



Investigation Report

Published: September 24, 2021



SAFETY ISSUES:

- Mixing of Incompatible Materials
- Hazard Analysis Program
- Storage and Handling of Incompatible Materials
- Batch Equipment and Ventilation System Design
- Gas Detection System
- Emergency Preparedness
- Double Initial Procedure Program
- Process Safety Culture
- Safety Management System that Addresses Process Safety
- Regulatory Coverage of Reactive Hazards



U.S. Chemical Safety and Hazard Investigation Board

The mission of the U.S. Chemical Safety and Hazard Investigation Board (CSB) is to
***drive chemical safety change through independent investigations
to protect people and the environment.***

The CSB is an independent federal agency charged with investigating, determining, and reporting to the public in writing the facts, conditions, and circumstances and the cause or probable cause of any accidental chemical release resulting in a fatality, serious injury, or substantial property damages.

The CSB issues safety recommendations based on data and analysis from investigations and safety studies. The CSB advocates for these changes to prevent the likelihood or minimize the consequences of accidental chemical releases.

More information about the CSB and CSB products can be accessed at www.csb.gov or obtained by contacting:

U.S. Chemical Safety and Hazard Investigation Board

1750 Pennsylvania Ave. NW, Suite 910
Washington, DC 20006
(202) 261-7600

The CSB was created by the Clean Air Act Amendments of 1990, and the CSB was first funded and commenced operations in 1998. The CSB is not an enforcement or regulatory body. No part of the conclusions, findings, or recommendations of the Board relating to any accidental release or the investigation thereof shall be admitted as evidence or used in any action or suit for damages arising out of any matter mentioned in such report. 42 U.S.C. § 7412(r)(6)(G).

CONTENTS

FIGURES.....	4
ABBREVIATIONS	5
EXECUTIVE SUMMARY	6
1 FACTUAL INFORMATION	10
1.1 AB Specialty Silicones, LLC	10
1.1.1 EM 652 Batch Process Description	11
1.1.2 Silicon Hydride Reactivity.....	13
1.1.3 Personnel.....	13
1.1.4 Hazard Analysis Program	14
1.1.5 Storage of Chemicals	14
1.1.6 Batch Equipment Design.....	15
1.1.7 Ventilation System Design	15
1.1.8 Gas Detection System	16
1.1.9 Emergency Preparedness.....	17
1.1.10 Double Initial Procedure Program	17
1.1.11 Previous Incidents	18
1.1.12 Regulatory Coverage	19
1.2 Post-Incident Chemical Reactivity Experiments	20
1.3 Hydrogen Properties	20
1.4 Ignition Source	21
1.5 Weather at Time of Incident.....	21
1.6 United States Silicones Market	21
2 INCIDENT DESCRIPTION	21
2.1 Manufacture of First Batch of EM 652	21
2.2 Start of Second Batch of EM 652	22
2.3 Ignition of Hydrogen Gas and Explosion.....	22
3 INCIDENT ANALYSIS	23
3.1 Mixing of Incompatible Materials.....	24
3.2 Hazard Analysis Program	26
3.3 Storage and Handling of Incompatible Materials.....	27

3.3.1	<i>Co-Location of Incompatible Materials</i>	27
3.3.2	<i>Similar Drums Storing Incompatible Chemicals</i>	27
3.3.3	<i>Industry Guidance on Storing Incompatible Materials</i>	28
3.4	Batch Equipment and Ventilation System Design	29
3.5	Gas Detection System	30
3.6	Emergency Preparedness	30
3.7	Double Initial Procedure Program	31
3.8	Process Safety Culture	32
3.9	Process Safety Management System.....	34
3.10	Regulatory Coverage of Reactive Hazards.....	37
3.10.1	<i>Controlling Hazards through Effective Process Safety Management Systems</i>	38
3.10.2	<i>CSB Reactive Hazard Study</i>	39
3.10.3	<i>Need for Coverage of Reactive Chemical Hazards in the PSM and RMP Regulations</i>	43
4	AB SPECIALTY POST-INCIDENT ACTIONS	43
5	CONCLUSIONS	44
5.1	Findings	44
5.2	Cause	47
6	RECOMMENDATIONS	48
6.1	Previously Issued Recommendations Reiterated in This Report	48
6.1.1	<i>Occupational Safety and Health Administration (OSHA)</i>	48
6.1.2	<i>Environmental Protection Agency (EPA)</i>	49
6.2	Recommendation to AB Specialty Silicones, LLC.....	49
7	KEY LESSONS FOR THE INDUSTRY	50
8	REFERENCES	51
	APPENDIX A—EM 652 PROCESS OPERATIONS	53
	APPENDIX B—HYDROGEN GENERATION CALCULATIONS	54
	APPENDIX C—CHEMICAL REACTIVITY EXPERIMENTS AND RESULTS	57
	APPENDIX D—CSB BLAST ANALYSIS	71
	APPENDIX E—CAUSAL ANALYSIS (ACCIMAP)	72

Figures

Figure 1. AB Specialty production facility in Waukegan, Illinois, before the incident	10
Figure 2. AB Specialty production building.	11
Figure 3. Production building layout.....	12
Figure 4. Exemplar AB Specialty batch tank with agitator and lid.....	13
Figure 5. Three similar AB Specialty storage drums. From left to right: 10% KOH, XL 10, and Acticide	15
Figure 6. Location of the emulsions area and the ventilation system components	16
Figure 7. Excerpt from EM 652 batch ticket warning of reactivity between XL 10 and acids and bases.....	17
Figure 8. Excerpt from the AB Specialty emergency training	17
Figure 9. AB Specialty double initial procedure in effect at the time of the incident	18
Figure 10. Two chemicals in similar drums involved in previous near-miss incident.....	19
Figure 11. Photographs of chemical reactivity test of XL 10, TD 6/12 Blend, and 10% KOH solution	20
Figure 12. Post-explosion photo of the AB Specialty facility.....	23
Figure 13. Chemical Reactivity Worksheet’s predicted incompatibility between siloxanes and KOH.....	27
Figure 14. Hierarchy of controls, illustrating the effectiveness of controls, from most to least effective	32
Figure 15. Examples of Management Strategies for Improving Process Safety Culture.	33
Figure 16. Cover of CCPS <i>Guidelines for Risk Based Process Safety</i>	34
Figure 17. Cover of CCPS <i>Essential Practices for Managing Chemical Reactivity Hazards</i>	36
Figure 18. NFPA instability rating analysis of substances in incident data from 1980 to 2001 examined in the CSB Reactive Hazard.....	40

Abbreviations

CCPS	Center for Chemical Process Safety
CFM	cubic feet per minute
CSB	U.S. Chemical Safety and Hazard Investigation Board
EHS	environmental health and safety
EPA	U.S. Environmental Protection Agency
KOH	potassium hydroxide
LEL	lower explosive limit
MCMT	methylcyclopentadienyl manganese tricarbonyl
MNT	mononitrotoluene
NAICS	North American Industry Classification System
NFPA	National Fire Protection Association
OSHA	U.S. Occupational Safety and Health Administration
PHA	process hazard analysis
PSI	process safety information
PSM	process safety management
QC	quality control
RFI	request for information
RMP	risk management plan
SEHSC	Silicones Environmental, Health and Safety Council of North America
SiH	silicon hydride
SVEP	severe violator enforcement program
TSR	technical service request

Executive Summary

On May 3, 2019, operators at the AB Specialty Silicones, LLC (AB Specialty) manufacturing facility in Waukegan, Illinois were performing a batch operation that involved manually adding and mixing chemicals in a tank inside the production building. During the operation, an operator pumped an incorrect chemical into the tank, which was incompatible with another chemical that was added to the tank. The incorrect, incompatible chemical was stored in an identical drum to one of the correct chemicals, the only differentiating markings being small labels on the drums, and bung caps. After the incompatible chemicals were mixed, the tank contents underwent a chemical reaction, causing a process upset in which the tank contents foamed and overflowed from the tank's top opening. A fog also formed. The CSB determined that the process upset produced hydrogen gas, which released inside the manufacturing facility's production building.

Soon after the hydrogen gas release started, it ignited, causing a massive explosion and fire. The explosion fatally injured four employees [Byron Biehn, Jeffrey Cummings, Daniel Nicklas, Allen Stevens], destroyed the facility's production building, and forced the company to cease some and relocate other operations until the production building could be rebuilt.

The Waukegan Fire Department and mutual aid from surrounding areas responded to the incident. Other agencies that investigated the incident include the Illinois Environmental Protection Agency (IEPA), the Environmental Protection Agency (EPA), the Occupational Safety and Health Administration (OSHA), and the U.S. Chemical Safety and Hazard Investigation Board (CSB).

Safety Issues

The CSB investigation evaluated the following safety issues:

- **Mixing of Incompatible Materials.** An AB Specialty operator pumped an incorrect chemical into a tank, which was incompatible with another chemical that was added to the tank. The chemicals reacted to produce hydrogen gas, which found an ignition source and ignited to cause the explosion. ([Section 3.1](#))
- **Hazard Analysis Program.** AB Specialty assessed proposed product manufacturing operations through what it called technical service requests (TSRs), which evaluated a mix of business and safety risks. AB Specialty's TSR process did not and was not intended to assess the hazards of performing a process operation or establish safeguards to reduce risk. ([Section 3.2](#))
- **Storage and Handling of Incompatible Materials.** AB Specialty did not have a written procedure requiring employees to segregate incompatible chemical drums in the production building's manufacturing area or remove ingredient containers after use. The incompatible chemicals that were mixed were stored in similar 55-gallon blue plastic drums. The similar appearance of the drums likely contributed to the operator adding the incorrect chemical to the tank. ([Section 3.3](#))
- **Batch Equipment and Ventilation System Design.** As a result of the tanks used in the EM 652 batch process having an open hatch-type lid and no vent pipe to direct gases to a safe location, the hydrogen

gas produced during the incident released directly into the production building, where workers were located. The ventilation system, including an air mover—designed to introduce outside air to the building and which was positioned near the location where the batch operation was being performed—may have helped distribute the hydrogen in the production building and mix it with air, creating a large and explosive gas cloud. ([Section 3.4](#))

