe operating limit marks the transition between the buffer zone and the unacceptable / unknown operating zone. The CCPS recommended taking immediate and predetermined actions when the process reaches the safe operating limit to return the process back to safe conditions and prevent the consequence of deviation from occurring. These actions are typically performed by operations personnel, such as a board operator or an outside operator [63, pp. 135-137].

The CCPS also stated that companies should consider the safety and environmental consequences of emergency pressure-relief systems that discharge into the air when setting safe operating limits [63, p. 136].

2.15.2 EVAL Reactor 2 Safe Operating Limit

Kuraray established safe operating limits for its equipment, including EVAL Reactor 2. Kuraray set the safe operating limit for EVAL Reactor 2 at 740 psi and 203°F—the reactor's mechanical design conditions. Nevertheless, Kuraray's operator training materials did not address safe operating limits, the consequence of deviating beyond the safe operating limits, or the predetermined steps that operators must take to return the process to a safe condition. In addition, Kuraray did not include the safe operating limits for EVAL Reactor 2 in its reactor startup procedures.

2.15.3 Consequence of Deviation

Kuraray's table of safe operating limits shows that the company accurately predicted the potential consequence of exceeding EVAL Reactor 2's safe operating limits. Kuraray identified that developing high pressure inside the reactor would result in a discharge of flammable ethylene (reactor vapor) through the emergency pressure-relief system into the air, resulting in a fire or explosion when this vapor cloud found an ignition source.

Although emergency pressure-relief systems are designed to function at a specific activation pressure, this safety equipment could activate within a few percentage points—above or below the design condition. Kuraray's safe operating limits did not consider that emergency pressure-relief systems do not precisely activate at their design conditions. As a result, when the emergency pressure-relief system activated at about 719 psi (3 percent below the designed activation pressure), the safe operating limit had not been reached, but the consequence of deviation occurred.

The CSB concludes that Kuraray set the safe operating limits for EVAL Reactor 2 too high to prevent activating the EVAL Reactor 2 emergency pressure-relief system effectively. The consequence of deviation occurred before the safe operating limit was reached. The CSB also concludes that the company did not follow the Center for Chemical Process Safety guidance to consider the atmospheric discharge from the reactor's emergency pressure-relief system when determining the safe operating limits for EVAL Reactor 2. Such an approach could necessitate a lower safe operating limit, where the procedures and operator training instruct board operators to take action at a specific pressure and carry out the predetermined actions to bring the process back to a safe condition.

2.15.4 Required Steps to Avoid or Correct Deviations

As the pressure within EVAL Reactor 2 continually increased, Kuraray's operators took some of the required steps intended to lower the pressure inside the reactor. Board Operator 1 closed the pressure control valve that supplied ethylene to the reactor. The board operators also opened the pressure control valve to send some reactor vapor to the flare. The board operators did not, however, increase reactor cooling or open the emergency open valve to lower the pressure by directing reactor vapor to the flare. One of the Kuraray board operators explained to CSB investigators that deciding when to use the emergency open valve was left up to each individual operator and based on their judgment and experience.

The CSB concludes that Kuraray's safe operating limits program did not ensure an effective response to the high-pressure conditions that developed inside EVAL Reactor 2. As a result, not all of the predetermined actions were taken, including increasing the cooling from the chilled water system or using the emergency open valve to lower the pressure by directing vapor from EVAL Reactor 2 to the flare system.

2.15.5 Zones of Operation

For EVAL Reactor 2, the targeted operating pressure was 595 psi, and Kuraray configured the control system with a High-Pressure alarm at 620 psi and a High-High-Pressure alarm at 640 psi. Finally, Kuraray set the safe operating limit at 740 psi. Although the company could have used these various limits to replicate the CCPS model using zones of operation, Kuraray's operating limits were vague and only referenced the normal operating pressure and the safe operating limit (740 psi).

Kuraray did not set a high-pressure limit for EVAL Reactor 2 that included an alarm upon which operators were expected to take the predetermined actions to return the reactor to a safe state. Kuraray expected its board operators to avoid reaching the safe operating limit of 740 psi of pressure in EVAL Reactor 2, but the company did not give its operators any guidance on exactly when they needed to open the emergency open valve to send reactor vapor to the flare or when to open the chilled liquid temperature control valve to cool the heat exchanger and lower the pressure inside the reactor.

Because Kuraray set the safe operating limits for EVAL Reactor 2 too high (at the 740 psi design condition for the emergency pressure-relief system), Kuraray did not provide its board operators the opportunity to take the predetermined actions to return the reactor pressure to a safe state and avoid the known consequence of deviation—a fire or explosion resulting from discharging ethylene vapor from the emergency pressure relief system and into the ambient air. Had the safe operating limit been set at the High-High-Pressure alarm limit of 640 psi, for example, Kuraray's board operators could have taken actions to prevent the emergency pressure-relief system from activating. Such actions could include fully opening the emergency open valve, stopping the steam flow to the jacket water system, and opening the chilled liquid flow to the reactor heat exchanger. The CSB concludes that had Kuraray included an effective response for safe operating limits in its procedures and trained its board operators to take the appropriate, predetermined steps at the High-High-Pressure alarm condition (640 psi), the company could have prevented the May 19, 2018, incident.

2.15.6 Safe Operating Limits Procedure

Kuraray's operating procedure on safe operating limits stated:

> Efforts to reduce pressures or temperatures should begin when normal conditions have been exceeded and every effort should be made to avoid reaching these upper limits.

Kuraray's board operators took actions intended to lower the pressure inside EVAL Reactor 2 shortly after reaching the target of 595 psi. These actions included closing the pressure control valve that supplied ethylene to the reactor and opening the pressure control valve that directed reactor vapor to the flare. Ultimately, however, the adverse safety consequence was realized without the pressure inside EVAL Reactor 2 ever reaching its safe operating limit. The pressure inside EVAL Reactor 2 steadily increased until it was high enough to activate the emergency pressure-relief system. This safety system discharged flammable ethylene vapor from the reactor into the air, resulting in a fire when this vapor cloud found an ignition source. Kuraray's safe operating limits procedure was not effective. Factors that contributed to the procedure's ineffectiveness included having the limits set too high, not including the limits within the operating procedures, and not making it easy for the board operators to remember that this reactor system was designed for a lower internal pressure than the other EVAL Reactors.

Kuraray's safe operating limits procedure also contained conflicting guidance. Kuraray's procedure first instructed its operators to take actions to reduce pressures or temperatures when normal operating conditions have been exceeded, but then the procedure informed its operators that the safe operating limits could be exceeded (with management approval) by relying on the material safety factors within the ASME code. Specifically, the Kuraray procedure stated:

> Most vessels at [Kuraray] are built to ASME specifications which include a 3X safety factor. Most materials of construction are 304 [stainless steel] or better. Most design temperatures are established by requirements and not by actual limitations. 304 [stainless steel] has no significant loss of material strength up to 300 [degrees Fahrenheit]. **Therefore in an emergency or other unusual conditions the limits as listed in the attachment** [the safe operating limits spreadsheet] **may be exceeded with management review and supervision**. Management will review or calculate the allowable conditions under such circumstances and issue specific written instructions and approval for the situation, normally through the Management of Change (MOC) system (emphasis added).

Importantly, the CCPS recommends that companies take the opposite position. The CCPS recommends that companies should not rely on the ASME code material safety factors when determining appropriate safe operating limits. In its 2012 book, *Guidelines for Engineering Design for Process Safety*, the CCPS stated:

> Often a safety factor is applied to critical design parameters to ensure that catastrophic failure of systems or components does not occur for unknown reasons. Examples of safety factors include ASME Code requirements for allowable stresses vs. yield stress of materials. ***Safe operating limits should be set to prevent system operation in this safety factor zone*** [63, p. 127] (emphasis added).

The 2017 book *Process Safety: Key Concepts and Practical Approaches* advocated for treating operating parameter excursions that go beyond the normal safe operating limits as an emergency condition requiring an urgent response:

> Emergency responses are distinguished from the normal, routine day-to-day operator or control system responses when slight, expected deviations from the standard, safe operating conditions occur […]. ***Thus, an "extra" response is needed to respond to processing conditions exceeding the normal, safe operating limits***. The extra responses may either be operator actions to an alarm combined with automatic actions, such as interlocks, that move the process into a safe state or shut the process down. At the risk of oversimplifying responses, the basic difference between a normal

> and an emergency response is the sense of urgency—emergencies require a much quicker response [118, pp. 293-294] (emphasis added).

Approaching or exceeding a safe operating limit should be viewed as an emergency condition requiring an urgent response. The safety purpose of a safe operating limits program is to communicate the point where troubleshooting is over, and immediate predetermined actions must take place to return the process to a safe condition. The CSB concludes that maintaining a set of safe operating limits with predetermined worker actions to ensure safety is not compatible with Kuraray's program, which calls for employees who are facing emergency process conditions to check with their management for a decision as to whether or not they should exceed the safety limits during this particular emergency situation by relying upon the material safety factors built into the ASME code.

The CSB recommends that Kuraray modify the EVAL Plant's safe operating limits program to prevent operating under conditions that rely upon equipment design safety factors, such as the American Society of Mechanical Engineers (ASME) code material safety factors. (*See* Recommendation 2018-03-I-TX-R11)

As described in Section 1.29.4, after the incident, Kuraray established a new set of safe operating limits for EVAL Reactor 2. Kuraray's new safe operating limits appear to be consistent with the approach that the CCPS recommends and uses operating zones. In addition, the new limits also consider the activation pressure of the emergency pressure-relief system.

2.16 Environmental Permit

At an Institution of Chemical Engineers (IChemE) conference in April 2000, Trevor Kletz presented his paper, *Green Intention, Red Result* [119, 120], in which he described accidents and hazards that arguably stemmed from well-intended changes made to protect the environment. Kletz provided his advice on how to implement environmental improvement changes without adversely affecting safety, stating:

> I am not, of course, opposed to attempts to reduce pollution and improve the environment. I do, however, suggest that before changing designs or methods of operation, for whatever reason, we try to foresee the results of those changes by using hazard and operability studies or other systematic methods … [42, pp. 288-289].
>
> We should also balance the risks to people against the risks to the environment and should not assume that the removal of risks to the environment must always come first [120, p. 7].

As the pressure within EVAL Reactor 2 steadily increased during the startup, Kuraray's board operators limited the flow of ethylene vapor to the flare because they were trying to avoid exceeding the environmental permit's VOC limits. As described in Section 2.14.2, Kuraray management restricted its board operators from using the emergency open valve, which could have directed even more ethylene vapor to the flare. The company did not have predetermined actions for its operators to take in response to the High- and High-High-Pressure alarms. In addition, Kuraray set the EVAL Reactor 2 safe operating limits too high, and the board operators did not remember the reactor's mechanical design conditions. Kuraray's safety management system did not prioritize keeping the reactor pressure below its alarm limits over the site's environmental permit constraint.

Based on the available evidence, Kuraray did not effectively balance the risks to people against the potential risks to the environment. The CSB concludes that Kuraray's desire to avoid exceeding its environmental permit limits contributed to the May 19, 2018, incident. Kuraray's ineffective safety management systems resulted in the desire to avoid exceeding the environmental permit limits for the company's flare system unduly influencing the board operators' response to the high-pressure conditions inside EVAL Reactor 2. In response to the abnormal operating conditions, too much heat was added to the reactor, and not enough vapor was sent to the flare. As a result, the pressure inside EVAL Reactor 2 continued to increase. When the emergency pressure-relief system finally activated, its discharge injured 23 workers.

As described in Section 1.29.3, after the incident, Kuraray updated the EVAL Reactor 2 operating procedure to clarify that the environmental permit limits for the flare system should be disregarded during an emergency because keeping the pressure within safe limits has the "highest priority."

2.17 Safety Management System Self-Assessment Audits

In its 2011 book, *Guidelines for Auditing Process Safety Management Systems*, the CCPS explained that auditing is a critical element of a process safety management system because it provides insight into the effectiveness of the existing management system and could itself contribute to making the system more effective [121, p. 1].

The CCPS defined a process safety management system as a "comprehensive sets of policies, procedures, and practices designed to ensure that barriers to episodic and potential process safety incidents are in place, in use, and effective" [121, p. 2].

The CCPS explained that it views an audit as "a systematic, independent review to verify conformance with established guidelines or standards" [121, p. 1]. The CCPS further stated that the systematic review of these management systems must "verify the suitability of these systems and their effective, consistent implementation" [121, p. 3]. In explaining how to perform an audit such that it drives improved management system effectiveness, the CCPS stated:

> A [process safety management system] audit involves examination of management system design, followed by evaluation of management system implementation. The design of the management system must be understood and then evaluated to determine if the system, when functioning as intended, will meet the applicable criteria. Then the auditor must evaluate the quality and degree of implementation since a well-designed system may not be backed up by consistent, thorough implementation [121, p. 4].

Both the EPA RMP Rule and the OSHA PSM Standard require companies to periodically self-assess their process safety management systems by performing compliance audits every three years.[a] In evaluating their management systems against the minimum safety requirements of the PSM Standard, OSHA expects employers to verify that their procedures and practices are both adequate and followed.[b] OSHA also requires employers to develop a report documenting the audit findings and the corrective actions taken to address the audit findings.[c] While OSHA acknowledges that there may be times when no action needs to be taken in response to an audit finding, the agency does require that "all actions taken, including an explanation when no action is taken on a finding, need to be documented" [87, p. 29].

As discussed in Section 1.26, Kuraray completed its most recent self-assessment audit in November 2015. Kuraray management did not document its reasons for not accepting 42 percent of the recommendations proposed by its audit team. In addition, the investigation of the incident on May 19, 2018, revealed many weak process safety management systems at Kuraray. Although Kuraray's self-assessment audit identified some important issues, including that the site's safety interlocks were not in alignment with industry standards, the self-assessment did not effectively explore the level of detail needed to address the management system failures associated with the May 19, 2018, incident. For example, the self-assessment did not identify that the EVAL Reactor 2 startup procedures did not inform operators about the lower design pressure of this reactor or include information about the high-pressure alarms and the expected alarm response operators should take to return the process to a safe condition. The self-assessment also did not address serious issues, including alarm management problems, the practice of writing nightly operating instructions that might conflict with operating procedures, disabling safety interlocks during operator troubleshooting, or important safety equipment not being used during upset conditions because Kuraray management restricted its use.

The CSB concludes that the investigation of the incident on May 19, 2018, revealed many weak process safety management systems at Kuraray, but the company's self-assessment audits of these systems did not achieve the level of detail required to address the management system failures that contributed to the May 19, 2018, incident.

In January 2017, EPA amended its RMP Rule in response to Executive Order 13650 [122, 123]. Among other safety improvements, EPA required some facilities to contract with an independent third party or assemble an audit team led by an independent third party, to perform a compliance audit after the facility had an RMP reportable accident [122, pp. 4699-4700]. EPA stated that "an independent, third-party perspective can provide insight on the facility's risk management program that may not otherwise be identified during an internal compliance audit" [122, p. 4620]. These new criteria could have applied to Kuraray following the May 19, 2018, incident, but the implementation of this requirement was delayed and eventually rolled back by EPA in December 2019 [124].

Although it is not presently a regulatory requirement, in light of the findings stemming from the CSB's investigation of the May 19, 2018, incident, the CSB believes that using an independent third party to

[a] The EPA's RMP Rule compliance audit requirements stem from 40 C.F.R. § 68.79, and the OSHA PSM Standard requirement can be found under 29 C.F.R. § 1910.119(o). While the language under these two federal safety regulations is nearly the same, EPA places the requirements on the owner or operator of the facility and OSHA directs the requirements to the employer.

[b] *See* 29 C.F.R. § 1910.119(o)(1).

[c] *See* 29 C.F.R. § 1910.119(o)(3).

audit the entirety of Kuraray's process safety management systems is likely to generate important safety benefits that will help the company prevent future safety incidents that could harm workers or members of the public, the benefits of which should substantially outweigh the assessment's cost.

The CSB recommends that Kuraray acquire the services of an independent third party to perform a comprehensive assessment of its EVAL Plant's process safety management systems. In addition to meeting the requirements outlined in **Appendix B** of this report, this comprehensive assessment should evaluate whether existing policies meet minimum federal process safety regulatory requirements and apply the Center for Chemical Process Safety model to verify both the suitability of these systems and their effective, consistent implementation. (*See* Recommendation 2018-03-I-TX-R12).

3 Conclusions

3.1 Findings

1. Among the many process safety management system failures that led to injuring the 23 workers at Kuraray, none was more significant than the design of the EVAL Reactor 2 emergency pressure-relief system's outlet piping. When the emergency pressure-relief system activated, this piping design directed flammable ethylene vapor through horizontally aimed piping toward an area where many workers were performing maintenance activities, including welding operations.

2. With well-designed outlet piping, the flammable ethylene vapor could have safely discharged vertically upward, likely limiting the incident consequences to activating the EVAL Reactor 2 emergency pressure-relief system and releasing ethylene into the environment.

3. Had Kuraray applied the lessons provided by previous chemical disasters, including the Union Carbide disaster in Bhopal, India, in 1984 and the BASF tragedy in Cincinnati, Ohio, in 1990 (which involved discharging chemicals from emergency pressure-relief systems in a manner that caused great harm to people), the company could have prevented the May 19, 2018, incident by ensuring the EVAL Reactor 2 emergency pressure-relief system discharged the flammable ethylene vapor to a safe location, with no harm to people.

4. The facts, conditions, and circumstances of the May 19, 2018, incident show that the emergency pressure-relief system for Kuraray's EVAL Reactor 2 did not discharge to a safe location.

5. There are many publications that provide industry safety guidance making clear that emergency pressure-relief systems must discharge to a safe location to prevent harm to people. Although Kuraray's corporate safety guidance recognized the potential severity of discharging emergency pressure-relief systems to an unsafe location, the company did not address this hazard for its EVAL Reactor 2 emergency pressure-relief system.

6. API 521, *Pressure-Relieving and Depressuring Systems*, does not provide users with guidance for safely discharging flammable vapor into the air from horizontally aimed emergency pressure-relief

system piping. Therefore, API 521 cannot serve as the sole safety design basis for an emergency pressure-relief system that horizontally discharges flammable vapor into the ambient air.

7. Kuraray could have prevented the May 19, 2018, incident by implementing its engineering firm's proposal to direct ethylene from emergency pressure-relief systems to a flare. The engineering firm's proposal called for containing the flammable ethylene from the emergency pressure-relief system within piping that directed the vapor to a flare for safe disposal instead of discharging the flammable ethylene vapor into the air (through horizontally aimed piping) near workers.

8. Kuraray did not adopt safety recommendations that its 2015 Process Hazard Analysis (PHA) team proposed after finding that atmospheric ethylene releases from some emergency pressure-relief systems, including the EVAL Reactor 2 emergency pressure-relief system, could harm workers by creating a flash fire or vapor cloud explosion.

9. Kuraray could have prevented the May 19, 2018, incident by applying one of the four safer strategies that API 521 specified to prevent vapor cloud explosions—redesigning equipment to avoid the scenario, flaring, containing the flammable material in a lower-pressure system, or applying high-integrity protective systems.

10. Kuraray's use of emergency pressure-relief systems with horizontally aimed outlet piping may be a systemic problem. The emergency pressure-relief system for EVAL Reactor 1 was designed to discharge flammable ethylene vapor horizontally toward a public road, which could place members of the public in harm's way. In addition, the CSB learned that the corporation might have used this dangerous design in all its EVAL facilities.

11. At the time of the incident, none of the contract workers located near the EVAL Reactor 2 emergency pressure-relief system were performing tasks associated with operating the reactor, responding to the abnormal reactor conditions, or were otherwise essential to the startup.

12. Neither Kuraray's operating procedures nor its operator training covered the known activities or conditions that should have prompted Kuraray's operations personnel to exclude nonessential personnel from the unit.

13. Kuraray had an unwritten safety practice to exclude nonessential personnel from a unit when reintroducing (pressuring or charging) ethylene into equipment after a turnaround, but the company lacked a formal exclusion zone to protect nonessential workers for the duration of the startup.

14. Kuraray's safety management systems did not consider the high-pressure conditions developing inside EVAL Reactor 2 as an upset condition that should halt the maintenance work being performed and prompt the evacuation of nonessential personnel.

15. When the flammable ethylene vapor was discharged from the reactor's emergency pressure-relief system, many nonessential workers were in harm's way, and the welding work they were performing likely supplied the ignition source that created the fire.

16. The safety of workers near the EVAL Reactor 2 emergency pressure-relief system was routinely at risk. Known scenarios that could generate high pressure inside the reactor could arise at any time, including cooling failure, loss of refrigeration, power failure, or even a simple malfunction of the control valve supplying ethylene to the reactor. With workers present, activating this safety system created a danger to their safety.

17. Because the emergency pressure-relief system did not discharge ethylene to a safe location, a portion of the area adjacent to EVAL Reactor 2 was a hazardous location for workers.

18. Kuraray did not demonstrate how its EVAL Reactor 2 emergency pressure-relief system conformed with recognized and generally accepted good engineering practices (RAGAGEP) or that this safety equipment was designed and operated in a safe manner.

19. Kuraray did not perform an evaluation, such as a dispersion analysis, to ensure that releasing ethylene vapor from the EVAL Reactor 2 emergency pressure-relief system through its horizontally aimed piping would discharge the flammable ethylene to a safe location.

20. Had Kuraray evaluated the safety of horizontally discharging high-pressure ethylene into the air when developing its Process Safety Information for the EVAL Reactor 2 emergency pressure-relief system, the safety risk to workers could have been identified, the outlet piping design problem could have been corrected, and the company could have prevented the May 19, 2018, incident.

21. On the day of the incident, none of the safeguards that Kuraray concluded should control the pressure inside the reactor without activating the EVAL Reactor 2 emergency pressure-relief system were effective.

22. Kuraray did not implement or effectively manage the disposition of the recommendation made by its 2015 PHA team to evaluate the potential safety impact on workers from ethylene that could be discharged into the air from emergency pressure-relief systems.

23. Had Kuraray effectively evaluated its 2015 PHA team’s recommendations to address the worker safety concerns related to potential ethylene releases from emergency pressure-relief systems before declining these safety recommendations, it is likely that the company could have identified the safety risk to workers, corrected the design problem with the EVAL Reactor 2 emergency pressure-relief system discharge location, and prevented the May 19, 2018, incident.

24. Kuraray had earlier warnings about the serious design problem with some of its emergency pressure-relief systems. By acting on these earlier warnings, Kuraray could have prevented the May 19, 2018, incident.

25. The design pressure differences between Kuraray’s four EVAL Reactors contributed to the incident. EVAL Reactor 2’s design pressure was 740 psi, which was 410 psi lower than the design pressure of the other three reactors.

26. Although Kuraray performed a methanol flush of its EVAL Reactors after some specific maintenance activities, the company did not have a written procedure or train its operators to perform the methanol

flush. A misstep during the methanol flush led Kuraray to disable an important safety interlock, which remained disabled as the startup proceeded.

27. Nightly operating instructions supplied by Kuraray management conflicted with the company's written operating procedures, resulting in unmanaged changes to the reactor startup that contributed to the May 19, 2018, incident.

28. Several operational causes that contributed to the incident on May 19, 2018, were not listed, described, explained, or otherwise covered by Kuraray's operator training manual.

29. Kuraray's safety management systems did not control the circulation of chilled liquid through the heat exchanger during startup, leading to an abnormal operating condition—liquid ethylene accumulation inside the reactor.

30. Kuraray's safety management systems enabled the reactor startup to continue despite the presence of an abnormal operating condition—the low temperature of the liquid inside the reactor. Kuraray lacked a procedure or other guidance explaining what actions its operators should take to correct the reactor's low-temperature condition. Although intended to hold ethylene vapor, the reactor now contained some cold liquid ethylene. Despite the abnormally low temperature, because nothing in Kuraray's safety management systems called for stopping the process, the startup continued.

31. As operators responded to the low-temperature condition inside EVAL Reactor 2, Kuraray's safety management systems allowed its nightly operating instructions to conflict with established written operating procedures, leading to another abnormal operating condition—high pressure within the reactor.

32. Kuraray did not have a program to manage abnormal operating conditions. The company could have prevented the May 19, 2018, incident by getting the right people involved, performing a hazard analysis, and developing a written plan to guide the response to the abnormally low-temperature conditions inside the reactor.

33. A formal safety review should have recognized the need to heat the reactor contents slowly and placed tighter limits on the allowable pressure inside EVAL Reactor 2. At a minimum, such a review should have found that the nightly operating instructions had deviated from the written operating procedures. Kuraray could have prevented the incident by adhering to the operating pressure and temperature targets specified in its written startup procedure.

34. Kuraray did not have an effective system to manage the disabling of safety interlocks and ensure that these critical systems were available before continuing startup activities.

35. Kuraray's control system flooded the board operators with alarms, which contributed to the incident by hindering the operators' ability to effectively review the process information and control the high-pressure conditions that developed within the reactor.

36. Kuraray's startup procedures lacked guidance or actions for the board operators to take in response to process alarms, which contributed to the incident.

37. Effective alarm system messaging could have helped Kuraray's board operators to better respond to the high-pressure conditions that developed inside the reactor, which could have prevented the activation of the reactor's emergency pressure-relief system.

38. The physical and procedural controls that Kuraray put in place to govern the use of the emergency open valve contributed to the incident by restricting the board operators from accessing or otherwise using the emergency open valve. The lack of a procedure or training directing when operators should use the emergency open valve also contributed to the incident.

39. Because Kuraray postponed the implementation of its PHA recommendation to control the opening of its emergency open valve automatically, this safeguard was not available during the EVAL Reactor 2 startup on May 19, 2018.

40. Kuraray could have lowered the pressure inside EVAL Reactor 2 and prevented the incident on May 19, 2018, by using effective control system automation. At a predetermined high-pressure condition inside EVAL Reactor 2, Kuraray could have had its control system automatically open the emergency open valve and directed enough ethylene vapor to the flare to prevent the emergency pressure-relief system from activating.

41. Kuraray should have provided its board operators with clear operating procedures and effective training without physically or procedurally restricting their access to the emergency open valve's panel board switch. By doing so, Kuraray's board operators could have prevented the incident by opening the emergency open valve to prevent the high-pressure conditions from activating the emergency pressure-relief system and discharging the flammable ethylene vapor into the air.

42. Kuraray set the safe operating limits for EVAL Reactor 2 too high to prevent activating the EVAL Reactor 2 emergency pressure-relief system effectively. The consequence of deviation occurred before the safe operating limit was reached. The company did not follow the Center for Chemical Process Safety guidance to consider the atmospheric discharge from the reactor's emergency pressure-relief system when determining the safe operating limits for EVAL Reactor 2.

43. Kuraray's safe operating limits program did not ensure an effective response to the high-pressure conditions that developed inside EVAL Reactor 2. As a result, not all of the predetermined actions were taken, including increasing the cooling from the chilled water system or using the emergency open valve to lower the pressure by directing vapor from EVAL Reactor 2 to the flare system.

44. Had Kuraray included an effective response for safe operating limits in its procedures and trained its board operators to take the appropriate, predetermined steps at the High-High-Pressure alarm condition (640 psi), the company could have prevented the May 19, 2018, incident.

45. Maintaining a set of safe operating limits with predetermined worker actions to ensure safety is not compatible with Kuraray's program, which calls for employees who are facing emergency process conditions to check with their management for a decision as to whether or not they should exceed the safety limits during this particular emergency situation by relying upon the material safety factors built into the ASME code.

46. Kuraray's desire to avoid exceeding the environmental permit limits contributed to the May 19, 2018, incident. Kuraray's ineffective safety management systems resulted in the desire to avoid exceeding the environmental permit limits for the company's flare system unduly influencing the board operators' response to the high-pressure conditions inside EVAL Reactor 2

47. The investigation of the incident on May 19, 2018, revealed many weak process safety management systems at Kuraray, but the company's self-assessment audits of these systems did not achieve the level of detail required to address the management system failures that contributed to the May 19, 2018, incident.

3.2 Cause

The U.S. Chemical Safety and Hazard Investigation Board (CSB) determined that the cause of the incident was Kuraray's long-standing emergency pressure-relief system design that discharged flammable ethylene vapor through horizontally aimed piping into the air, near workers. Had Kuraray's emergency pressure-relief system discharged vapor from the reactor to a **safe location,** the flammable ethylene gas should not have harmed any workers.

Kuraray's long chain of weakly implemented management system elements that made up its overall process safety management system also contributed to the incident. In addition to the management system elements that Kuraray used to manage the EVAL reactor's emergency pressure-relief system, other elements contributed by allowing high-pressure conditions to develop inside the chemical reactor system (EVAL Reactor 2). The combination of these ineffective management system elements culminated with the reactor's emergency pressure-relief system activating and discharging flammable ethylene vapor into the air, where it ignited near nonessential workers (that is, workers who were not essential to the startup of the chemical reactor).

Kuraray's safety management systems also fostered inconsistent practices for keeping nonessential personnel from being physically present within the unit during critical events and activities—such as unit startups or when upset process conditions develop—which contributed to the injuries suffered. Kuraray could have prevented these injuries by implementing a policy to exclude workers not involved in the startup. Furthermore, Kuraray could have taken protective actions during upset conditions to prevent worker injuries. For example, when the reactor's high-pressure alarm sounded (signaling upset conditions), Kuraray should have stopped work and evacuated the workers from the area.

4 Recommendations

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

4.1 Kuraray America, Inc.

2018-03-I-TX-R1

Develop and implement an emergency pressure-relief system design standard to ensure that each of these safety systems will discharge to a safe location. Include a requirement to periodically evaluate the site's emergency pressure-relief systems and make appropriate modifications to ensure that each of these systems discharge to a safe location such that material that could discharge from these safety systems will not harm people.

2018-03-I-TX-R2

Implement a site-wide system to evacuate nonessential personnel during upset conditions and exclude nonessential workers from being near equipment during transient operating modes, such as startup.

2018-03-I-TX-R3

Develop and implement a system requiring a periodic evaluation of the adequacy and effectiveness of any safeguard used to mitigate or otherwise lower the risk of process safety hazards. This safeguard protection analysis should be based on the requirements of Cal/OSHA's Process Safety Management for Petroleum Refineries regulations or an appropriate equivalent methodology.

2018-03-I-TX-R4

Develop and implement a policy detailing how to effectively address recommendations generated from company process safety management systems, including audits, incident investigations, management of change, and process hazard analysis that is consistent with existing OSHA guidance. Include a periodic training requirement for managers and other employees involved with evaluating and managing proposed recommendations to help ensure proposed safety improvements are effectively evaluated and appropriately implemented.

2018-03-I-TX-R5

Review the Center for Chemical Process Safety guidance on recognizing catastrophic incident warning signs and then develop and implement a program for the EVAL Plant that incorporates warning signs into its safety management system.

2018-03-I-TX-R6

Clarify the lower equipment design pressure of the EVAL Reactor 2 within the operator training systems, written procedures, and in the control system interface.

2018-03-I-TX-R7

Develop and implement a program to ensure that the company's EVAL Plant nightly operating instructions do not conflict with its written operating procedures. Ensure that employees use the management of change system when changes to the written operating procedures are desired. Additionally, develop and implement a written procedure and conduct training on how to perform the EVAL Reactor methanol flush operation.

2018-03-I-TX-R8

Strengthen the EVAL Plant's operator training program by 1) including the known activities, such as bringing ethylene back into the unit, upset conditions like the reactor's High-High-Pressure alarm, and providing guidance or otherwise clarifying when nonessential personnel should be excluded from being in the unit; 2) including alarm setpoints and actions that operators should take in response to specific process alarms, such as high pressure inside an EVAL Reactor; 3) including directions on when operators should use the emergency open valve; and 4) including safe operating limits, the consequence of deviating beyond the safe operating limits, and the predetermined steps operators need to take to return the process to a safe condition.

2018-03-I-TX-R9

Complete the alarm management efforts at the EVAL Plant and implement a continual program to meet or be lower than the alarm rate performance targets established in ISA 18.2.

2018-03-I-TX-R10

Improve the EVAL Plant's safety management system by 1) controlling when chilled liquid is circulated through the heat exchanger during startup; 2) enhancing recognition of liquid ethylene accumulation and response to low-temperature conditions inside an EVAL Reactor through alarms, written procedures, and operator training; 3) implementing a system to manage abnormal operating conditions effectively by, at a minimum, including appropriate technical representation, performing a hazard analysis of temporary or troubleshooting operations, and providing management oversight of any abnormal condition; 4) updating the written startup procedures to include guidance on the appropriate operator actions to take in response to process alarms; 5) using control system guidance to aid operator response to abnormal or upset conditions to keep the process within the safe operating limits; and 6) removing the physical and procedural controls used at the EVAL Plant to restrict board operators from accessing or using the emergency open valve, and updating the written procedures and operator training to provide guidance on when to open the emergency open valve.

2018-03-I-TX-R11

Modify the EVAL Plant's safe operating limits program to prevent operating under conditions that rely upon equipment design safety factors, such as the American Society of Mechanical Engineers (ASME) code material safety factors.

2018-03-I-TX-R12

Acquire the services of an independent third party to perform a comprehensive assessment of its EVAL Plant's process safety management systems. In addition to meeting the requirements outlined in Appendix B of this report, this comprehensive assessment should evaluate whether existing policies meet minimum federal process safety regulatory requirements and apply the Center for Chemical Process Safety model to verify both the suitability of these systems and their effective, consistent implementation.

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Appendix A: Timeline[a]

A.1 1986

Kuraray completed building EVAL Units 1 and 2 in 1986. **Figure 34** shows the Kuraray site in 1995 after EVAL Units 1 and 2 were complete. Kuraray completed EVAL Unit 3 in 1996 and EVAL Unit 4 in 2007. When Kuraray built these units, available guidance published by API—including API 520, *Sizing, Selection, and Installation of Pressure-Relieving Devices in Refineries* and API 521, *Guide for Pressure-Relieving and Depressuring Systems*—called for aiming flammable hydrocarbon vapor discharges from emergency pressure-relief systems vertically upward into the air.

Figure 34. EVAL Units 1 and 2. (Credit: Google Earth)

During the design and construction of these EVAL Units, the emergency pressure-relief system standards available to Kuraray included:

[a] Various sources of information were relied upon to construct this incident timeline. These sources included both control system information and event logs. The estimate used for the time difference between the control system and the event logs was generally accurate but using this adjustment for some events appeared to place the events out of sequence.

- API 520 Part 1—Recommended Practice for the Design and Installation of Pressure-Relieving Systems in Refineries, Part I—Design, 1976 [125];
- API 520 Part 2—*Recommended Practice for the Design and Installation of Pressure-Relieving Systems in Refineries*, Part II—Installation, 1963 (Reaffirmed in 1973) [126]; and
- API 521—Guide for Pressure-Relieving and Depressuring Systems, 1982 [127].

Like the current version of API 521, the 1982 edition promoted directing emergency pressure-relief systems into the air if the discharge did not produce an unacceptable outcome, such as creating a hazard to workers. API 521 stated:

> In many situations, pressure relief vapor streams may be safely discharged directly to the atmosphere. This has been demonstrated by many years of safe operation with atmospheric releases from properly installed vapor pressure relief valves. Technical work sponsored by the API[a] has also shown that within the normal operational range of conventional safety relief devices, well-defined flammable zones can be predicted for most such vapor releases. With proper recognition of the appropriate design parameters, vapor releases to the atmosphere can provide for the highest degree of safety. Atmospheric discharge eliminates the significant problems associated with analysis of system loads, proper sizing of piping, mechanical design criteria and considerations of the back pressure on safety relief valves where closed release systems are used. Where feasible, this arrangement offers significant advantages over the alternative methods of disposal because of its inherent simplicity, dependability, and economy. The decision to discharge hydrocarbons or other flammable or hazardous vapors to the atmosphere requires careful attention to ensure that disposal can be accomplished without creating a potential hazard or causing other problems, such as the formation of flammable mixtures at grade level or on elevated structures, exposure of personnel to toxic vapors or corrosive chemicals, ignition of relief streams at the point of emission, excessive noise levels and air pollution [127, p. 25].

Consistent with API 521, the design part of API 520 also acknowledged that directing emergency pressure-relief systems into the air was safe if the discharge did not produce an unacceptable outcome, such as creating a hazard to workers.

> If the equipment location is such that the discharge of vapor directly to the atmosphere can be tolerated, such discharge should be limited to those vapors which will not condense in appreciable quantities at the lowest atmospheric temperature for that locality. Safety-valve discharge of noncondensing gases directly to the atmosphere can be considered safe if

[a] "Hoehne, V. O., Luce, R. G., and Miga, L. W., *The Effect of Velocity, Temperature, and Gas Molecular Weight on Flammability Limits in Wind-Blown Jets of Hydrocarbon Gases*, report to the American Petroleum Institute, Battelle Memorial Institute, Columbus Ohio, 1970" [127, p. 41].

> the location is such that ignition of such discharge can be tolerated with regard to the hazard to personnel or adjacent equipment and structures. Quenching steam may be piped into atmospheric discharge of safety valves to minimize the hazard of ignition. (For a discussion of vapors discharged directly to the atmosphere, see API RP 521) [125, p. 20].

The 1982 version of API 521 relied on discharging flammable hydrocarbon vapor vertically upward to disperse releases from emergency pressure-relief systems safely into the air. API 521 stated:

> When hydrocarbon relief streams comprised entirely of vapors are discharged into the atmosphere, mixtures in the flammable range will unavoidably occur downstream of the outlet as the vapor mixes with air. Under most circumstances where individual [emergency pressure-relief] valves discharge **vertically upward** through their own stacks, this flammable zone will be confined to a rather limited definable pattern at elevations above the level of the release [127, p. 25] (emphasis added).