- **Gas Detection and Alarm System.** The AB Specialty production building did not have a hydrogen gas or flammable gas detection and alarm system to warn employees of a hazardous atmosphere. The lack of a system to detect hydrogen gas and automatically activate an alarm contributed to personnel remaining inside the production building between the start of the hydrogen release and the time of ignition. ([Section 3.5](#))
- **Emergency Preparedness.** During the incident, workers recognized that a process upset had occurred when the tank contents foamed, overflowed the tank, and a fog formed. However, despite recognizing the process upset, the workers did not recognize the immediate hydrogen hazard created by the upset. Hydrogen is a colorless and odorless gas indistinguishable from air without the use of additional technology, such as gas detectors. Without gas detectors and alarms alerting of the hazardous conditions, or effective training, the workers did not realize the necessity to evacuate. ([Section 3.6](#))
- **Double Initial Procedure Program.** AB Specialty developed a double initial procedure practice in 2014 in an effort to prevent employees from charging the wrong materials to batch processes, which was proceduralized in 2019. The occurrence of the May 3 incident indicates that AB Specialty’s double initial procedure program did not prevent a wrong material from being added to the tank. ([Section 3.7](#))
- **Process Safety Culture.** In the years leading up to the incident, AB Specialty exhibited characteristics of a weak process safety culture, including the lack of engineering controls to mitigate employee exposure to known hydrogen gas risks and heavy reliance on procedural controls as primary safeguards, among others. In addition, the company did not require incompatible chemicals to be visibly differentiated or perform a thorough hazard analysis of the EM 652 batch process after a 2014 drum explosion. ([Section 3.8](#))
- **Safety Management System that Addresses Process Safety.** AB Specialty did not have a safety management system that addressed process safety in place at the time of the incident. Industry best practice publications provide guidance on establishing process safety management systems for facilities with known or potential reactive chemical hazards. ([Section 3.9](#))
- **Regulatory Coverage of Reactive Hazards.** While AB Specialty processed chemicals capable of undergoing a highly hazardous chemical reaction that resulted in a large explosion and four fatalities, the chemicals used at the AB Specialty facility are not listed for coverage in either the Occupational Safety and Health Administration (OSHA) Process Safety Management (PSM) Standard or the Environmental Protection Agency (EPA) Risk Management Plan (RMP) Rule. As such, AB Specialty was not required to implement baseline process safety management system elements to manage the safety of its processes under these regulations. ([Section 3.10](#))

Cause

The CSB determined that the cause of the incident were deficiencies in AB Specialty's operations, policies, and practices including its hazard analysis program, methods used to store and handle incompatible materials, its double initial procedure program, process safety culture weaknesses, and the lack of a safety management system addressing process safety. These deficiencies led to an operator mixing incompatible chemicals, causing a reaction that produced hydrogen gas, which released and ignited in the AB Specialty production building. Contributing to the severity of the incident were AB Specialty's batch equipment and ventilation system design, the lack of a gas detection and alarm system, and ineffective emergency preparedness.

Recommendations

Previously Issued Recommendations Reiterated in This Report

To Occupational Safety and Health Administration (OSHA)

2001-01-H-R1

Amend the Process Safety Management Standard (PSM), 29 CFR 1910.119, to achieve more comprehensive control of reactive hazards that could have catastrophic consequences.

- Broaden the application to cover reactive hazards resulting from process-specific conditions and combinations of chemicals. Additionally, broaden coverage of hazards from self-reactive chemicals. In expanding PSM coverage, use objective criteria. Consider criteria such as the North American Industry Classification System (NAICS), a reactive hazard classification system (e.g., based on heat of reaction or toxic gas evolution), incident history, or catastrophic potential.
- In the compilation of process safety information, require that multiple sources of information be sufficiently consulted to understand and control potential reactive hazards. Useful sources include:
 - Literature surveys (e.g., *Bretherick's Handbook of Reactive Chemical Hazards*, *Sax's Dangerous Properties of Industrial Materials*)
 - Information developed from computerized tools (e.g., ASTM's CHETAH, [CCPS]'s The Chemical Reactivity Worksheet)
 - Chemical reactivity test data produced by employers or obtained from other sources (e.g., differential scanning calorimetry, thermogravimetric analysis, accelerating rate calorimetry)
 - Relevant incident reports from the plant, the corporation, industry, and government
 - Chemical Abstracts Service
- Augment the process hazard analysis (PHA) element to explicitly require an evaluation of reactive hazards. In revising this element, evaluate the need to consider relevant factors, such as:
 - Rate and quantity of heat or gas generated
 - Maximum operating temperature to avoid decomposition
 - Thermal stability of reactants, reaction mixtures, byproducts, waste streams, and products

- Effect of variables such as charging rates, catalyst addition, and possible contaminants
- Understanding the consequences of runaway reactions or toxic gas evolution

To Environmental Protection Agency (EPA)

2001-01-H-R3

Revise the Accidental Release Prevention Requirements, 40 CFR 68, to explicitly cover catastrophic reactive hazards that have the potential to seriously impact the public, including those resulting from self-reactive chemicals and combinations of chemicals and process-specific conditions. Take into account the recommendations of this report to OSHA on reactive hazard coverage. Seek congressional authority if necessary to amend the regulation.

New Recommendations

To AB Specialty Silicones, LLC

Ensure hydrogen gas detection and alarm systems are properly installed, maintained, and configured based on the facility's application and environment, manufacturer specifications, current codes, standards, and industry good practice guidance. The program must address sensor technology selection, installation, calibration, inspection, maintenance, sensor replacement, training, and routine operations.

Establish a safety management system that addresses process safety at the AB Specialty Waukegan, Illinois facility. Include in that system elements recommended in industry guidance publications, for example, Center for Chemical Process Safety (CCPS) publications *Guidelines for Risk Based Process Safety* and *Guidelines for Implementing Process Safety Management*.

Incorporate into operations and activities at AB Specialty the specific elements recommended in CCPS's *Essential Practices for Managing Chemical Reactivity Hazards*, which are:

1. Put into place a system to manage chemical reactivity hazards
2. Collect reactivity hazard information
3. Identify chemical reactivity hazards
4. Test for chemical reactivity
5. Assess chemical reactivity risks
6. Identify and implement process controls and risk management options
7. Document chemical reactivity risks and management decisions
8. Communicate and train on chemical reactivity hazards
9. Investigate chemical reactivity incidents
10. Review, audit, manage change in, and improve hazard management practices and programs

1 Factual Information

This section details the facts gathered by the CSB investigation team.

1.1 AB Specialty Silicones, LLC

AB Specialty Silicones, LLC (AB Specialty) is a U.S. manufacturer and worldwide distributor of specialty silicone chemicals, headquartered in Waukegan, Illinois (**Figure 1**) [1]. The company manufactures silicone products used in a wide variety of applications, including personal care, roof coatings, chemical manufacturing, adhesives, sealants, and other coatings. AB Specialty markets its brand under the name Andisil® [1].



Figure 1. AB Specialty production facility in Waukegan, Illinois, before the incident. (Credit: Google Earth)

1.1.1 EM 652 Batch Process Description

The AB Specialty operation took place inside a production building. The production building was divided into two adjoining areas known as the “High Bay” and the “Low Bay,” named after the physical heights of the structures (**Figure 2**). These bays were subdivided into different production areas, including the “emulsions area,” in which the incident occurred (**Figure 3**), and were equipped with reactors, tanks, storage vessels, and other equipment for the manufacture of various silicone products.



Figure 2. AB Specialty production building. (Credit: Google Maps with annotations by CSB)

At the time of the incident, AB Specialty was manufacturing an emulsion^a

commercially branded as Andisil[®] EM 652 (EM 652),^b a waterproofing agent, in the Low Bay emulsions area (**Figure 3**). AB Specialty manufactured EM 652 using a batch process. AB Specialty had been producing EM 652 since 2013 as necessary.

Because AB Specialty manufactured other emulsions and did not make the same emulsion products continuously, AB Specialty used different tanks to perform the EM 652 batch process based on equipment availability. The EM 652 batches were made in tanks that were loosely sealed with a hatch-type lid (**Figure 4**).^c Workers would open the lids of these tanks during the production process to, among other things, perform visual observations.

^a An emulsion is a heterogeneous mixture or system, consisting of at least one immiscible liquid intimately dispersed in another in the form of droplets [40].

^b EM 652 is an emulsion of methylhydrogen dimethyl siloxane copolymer, octyltriethoxysilane, and water.

^c The tanks used in the EM 652 batch process were atmospheric.

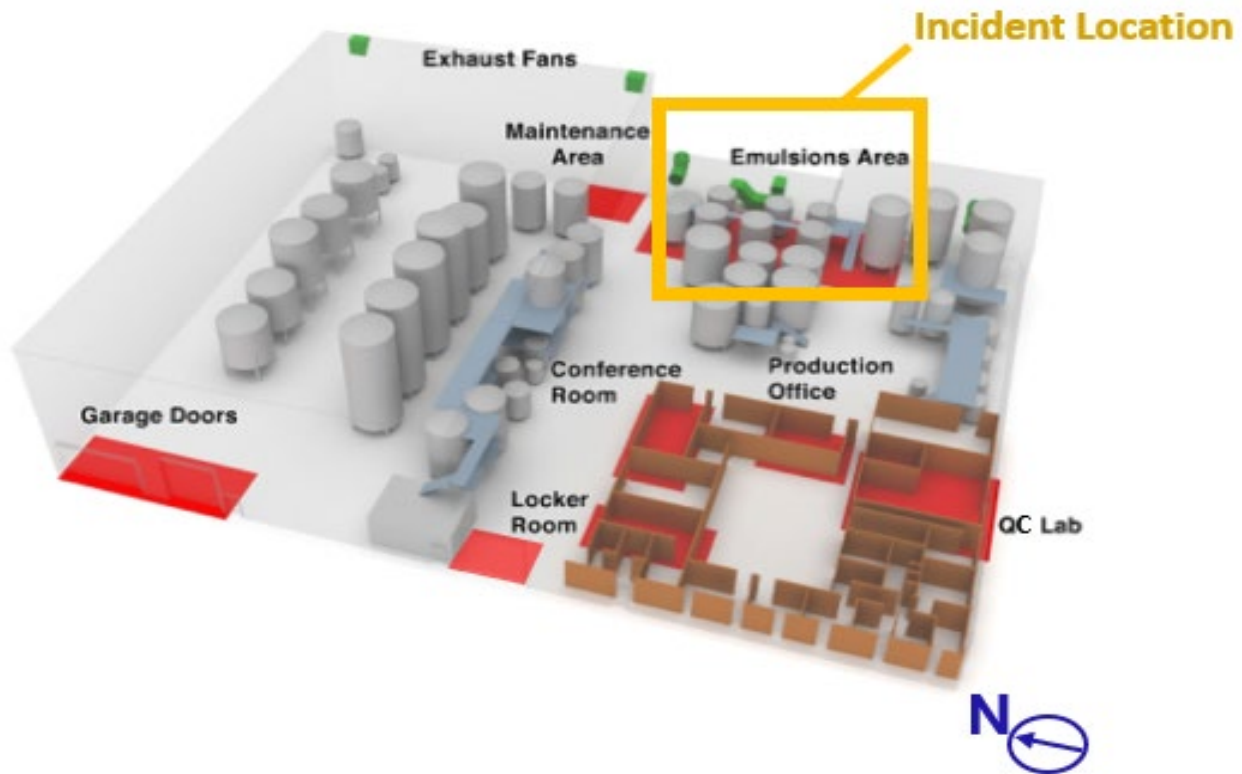


Figure 3. Production building layout. (Credit: CSB)

For each individual batch,^a AB Specialty specified on a form known as a “batch ticket” the sequential operation steps and the chemical ingredients and quantities required for the batch operation. Operators would add chemical ingredients to tanks in the order and quantity specified on the batch ticket, either using automatic feeds or by manual addition. Operators were required to have a co-worker or supervisor verify the product name, product code, and lot number on the raw material containers and then initial the batch ticket before adding them to the batch, as part of a “double initial procedure” program.