Further demonstrating that atmospheric discharges of flammable hydrocarbon should be discharged vertically upward, API 521 relied on the same studies it uses today to show that vertical discharge helps prevent flammable concentrations below the discharge point and limits the horizontal distance of flammable vapor clouds. API 521 stated:

> Based on these data, it can be concluded that where high discharge velocities are achieved, the hazard of flammable concentrations below the level of the discharge point is negligible. This confirms the many years of experience with vapor releases from safety relief valves discharging directly to the atmosphere without accumulation of flammable concentrations [127, p. 26].
>
> The studies demonstrated the adequacy of the general industry practice of locating safety relief valve stacks to the atmosphere at least 50 feet (15 meters) horizontally from any structures or equipment running to a higher elevation than the discharge point. This would be adequate in most cases to prevent flammable vapors from reaching the higher structures. There should also be no concern with these jet momentum releases, about large clouds of flammable vapors or flammable conditions existing at levels below the release level of the stack. These recent studies have generally verified the long-standing experience relative to the safety of vapor releases vertically to the atmosphere from atmospheric safety relief valve discharge stacks [127, p. 27].
>
> Where the atmospheric vent handles combustible vapors, the outlet from the vent should be elevated approximately 10 feet (3 meters) above any adjacent equipment, building, chimney, or other structure. Provision must

> be made for drainage of each vent pipe so that liquid cannot accumulate in the vent [127, p. 43].

Although API 521 guided users on outlet piping configuration, the industry standard also referred readers to API 520. API 521 stated that piping "installation details should conform to those specified in API Recommended Practice 520, Part II" [127, p. 44]. **Figure 35** shows that even the 1963 and 1973 editions of API 520 recommended aiming the outlet piping from emergency pressure-relief systems vertically upward [126, p. 5].

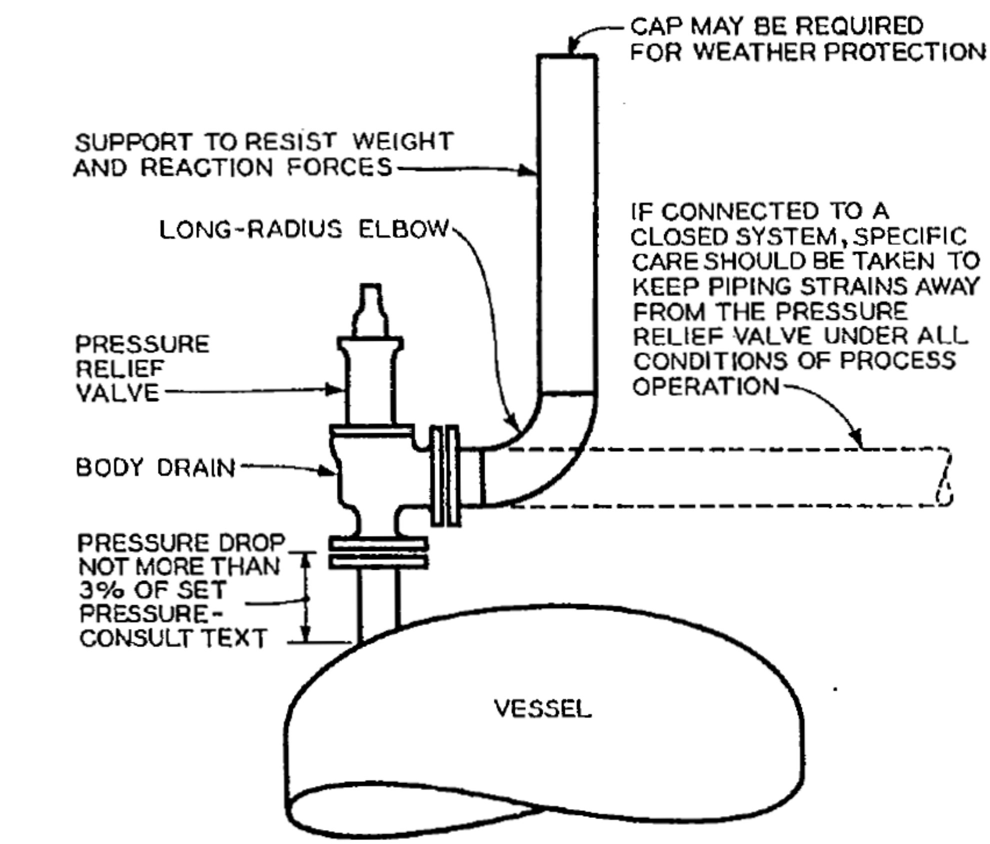

FIG. 1—Recommended Typical Pressure Relief Valve Installation Without Shutoff Valve.

Figure 35. Emergency Pressure-Relief System Piping. (Credit: API)

A.2 1986 – 1989

Kuraray had an incident where an emergency pressure-relief system activated and discharged flammable ethylene vapor into the air. The incident triggered ground-level flammable gas detector alarms, but the flammable ethylene vapor did not ignite.

A.3 2011

Kuraray began engineering work to ensure that it had proper designs for the site's emergency pressure-relief systems. This project systematically reviewed the design of Kuraray's emergency pressure-relief systems. Among other things, this project's objectives included evaluating the adequacy of the existing design for "current plant configuration and operating conditions." Kuraray hired an engineering firm to perform these services. Notably, the project's scope did not include a dispersion study of potential flammable hydrocarbon vapor releases into the air. Kuraray's project records do not show that the engineering firm was tasked with evaluating the individual emergency pressure-relief systems to ensure they were discharged to a safe location.

A.4 2013

The engineering firm Kuraray hired in 2011 to validate the site's emergency pressure-relief systems found safety concerns with some existing emergency pressure-relief system designs. These concerns included the potential for liquid ethylene to be released into the air, creating a vapor cloud explosion. The engineering firm submitted a proposal for a project to direct ethylene from emergency pressure-relief systems to a flare to address these concerns. This proposal included the EVAL Reactor 2 emergency pressure-relief system. Kuraray did not implement this proposal.

A.5 2014

Following the March 23, 2005, vapor cloud explosion at the BP Texas City refinery, API strengthened its industry standard for emergency pressure-relief systems to help prevent vapor cloud explosions resulting from the atmospheric discharge of flammable chemicals. Safety guidance provided by API 521 now called for using one of four safer strategies to prevent vapor cloud explosions—redesigning equipment to avoid the scenario, flaring, containing the flammable material in a lower-pressure system, or applying high-integrity protective systems [40, 37].[a]

A.6 2015

On March 22, 2015, Kuraray had another incident where an emergency pressure-relief system discharged flammable ethylene vapor into the air. As with the incident from the 1980s, the ethylene vapor cloud did not ignite. Kuraray's 2015 PHA team reviewed this incident and found that potential ethylene releases from some of the site's emergency pressure-relief systems (including EVAL Reactor 2) could result in a flash fire or a vapor cloud explosion.

The PHA team recommended that Kuraray perform a study to evaluate these potential ethylene releases from emergency pressure-relief systems and their safety impact on personnel. Kuraray did not adopt this safety recommendation, nor did the company adopt other recommendations made by its PHA team,

[a] A high integrity protection system is a "system composed of sensors, logic solvers, and final control elements for the purpose of taking the process to a safe state when predetermined conditions are met" [37, p. 9, 38, p. 8].

despite the finding that atmospheric ethylene releases from some emergency pressure-relief systems, including the EVAL Reactor 2 emergency pressure-relief system, could harm workers.

Kuraray's 2015 PHA recommended upgrading and automating the emergency open valve that directs reactor vapor to the flare (**Figure 13**). At a pressure above the EVAL Reactor 2 High-High-Pressure alarm, the recommendation called for the control system to take over and fully open the emergency open valve to reduce the pressure inside the reactor. Although the original action item Kuraray developed to implement this recommendation called for making this change in time for the post-turnaround startup in the spring of 2018, the work to complete this action item was postponed to 2019.

Kuraray completed its most recent self-assessment audit in November 2015. Kuraray's self-assessment audit developed 64 proposed recommendations in 11 of the 14 PSM elements. During Kuraray's management review, only 37 of the recommendations were accepted and assigned corrective actions and due dates to track completion. Kuraray management did not accept the other 27 recommendations (42 percent).

A.7 2018

A.7.1 April 6, 2018

Kuraray started its 2018 maintenance turnaround.

A.7.2 April 22, 2018

During the turnaround, Kuraray replaced an existing ammonia-based refrigeration system with a new system that used a hydrofluorocarbon refrigerant. During the commissioning of this new chilled liquid refrigeration system, Kuraray prepared to start flowing chilled liquid through process equipment, including the EVAL Reactor 2 heat exchanger. To enable the circulation of chilled liquid, a Kuraray board operator fully opened (100 percent open) the temperature control valve to the heat exchanger (**Figure 10**). Kuraray board operators did not further adjust the control valve position until the morning of the incident, May 19, 2018. Although a path for chilled liquid circulation was set up, Kuraray personnel did not start flowing chilled liquid through this equipment.

A.7.3 May 10, 2018

Kuraray cleared and restricted the entry of nonessential personnel when operations personnel introduced ethylene back into the facility.

A.7.4 May 14, 2018

Kuraray began circulating chilled liquid through the EVAL Reactor 2 heat exchanger. After achieving a stable circulation of chilled liquid, the chilled liquid supply temperature averaged 4°F.

A.7.5 May 15, 2018

Kuraray operations personnel started removing oxygen from EVAL Reactor 2. To do this, Kuraray used nitrogen to displace the oxygen from the reactor. Kuraray's procedure called for operators to add nitrogen to the reactor, increasing the pressure to a target of 60 psi. After reaching 60 psi, Kuraray operators directed the nitrogen and oxygen into the air until the pressure inside EVAL Reactor 2 reached the target pressure of 10 psi. To achieve the desired oxygen concentration in the reactor, Kuraray operators repeated this process several times. Although Kuraray's procedure called for 60 and 10 psi as the target pressures, 40 to 58 psi was the range during the pressure increases, and 10 to 2 psi was the range during the pressure decreases.

A.7.6 May 16, 2018

Kuraray operators completed the process of removing oxygen from EVAL Reactor 2.

A.7.7 May 17, 2018

Kuraray cleared out nonessential personnel as operators worked to bring ethylene back into EVAL Reactor 2. Kuraray operations personnel started removing nitrogen from EVAL Reactor 2. The process was similar to Kuraray's process for removing oxygen, but this process used ethylene to replace the nitrogen. Kuraray operators added ethylene to the reactor using the ethylene pressure control valve and then increased the pressure inside the reactor to a target of 60 psi. After reaching 60 psi, Kuraray operators directed the ethylene and nitrogen through the pressure control valve (**Figure 12**) and the emergency open valve to the flare (**Figure 13**) until the pressure inside EVAL Reactor 2 reached the target pressure of 10 psi.

To achieve the desired nitrogen concentration in the reactor, Kuraray operators repeated this process several times. Although Kuraray's procedure called for 60 and 10 psi as the target pressures, 49 to 67 psi was the range during the pressure increases, and 13 to 4 psi was the range during the pressure decreases.

At about 11:57 p.m., Kuraray operators completed the process of removing nitrogen from EVAL Reactor 2 by replacing the nitrogen with ethylene. At the end of this process, the pressure inside EVAL Reactor 2 was 63 psi, and the temperature was 74°F.

During the nitrogen removal, the chilled liquid circulated through the heat exchanger at about 4°F. As part of the company's alarm management work, Kuraray disabled its EVAL Reactor 2 low-temperature alarms. Before Kuraray implemented its alarm management effort, EVAL Reactor 2 was equipped with a Low-Temperature alarm set at 25°F and a Low-Low-Temperature alarm set at 20°F. The chilled liquid lowered the temperature in the piping from the heat exchanger to the reactor enough to reach the former Low-Temperature alarm limit (25°F) at 2:53 a.m. and the former Low-Low-Temperature alarm (20°F) at 3:15 a.m. The temperature rose above the former alarm limits at 5:13 a.m. The temperature dropped below the former Low-Temperature alarm limit again from 7:03 a.m. – 9:29 a.m., 11.25 a.m. – 2:14 p.m., 4:43 p.m. – 7:09 p.m., 7:53 p.m. – 10:34 p.m., and from 11:11 p.m. – 5:02 a.m. the next morning (May 18, 2018).

A.7.8 May 18, 2018

After using ethylene to replace the nitrogen inside the reactor, Kuraray's startup procedure called for sampling the reactor vapor to ensure the nitrogen was effectively removed. The next step in this procedure required raising the pressure inside the reactor to 150 psi and adjusting the temperature to 86°F.[a] Kuraray operators raised the pressure to 112 psi. The reactor temperature was 72°F.

In addition to operating procedures, Kuraray management supplied nightly operating instructions. The operating instructions from the previous night (May 17, 2018) included directions for starting methanol flushes to EVAL Reactor 2. Although not covered by a written procedure, Kuraray performed methanol flushes to remove any water left in the reactor. Kuraray operators added methanol to EVAL Reactor 2 from 1:50 a.m. to 4:13 a.m. During this time, the liquid level in the reactor rose to about 2 percent.

Nightly operating instructions also directed operators to add ethylene to the reactor to reach the target pressure of 595 psi. At every 100 psi, the nightly operating instructions required operators to check for leaks by spraying a soap solution on piping and vessel connections. Using this technique, ethylene leaks should appear as soap bubbles. Operators began adding ethylene to increase the pressure inside EVAL Reactor 2 at 3:00 p.m. Increasing the pressure inside the reactor above 150 psi at this point in the startup was one of several deviations from Kuraray's operating procedures, which called for starting the flush batch before or at the same time as increasing the reactor pressure. Kuraray operations personnel did not start working on the flush batch procedure until May 19, 2018, at 10:05 a.m., 23 minutes before the incident. By following the normal startup sequence as written in Kuraray's operating procedures, board operators should have limited the pressure inside EVAL Reactor 2 to:

- 565 psi when adding ethylene to increase the pressure inside the reactor; or
- 495 psi at a maximum temperature of 137°F when heating the reactor contents while adding ethylene to increase the pressure inside the reactor.

5:38 p.m.

The pressure inside EVAL Reactor 2 reached 200 psi, the reactor liquid temperature was 86°F, and the reactor liquid level was 4 percent.

A.7.8.1 8:06 p.m.

The pressure inside EVAL Reactor 2 reached 300 psi, the reactor liquid temperature was 85°F, and the reactor liquid level was 5 percent.

A.7.8.2 11:25 p.m.

The pressure inside EVAL Reactor 2 reached 400 psi, the temperature was 83°F, and the reactor liquid level was 6 percent. Exceeding 400 psi inside the reactor was significant because pressure above 400 psi

[a] A review of the printed copy of this procedure used during the startup showed that no Kuraray board operator ever initialed or otherwise marked this step as completed.

with the chilled liquid circulating through the heat exchanger at 4°F created conditions that could condense the ethylene vapor to a liquid. Liquid ethylene flowed from the heat exchanger into the reactor over the next several hours, as shown by the decreasing reactor temperature and the increasing reactor liquid level. Kuraray board operators were not aware that liquid ethylene was flowing from the heat exchanger and accumulating inside the reactor.

A.7.9 May 19, 2018

A.7.9.1 2:47 a.m.

The pressure inside EVAL Reactor 2 reached 450 psi, the reactor liquid temperature was 33°F, and the liquid level was 9 percent.

A.7.9.2 6:41 a.m.

Board Operator 1 opened the pressure control valve that supplied ethylene to the reactor from 40 to 41 percent open to increase the flow of ethylene (**Figure 12**). The pressure inside EVAL Reactor 2 reached 470 psi, the reactor liquid temperature was 17°F, and the liquid level was 12 percent.

A.7.9.3 6:47 a.m.

Board Operator 1 opened the pressure control valve that supplied ethylene to the reactor from 41 to 42 percent open to increase the flow of ethylene. The pressure inside EVAL Reactor 2 was 470 psi, the liquid temperature was 17°F, and the liquid level was 12 percent.

A.7.9.4 6:49 a.m.

Board Operator 1 switched the operating mode for the reactor pressure control valve (**Figure 12**) that sends reactor vapor to the flare from manual to automatic and lowered the setpoint from 695 to 650 psi.

A.7.9.5 7:00 a.m.

While reviewing control system information on process conditions, Supervisor 1 saw that the EVAL Reactor 2 temperature was cold, about 18°F, and he instructed Board Operator 1 to close the temperature control valve that supplied chilled liquid to the reactor's heat exchanger (**Figure 10**).

The pressure inside EVAL Reactor 2 was 472 psi, the reactor liquid temperature was 18°F, and the liquid level was 12 percent.

During the startup of EVAL Reactor 2, Kuraray's control system provided the board operators with alarms. Between 7:00 a.m. and 10:28 a.m., the control system event log recorded 552 alarms.

A.7.9.6 7:04 a.m.

Board Operator 1 closed the temperature control valve that supplies chilled liquid to the reactor heat exchanger from 0 to 100 percent. This temperature controller was reverse-acting, meaning that 0 percent indicated that the valve was fully open, and 100 percent indicated that the valve was fully closed (**Figure 10**). The reactor liquid temperature was 18°F, and the reactor pressure was 475 psi.

A.7.9.7 7:08 a.m.

Board Operator 1 opened the control valve that injected steam into the jacket water supply from 0 to 30 percent open to increase the jacket water temperature. The jacket water temperature was 81°F.

Kuraray was now heating the contents of EVAL Reactor 2 while ethylene was flowing into the reactor to increase the pressure. Under these conditions, the operating procedure called for limiting the pressure inside the reactor to 495 psi. Kuraray operators were not following this procedure. They were instead following the conflicting nightly operating instructions that directed them to increase the pressure inside EVAL Reactor 2 to a target of 595 psi.

A.7.9.8 7:09 a.m.

Board Operator 1 opened the control valve that injected steam into the jacket water supply from 30 to 35 percent open to increase the jacket water temperature. The jacket water temperature was 81°F.

A.7.9.9 7:11 a.m.

The pressure inside EVAL Reactor 2 reached 495 psi. Had Kuraray followed the operating procedures instead of the nightly operating instructions, the pressure should have been held at 495 psi until the flush batch was transferred into EVAL Reactor 2. The operating procedure called for holding the reactor at 495 psi with a maximum reactor temperature of 137°F "to prevent exceeding [595 psi], which could require venting excess pressure to the flare." The operating procedure did not call for heating the reactor contents until after transferring the flush batch into the reactor. Kuraray operators had not yet started step 1 of the flush batch procedure. The startup procedure for the flush batch did not call for heating the reactor until step 15.

A.7.9.10 7:14 a.m.

Board Operator 1 closed the pressure control valve that supplied ethylene to the reactor from 42 to 35 percent open to reduce the flow of ethylene (**Figure 6**). The reactor pressure was 507 psi.

A.7.9.11 7:15 a.m.

The pressure inside EVAL Reactor 2 was 509 psi, the reactor liquid temperature was 23°F, and the liquid level was 12 percent.

A.7.9.12 7:21 a.m.

Board Operator 1 closed the pressure control valve that supplied ethylene to the reactor from 35 to 0 percent open to stop the flow of ethylene. The reactor pressure was 523 psi.

Board Operator 1 opened the control valve that injected steam into the jacket water supply from 35 to 40 percent open to increase the jacket water temperature. The jacket water temperature was 68°F. As Board Operator 1 further increased the jacket water temperature after this time, some of the ethylene liquid transitioned to vapor. By warming the reactor walls with increased jacket water temperature and creating more ethylene vapor in the reactor, the pressure inside the reactor continued to increase.

A.7.9.13 7:26 a.m.

Board Operator 1 closed the control valve that injected steam into the jacket water supply from 40 to 30 percent open to reduce the heating of the jacket water system. The jacket water temperature was 62°F, and the reactor pressure was 532 psi.

A.7.9.14 7:30 a.m.

The pressure inside EVAL Reactor 2 was 539 psi, the reactor liquid temperature was 28°F, and the liquid level was 12 percent.

Between 7:00 a.m. and 7:30 a.m., the control system event log recorded 27 alarms.

A.7.9.15 7:37 a.m.

Kuraray operations personnel were troubleshooting to find out why they could not get the inventory of methanol from the methanol flush inside EVAL Reactor 2 to flow from the reactor to downstream equipment. During this troubleshooting, Board Operator 1 manually activated the EVAL Reactor 2 High-High-Pressure safety interlock. Although activating this interlock was not successful in getting liquid to flow from the reactor to downstream equipment, the interlock activation fully opened (100 percent open) the chilled liquid temperature control valve (**Figure 10**), establishing chilled liquid flow through the heat exchanger and allowing some ethylene vapor to condense to a liquid.

A.7.9.16 7:41 a.m.

Board Operator 1 opened the control valve that injected steam into the jacket water supply from 0 to 35 percent open to increase the jacket water temperature. The jacket water temperature was 64°F, and the reactor pressure was 529 psi.

Using a physical switch on the panel board, Board Operator 1 turned the High-High-Pressure safety interlock to the "off" position. This panel board switch allowed Kuraray operators to put the interlock in three positions—on, off, and manual activation of the interlock. As the startup continued, this interlock was not turned back on. With this safety interlock off, the chilled liquid temperature control valve did not automatically open when the pressure inside the EVAL Reactor 2 reached the High-High-Pressure alarm condition of 640 psi.

The EVAL Reactor 2 startup continued, despite this safety interlock being disabled.

A.7.9.17 7:45 a.m.

The pressure inside EVAL Reactor 2 was 514 psi, the reactor liquid temperature was 26°F, and the liquid level was 12 percent.

A.7.9.18 7:49 a.m.

Kuraray operations personnel identified the problem that had been preventing liquid from flowing from EVAL Reactor 2 to downstream equipment. A valve misalignment (a closed manual valve that needed to be open) was found. Kuraray operators opened the misaligned valve, and liquid began flowing from the bottom of EVAL Reactor 2 to downstream equipment. After this point, some of the decreases in the reactor's liquid level can be attributed to liquid flowing out of the reactor.

A.7.9.19 7:53 a.m.

Board Operator 1 opened the pressure control valve that supplied ethylene to the reactor from 0 to 10 percent open to increase the flow of ethylene. The reactor pressure was 504 psi.

A.7.9.20 7:54 a.m.

Board Operator 1 closed the pressure control valve that supplied ethylene to the reactor from 10 to 5 percent open to reduce the flow of ethylene. The reactor pressure was 503 psi.

Board Operator 1 opened the control valve that injected steam into the jacket water supply from 35 to 40 percent open to increase the jacket water temperature. The jacket water temperature was 85°F.

A.7.9.21 7:55 a.m.

Board Operator 1 opened the control valve that injected steam into the jacket water supply from 40 to 45 percent open to increase the jacket water temperature. The jacket water temperature was 86°F, and the reactor pressure was 502 psi.

A.7.9.22 8:00 a.m.

The pressure inside EVAL Reactor 2 was 501 psi, the reactor liquid temperature was 23°F, and the liquid level was 12 percent.

Between 7:30 a.m. and 8:00 a.m., the control system event log recorded 56 alarms.

A.7.9.23 8:05 a.m.

Board Operator 1 opened the control valve that injected steam into the jacket water supply from 45 to 50 percent open to increase the jacket water temperature. The jacket water temperature was 98°F, and the reactor pressure was 501 psi.

A.7.9.24 8:15 a.m.

The pressure inside EVAL Reactor 2 was 508 psi, the reactor liquid temperature was 24°F, and the liquid level was 12 percent.

A.7.9.25 8:21 a.m.

Board Operator 1 opened the control valve that injected steam into the jacket water supply from 50 to 60 percent open to increase the jacket water temperature (**Figure 11**). The jacket water temperature was 115°F, and the reactor pressure was 513 psi.

A.7.9.26 8:30 a.m.

The pressure inside EVAL Reactor 2 was 520 psi, the reactor liquid temperature was 25°F, and the liquid level was 12 percent.

Between 8:00 a.m. and 8:30 a.m., the control system event log recorded 79 alarms.

A.7.9.27 8:31 a.m.

Board Operator 1 closed the chilled liquid temperature control valve (**Figure 10**).

A.7.9.28 8:39 a.m.

Board Operator 1 closed the control valve that injected steam into the jacket water supply from 60 to 50 percent open to decrease the jacket water temperature. The jacket water temperature was 131°F, and the reactor pressure reached 569 psi.

A.7.9.29 8:44 a.m.

At 596 psi, the pressure inside EVAL Reactor 2 reached the targeted operating pressure of 595 psi per the nightly operating instructions Kuraray management issued on May 17, 2018.

A.7.9.30 8:45 a.m.

The pressure inside EVAL Reactor 2 was 601 psi, the reactor liquid temperature was 46°F, and the liquid level was 11 percent.

A.7.9.31 8:46 a.m.

Board Operator 1 closed the pressure control valve that supplied ethylene to the reactor from 5 to 0 percent open to stop the flow of ethylene (**Figure 6**). The jacket water temperature was 127°F, and the pressure inside the reactor was 606 psi. After this point, the ethylene pressure control valve remained closed for the duration of the incident. No more ethylene was added to the system. After Board Operator 1 closed the ethylene pressure control valve, the continually increasing pressure inside EVAL Reactor 2 resulted from increasing the jacket water temperature and not directing enough vapor from the reactor to the flare.

A.7.9.32 8:48 a.m.

Board Operator 1 switched the operating mode for the reactor pressure control valve (**Figure 12**) that sends reactor vapor to the flare from automatic to manual. The reactor pressure was 613 psi.

Board Operator 1 opened the pressure control valve from 0 to 20 percent open to send reactor vapor to the flare.

A.7.9.33 8:51 a.m.

The High-Pressure alarm for the ethylene pressure control valve to the reactor was activated at 620 psi. The ethylene supply pressure control valve remained closed (0 percent open), and the pressure control valve that sends reactor vapor to the flare remained at 20 percent open. The jacket water temperature was 120°F.

A.7.9.34 8:53 a.m.

The High-Pressure alarm for the ethylene pressure control valve to the reactor was acknowledged.

A.7.9.35 8:54 a.m.

Board Operator 1 opened the pressure control valve from 20 to 50 percent open to send more reactor vapor to the flare. The pressure inside the reactor was 630 psi.

A.7.9.36 8:56 a.m.

Board Operator 1 opened the pressure control valve from 50 to 60 percent open to send more reactor vapor to the flare. The pressure inside the reactor was 634 psi.

Board Operator 1 closed the control valve that injected steam into the jacket water supply from 50 to 35 percent open to decrease the jacket water temperature. The jacket water temperature was 119°F.

A.7.9.37 9:00 a.m.

The pressure inside EVAL Reactor 2 was 639 psi, the reactor liquid temperature was 63°F, and the liquid level was 11 percent.

Between 8:30 a.m. and 9:00 a.m., the control system event log recorded 156 alarms.

A.7.9.38 9:01 a.m.

The High-High-Pressure alarm for the ethylene pressure control system to the reactor was activated at 640 psi.

A.7.9.39 9:02 a.m.

Control system records show that the High-High-Pressure alarm for the ethylene pressure control system to the reactor was acknowledged.

A.7.9.40 9:03 a.m.

Board Operator 1 opened the pressure control valve from 60 to 80 percent open to send more reactor vapor to the flare. The pressure inside the reactor was 646 psi, and the jacket water temperature was 116°F.

A.7.9.41 9:10 a.m.

Board Operator 1 opened the control valve that injected steam into the jacket water supply from 35 to 45 percent open to increase the jacket water temperature. The jacket water temperature was 119°F, and the pressure inside the reactor was 652 psi.

A.7.9.42 9:11 a.m.

The pressure inside EVAL Reactor 2 exceeded the ethylene supply pressure. Further pressure increases inside EVAL Reactor 2 from this point forward are likely the result of vaporizing liquid ethylene and further heating of the ethylene vapor.

A.7.9.43 9:12 a.m.

Board Operator 1 opened the pressure control valve from 80 to 100 percent open to send more reactor vapor to the flare. The jacket water temperature was 123°F, and the pressure inside the reactor was 654 psi.

A.7.9.44 9:13 a.m.

Board Operator 1 closed the pressure control valve from 100 to 50 percent open to reduce the flow of reactor vapor to the flare. The pressure control valve was fully open (100 percent open) for 45 seconds. The pressure inside the reactor was 654 psi, and the jacket water temperature was 124°F.

A.7.9.45 9:15 a.m.

The control system activated the high VOC flare alarm and was acknowledged. The pressure inside EVAL Reactor 2 was 658 psi, the reactor liquid temperature was 72°F, and the liquid level was 10 percent.

A.7.9.46 9:18 a.m.

Board Operator 1 opened the pressure control valve from 50 to 80 percent open to send more reactor vapor to the flare. The pressure inside the reactor was 663 psi, and the jacket water temperature was 130°F.

A.7.9.47 9:22 a.m.

Board Operator 1 closed the pressure control valve from 80 to 60 percent open to reduce the flow of reactor vapor to the flare.

Board Operator 1 closed the pressure control valve from 60 to 50 percent open to reduce the flow of reactor vapor to the flare.

Board Operator 1 raised the setpoint for the reactor EVAL Reactor 2 pressure control valve from 650 to 700. The pressure inside EVAL Reactor 2 was 667 psi, and the jacket water temperature was 131°F.

A.7.9.48 9:27 a.m.

Board Operator 1 closed the pressure control valve from 50 to 30 percent open to reduce the flow of reactor vapor to the flare. The pressure inside the reactor was 674 psi, and the jacket water temperature was 129°F.

A.7.9.49 9:29 a.m.

Board Operator 1 closed the pressure control valve from 30 to 0 percent open to stop the flow of reactor vapor to the flare. The pressure inside the reactor was 677 psi, and the jacket water temperature was 128°F.

A.7.9.50 9:30 a.m.

The pressure inside EVAL Reactor 2 was 679 psi, the reactor liquid temperature was 82°F, and the liquid level was 10 percent.

Between 9:00 a.m. and 9:30 a.m., the control system event log recorded 137 alarms.

A.7.9.51 9:31 a.m.

Board Operator 1 closed the control valve that injected steam into the jacket water supply from 45 to 35 percent open to decrease the jacket water temperature. The jacket water temperature was 127°F, and the pressure inside the reactor was 680 psi.

A.7.9.52 9:45 a.m.

The pressure inside EVAL Reactor 2 was 692 psi, the reactor liquid temperature was 88°F, and the liquid level was 10 percent.

A.7.9.53 9:55 a.m.

Board Operator 1 opened the pressure control valve from 0 to 30 percent open to send more reactor vapor to the flare. The pressure inside the reactor was 699 psi, and the jacket water temperature was 126°F.

A.7.9.54 9:58 a.m.

Board Operator 1 closed the pressure control valve from 30 to 0 percent open to stop the flow of reactor vapor to the flare. The pressure inside EVAL Reactor 2 reached 700 psi. The jacket water temperature was 126°F.

A.7.9.55 10:00 a.m.

The pressure inside EVAL Reactor 2 was 701 psi, the reactor liquid temperature was 93°F, and the liquid level was 10 percent.

Between 9:30 a.m. and 10:00 a.m., the control system event log recorded 48 alarms.

A.7.9.56 10:02 a.m.

The control system displayed a visual operating guideline message stating, “High Flare VOC Emissions Reduce, Reduce Purging.” Kuraray used this instruction to direct operators to reduce the flow of ethylene to the flare to prevent exceeding its environmental permit limit. The pressure inside the reactor was 702 psi, and the jacket water temperature was 126°F.

A.7.9.57 10:03 a.m.

Board Operator 1 opened the pressure control valve from 0 to 30 percent open to send more reactor vapor to the flare. The pressure inside the reactor was 702 psi, and the jacket water temperature was 126°F.

Board Operator 1 closed the control valve that injected steam into the jacket water supply from 35 to 30 percent open to decrease the jacket water temperature (**Figure 11**). After this point, the steam flow to the jacket water supply was not adjusted for the duration of the incident.

A.7.9.58 10:05 a.m.

Supervisor 1 asked Board Operator 2 to take control of EVAL Reactor 2 from Board Operator 1. Board Operator 1 continued focusing on starting up the distillation column, and Board Operator 2 focused on performing the flush batch for EVAL Reactor 2. Kuraray had not begun any of the flush batch startup procedure steps. The reactor still held a 9.6 percent liquid level that likely included methanol and water from the methanol flush. The pressure inside EVAL Reactor 2 was 703 psi.

A.7.9.59 10:07 a.m.

Kuraray operators stopped flowing liquid from the bottom of EVAL Reactor 2 to downstream equipment. The reactor liquid level in EVAL Reactor 2 was 9.5 percent.

A.7.9.60 10:10 a.m.

Board Operator 2 began using the control system in preparing to start the flush batch for EVAL Reactor 2. The pressure inside the reactor was 705 psi, and the jacket water temperature was 124°F.

A.7.9.61 10:15 a.m.

Board Operator 2 opened the pressure control valve from 30 to 35 percent open to send more reactor vapor to the flare. The pressure inside the reactor was 708 psi, and the jacket water temperature was 124°F.

Thirty-six seconds later, Board Operator 2 closed the pressure control valve from 35 to 0 percent open to stop the flow of reactor vapor to the flare.

The pressure inside EVAL Reactor 2 was 708 psi, the reactor liquid temperature was 97°F, and the liquid level was 9 percent.

A.7.9.62 10:17 a.m.

The control system displayed a visual operating guideline message stating, "High Flare VOC Emissions Reduce, Reduce Purging." Kuraray used this instruction to direct operators to reduce the flow of ethylene to the flare to prevent exceeding their environmental permit limit.

The pressure inside the reactor was 709 psi, and the jacket water temperature was 124°F.

A.7.9.63 10:26 a.m.

Board Operator 2 opened the pressure control valve from 0 to 45 percent open to send more reactor vapor to the flare (**Figure 12**). The pressure inside the reactor was 716 psi, and the jacket water temperature was 125°F.

A.7.9.64 10:28 a.m.

The pressure inside EVAL Reactor 2 was 719 psi. The rupture disc burst and the emergency pressure-relief valve lifted, discharging ethylene into the air through horizontally aimed piping. The jacket water temperature was 125°F.

An operating welding machine sitting on the bed of a pickup truck (**Figure 16**) likely ignited the ethylene vapor.

Workers in the immediate area of the ethylene release and fire urgently tried to evacuate from the area. In doing so, some workers were injured as they jumped from the second or third story of the plant structure and ran or otherwise exited the area, tripping and falling or suffering sprains along the way. Kuraray reported that the incident injured a total of 23 workers [12].

Between 10:00 a.m. and 10:28 a.m., the control system event log recorded 49 alarms.

A.7.9.65 10:29 a.m.

Board Operator 2 fully opened (100 percent open) the pressure control valve to send more reactor vapor to the flare. Also, Supervisor 1 instructed Board Operator 2 to open the emergency open valve to maximize the flow of reactor vapor directed to the flare (**Figure 13**). The pressure inside the reactor was 686 psi. Most of the ethylene discharged into the air was burning.

A.7.9.66 10:30 a.m.

The pressure inside EVAL Reactor 2 was 588 psi, the reactor liquid temperature was 98°F, and the liquid level was 8 percent.

A.7.9.67 10:31 a.m.

Enough ethylene vapor was released to reduce the pressure inside EVAL Reactor 2, allowing the spring-loaded emergency pressure-relief valve to close and extinguish the fire.

Appendix B: Third-Party Audit[a]

The CSB modeled its recommendation for Kuraray to perform an independent third-party audit using January 13, 2017, RMP language. The CSB modified the EPA's regulatory language to retain the safety improvements of using an independent third party without the legal framework imposed by the requirements of a government regulatory agency. Because this safety recommendation focuses on improving Kuraray's overall safety management systems, the CSB is recommending that the third-party audit evaluate the company's program against both the PSM Standard and the RMP Rule.

(a) *Applicability*. Kuraray America, Inc. shall engage a third party to conduct an audit that evaluates conformance with the provisions of the PSM Standard and the RMP Rule.

(b) *Third-party auditors and auditing teams*. Kuraray America, Inc. shall either:

(1) Engage a third-party auditor meeting all of the competency and independence criteria in paragraph (c) of this section; or

(2) Assemble an auditing team led by a third-party auditor meeting all of the competency and independence criteria in paragraph (c) of this section. The team may include:

(i) Other employees of the third-party auditor firm meeting the independence criteria of paragraph (c)(2) of this section; and

(ii) Other personnel not employed by the third-party auditor firm, including facility personnel.

(c) *Third-party auditor qualifications*. Kuraray America, Inc. shall determine and document that the third-party auditor(s) meet the following competency and independence requirements:

(1) *Competency requirements*. The third-party auditor(s) shall be:

(i) Knowledgeable of the requirements of this part;

(ii) Experienced with the stationary source type and processes being audited and applicable recognized and generally accepted good engineering practices; and

(iii) Trained or certified in proper auditing techniques.

(2) *Independence requirements*. The third-party auditor(s) shall:

(i) Act impartially when performing all activities under this section;

(ii) Receive no financial benefit from the outcome of the audit, apart from payment for auditing services. For purposes of this paragraph, retired employees who otherwise satisfy the third-party auditor

[a] *See* https://www.govinfo.gov/content/pkg/FR-2017-01-13/pdf/2016-31426.pdf at pages 4700 through 4701.

independence criteria in this section may qualify as independent if their sole continuing financial attachments to Kuraray America, Inc. are employer-financed or managed retirement and/or health plans;

(iii) Not have conducted past research, development, design, construction services, or consulting for Kuraray America, Inc. within the last two years. An audit firm with personnel who, before working for the auditor, conducted research, development, design, construction, or consulting services for Kuraray America, Inc. within the last two years as an employee or contractor may meet the requirements of this subsection by ensuring such personnel do not participate in the audit, or manage or advise the audit team concerning the audit;

(iv) Not provide other business or consulting services to Kuraray America, Inc., including advice or assistance to implement the findings or recommendations in an audit report, for a period of at least two years following submission of the final audit report;

(v) Ensure that all third-party personnel involved in the audit sign and date a conflict-of-interest statement documenting that they meet the independence criteria of this paragraph; and

(vi) Ensure that all third-party personnel involved in the audit do not accept future employment with Kuraray America, Inc. for a period of at least two years following submission of the final audit report.

(3) The auditor shall have written policies and procedures to ensure that all personnel follow the competency and independence requirements of this section.