The first steps of the batch manufacture of EM 652 specified on the batch ticket included mixing multiple drums of a polymer branded as Andisil® XL 10 (XL 10)^b with a surfactant called TD 6/12 Blend in a tank (**Figure 4**).^c These steps were followed by subsequent chemical additions and mixing using additional process equipment and operations as described in **Appendix A**. The batch ticket in use at the time of the incident was not found after the incident.

At the completion of the EM 652 batch manufacturing process, AB Specialty required the operators to provide the quality control (QC) department with a sample of the final product. A QC chemist would then conduct several quality tests to ensure the product was within specification before approving the batch to be packaged. In

^a AB Specialty assigns a different lot number for each batch.

^b XL 10 is a methylhydrogensiloxane dimethylsiloxane copolymer, stored in 55-gallon blue plastic drums.

^c TD 6/12 Blend is an ethoxylated tridecyl alcohol (TD) surfactant, stored in 2,200-pound totes.

the event the pH of the final EM 652 product was out of specification, the QC chemist would issue a written order for an operator to adjust the pH of the final EM 652 product by adding an acid (i.e., glacial acetic acid) or a base (i.e., potassium hydroxide [KOH]) to the product. AB Specialty used a solution of 10 percent KOH in water (10% KOH) when the pH of the product needed to be increased. The EM 652 batch ticket did not list 10% KOH as an ingredient that may be added to the final EM 652 product for pH adjustment. Once the QC chemist confirmed the final product was within specification, the operators would then package the product into containers for later distribution to customers.

1.1.2 Silicon Hydride Reactivity

The XL 10 chemical used in the EM 652 batch process is a type of siloxane copolymer containing silicon hydride (SiH) bonds. Compounds with SiH bonds—including XL 10—react readily with, among other substances, aqueous bases.^a This reaction results in the rapid production of hydrogen [2, pp. 1-2], which is a flammable gas.^b The AB Specialty safety data sheet for XL 10 states, “water, ... [and] acidic or basic materials, ... when in contact with product, liberate flammable hydrogen gas, which can form explosive mixtures in air.” The details of the reaction between compounds with SiH bonds and aqueous bases are in **Appendix B**.

1.1.3 Personnel

In May 2019, at the time of the incident, AB Specialty had approximately 91 employees. AB Specialty’s Waukegan facility production employees worked three shifts. The first shift was 6:00 a.m.–2:30 p.m. The second shift was 2:00 p.m.–10:30 p.m. The third shift was 10:00 p.m.–6:30 a.m. On the day of the incident, there were eight employees working at the facility on the second shift, including Shift Supervisor 1, a QC chemist, and six operators. At the time of the incident, a shift supervisor for the third shift was also at the facility.

This report describes the actions of Operator 1, Operator 2, Operator 3, and Shift Supervisor 1. Table 1 indicates the years of experience at the time of the incident and relevant training of these employees. Operators who worked with the EM 652 batch process were also made aware of the XL 10 reactivity with acids and bases by a warning note contained in the EM 652 batch ticket (see Section 1.1.9).



Figure 4. Exemplar AB Specialty batch tank with agitator and lid. (Credit: AB Specialty)

^a An aqueous base is a compound (e.g., KOH) dissociated in a water solution with a pH greater than 7.

^b For an SiH compound to produce hydrogen, three conditions, known as the “gassing triangle,” are needed. These conditions are the presence of an SiH bond, a proton donor (or available hydrogen source such as water), and a catalyst [2, p. 3].

Table 1. AB Specialty Employee Experience and Training

Employee	Years of Experience at AB Specialty	Date of Most Recent Double Initial Procedure Program Training (described in Section 1.1.10)	Date of Most Recent Annual Emergency Training (described in Section 1.1.9)
Operator 1	2 years	April 17, 2019	November 15, 2018
Operator 2	1.5 years	April 17, 2019	November 13, 2018
Operator 3	1 year	April 17, 2019	April 18, 2018
Shift Supervisor 1	9 years	April 17, 2019	November 13, 2018

1.1.4 Hazard Analysis Program

AB Specialty assessed proposed product manufacturing operations through what it called technical service requests (TSRs). The aim of the TSR process was to answer the questions “Can we do it?”—through assessing the company’s existing application and chemistry knowledge, technology and capital utilization, and determining regulatory requirements—and “Should we do it?”—through assessing the market and revenue projections. The TSR procedure also tasked decision makers to answer safety-related questions, including “Is the product hazardous?” and “Are appropriate engineering controls in place?”

Spreadsheets provided to the CSB from AB Specialty indicate the EM 652 product underwent the TSR process in October 2014 and June 2018. No hazards or safeguards were documented on either TSR spreadsheet.

1.1.5 Storage of Chemicals

AB Specialty did not have a written procedure requiring employees to segregate the 10% KOH and XL 10 drums in the emulsions area or to remove ingredient containers from the emulsions area after use. Some chemical ingredients used in the production of EM 652, including 10% KOH and XL 10, were stored in similar 55-gallon blue plastic drums (**Figure 5**). The drums were equipped with two bung caps, often either yellow or white; the XL 10 drums typically had one white and one yellow bung cap,^a and the 10% KOH drums usually had two white bung caps. Once these bung caps were removed, the drums looked nearly identical. Therefore, AB Specialty relied on its operators to confirm drum content based on the label affixed to the side of the drum, which used small text for the chemical name, as shown in **Figure 5**.

^a The XL 10 yellow bung cap was for venting.



Figure 5. Three similar AB Specialty storage drums. From left to right: 10% KOH, XL 10, and Acticide. (Credit: CSB)

1.1.6 Batch Equipment Design

AB Specialty used tanks to charge and mix raw ingredients during the manufacture of some products, including emulsions. These tanks were atmospheric and equipped with hatch-type lids that did not seal and were often left open during the entire batch process. While some of the tanks used for the emulsion processes were equipped with vent pipes to divert any produced gases outside the building or to a process ventilation system, most of the tanks were not designed with this feature, and the tank in which the reaction occurred on the night of the incident was not equipped with a vent pipe.

1.1.7 Ventilation System Design

The Low Bay and the High Bay shared a mechanical ventilation system that consisted of air movers and exhaust fans throughout the building. In the production building emulsions area (where the incident occurred), there was one main air mover of 12,000 cubic feet per minute (CFM), as well as one smaller air mover, of 2,000 CFM, on the Low Bay roof. The main air mover provided approximately 86 percent of the total makeup air flow into the production building and could be operated manually. The Low Bay area had four 1,500 CFM roof exhaust fans,

two 1,500 CFM wall exhaust fans, and one 5,000 CFM roof exhaust fan that ran continuously. In addition, on the High Bay end, there were two exhaust fans with a total capacity of about 44,000 CFM. These exhaust fans did not run continuously and had to be manually activated by a switch located in the maintenance area. **Figure 6** shows the location of the emulsions area (yellow box), the main air mover (red box), and exhaust fans (blue boxes) visible on the side of the production building.



Figure 6. Location of the emulsions area and the ventilation system components. (Credit: Google Maps with annotations by CSB)

1.1.8 Gas Detection and Alarm System

The AB Specialty production building did not have a hydrogen gas or flammable gas detection and alarm system to warn employees of a hazardous atmosphere. AB Specialty employees told the CSB that the facility had installed two fixed lower explosive limit (LEL) gas detector systems in the Low Bay around October 2018 for a trial evaluation, using hydrogen, methane, and hydrogen sulfide as the calibration gases. These detectors were not specifically installed to detect hydrogen produced from the EM 652 process; rather, they were installed in a different area of the Low Bay. AB Specialty was evaluating both gas detectors and had not approved either for official use. Around March 2019, during a scheduled maintenance activity, AB Specialty employees found that the two gas detectors had failed; they had unresponsive sensors. AB Specialty employees concluded the sensors' exposure to silicone in the production environment caused the failures. An AB Specialty manager estimated the sensors to have a life cycle of approximately "two months." Another told the CSB that the installed "hydrogen gas detection system was not working given no hydrogen gas detection system will work in a silicone environment." Published literature warns that catalytic gas detectors, the technology that was under evaluation by AB Specialty, can be poisoned—thus decreasing the sensor life—when exposed to silicone [3, p. 38], [4, p. 234], [5, p. 14], which was prevalent at the AB Specialty facility. AB Specialty did not establish a sensor maintenance program, did not implement design changes to prevent silicone contact with the sensors, and did not replace the sensors by the time of the May 3, 2019, incident.

1.1.9 Emergency Preparedness

The batch ticket for the EM 652 batch process warned that XL 10 was reactive with acids and bases and could generate hydrogen (**Figure 7**):

NOTE: XL 10 CONTAINS METHYL HYDROGEN UNITS WHICH ARE VERY REACTIVE. IT CAN GENERATE HYDROGEN GAS IN THE PRESENCE OF ACIDS AND BASES. RINSE TANKS BEFORE CHARGING XL 10.

Figure 7. Excerpt from EM 652 batch ticket warning of reactivity between XL 10 and acids and bases. (Credit: AB Specialty)

AB Specialty also provided employees with training on what to do during process emergencies, performing yearly emergency drills and critiques with their personnel. Shown below in **Figure 8** is an excerpt from the AB Specialty emergency training.

PROCESS EMERGENCY

- Abnormal process situations occurring that could result in excessive equipment pressurization, hazardous material releases, or flammable or toxic vapor releases from the processing area
- If the safety of plant occupants was compromised as a result, a plant wide evacuation must occur and the incident command system activated
- Defensive actions to these situations could include: opening system vent lines, shutting down heating systems, applying cooling, shutting down agitation, shutting down sump drain pumps, opening doors for plant ventilation – these actions should only be taken if safe to do so.

Figure 8. Excerpt from the AB Specialty emergency training. (Credit: AB Specialty)

1.1.10 Double Initial Procedure Program

AB Specialty developed a double initial procedure practice in 2014 in an effort to prevent employees from charging the wrong materials to batch processes and as a part of AB Specialty’s compliance with the FDA’s cosmetic good manufacturing practice (“GMP”) requirement that “weighing and measuring of raw materials” be “checked by a second person, and containers holding the materials” be “properly identified” [6]. It became proceduralized in 2019. The double initial procedure is shown in **Figure 9**. The batch ticket has designated areas for employees to initial while executing the double initial procedure. The AB Specialty second shift employees—the employees working at the time of the incident—were most recently trained on the double initial

procedure on April 17, 2019.

Double Initial Procedure

Scope: The double initial procedure will make sure that the correct product is being charged when needed. **You should not charge any material that has not been verified by a supervisor/operator.**

This procedure applies to any charging activities into reactors, blend tanks, emulsion tanks, bulk tanks, uprights, and repacks.