(d) *Third-party auditor responsibilities*. Kuraray America, Inc. shall ensure that the third-party auditor:

(1) Manages the audit and participates in audit initiation, design, implementation, and reporting;

(2) Determines appropriate roles and responsibilities for the audit team members based on the qualifications of each team member;

(3) Prepares the audit report and where there is a team, documents the full audit team's views in the final audit report;

(4) Certifies the final audit report and its contents as meeting the requirements of this section; and

(5) Provides a copy of the audit report to Kuraray America, Inc.

(e) *Audit report*. The audit report shall:

(1) Identify all persons participating on the audit team, including names, titles, employers and/or affiliations, and summaries of qualifications. For third-party auditors, include information demonstrating that the competency requirements in paragraph (c)(1) of this section are met;

(2) Describe or incorporate by reference the policies and procedures required under paragraph (c)(3) of this section;

(3) Document the auditor's evaluation for each covered process of Kuraray America, Inc.'s conformance with the PSM Standard and RMP Rule to determine whether the procedures and practices developed by Kuraray America, Inc. under the PSM Standard and RMP Rule are adequate and being followed;

(4) Document the findings of the audit, including any identified conformance or performance deficiencies;

(5) Summarize any significant revisions (if any) between draft and final versions of the report; and

(6) Include the following certification, signed and dated by the third-party auditor or third-party audit team member leading the audit:

I certify that this audit report was prepared under my direction or supervision in accordance with a system designed to assure that qualified personnel properly gather and evaluate the information upon which the audit is based. I further certify that the audit was conducted, and this report was prepared under the requirements of the PSM Standard and RMP Rule and all other applicable auditing, competency, independence, impartiality, and conflict of interest standards and protocols. Based on my personal knowledge and experience or an inquiry of personnel involved in the audit, the information submitted herein is true, accurate, and complete.

(f) *Third-party audit findings*

(1) *Findings response report*. Kuraray America, Inc. shall determine an appropriate response to each of the findings in the audit report and develop a findings response report that includes:

(i) A copy of the final audit report;

(ii) An appropriate response to each of the audit report findings;

(iii) A schedule for promptly addressing deficiencies; and

(iv) A certification, signed and dated by a senior corporate officer, or an official in an equivalent position, of Kuraray America, Inc., stating: I certify under penalty of law that I have engaged a third-party to perform or lead an audit team to conduct a third-party audit under the requirements the PSM standard and the RMP Rule, and that the attached audit report was received, reviewed, and responded to under my direction or supervision by qualified personnel. I further certify that appropriate responses to the findings have been identified, and deficiencies were corrected or are being corrected, consistent with the requirements of the PSM Standard and RMP Rule. Based on my personal knowledge and experience or an inquiry of personnel involved in evaluating the report findings and determining appropriate responses to the findings, the information submitted herein is true, accurate, and complete.

(2) *Schedule implementation*. Kuraray America, Inc. shall implement the schedule to address deficiencies identified in the audit findings response report in paragraph (f)(1)(iii) of this section and document the action taken to address each deficiency, along with the date completed.

(3) *Submission to the Board of Directors*. Kuraray America, Inc. shall provide a copy of each document required under paragraphs (f)(1) and (2) of this section, when completed, to Kuraray America, Inc.'s audit committee of the Board of Directors, or other comparable committee or individual, as appropriate.

Appendix C: Accident Map

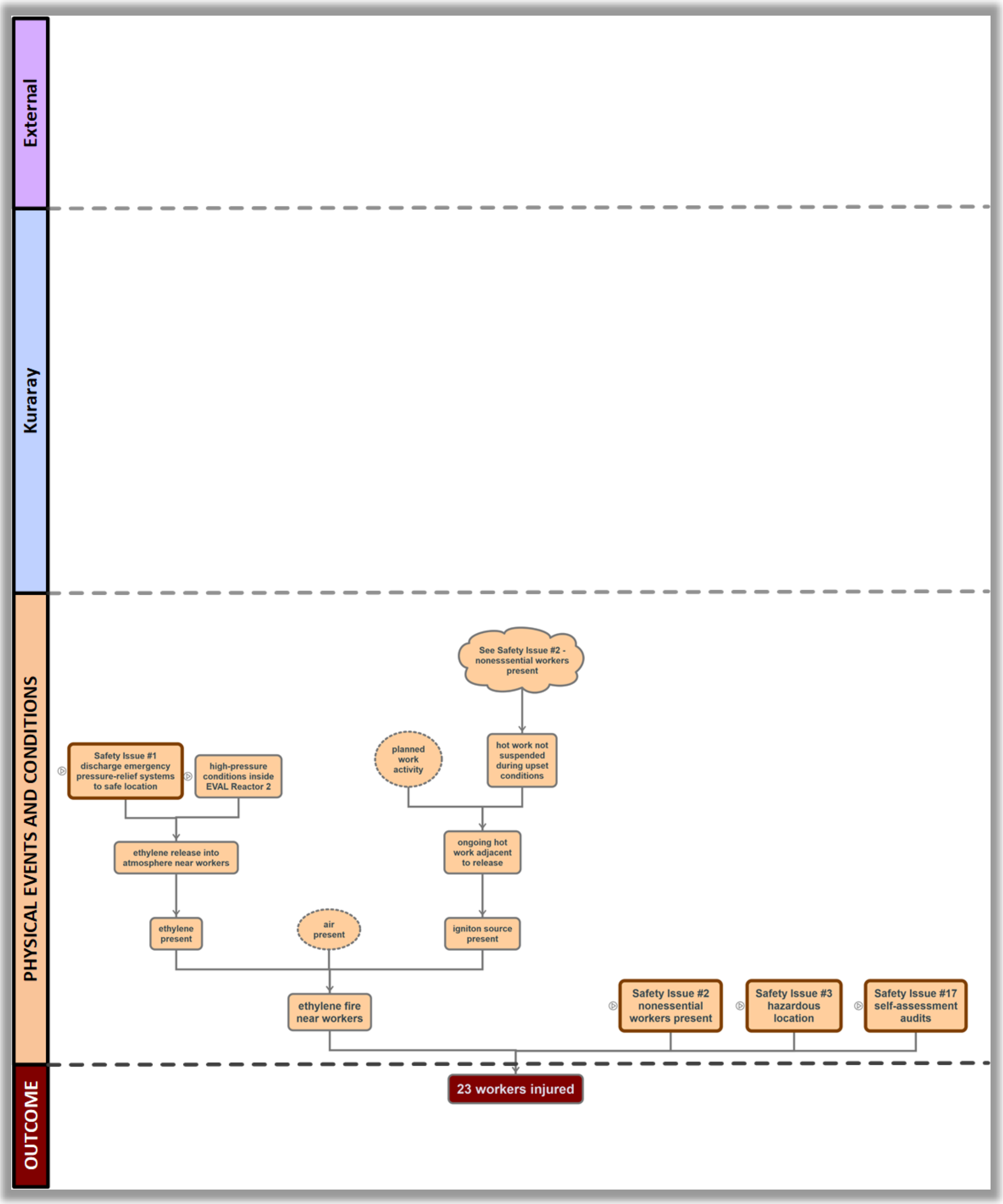

Figure 36. AcciMap part 1 of 19. (Credit: CSB)

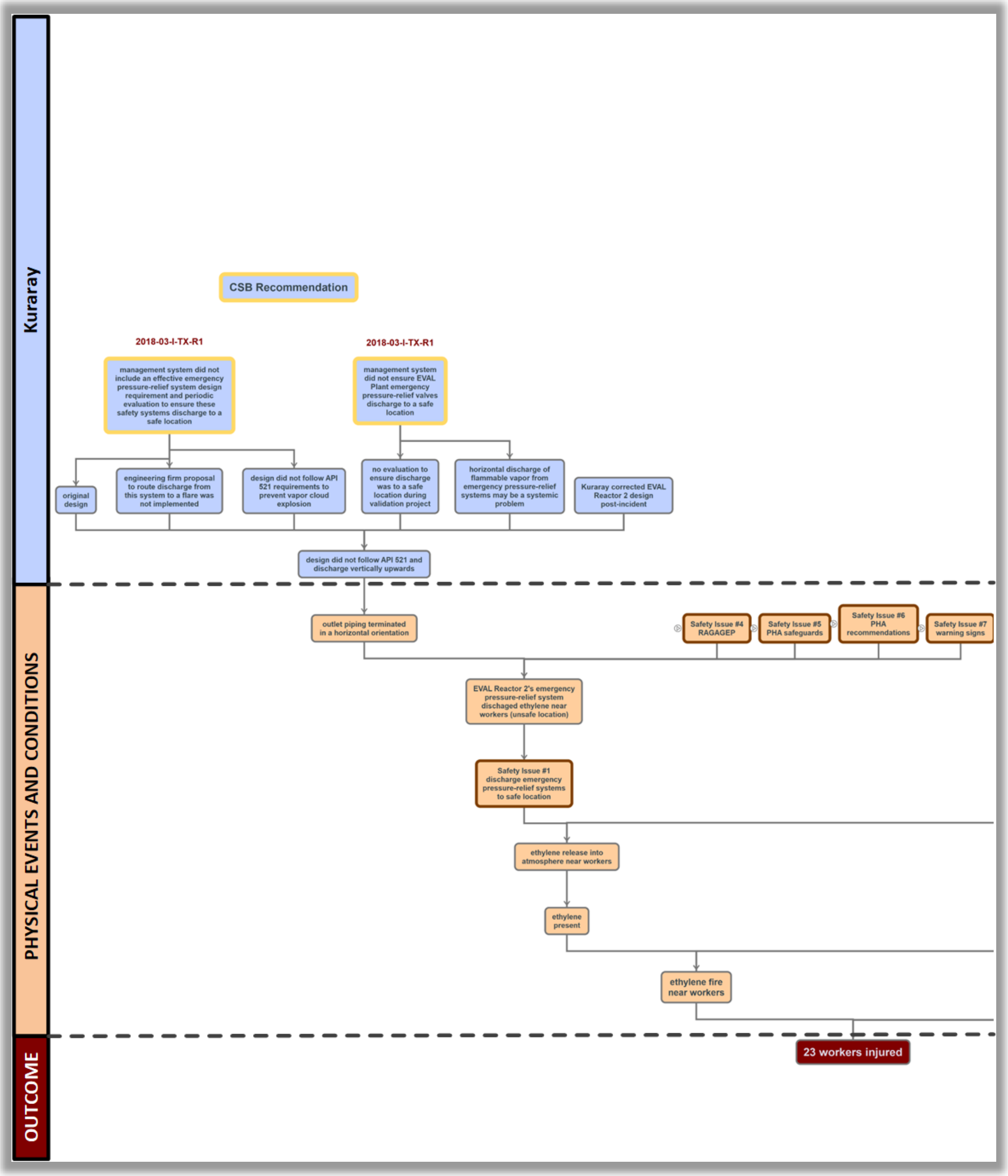

Figure 37. AcciMap part 2 of 19, Safety Issue #1. (Credit: CSB)

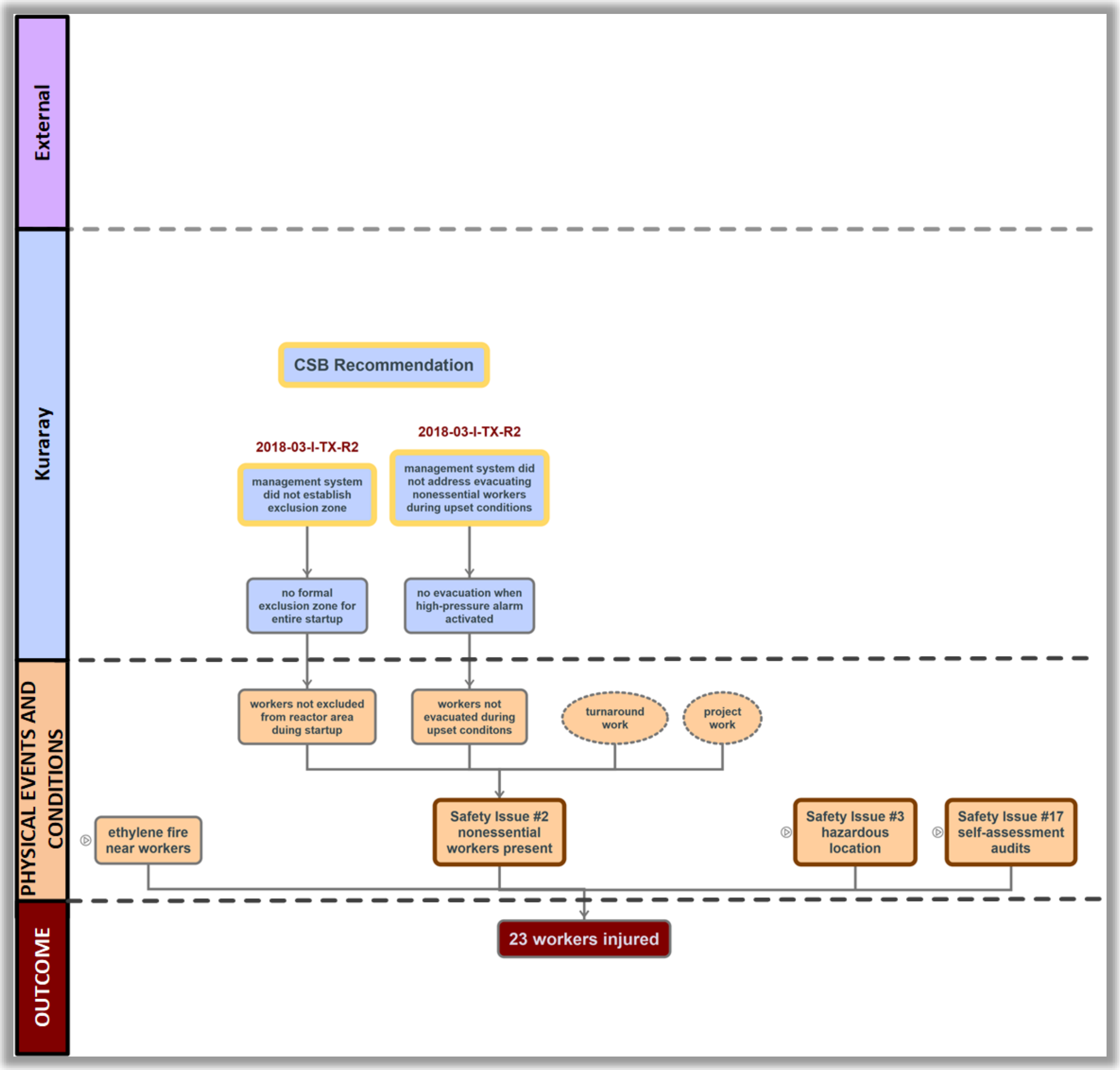

Figure 38. AcciMap part 3 of 19, Safety Issue #2. (Credit: CSB)

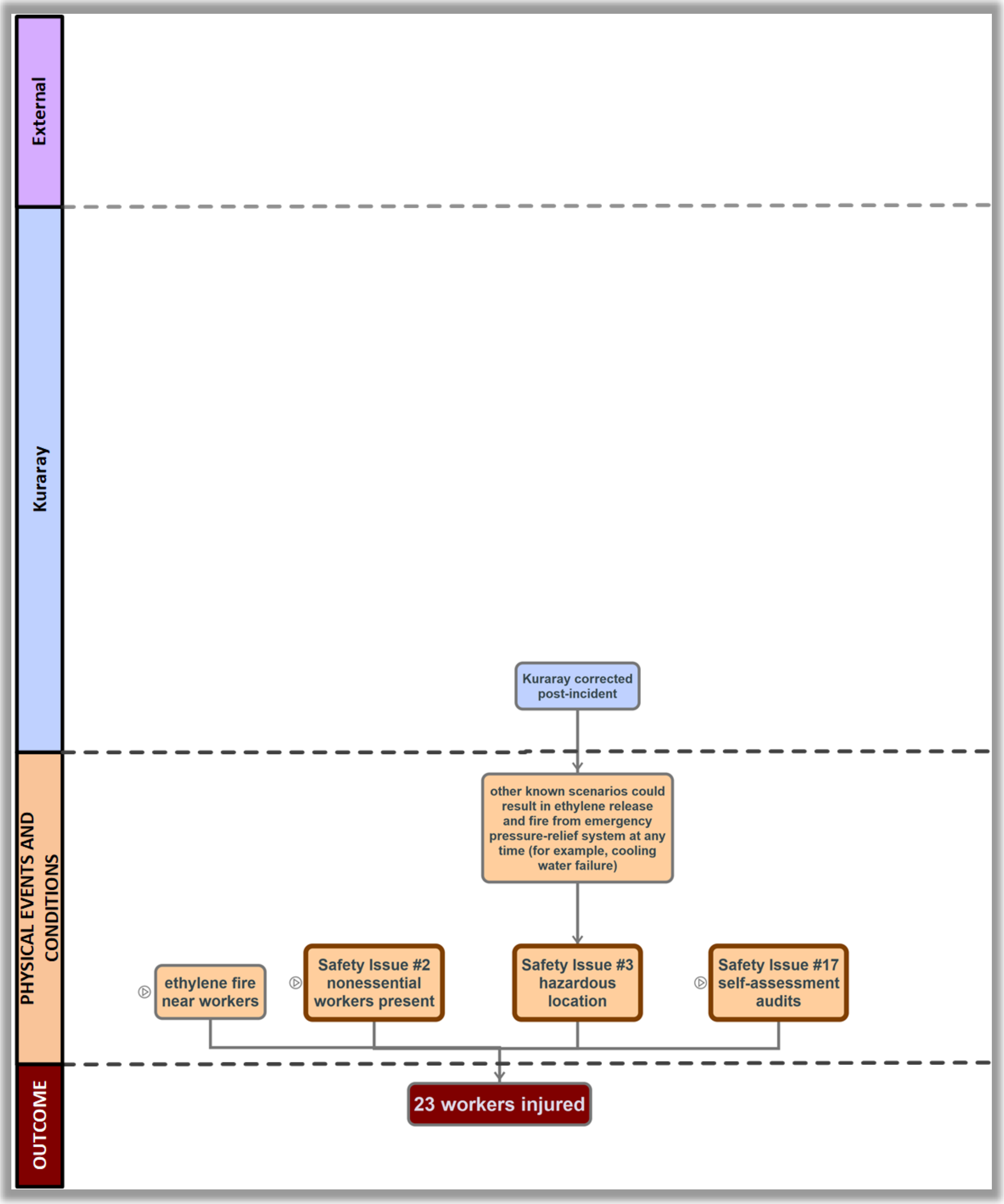

Figure 39. AcciMap part 4 of 19, Safety Issue #3. (Credit: CSB)