1. Verify the material you need and pull it from its location to charge
2. Once material is pulled and ready to charge verify your code (and lot numbers) by comparing the code on the label of the container/bulk tank to the code on the log.
3. Write the full code number and lot numbers on the log.
4. **Before charging find a supervisor or another operator to verify steps 1-3.**
5. Once verified the supervisor / operator will initial that it is the proper material to charge and the lot numbers and codes are correct.
6. **Once you have completed these steps(1-5) only at this point can you begin charging the material**

NOTE:

- **Do not charge the material and then go get the double initial.**
- **Do not double initial anything that you did not verify yourself before it was charged.**
- **If no one is around at the time then do not charge the material until it has been verified and double initialed first**

Figure 9. AB Specialty double initial procedure in effect at the time of the incident. (Credit: AB Specialty)

1.1.11 Previous Incidents

1.1.11.1 2014 EM 652 Explosion

In April 2014, a drum containing EM 652 exploded as an operator inserted a charging wand into the drum. The operator sustained short-term hearing loss from the explosion. AB Specialty determined that static discharge from the movement of the charge pipe likely ignited the “explosive mixture that existed in the drum head space,” which AB Specialty determined contained hydrogen gas. AB Specialty concluded that a “lack of a comprehensive hazard analysis,” among other things, contributed to the incident.

1.1.11.2 2019 Inadvertent Mixing Near-Miss Event

In March 2019 (about two months prior to this incident), AB Specialty experienced a near-miss event involving two chemicals stored in similar 55-gallon blue metal drums. In that event, an AB Specialty employee requested two drums of a chemical for use in a batch process. When the drums arrived in the process area, the employee looked at the affixed label on one of the drums and verified that it was the correct material. The employee then charged the material in that drum to the batch, and when that drum was empty, he began the process of charging the second drum to the batch. At that point, the employee looked at the label on the second drum and realized it was not the correct material. He immediately stopped the batch process and notified management. Aside from the printed text on the paper label, the two drums looked identical (**Figure 10**). AB Specialty logged this incident as a near miss, made the double initial practice a written procedure, and retrained all production employees. The procedure required that chemicals be verified by two employees, with those employees both initialing the batch ticket before charging chemicals to a batch.



Figure 10. Two chemicals in similar drums involved in previous near-miss incident. (Credit: AB Specialty)

1.1.12 Regulatory Coverage

The AB Specialty operation is not regulated by the U.S. Environmental Protection Agency (EPA) Risk Management Plan (RMP) Rule,^a nor by the Occupational Safety and Health Administration (OSHA) Process Safety Management (PSM) Standard,^b because the chemicals used at the facility are not listed for coverage by

^a 40 CFR 68.

^b 29 CFR 1910.119.

either regulation. These regulations require process safety management systems at facilities that process certain hazardous chemicals at or above threshold quantities to protect workers, the public, and the environment.

1.2 Post-Incident Chemical Reactivity Experiments

After the incident, experimental reactivity tests were conducted using the chemicals known to be in the emulsions area at the time of the incident. **Appendix C** describes the testing results.

Of the multiple experiments conducted using various chemical mixtures, only one chemical combination resulted in the generation of a large quantity of flammable gas and produced foaming similar to what was observed the night of the incident. In that test, XL 10 and TD 6/12 Blend were mixed using the ratio indicated on the EM 652 batch ticket, and then 10% KOH was added to the mixture. Within about 25 seconds, the mixture turned white and foamy, formed gas, and overflowed the container (**Figure 11**). The produced gas was also tested and confirmed to be hydrogen, which was the expected gas based on the known reactivity between XL 10 and aqueous KOH.

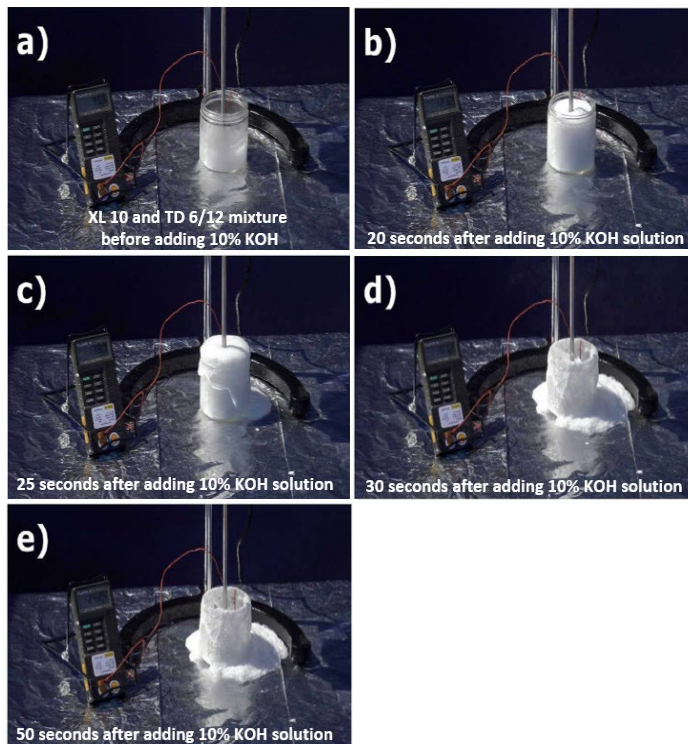


Figure 11. Photographs of chemical reactivity test of XL 10, TD 6/12 Blend, and 10% KOH solution. (Credit Crane)

1.3 Hydrogen Properties

Hydrogen gas is odorless and colorless. It is flammable in air at concentrations between a lower explosive limit of 4 volume percent and an upper explosive limit of 75 volume percent.

1.4 Ignition Source

It was not possible to identify the specific ignition source that initiated the explosion. Multiple potential ignition sources were present in the production building, including electrical equipment, wiring, and installation methods that were not intrinsically safe. Other sources, such as a spark from a dropped or thrown tool, electrostatic discharge, the use of heavy machinery, personal electronic devices (cell phones, etc.), and so on, also may have initiated the explosion. See **Appendix D** for more information on potential ignition sources.

1.5 Weather at Time of Incident

Data from the Waukegan Regional Station indicates that on May 3, 2019 at 8:55 p.m., the temperature was 44°F, and a 7 mile per hour wind was blowing from the east north east direction. The dew point was 36°F, and the relative humidity was 73%. It was mostly cloudy [7].

1.6 United States Silicones Market

The CSB requested from the American Chemistry Council's Silicones Environmental, Health, and Safety Center (SEHSC) information on the total silicone chemical manufacturing capacity in the United States. The SEHSC response to the request stated that “[i]n 2020, publicly available market data indicates that the total North American silicones market is approximately 400,000 metric tonnes.”

2 Incident Description

AB Specialty scheduled the manufacture of two back-to-back batches of EM 652 starting May 2, 2019, in the Low Bay emulsions area.

2.1 Manufacture of First Batch of EM 652

During the first shift on May 2, 2019, the first shift operators obtained the first printed process batch ticket from the production office detailing the operation steps for the first of two batches. The first shift operators then staged the required chemical ingredients—including XL 10, TD 6/12 Blend, and other chemicals—near the tanks in the emulsions area of the production building. The EM 652 batch operation required the use of eight XL 10 drums.^a The first shift operators then performed the batch operation, which went without incident. At 2:00 p.m., the second shift operations personnel arrived.

Over the span of the second and third shifts, the operators delivered two sequential product samples to the QC department. The QC department found the pH of both samples to be too low, and in both cases required the operators to increase the pH of the EM 652 product by adding 10% KOH. The operators brought 10% KOH into the emulsions area and added the specified amounts of 10% KOH to the EM 652 product.

^a The EM 652 batch required 3,348 pounds of XL 10, which is equivalent to seven full drums (each containing 440 pounds) and a partial drum.

After 4:30 p.m. on May 3, 2019, the QC department confirmed the EM 652 product was within the required specification and approved its packaging, which a second shift operator (Operator 1) performed after 6:30 p.m.

The CSB determined that, in preparation for the second EM 652 batch, operators likely left partial containers of leftover ingredients from the first batch—including XL 10, TD 6/12 Blend, and 10% KOH—in the emulsions area of the production building for use in the second batch.

2.2 Start of Second Batch of EM 652

During the evening of May 3, 2019, a total of nine employees were in the AB Specialty production building, four of whom this report identifies as Operator 1, Operator 2, Operator 3, and Shift Supervisor 1 as described in Section 1.1.3.^a

Before 8:00 p.m., Operator 1 likely obtained the printed batch ticket^b for the second EM 652 batch. This batch also required the use of eight XL 10 drums. The CSB determined there were likely also two or three drums containing 10% KOH in the production area,^c possibly leftover from the previous EM 652 batch operation. As a result, there were up to eleven nearly identical drums containing incompatible chemicals (XL 10 and 10% KOH) in the immediate process area at the start of the second batch.

Operator 1 then started the batch. Operator 1 charged XL 10 and TD 6/12 Blend, the first two ingredients of the EM 652 process, to the tank. At some point, while completing these initial process steps, Operator 1 also likely misidentified the 10% KOH drum(s) that remained in the emulsions area after the first batch for XL 10 and added 10% KOH into the tank.^d

As discussed above in Sections 1.1.2 and 1.2, aqueous KOH is highly reactive with compounds containing SiH bonds, such as XL 10. The reaction of these chemicals produces hydrogen gas. Shortly after the XL 10, 10% KOH, and TD 6/12 Blend were mixed, the batch tank contents started to foam and overflow from the batch tank top opening, and a fog also formed and spread through the Low Bay. The CSB determined that the process upset produced hydrogen gas (see **Appendixes B, C, and D**).

2.3 Ignition of Hydrogen Gas and Explosion

Operator 1 started yelling. Shift Supervisor 1 and Operator 2 ran to the emulsions area in response. The supervisor and operator saw the hazy fog and the foam overflowing from the tank's top lid onto the floor. Shift Supervisor 1 and Operator 2 asked Operator 1 what was happening. Operator 1 said "it's mixing XL 10 and TD 6/12"—the first two ingredients of the EM 652 batch manufacturing process. While Shift Supervisor 1, Operator 1, and Operator 2 were talking, Operator 3 said he observed the tank making a "very strange sound" and the tank was "erupt[ing]" material onto the floor. Operator 2 said he observed material "foaming out the tank and it was

^a The other five (5) employees were not reported as being in the emulsion area around the time of the incident.

^b This batch ticket was not found after the incident.

^c According to the AB Specialty's inventory system "SAGE," four 10% KOH drums were denotated as being in the production area on May 3, 2019, one full and three partial drums. Post-incident, the full 10% KOH drum was evidently located, leaving approximately two or three partial drums possibly in the area.

^d As stated in Appendix B, post-incident analysis indicates that the required amount of XL 10 had been added to the second EM 652 batch; however, the amount of TD 6/12 Blend added to the tank was undetermined.

really smoky, hazy.” Operator 2 stated that he felt the area get hotter. The workers interviewed by the CSB did not realize that material releasing during the upset was hazardous. There were no flammable gas detectors or hydrogen gas detectors to warn workers of the released hydrogen. The workers did not evacuate the building.

Shift Supervisor 1 directed workers to take action to ventilate the hazy vapor from the building. He asked Operator 2 to open a garage door near the locker room. Shift Supervisor 1 also told Operator 3 to go to the maintenance area and turn on the switch for the fans. This switch would turn on the exhaust fans located in the High Bay (**Figure 3**), which did not run continuously. Before Operator 2 could fully open the garage door and before Operator 3 turned on the fan switch, at about 9:35 p.m., the hydrogen gas ignited, causing a massive explosion and fire.

The building was destroyed by the explosion (**Figure 12**).^a Debris extended for several hundred feet from the building, and nearby business properties were also damaged. Four AB Specialty employees (Operator 1, Shift Supervisor 1, a shift supervisor for a separate shift, and a QC chemist) were fatally injured by the explosion, and Operator 3 was injured.