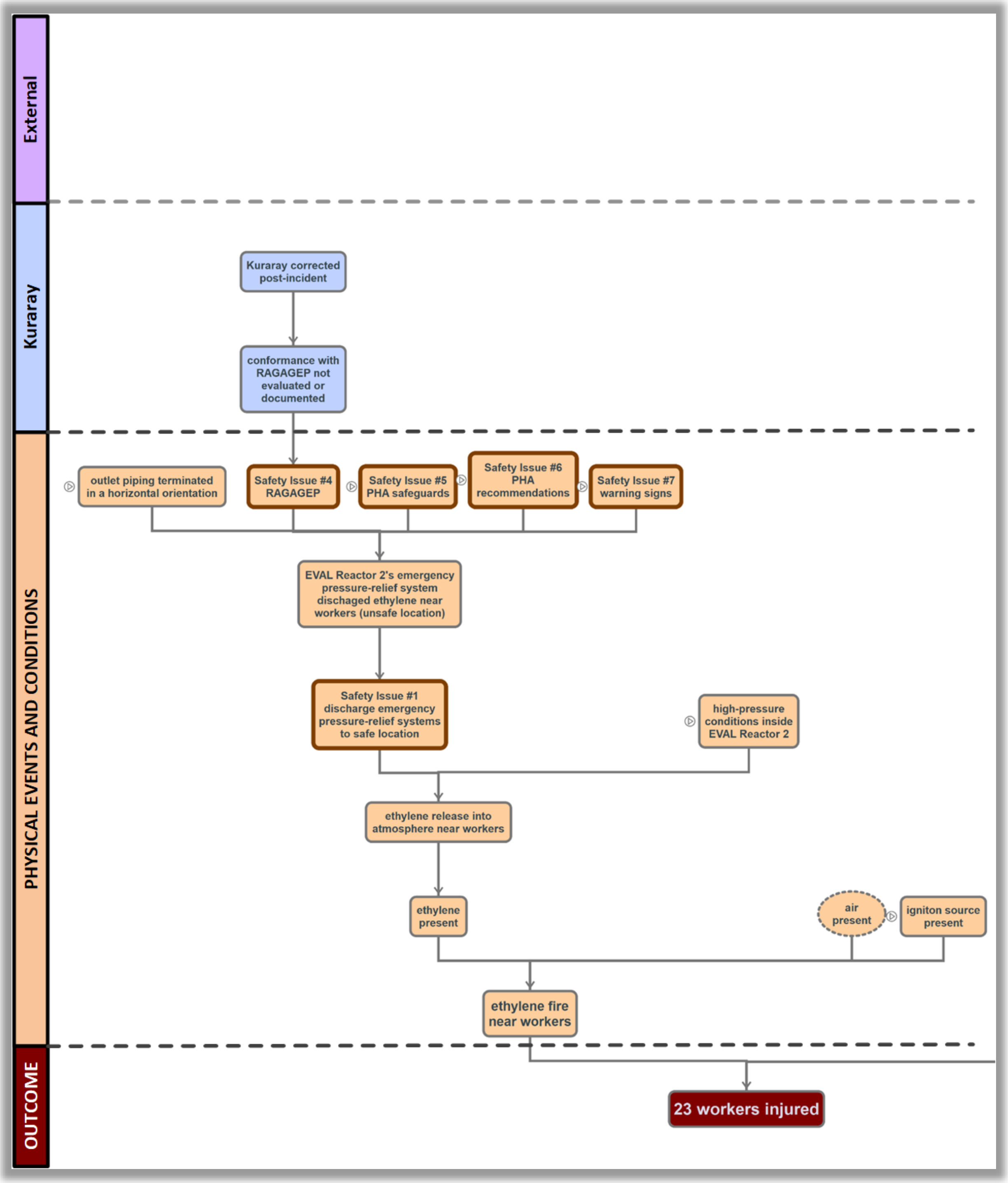

Figure 40. AcciMap part 5 of 19, Safety Issue #4. (Credit: CSB)

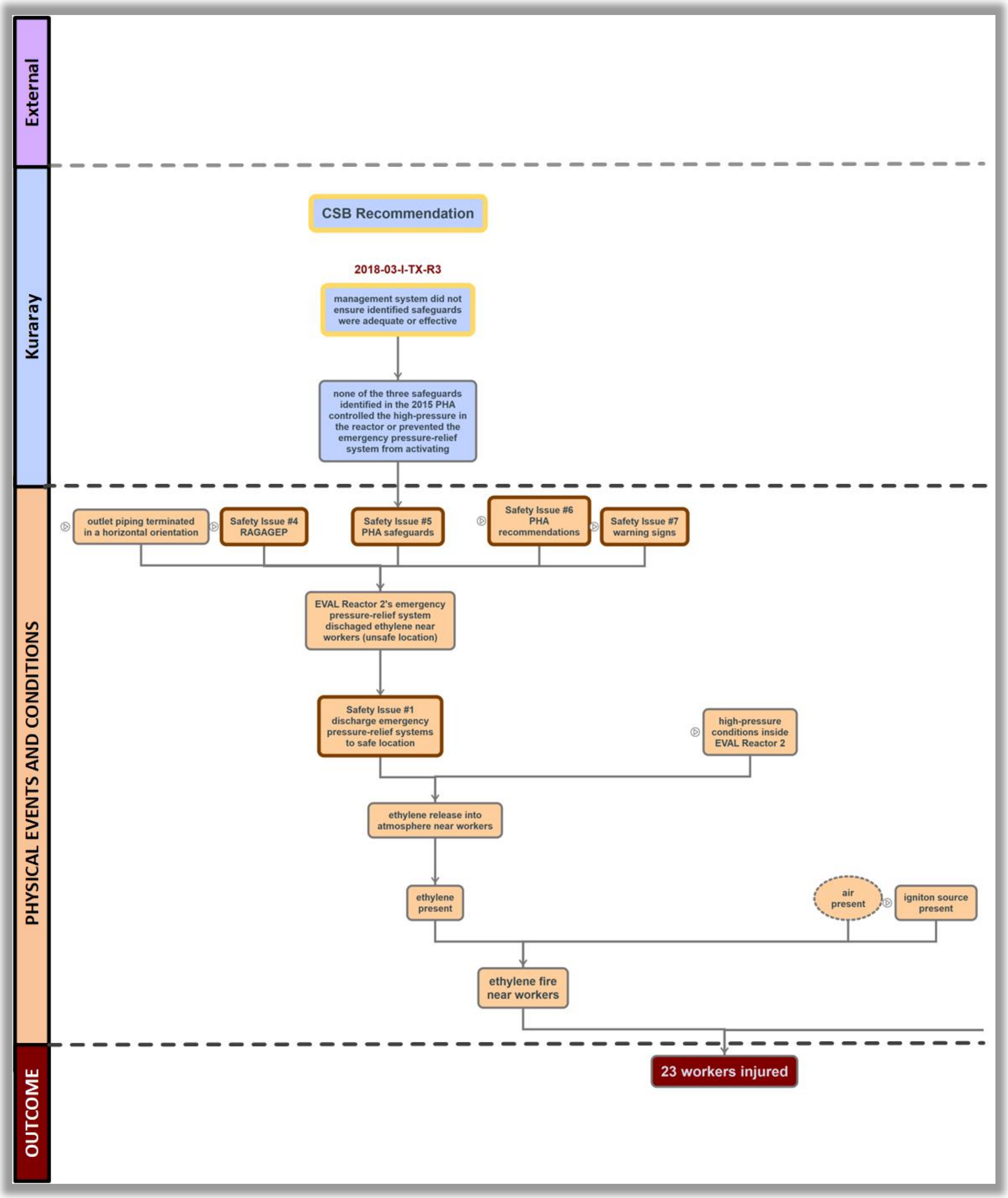

Figure 41. AcciMap part 6 of 19, Safety Issue #5. (Credit: CSB)

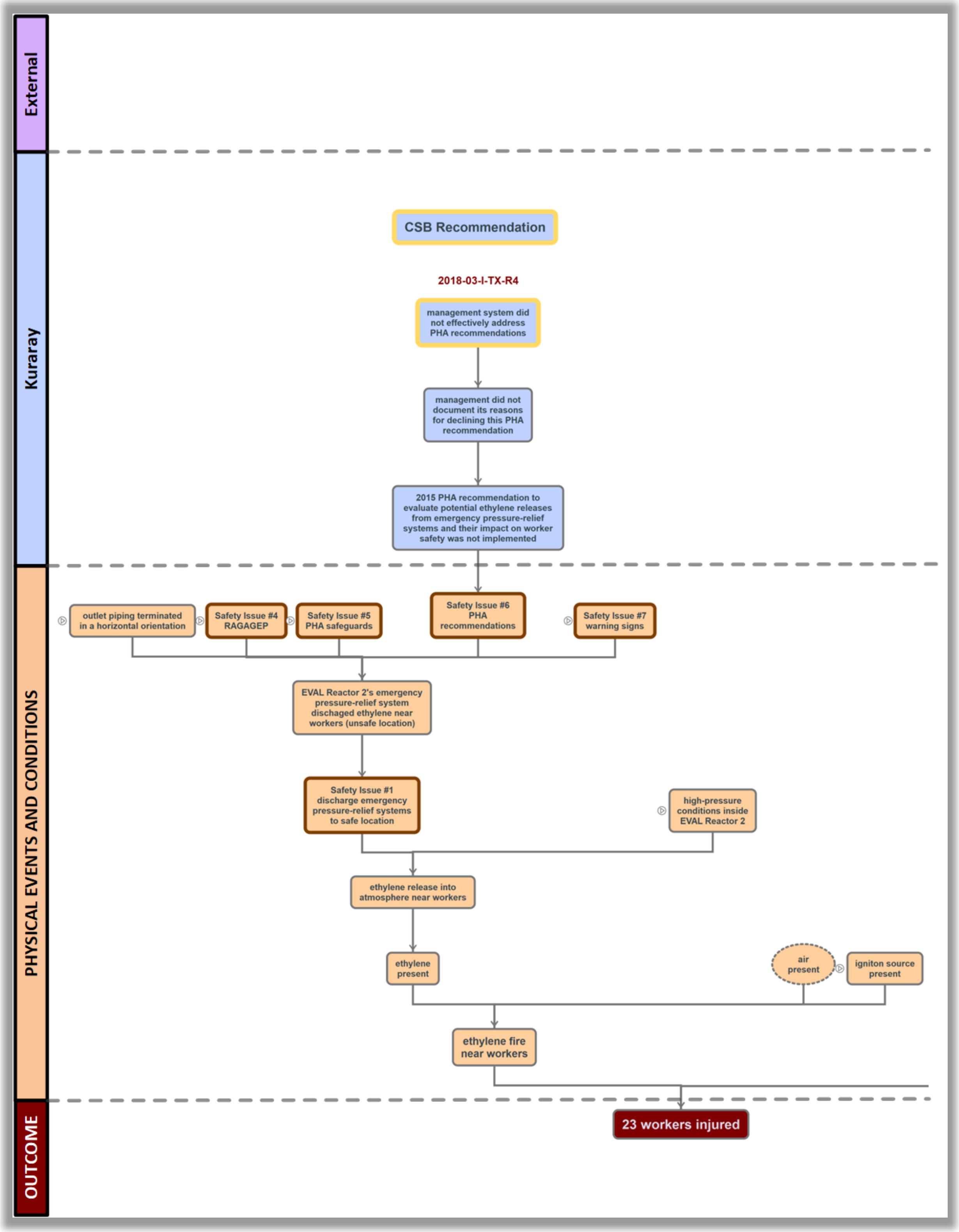

Figure 42. AcciMap part 7 of 19, Safety Issue #6. (Credit: CSB)

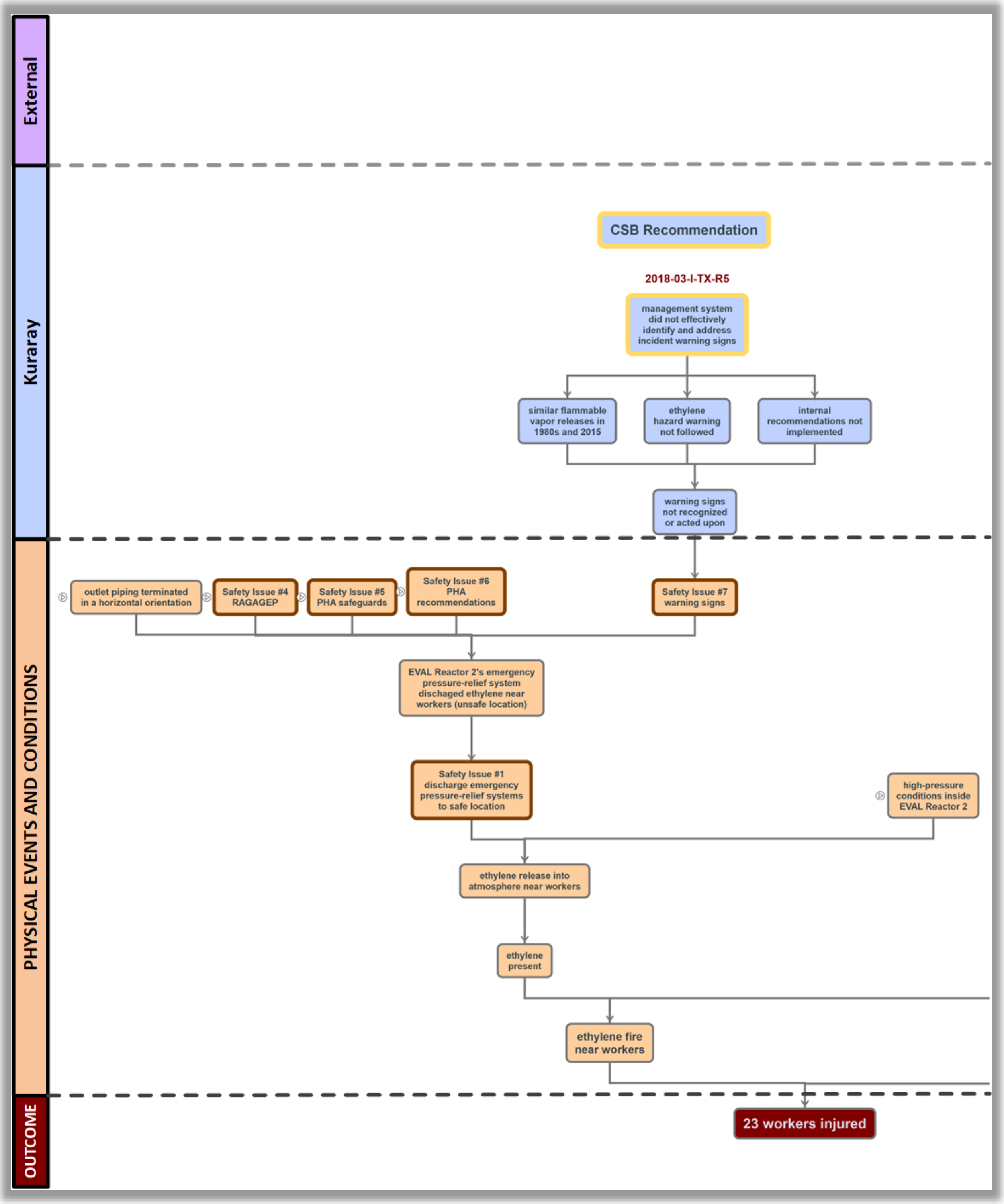

Figure 43. AcciMap part 8 of 19, Safety Issue #7. (Credit: CSB)

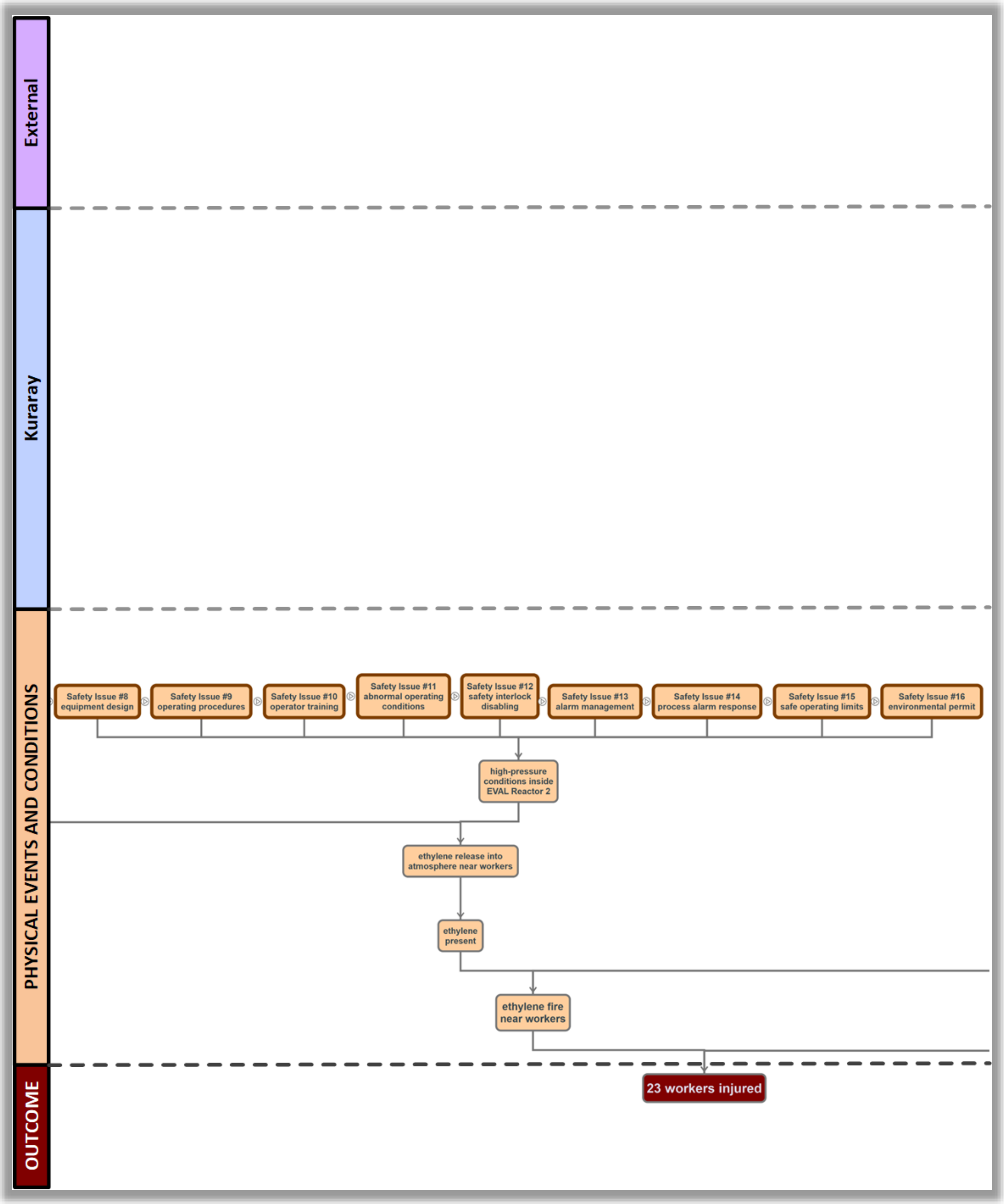

Figure 44. AcciMap part 9 of 19, safety issues #8 through #16. (Credit: CSB)

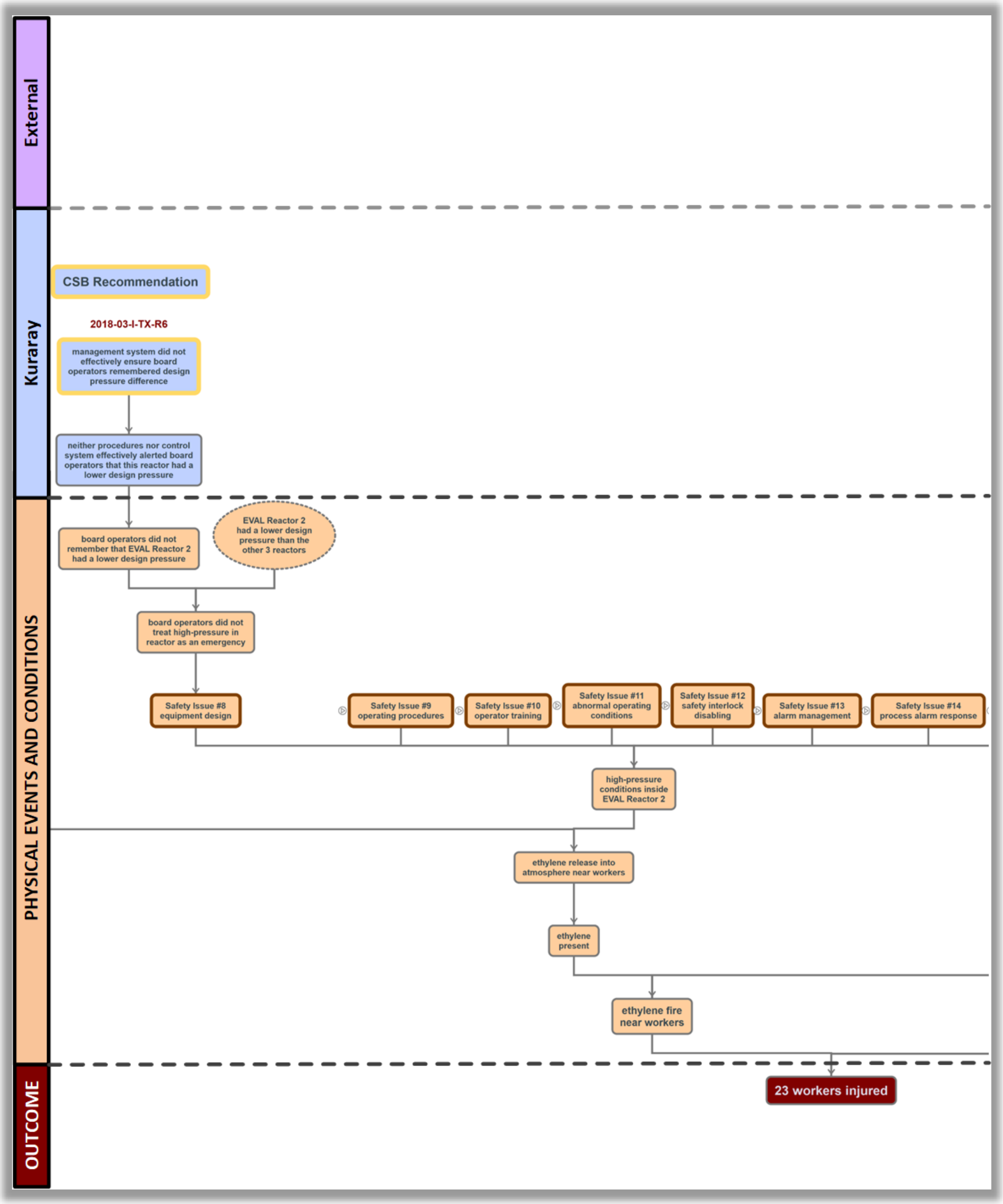

Figure 45. AcciMap part 10 of 19, Safety Issue #8. (Credit: CSB)

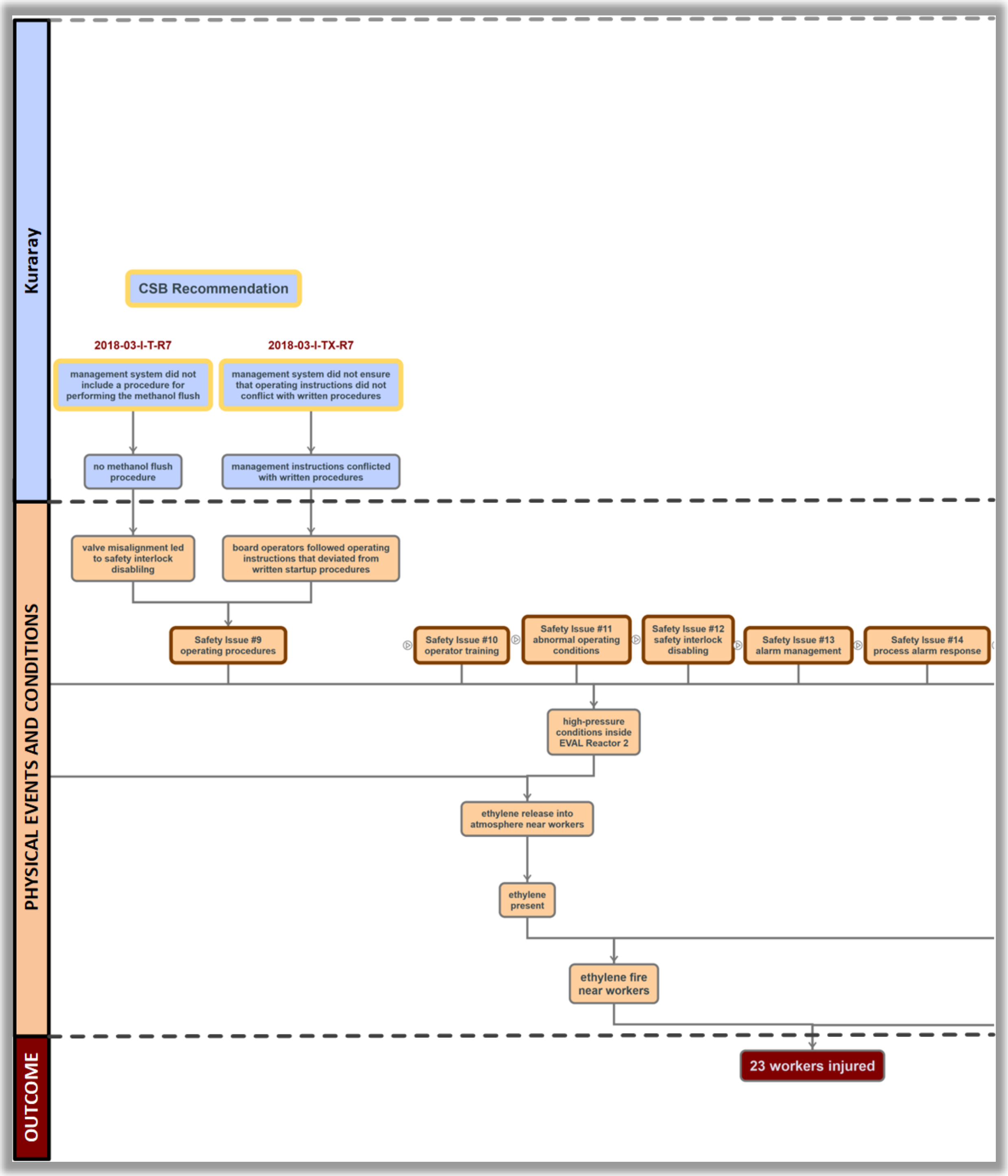

Figure 46. AcciMap part 11 of 19, Safety Issue #9. (Credit: CSB)

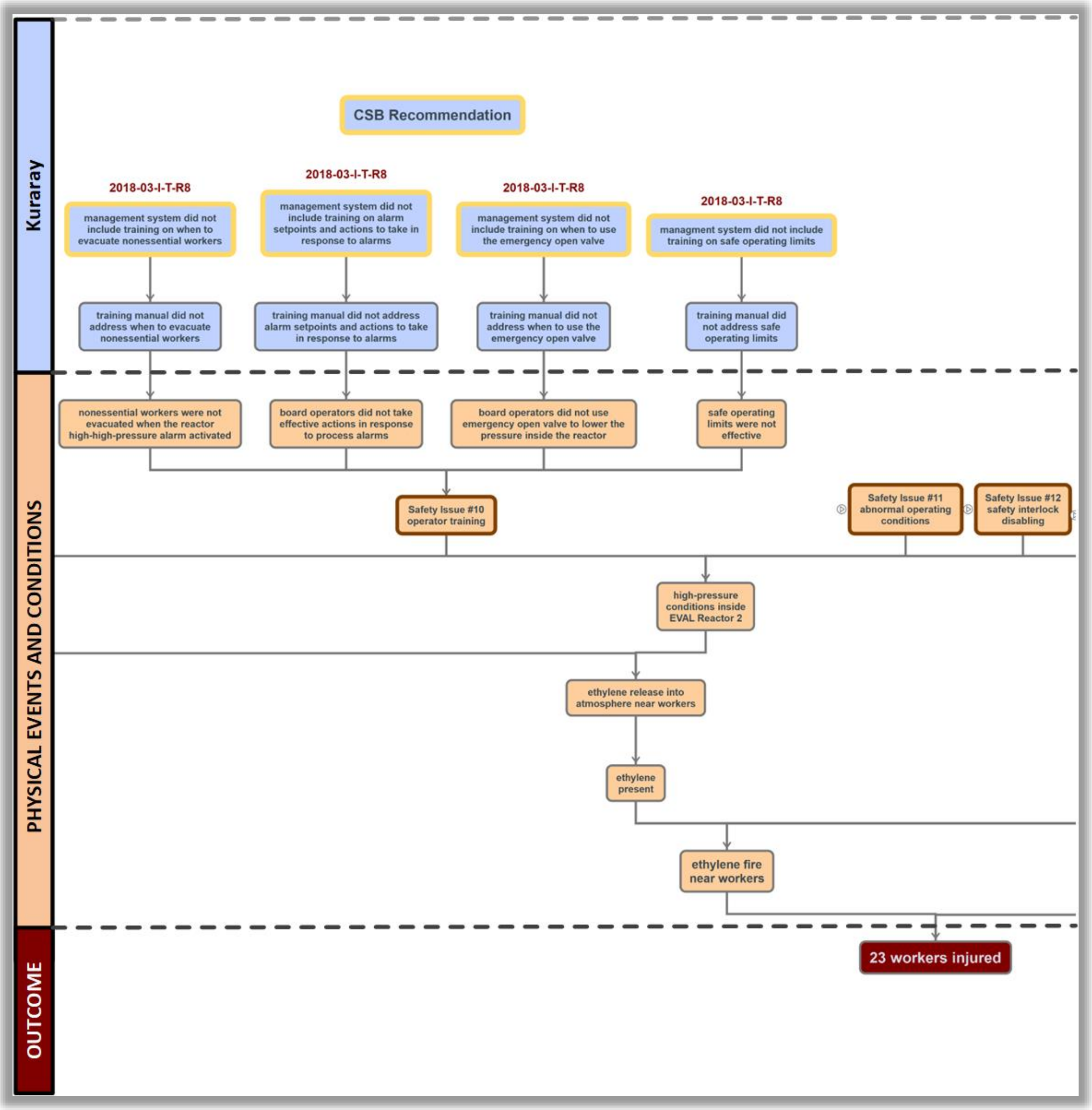

Figure 47. AcciMap part 12 of 19, Safety Issue #10. (Credit: CSB)

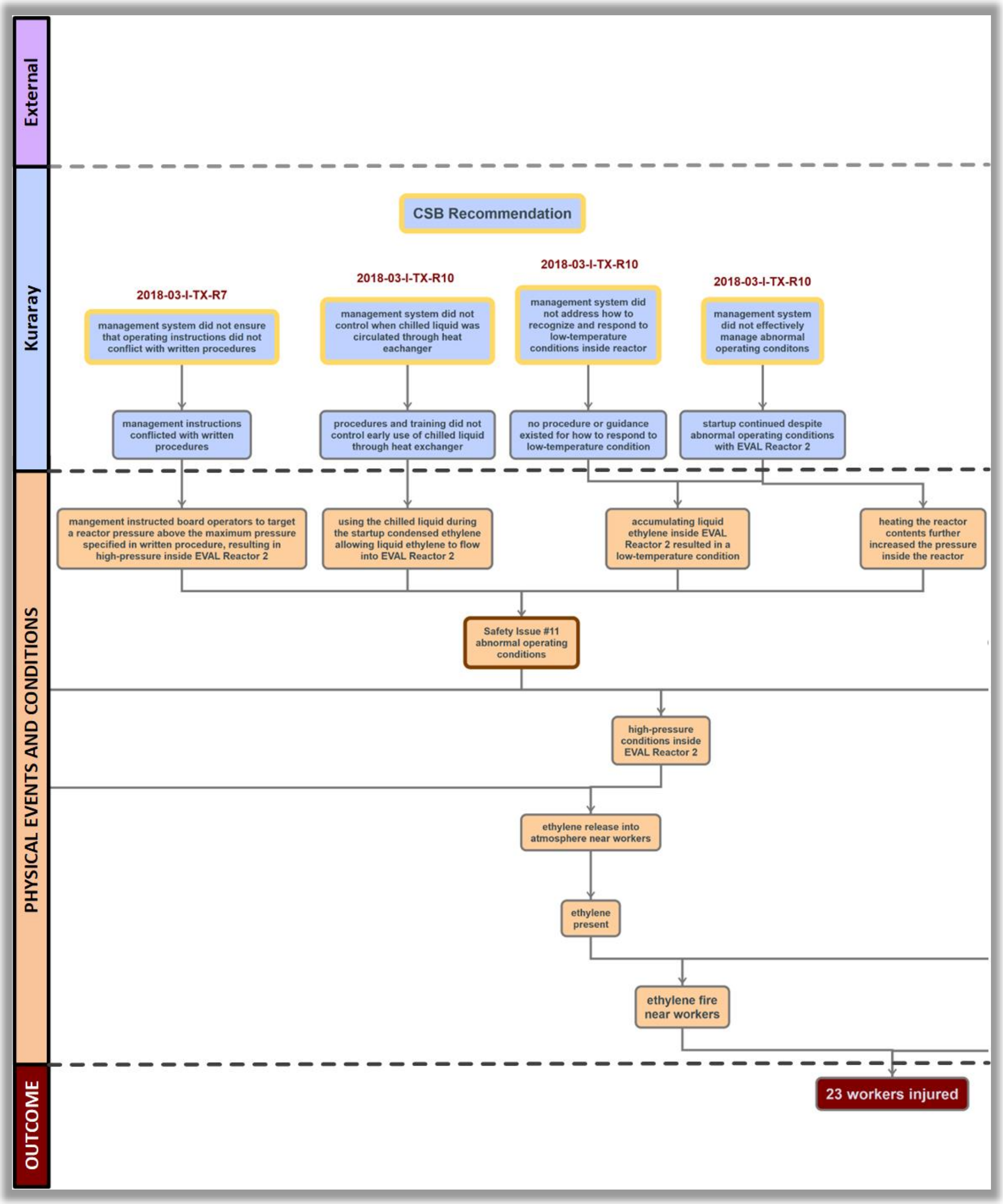

Figure 48. AcciMap part 13 of 19, Safety Issue #11. (Credit: CSB)

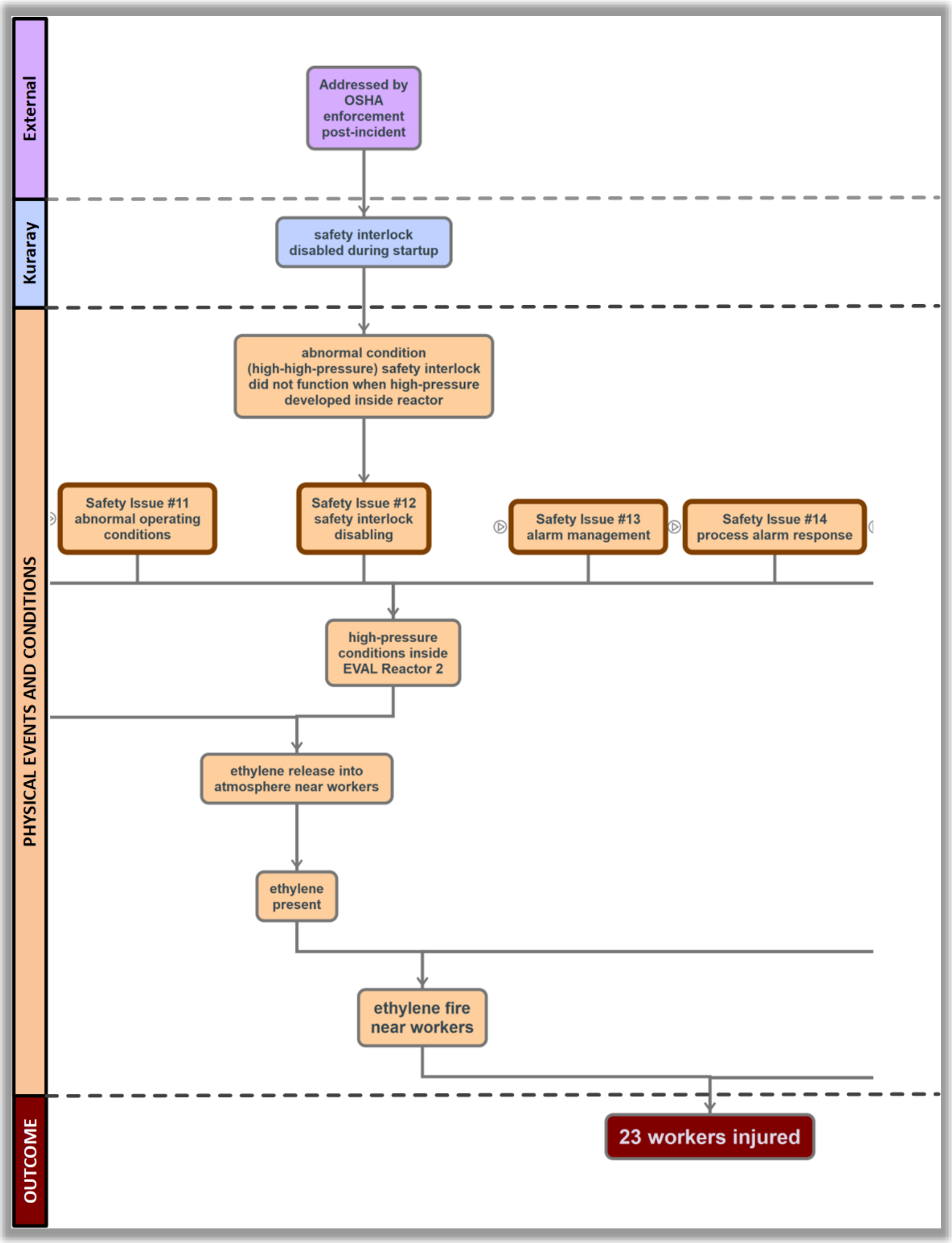

Figure 49. AcciMap part 14 of 19, Safety Issue #12. (Credit: CSB)