Figure 12. Post-explosion photo of the AB Specialty facility. (Credit: CSB)

3 Incident Analysis

The CSB determined that weather was not a factor in the outcome of this incident.

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

- Mixing of Incompatible Materials

^a As of this report, AB Specialty has rebuilt the production building that experienced the explosion.

- Hazard Analysis Program
- Storage and Handling of Incompatible Materials
- Batch Equipment and Ventilation System Design
- Gas Detection and Alarm System
- Emergency Preparedness
- Double Initial Procedure Program
- Process Safety Culture
- Safety Management System that Addresses Process Safety
- Regulatory Coverage of Reactive Hazards

The graphical causal analysis (AcciMap) is in **Appendix E**.

3.1 Mixing of Incompatible Materials

During the back-to-back EM 652 batch operations, operators likely left some of the remaining chemical ingredients from the first batch—including XL 10, TD 6/12 Blend, and 10% KOH—in the Low Bay emulsions area for use in making the second batch. This was a normal practice at the site when running back-to-back batches. To understand whether the incident was a result of mixing incompatible^a materials, experimental reactivity tests were conducted using the chemicals known to be in the emulsions area at the time of the incident, as described in Section 1.2. Of the multiple experiments conducted using various chemical mixtures, only one chemical combination resulted in the generation of a large quantity of flammable gas and produced foaming similar to what was observed the night of the incident. In that test, XL 10 and TD 6/12 Blend were mixed using the ratio indicated on the EM 652 batch ticket, and then 10% KOH was added to the mixture. Within about 25 seconds, the mixture turned white and foamy, formed gas, and overflowed the container (**Figure 11**). The produced gas was also tested and confirmed to be hydrogen, which was the expected gas based on the known reactivity between XL 10 and aqueous KOH.

Based on this chemical reactivity experiment, the consistency of the appearance of the produced foam with witness observations, the production of flammable hydrogen gas, the consistency of the chemicals with those known to be in the emulsions area before the incident, and consistency between the calculated amount of hydrogen that could be produced and the quantity of hydrogen determined through blast modeling that could result in the observed blast damage (see **Appendix B** and **Appendix D**), the CSB concludes:

- There is sufficient evidence to determine that the combination of three chemicals—XL 10, TD 6/12 Blend, and 10% KOH—caused the chemical reaction leading to the explosion at AB Specialty on May 3, 2019.
- Operator 1 added 10% KOH to the tank with XL 10 and TD 6/12 Blend, which reacted to produce hydrogen gas that subsequently ignited to cause the explosion.

^a Incompatible materials are materials that, when mixed, cause an undesired consequence [19, p. 59].

- The batch ticket did not include 10% KOH, and 10% KOH was not intended to be introduced to the batch at this point in the process.
- The process upset produced hydrogen gas, though secondary reactions and associated reaction products were also possible, but were not considered causal to the explosion.

Operator 1 had been working at AB Specialty for nearly two years in the production department and had experience with manufacturing batch products by following procedures contained on batch tickets. Operator 1 also communicated to Operator 2 after the process upset began that the batch tank was “mixing XL 10 and TD 6/12”—the first two ingredients of the EM 652 process. Operator 1 did not state that he had added any other ingredients to the EM 652 batch to Operator 2 when they were trying to understand what caused the process upset.

The CSB concludes:

- Operator 1 was an experienced operator who had previously performed batch operations at AB Specialty.
- Because Operator 1 was fatally injured in the incident, the CSB investigation team could not obtain his account of the events leading to the incident. However, based on interviews with surviving personnel, the CSB investigation team concluded that Operator 1 did not know what had caused the process upset.

As discussed in Section 3.2, AB Specialty did not sufficiently analyze the hazards of the process or implement effective controls to prevent the mixing of 10% KOH and XL 10. As discussed in Section 3.3, AB Specialty allowed both 10% KOH and XL 10 to be staged or stored in the emulsions area near each other and allowed them to be contained in nearly identical blue 55-gallon drums. As discussed in Section 3.7, AB Specialty’s double initial procedure program did not prevent this incident. Other sections discuss additional gaps with AB Specialty’s safety culture and safety management system.

The CSB concludes:

- Numerous proximate safety gaps could have caused or contributed to the introduction of XL 10, TD 6/12 Blend, and 10% KOH in the quantities required to produce the reaction and subsequent explosion, including deficiencies in the methods AB Specialty stored and handled incompatible materials— such as allowing incompatible materials to be stored near each other in nearly identical blue 55-gallon drums, and failures with AB Specialty’s procedural controls—including operator and supervisor non-adherence to the company’s double initial procedure.
- There is insufficient evidence to determine the degree to which any one company-level gap or failure contributed to the introduction of 10% KOH to the batch process. Rather, this incident demonstrates there were multiple safety gaps leading to the incident, and all should be corrected to prevent future similar incidents.

Section 3.9 details a recommendation CSB is issuing to AB Specialty to correct these gaps that contributed to the incident.

3.2 Hazard Analysis Program

AB Specialty assessed proposed product manufacturing operations through technical service requests (TSRs). While the TSR procedure required assessing potential risks associated with projects, these risks were a mix of business and safety risks. The safety risk evaluations were primarily aimed to determine whether the facility had the necessary equipment to perform the proposed operation, or if new equipment needed to be purchased. Spreadsheets provided to the CSB from AB Specialty indicates the EM 652 product underwent the TSR process in October 2014 and June 2018. No hazards or safeguards were documented on either TSR spreadsheet. The CSB concludes:

- AB Specialty's technical service request process did not and was not intended to assess the hazards of performing a process operation or to establish safeguards to reduce risk.

As described in Section 1.1.11.1, AB Specialty concluded in an investigation report that its lack of a comprehensive hazard analysis contributed to a 2014 drum explosion. The CSB concludes:

- AB Specialty did not take sufficient action to improve its hazard analysis program after finding that a lack of a comprehensive hazard analysis contributed to its 2014 drum explosion.
- AB Specialty did not perform a thorough hazard analysis of the EM 652 batch process despite known associated hazards and likelihood for the product and individual chemical component(s) to produce hydrogen.
- Due to the lack of an effective hazard analysis program, AB Specialty did not identify the hazards associated with (1) storing reactive chemicals in similar containers, (2) the practice of allowing incompatible materials to be stored near each other, (3) the ventilation system and batch tank design, (4) the lack of a gas detection system, or (5) its insufficient emergency preparedness.

The Chemical Reactivity Worksheet [8] is a free, publicly available, and commonly used industry tool to identify known chemical incompatibility hazards. Companies can use the Chemical Reactivity Worksheet to determine whether any chemicals used at the site are incompatible with other chemicals. The CSB used the Chemical Reactivity Worksheet to determine whether it could predict the incompatibility hazard between XL 10 (a siloxane) and KOH. Using the inputs *siloxane* and *KOH*, the Chemical Reactivity Worksheet predicted that the two chemicals are incompatible and could produce hydrogen if mixed (**Figure 13**). The CSB concludes that using public resources such as the Chemical Reactivity Worksheet to identify reactive hazards is a way companies can gather process safety information (PSI) for use in process hazard analyses (PHAs) to identify process hazards and establish safeguards to protect from those hazards. Gathering PSI and performing PHAs are elements of a process safety management system, discussed in Sections 3.9 and 3.10 of this report. AB Specialty did not have a safety management system that addressed process safety in place to identify process hazards or establish safeguards.

Hazard Report For: [reactive group] Siloxanes and POTASSIUM HYDROXIDE, SOLUTION
COMPATIBILITY PREDICTION:
INCOMPATIBLE - Hazardous reactivity issues are expected
HAZARD SUMMARY:
Reaction products may be flammable Reaction liberates gaseous products and may cause pressurization
POTENTIAL GASES:
Hydrogen

Figure 13. Chemical Reactivity Worksheet's predicted incompatibility between siloxanes and KOH. (Credit: Center for Chemical Process Safety, Chemical Reactivity Worksheet [8])

The CSB also found that AB Specialty did not include on the batch ticket that 10% KOH may be added to the final EM 652 product for pH adjustment. The CSB concludes that all chemicals that could be added to a batch must be listed on the batch ticket. During PHAs, this practice will provide the opportunity for individuals who are knowledgeable of the reactivity hazard to identify ways to prevent hazardous chemical reactions.

3.3 Storage and Handling of Incompatible Materials

3.3.1 Co-Location of Incompatible Materials

Operators likely left two or three drums of 10% KOH in the emulsions area after its use in the first batch, for possible use in the second batch. This would have caused the 10% KOH to remain co-located with incompatible XL 10, which was required for use in the second batch. AB Specialty did not have a written procedure requiring employees to segregate the 10% KOH and XL 10 drums in the emulsions area or to remove leftover ingredient containers after use. The CSB concludes:

- Up to eleven nearly identical drums containing incompatible chemicals were in the immediate process area at the start of the second batch.
- AB Specialty's lack of procedures likely led to incompatible 10% KOH and XL 10 remaining in the emulsions area after their use in the first batch, contributing to the mixing of these two chemicals on the night of the incident.

3.3.2 Similar Drums Storing Incompatible Chemicals

Some chemical ingredients used in the production of EM 652, including 10% KOH and XL 10, were stored in similar 55-gallon blue plastic drums (**Figure 5**). The drums were equipped with two bung caps, often either yellow or white; the XL 10 drums typically had one white and one yellow bung cap, and the 10% KOH drums

usually had two white bung caps. The CSB concludes that once the drum bung caps were removed, the drums that stored 10% KOH and XL 10 looked nearly identical. Therefore, AB Specialty relied on its operators to confirm drum content based on the label affixed to the side of the drum, which used small text for the chemical name, as shown in **Figure 5**.

The CSB concludes that the similar appearance of the XL 10 and 10% KOH drums likely contributed to Operator 1 adding the incorrect chemical to the EM 652 batch process. AB Specialty experienced another similar mixing incident involving two separate chemicals stored in identical drums, as described in Section 1.1.11.2.

3.3.3 Industry Guidance on Storing Incompatible Materials

The CSB concludes that in batch operations that rely on operators to gather and mix chemicals, it is critical that batch processing facilities reduce the risk of human error by making it easy to do the job right and hard to do the job wrong. Various industry publications, such as Center for Chemical Process Safety (CCPS) books, industry conference papers, and trade association guidance documents, give example strategies for reducing the likelihood of mixing reactive and incompatible materials, including the following:

- Increasing the inherent safety of the process, for example by substituting incompatible materials with less hazardous chemicals [9]
- Storing incompatible materials in different-colored containers [10], [11]. This strategy does not need to be overly burdensome. It could include requesting different packaging from the supplier, or simply applying highly visible differentiating markings to the drums upon receipt, such as an assigned tape or paint color applied around the circumference of the drums
- Storing incompatible materials on separate, dedicated, color-coded pallets [10]
- Designating separate storage areas for reactive chemicals [10], [11]
- Implementing a material bar-coding system to verify chemicals [12], [11]
- Staging chemicals in the process area when they are about to be charged instead of staging all materials at the start of the batch process [12]. At AB Specialty, this could have been performed by allowing only the quality control (QC) department to have access to the 10% KOH, and requiring the QC department to provide the operations group with only the amount of 10% KOH needed to adjust the pH^a
- Using hard piping where possible [11]

In addition to these reactive hazard references, the CSB identified two additional industry guidance documents specifically related to hydrogen-bonded silicon compounds, the category of chemicals involved in this incident (XL 10 is a siloxane polymer with SiH bonds). These guidance documents are the 2016 *Materials Handling Guide: Hydrogen-Bonded Silicon Compounds*, developed by the Operating Safety Committee of the Silicones Environmental, Health and Safety Council of North America (SEHSC), CES-Silicones Europe, in partnership

^a The AB Specialty QC department was not set up to perform this function at the time of the incident.

with the Silicones Industry Association of Japan [2],^a and *Safe Handling of Silicon Hydride Containing Polysiloxanes*, developed by Dow [13]. These documents provide guidance to prevent mixing of SiH chemicals with incompatible materials, including:

- Use of a bar coding system. The guidance states, “some companies use a bar coding system to enter the identity of the materials into a computer control system that will only allow the batch sequence to proceed if the correct materials have been made available.” [2]
- “A Process Hazard Analysis should be completed for all processes using SiH siloxane particularly where exothermic reactions ... are being performed. The aim of this analysis is to identify situations where runaway reactions or cross contamination could occur and identify procedural and engineering measures that should be put in place.” [13]

3.4 Batch Equipment and Ventilation System Design

AB Specialty used atmospheric batch tanks to charge and mix raw ingredients during the manufacture of some products including emulsions. These tanks were equipped with hatch-type lids that did not seal and were often left open during the entire batch process. While some of the tanks used in the emulsion processes were equipped with vent pipes to divert any produced gases outside the building or to a process ventilation system, most of the tanks were not designed with this feature, and the tank in which the reaction occurred on the night of the incident was not equipped with a vent pipe.

The CSB concludes:

- As a result of the tank having an open hatch-type lid and no vent pipe to vent gases to a safe location, the hydrogen gas produced during the incident vented directly into the production building, where workers were located.
- The ventilation system, which included a manually operated air mover designed to introduce outside air to the building and was positioned near the location where EM 652 was being manufactured,^b may have helped distribute the hydrogen in the production building and mix it with air, creating a large and explosive gas cloud.^c
- An alternative ventilation design, such as local exhaust ventilation or an extraction system, in which building air discharge fans and vents are located in the process area could have vented released hazardous gases to a safe location, and in this case could have reduced the severity of the explosion.

^a In 2013, SEHSC transitioned to become the Silicones Environmental, Health, and Safety Center (still SEHSC), a sector group of the American Chemistry Council.

^b The production building’s ventilation system is described in Section 1.1.7.

^c Post-incident blast analysis determined the ignition source may have been located towards the middle of the Low Bay building near a process area containing reactors. See **Appendix D**.

3.5 Gas Detection and Alarm System

The AB Specialty production building did not have a hydrogen gas or flammable gas detection and alarm system to warn employees of a hazardous atmosphere. The CSB concludes:

- The lack of a system to detect hydrogen gas and automatically activate an alarm contributed to personnel remaining inside the production building between the start of the hydrogen release and the time of ignition, thereby contributing to the severity of the event.

Approximately five months into AB Specialty’s trial evaluation of using fixed LEL gas detectors, the sensors were found failed. AB Specialty employees concluded the sensors’ exposure to silicone in the production environment caused the failures. An AB Specialty manager estimated the sensors to have a life cycle of approximately “two months.” Another told the CSB that the installed “hydrogen gas detection system was not working given no hydrogen gas detection system will work in a silicone environment.” Published literature warns that catalytic gas detectors, the technology that was under evaluation by AB Specialty, can be poisoned—thus decreasing the sensor life—when exposed to silicone [3, p. 38], [4, p. 234], [5, p. 14], which was prevalent at the AB Specialty facility. AB Specialty did not replace the sensors by the time of the May 3, 2019, incident. Although the detectors failed over time, a proper maintenance program for these sensors could have ensured that there were working detectors at the time of the incident. The CSB concludes:

- There are numerous gas detection technologies, each with advantages and disadvantages [14, p. 313], [15]. Not all gas detection technologies will work with all materials (e.g., hydrogen gas, silicone, etc.).
- Facilities must communicate the planned application and operating environment^a with the gas detector manufacturer to help ensure the correct sensor technology is selected, properly installed, and adequately maintained.
- AB Specialty should identify and install a hydrogen gas detection and alarm system, and associated preventive maintenance program, that is effective in AB Specialty’s unique production environment.

The CSB issues a recommendation to AB Specialty to develop hazardous gas detection and alarm programs and associated procedures based on manufacturer specifications, current codes, standards, and industry good practice guidance, for all hazardous gases that could be released near workers, including hydrogen. The program must address proper installation, calibration, inspection, maintenance, training, and routine operations. Ensure such hazardous gas detection and alarm systems are functional at all times.

3.6 Emergency Preparedness

During the incident, workers recognized that a process upset had occurred when the tank contents foamed, overflowed the tank, and a fog formed. However, despite recognizing the process upset, the workers did not recognize the immediate hydrogen hazard created by the upset. Hydrogen is a colorless and odorless gas indistinguishable from air without the use of additional technology, such as gas detectors. The CSB concludes:

- Without gas detectors and alarms alerting of the hazardous conditions, or effective training, the workers did not realize the necessity to evacuate.

^a Building conditions to consider include parameters such as humidity, temperature, pressure, and the presence of gases.

- For chemicals that could experience hazardous chemical reactions, companies need to ensure that workers have the appropriate resources—such as through technology and training—to recognize the signs of an adverse reaction and to respond appropriately.

3.7 Double Initial Procedure Program

AB Specialty developed a written double initial procedure process with training in 2019 in an effort to prevent employees from charging the wrong materials to batch processes. The CSB concludes that the occurrence of the May 3 incident indicates that AB Specialty’s double initial procedure program did not prevent a wrong material from being added to the tank.

The CSB was unable to determine the specific reason for the program failure on the day of the incident because the operator performing the operation was fatally injured in the incident, and the batch ticket in use at the time of the incident, which would have also included the two employees’ initials in the event the double initial procedure was followed, was never recovered. However, the CSB concludes:

- Numerous safety gaps could have caused or contributed to the mixing of the incompatible chemicals, including insufficient guidance for operators and supervisors for all phases necessary to prevent known catastrophic chemical reactions; insufficient or incomplete training for operators and supervisors on the existing procedures; insufficient training on the potential for hydrogen to be produced with XL 10; and insufficient reinforcement of strictly adhering to all procedures.

Procedural controls used in industry such as the double initial procedure or crosschecking of materials by a second person [2] are low on the hierarchy of controls—that is, they are more likely to fail than are engineering controls and safeguards. The hierarchy of controls is a method to effectively reduce risk by applying, in order of effectiveness, inherently safer design, passive safeguards, active safeguards, and procedural safeguards (**Figure 14**). This strategy promotes a tiered or hierarchical approach to risk management. The higher a control is in the hierarchy, the more effective the risk reduction it achieves. The CSB concludes:

- Applying the hierarchy of controls at the design phase is the best opportunity to ensure that process hazards are properly analyzed and risks are effectively reduced, before the design is implemented in the field.
- After the design phase, when construction is complete and the process is operating, process safety management system elements such as PHAs are important opportunities to apply the hierarchy of controls to further reduce risk throughout the life of a process.

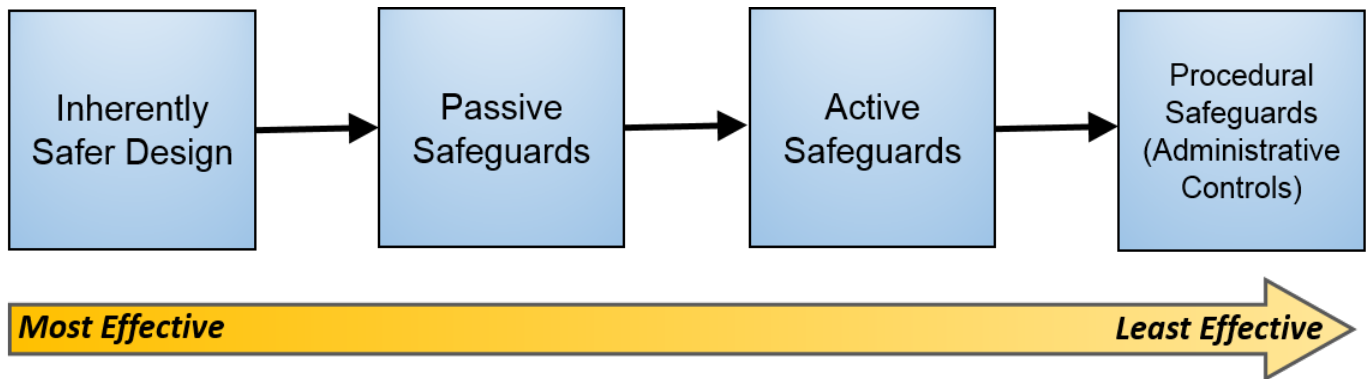


Figure 14. Hierarchy of controls, illustrating the effectiveness of controls, from most to least effective. (Credit: CSB based on CCPS [16])

3.8 Process Safety Culture

Process incidents often initiate when existing company processes, procedural, or policy gaps coincide with actions at the front line, such as how the overarching safety program gaps led to the mixing of incompatible materials and the consequences of the May 3, 2019 AB Specialty incident. To prevent this type of process incident, organizations must develop a culture that promotes effective safety management systems that address process safety.

For more than the past decade, the chemical process industry has increasingly focused on process safety culture (safety culture). An organization's safety culture is determined by the quality of its written safety management programs (e.g., operating procedures, written policies) and the quality of implementing those programs by individuals in the organization, ranging from top-level management to the operator. The Center for Chemical Process Safety has labeled these two facets as *Conduct of Operations* and *Operational Discipline*, respectively [17].

Improving an organization's process safety culture starts with management. Managers can help to set a high bar for the organization's commitment to implementing effective safety management programs and company expectations (i.e., operational discipline) by following the below examples (**Figure 15**) from the CCPS book *Conduct of Operations and Operational Discipline – For Improving Process Safety in Industry* [17, p. 5].



Figure 15. Examples of Management Strategies for Improving Process Safety Culture. (Credit: CCPS *Conduct of Operations and Operational Discipline – For Improving Process Safety in Industry* [17, p. 5]).

In the years leading up to the incident, AB Specialty exhibited characteristics of a weak process safety culture. The weaknesses below contributed to the May 3 incident, reflecting serious deficiencies in AB Specialty’s systems to manage process safety:

- 1) AB Specialty did not implement engineering controls to mitigate the risk of exposing workers to potentially hazardous conditions during the EM 652 process, which was known to contain ingredients that could generate hydrogen when mixed;
- 2) AB Specialty did not perform a thorough hazard analysis of the EM 652 process following the 2014 drum explosion after the investigation of that incident concluded a “lack of a comprehensive hazard analysis,” among other things, contributed to the incident (described in Sections 1.1.11.1 and 3.2);
- 3) Procedural controls are lower on the hierarchy of controls, but they were the primary safeguards used by AB Specialty to prevent a wrong chemical from being added to a batch process. AB Specialty did not have a policy requiring the effectiveness of their safeguards to be analyzed; and
- 4) AB Specialty did not require incompatible materials to be stored separately, did not require the removal of partial drums from the process area after use, and did not require incompatible chemicals to be visibly differentiated.