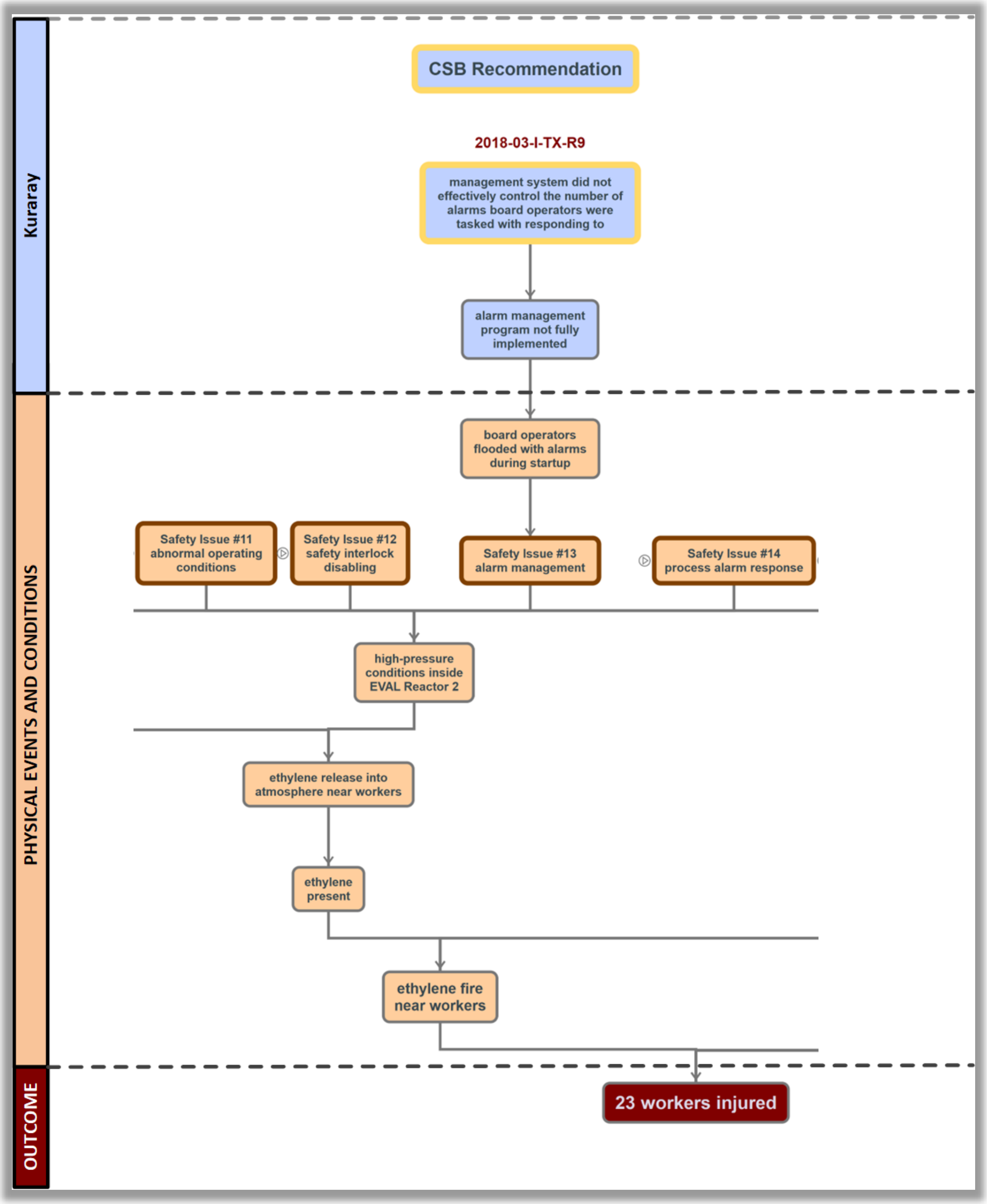

Figure 50. AcciMap part 15 of 19, Safety Issue #13. (Credit: CSB)

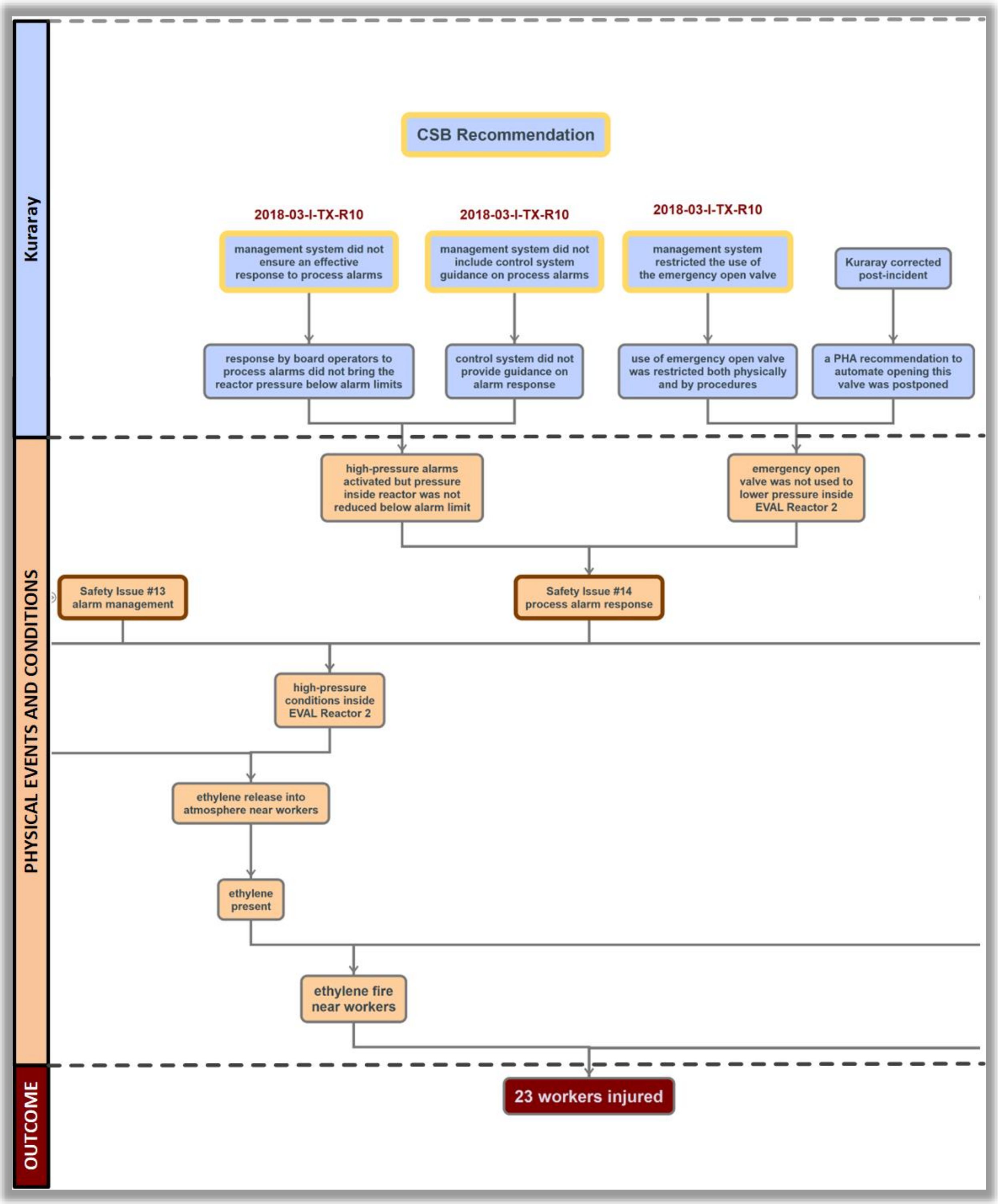

Figure 51. AcciMap part 16 of 19, Safety Issue #14. (Credit: CSB)

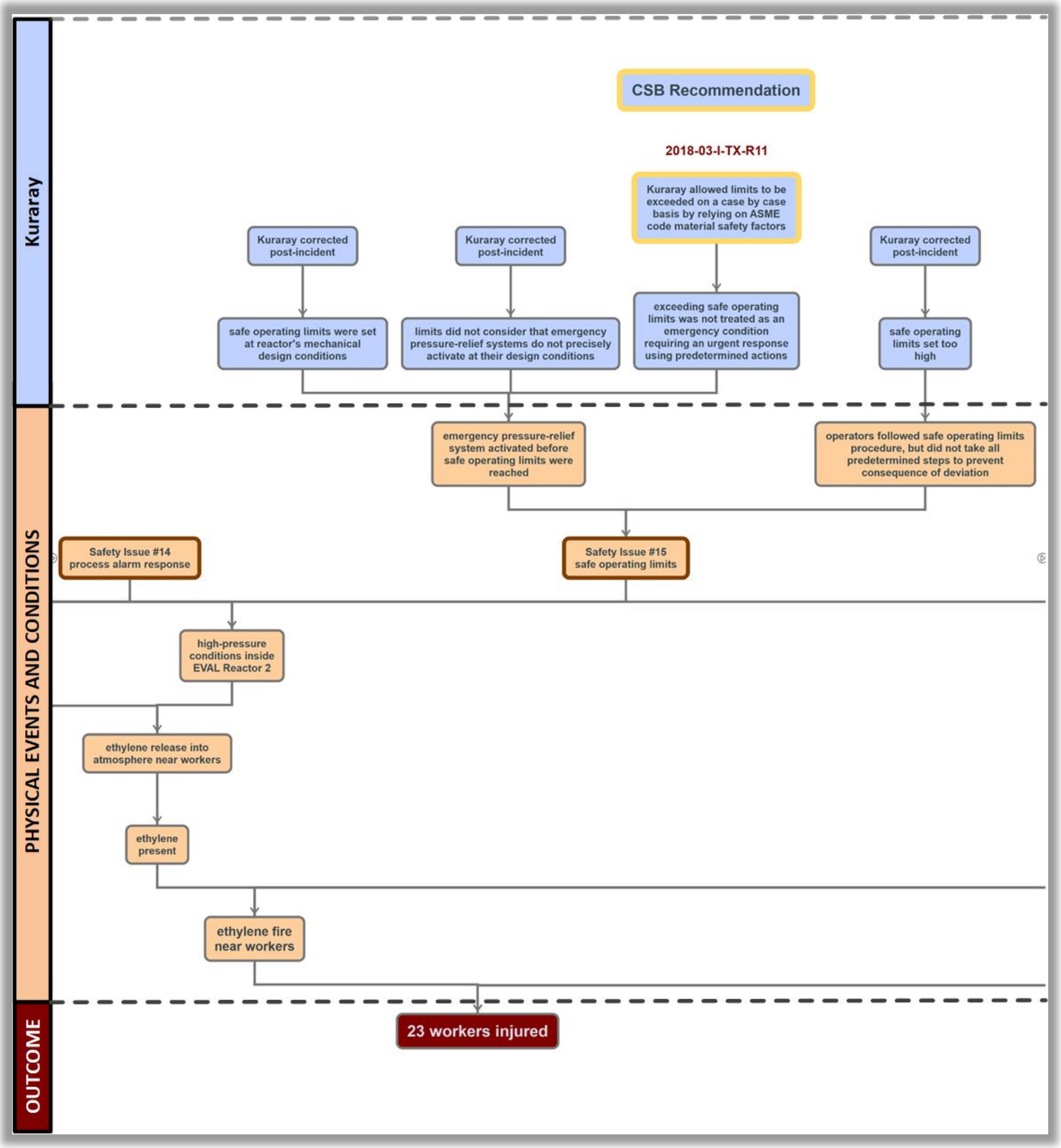

Figure 52. AcciMap part 17 of 19, Safety Issue #15. (Credit: CSB)

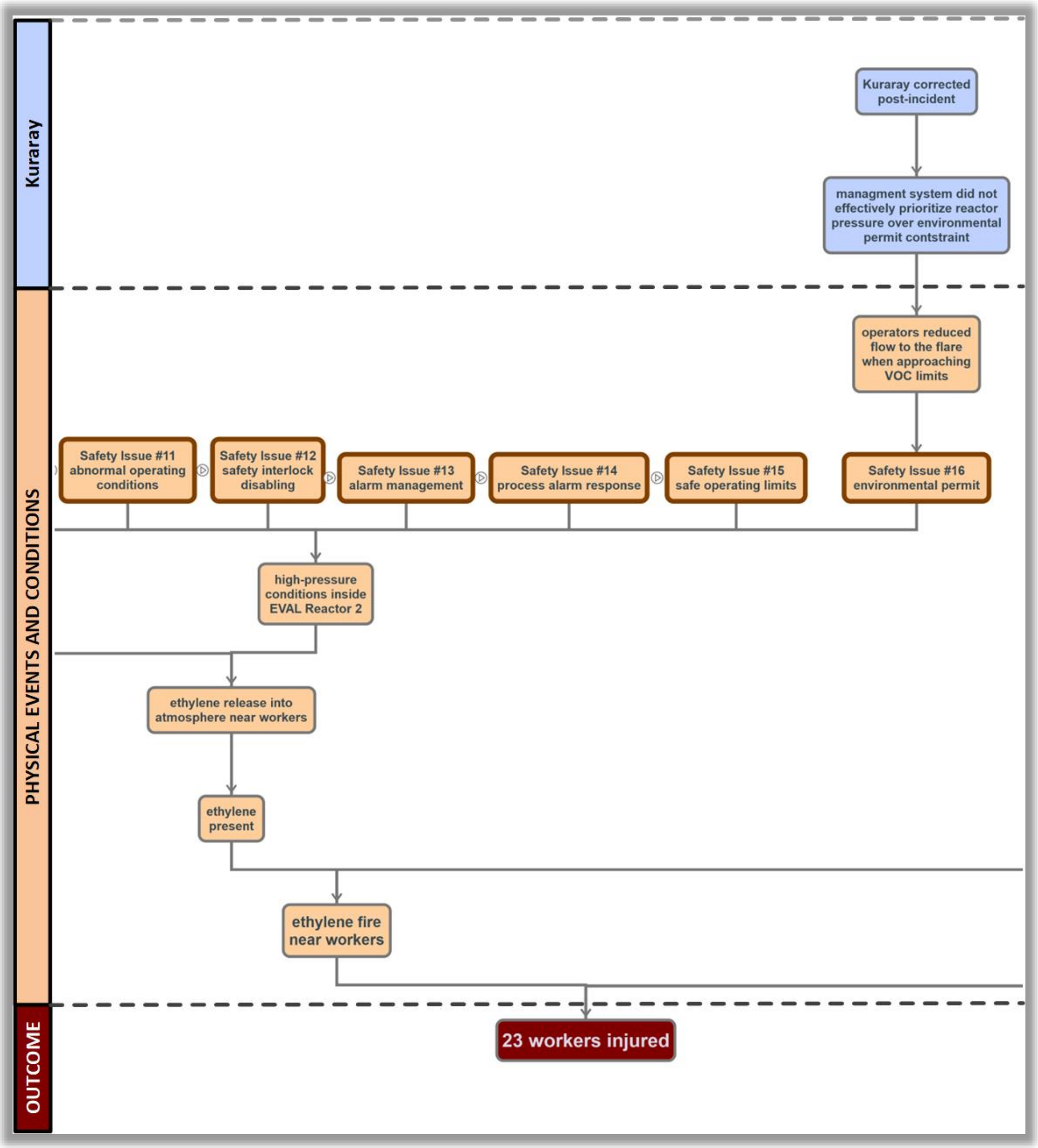

Figure 53. AcciMap part 18 of 19, Safety Issue #16. (Credit: CSB)

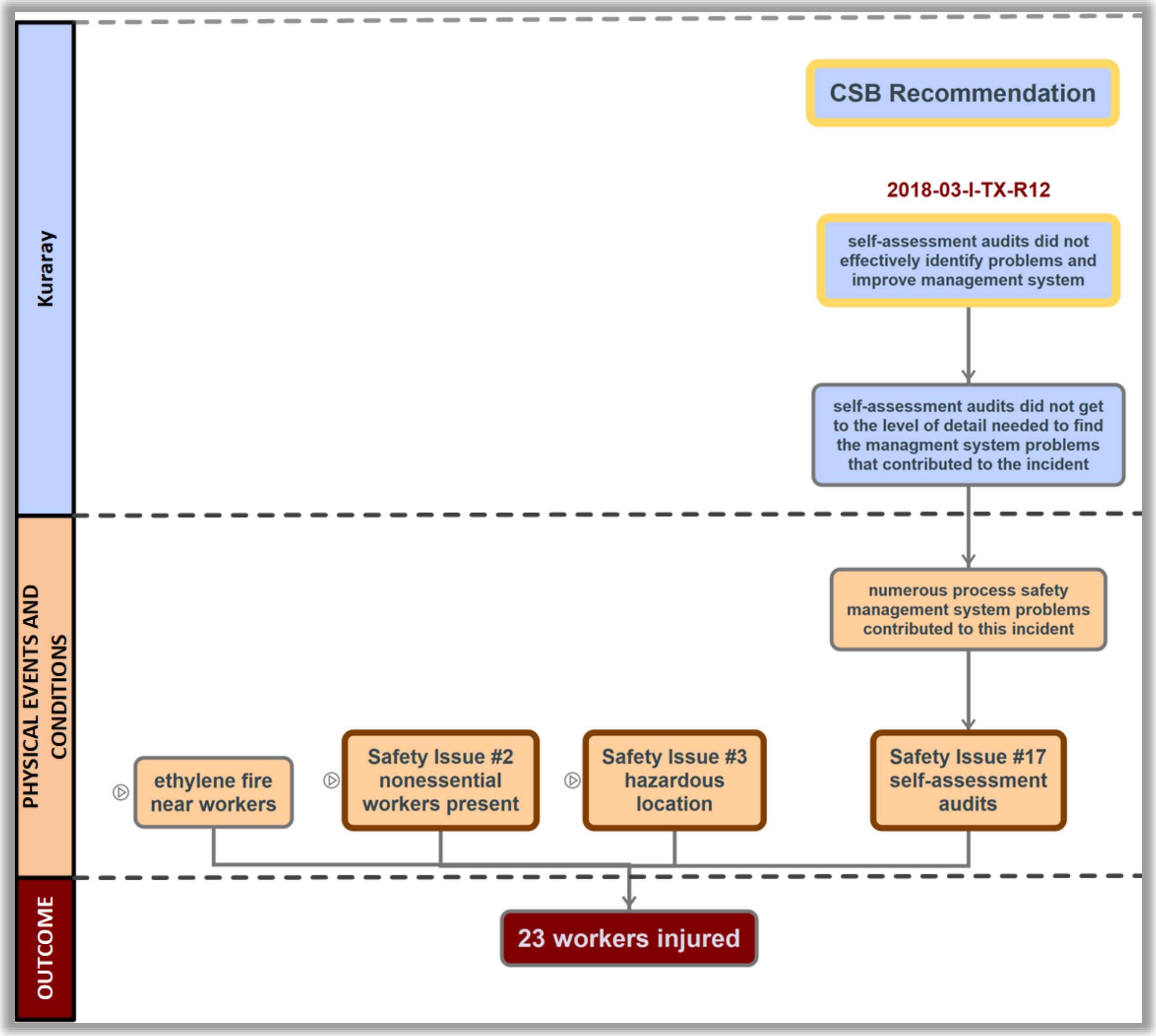

Figure 54. AcciMap part 19 of 19, Safety Issue #17. (Credit: CSB)

U.S. Chemical Safety and Hazard Investigation Board

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

Steve Owens
Interim Executive Authority

Sylvia E. Johnson, Ph.D.
Member