In its book *Guidelines for Risk Based Process Safety* (**Figure 16**) CCPS provides example methods a facility can employ to improve its process safety culture. These include:

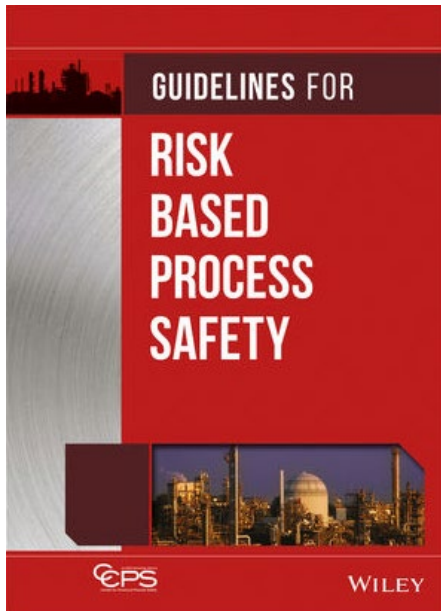


Figure 16. Cover of CCPS *Guidelines for Risk Based Process Safety*.
(Credit: CCPS [18])

- (1) *Establish process safety as a core value*
- (2) *Provide strong leadership [for process safety];*
- (3) *Establish and enforce high standards of [process safety] performance;*
- (4) *Maintain a sense of vulnerability;*
- (5) *Empower individuals to successfully fulfill their process safety responsibilities;*
- (6) *Defer to expertise;*
- (7) *Ensure open and effective communications;*
- (8) *Establish a questioning / learning environment;*
- (9) *Foster mutual trust;*
- (10) *Provide timely response to process safety issues and concerns; and*
- (11) *Provide continuous monitoring of [process safety] performance [18, pp. 39-66].*

The CSB concludes:

- AB Specialty knew that the EM 652 process and the individual ingredient, XL 10, could produce hydrogen gas.
- It is reasonable to assume that AB Specialty knew that hydrogen gas is colorless, lacks olfactory indications, and is flammable in air at concentrations between a lower explosive limit of 4 volume percent and an upper explosive limit of 75 volume percent.
- AB Specialty had a weak process safety culture.
- Implementing the process safety culture guidance in CCPS's *Guidelines for Risk Based Process Safety* can help AB Specialty improve its process safety culture.

3.9 Safety Management System that Addresses Process Safety

To prevent process incidents, organizations must establish effective safety management systems that address process safety, as described in Section 1.1. AB Specialty did not have a process safety management system in place at the time of the incident. The CSB concludes:

- Effective safety management systems that address process safety are critical to prevent future reactive chemical incidents.
- Safety at the Waukegan, Illinois AB Specialty facility would improve from an established safety management system that addresses process safety at the AB Specialty Waukegan, Illinois facility.

Currently, there are industry publications that provide guidance on developing process safety management systems to control process hazards. In 2007, the Center for Chemical Process Safety (CCPS) published its guidance book *Guidelines for Risk Based Process Safety* [18], which details 20 elements of an effective process safety management system, including: (1) process safety culture, (2) compliance with standards, (3) process safety competency, (4) workforce involvement, (5) stakeholder outreach, (6) process knowledge management, (7) hazard identification and risk analysis, (8) operating procedures, (9) safe work practices, (10) asset integrity and reliability, (11) contractor management, (12) training and performance assurance, (13) management of change, (14) operational readiness, (15) conduct of operations, (16) emergency management, (17) incident investigation, (18) measurement and metrics, (19) auditing, and (20) management review and continuous improvement. In addition to this safety management system guidance, CCPS had also published in 2003 a guidance book specifically about managing hazards relating to chemical reactivity, titled *Essential Practices for Managing Chemical Reactivity Hazards* (**Figure 17**). The stated purpose of that book is as follows:

to contribute to a continued reduction in the number and severity of incidents involving uncontrolled chemical reactions in the workplace. The objective of [the book] is to convey the essentials of managing chemical reactivity hazards ... [and] should result in a management system that will, on an ongoing basis:

1. Commit to managing chemical reactivity hazards throughout the entire facility lifetime.
2. Identify all chemical reactivity hazards.
3. Understand the situations that can cause uncontrolled reactions.
4. Reduce hazards where feasible, resulting in an inherently safer facility.
5. Prevent chemical reactivity incidents by designing, constructing, operating, and maintaining the facility in such a way that all chemical reactivity hazards are contained and controlled.
6. Mitigate (reduce the severity of) incidents that may occur despite prevention efforts. [19, p. 3]

The CCPS reactivity hazard management practices overlap with established process safety management systems, including the OSHA PSM Standard and the CCPS Risk-Based Process Safety management system [18], making implementation of these practices part of many of the existing processes at facilities with an established process safety management framework. The CCPS reactivity hazard management practices are detailed below. Listed in parentheses after each practice are the OSHA PSM element^a and the CCPS risk-based process safety element^b that each practice falls under:

^a The OSHA PSM regulation includes 14 elements: (1) employee participation, (2) process safety information, (3) process hazard analysis, (4) operating procedures, (5) training, (6) contractors, (7) pre-startup safety review, (8) mechanical integrity, (9) hot work permit, (10) management of change, (11) incident investigation, (12) emergency planning and response, (13) compliance audits, and (14) trade secrets. See 29 CFR 1910.119.

^b The CCPS developed and recommends what it calls a “Risk-Based Process Safety” management system. The system includes 20 elements: (1) process safety culture, (2) compliance with standards, (3) process safety competency, (4) workforce involvement, (5) stakeholder outreach, (6) process knowledge management, (7) hazard identification and risk analysis, (8) operating procedures, (9) safe work practices, (10) asset integrity and reliability, (11) contractor management, (12) training and performance assurance, (13) management of change, (14) operational readiness, (15) conduct of operations, (16) emergency management, (17) incident investigation, (18) measurement and metrics, (19) auditing, and (20) management review and continuous improvement.

1. **Put into place a system to manage chemical reactivity hazards.** This practice establishes an organized method to identify and control chemical reactivity hazards (*OSHA PSM / CCPS risk-based process safety*).
2. **Collect reactivity hazard information.** This practice can be done through collecting and accessing sources including but not limited to safety data sheets, the CCPS Chemical Reactivity Worksheet [8], the National Institute for Occupational Safety and Health Pocket Guide [20], National Fire Protection Association publications, and other internal or public documents on chemical reactivity hazards (*process safety information / process knowledge management*).
3. **Identify chemical reactivity hazards.** This practice involves using the sources collected in step 2 to determine the reactivity hazards of chemicals used at the facility (*process hazard analysis / hazard identification and risk analysis*).
4. **Test for chemical reactivity.** This practice may be necessary when reactivity data is not available from other sources (*process safety information / process knowledge management*).
5. **Assess chemical reactivity risks.** This practice involves assessing how chemical reactivity hazards may lead to adverse events at the specified facility (*process hazard analysis / hazard identification and risk analysis*).
6. **Identify process controls and risk management options.** This practice involves using inherently safer design as well as passive, active, or procedural safeguards to eliminate or control hazards. Strategies could include using alternative chemicals that are less hazardous, using bar code systems for chemicals used in the process, installing chemical detection alarm systems, using ventilation systems to remove hazardous reaction products, and so on (*process hazard analysis / hazard identification and risk analysis*).
7. **Document chemical reactivity risks and management decisions.** This practice includes documenting the technical basis for procedures, controls, and process design; documenting past incidents, investigation findings, and corrective actions; retaining research and development information; and so on (*process safety information, process hazard analysis, operating procedures / process knowledge management, hazard identification and risk analysis*).
8. **Communicate and train on chemical reactivity hazards.** This practice includes regularly training employees and contractors on chemical reactivity hazards. (*training, contractors / training and performance assurance, hazard identification and risk analysis*).

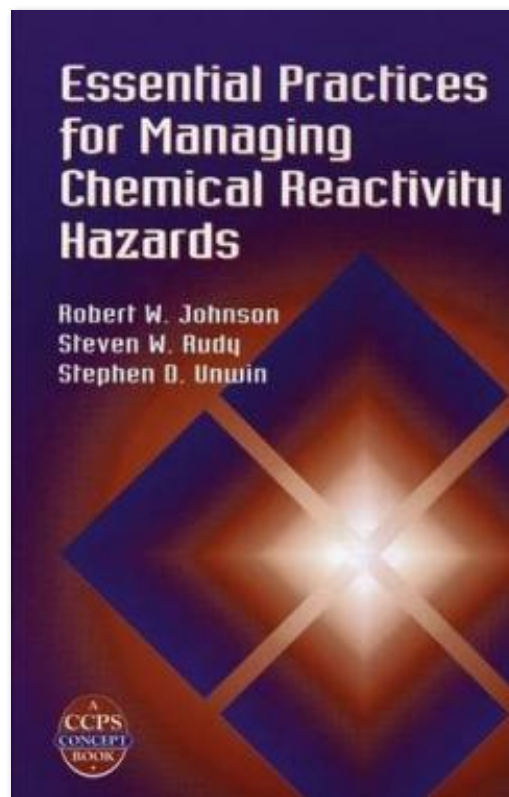


Figure 17. Cover of CCPS *Essential Practices for Managing Chemical Reactivity Hazards*. (Credit: CCPS [19])

9. **Investigate chemical reactivity incidents.** This practice involves reporting and investigating every incident or near miss involving or that could have involved chemical reactivity hazards, with the objective to prevent future similar events (*incident investigation / incident investigation*).
10. **Review, audit, manage change in, and improve hazard management practices and programs.** This practice leads to continual improvement of the reactive hazard management program (*compliance audits, management of change / auditing, management of change, process safety competency*).

The CSB issues a recommendation to AB Specialty to establish a process safety management system at the AB Specialty Waukegan, Illinois facility. Include in that system elements recommended in industry guidance publications, for example Center for Chemical Process Safety (CCPS) publications *Guidelines for Risk Based Process Safety* and *Guidelines for Implementing Process Safety Management*. The CSB also recommends that AB Specialty incorporate into operations and activities the specific elements recommended in CCPS's *Essential Practices for Managing Chemical Reactivity Hazards*, which are:

1. Put into place a system to manage chemical reactivity hazards
2. Collect reactivity hazard information
3. Identify chemical reactivity hazards
4. Test for chemical reactivity
5. Assess chemical reactivity risks
6. Identify and implement process controls and risk management options
7. Document chemical reactivity risks and management decisions
8. Communicate and train on chemical reactivity hazards
9. Investigate chemical reactivity incidents
10. Review, audit, manage change in, and improve hazard management practices and programs

3.10 Regulatory Coverage of Reactive Hazards

Chemical reactions can rapidly release heat, energy, and hazardous byproducts, and *uncontrolled* chemical reactions—like the one experienced in the AB Specialty incident—can lead to major explosions, fires, or toxic emissions that can cause death, injury, property damage, and negative effects in the environment.

To manage chemical process safety and to help prevent major incidents, in 1992 OSHA promulgated the PSM Standard (29 CFR 1910.119), and in 1996 the EPA promulgated its Risk Management Plan (RMP) Rule (40 CFR 68). These regulations require chemical facilities to manage process safety to protect workers, members of the public, and the environment. Each regulation covers facilities that process certain chemicals; the OSHA PSM Standard covers processes using flammable materials and individually listed chemicals that present a range of hazards, and the EPA RMP rule identifies covered substances based on flammability and toxicity.

While these regulations achieve improved process safety for many chemical processing facilities in the United States, they contain a critical coverage gap: neither standard adequately covers facilities processing chemicals that could undergo hazardous chemical reactions. Significantly, while AB Specialty processed chemicals capable of undergoing a highly hazardous chemical reaction that resulted in a large explosion and four fatalities, the chemicals used at the AB Specialty facility are not listed for coverage in either the OSHA PSM or EPA RMP regulations. AB Specialty was not covered by the OSHA PSM or EPA RMP regulations and was not required to implement baseline process safety management system elements to manage the safety of its processes under these regulations.

When no OSHA standard addresses a specific hazard, OSHA may use paragraph 5(a)(1) of the OSH Act (known as the General Duty Clause) to cite an employer. The General Duty Clause states:

Each employer shall furnish to each of his employees employment and a place of employment which are free from recognized hazards that are causing or likely to cause death or serious physical harm to his employees.

Therefore, the CSB concludes that in the absence of a standard addressing a specific hazard, AB Specialty was still responsible for creating a workplace that was safe for its employees and protecting them from hazards, pursuant to OSHA’s General Duty Clause. OSHA conducted their own inspection of AB Specialty, issued multiple willful violations, proposed a penalty of approximately \$1.6 million, and placed the company in the Severe Violator Enforcement Program (SVEP)^a [21], [22]. At the time of this report, AB Specialty has contested the citations and remains in the SVEP.

3.10.1 Controlling Hazards through Effective Process Safety Management Systems

The OSHA PSM Standard includes 14 elements, which together constitute a *process safety management system*. The EPA RMP rule has elements similar to those of the OSHA PSM Standard. OSHA states that “the key provision of PSM is process hazard analysis (PHA)—a careful review of what could go wrong and what safeguards must be implemented to prevent releases of hazardous chemicals” [23]. The PSM Standard states that “the process hazard analysis shall be performed by a team with expertise in engineering and process operations.... The employer shall establish a system to promptly address the team’s findings and recommendations; assure that the recommendations are resolved in a timely manner and that the resolution is documented; document what actions are to be taken; complete actions as soon as possible; develop a written schedule of when these actions are to be completed; [and] communicate the actions to operating, maintenance and other employees whose work assignments are in the process and who may be affected by the recommendations or actions.”^b

^a OSHA’s [Severe Violator Enforcement Program](#) concentrates resources to inspect “employers who have demonstrated indifference to their OSH Act obligations by committing willful, repeated, or failure-to-abate violations. Enforcement actions for severe violator cases include mandatory follow-up inspections, increased company/corporate awareness of OSHA enforcement, corporate-wide agreements, where appropriate, enhanced settlement provisions, and federal court enforcement” [42].

^b 29 CFR 1910.119(e).

The CSB concludes:

- AB Specialty did not perform an effective process hazard analysis.
- An effective process hazard analysis could have identified the hazards discussed in this report, including hazards associated with (1) mixing of incompatible chemicals, (2) storing incompatible materials in the emulsions area in similar drums, (3) batch tanks that were not equipped to vent hazardous gases to a safe location, and (4) a ventilation system that could disperse flammable gases throughout the production building. The process hazard analysis could also have identified corrective actions to control these hazards and could have identified the need for a hydrogen detection and alert system.
- AB Specialty is not covered by process safety management regulations requiring a process hazard analysis be conducted.

3.10.2 CSB Reactive Hazard Study

In 2002, the CSB published a hazard investigation report called *Improving Reactive Hazard Management* (known as the Reactive Hazard Study). In that study, the CSB examined the process safety of chemical reactivity hazards in the United States and analyzed 167 known reactive chemical incidents that occurred between 1980 and 2001. Some of the objectives of the study were to determine the impacts of reactive chemical incidents; examine how industry, OSHA, and the EPA address reactive chemical hazards; and develop recommendations for reducing the number and severity of reactive chemical incidents [24, p. 3].

The CSB Reactive Hazard Study found that while the OSHA PSM Standard does cover some reactive chemicals, many other reactive chemicals that could contribute to catastrophic incidents are not covered. The PSM Standard covers flammable chemicals (based on flashpoint) and a specified list of 137 toxic and reactive chemicals at facilities that process certain threshold quantities of those chemicals. Of the 137 toxic and reactive chemicals covered by the OSHA PSM Standard, the Standard considers only 38 to be highly reactive. These 38 chemicals were selected for coverage by the PSM Standard from an existing list of chemicals identified and rated by the National Fire Protection Association (NFPA) because of their instability rating (formerly reactivity rating) of 3 or 4, on a scale of 0 to 4. The CSB found that this coverage technique is inadequate because, of the 167 incidents studied in the Reactive Hazard Study, only about 10 percent involved chemicals that had an NFPA instability rating of 3 or 4. The CSB then examined the effect if the PSM Standard coverage were expanded to also include NFPA instability ratings of 1 and 2, but found that this approach would still address fewer than half of the chemicals involved in the 167 incidents studied (**Figure 18**) [24, pp. 48-49]. Importantly, neither KOH nor AB Specialty's XL 10 (methylhydrogensiloxane dimethylsiloxane copolymer), which reacted to cause the May 3, 2019, incident, is covered by the OSHA PSM Standard.

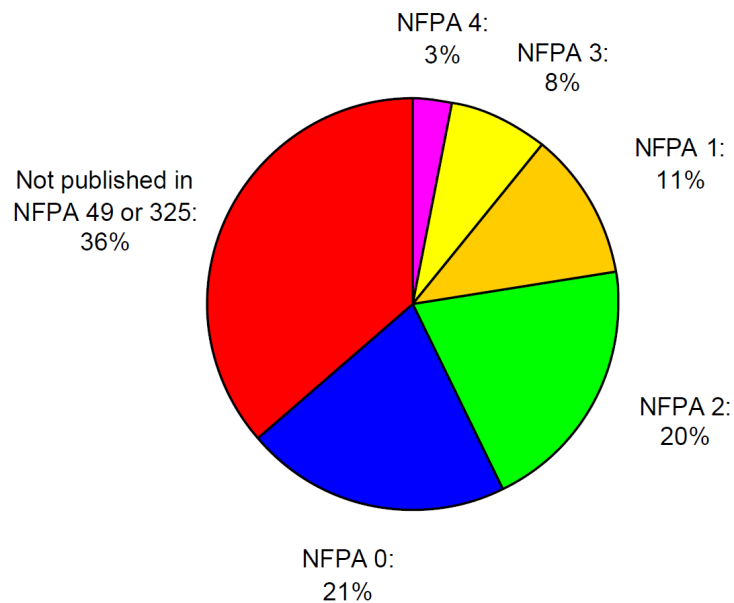


Figure 18. NFPA instability rating analysis of substances in incident data from 1980 to 2001 examined in the CSB Reactive Hazard Study. (Credit: CSB [24, p. 48])

The CSB Reactive Hazard Study gave the following critique of the use of the NFPA classification system to determine regulatory coverage of reactive hazards:

For the purpose of the OSHA PSM Standard, NFPA instability ratings have the following limitations with respect to identifying reactive hazards:

- They were originally designed for initial emergency response purposes, not for application to chemical process safety.
- They address inherent instability only, not reactivity with other chemical substances (with the exception of water) or chemical behavior under nonambient conditions.
- NFPA Standard 49—on which the OSHA PSM-listed highly reactive chemicals are based—covers only 325 chemical substances, a very small percentage of the chemicals used in industry.
- The OSHA PSM Standard lists 137 highly hazardous chemicals—only 38 of which are considered highly reactive based on NFPA instability ratings of “3” or “4.”
- The NFPA ratings were established by a system that relies, in part, on subjective criteria and judgment. [24, p. 6]

The CSB concluded in the Reactive Hazard Study that “[t]he OSHA PSM Standard has significant gaps in coverage of reactive hazards because it is based on a limited list of individual chemicals with inherently reactive properties,” and “NFPA instability ratings are insufficient as the sole basis for determining coverage of reactive hazards in the OSHA PSM Standard” [24, p. 10].

The CSB also found significant gaps with the EPA RMP rule. The CSB found that the EPA RMP rule does not specifically target reactive chemicals. Regarding the EPA RMP rule, the CSB Reactive Hazard Study stated:

When developing the [EPA RMP] list of [covered] substances, EPA considered only the inherent characteristics of a chemical that indicate a severe threat due to exposure. Well-defined criteria were used for toxicity and flammability. However, because of the complexities of site-specific factors and process conditions, EPA was unable to determine any inherent characteristic as an indicator of reactivity. EPA concluded that there was “insufficient technical information for developing criteria for identifying reactive substances.” Consequently, the January 1994 list of 130 chemicals does not contain any substances listed due to reactive hazards. [24, p. 60]

Similar to the gap in the OSHA PSM Standard, the chemicals involved in the AB Specialty incident are not covered by the EPA RMP program. The CSB concluded in the Reactive Hazard Study that “the EPA RMP has significant gaps in coverage of reactive hazards” [24, p. 61].

Based on these observed difficulties experienced by both OSHA and the EPA with predefining reactive chemicals to be covered by the PSM Standard and RMP rule, the CSB concluded in the Reactive Hazard Study that “[u]sing lists of chemicals is an inadequate approach for regulatory coverage of reactive hazards. Improving reactive hazard management requires that both regulators and industry address the hazards from *combinations of chemicals* and *process-specific conditions* rather than focus exclusively on the inherent properties of individual chemicals” [24, p. 10] (emphasis added).

The CSB recommended to OSHA, in part, the following:

Amend the Process Safety Management Standard (PSM), 29 CFR 1910.119, to achieve more comprehensive control of reactive hazards that could have catastrophic consequences. Broaden the application to cover reactive hazards resulting from process-specific conditions and combinations of chemicals. Additionally, broaden coverage of hazards from self-reactive chemicals. In expanding PSM coverage, use objective criteria. Consider criteria such as the North American Industry Classification System (NAICS), a reactive hazard classification system (e.g., based on heat of reaction or toxic gas evolution), incident history, or catastrophic potential. [24, p. 89]

The CSB also issued a recommendation to the EPA, stating:

Revise the Accidental Release Prevention Requirements, 40 CFR 68, to explicitly cover catastrophic reactive hazards that have the potential to seriously impact the public, including those resulting from self-reactive chemicals and combinations of chemicals and process-specific conditions. [24, p. 91]

Neither OSHA nor the EPA has implemented these recommendations [25], and reactive chemicals still are not adequately covered by either regulatory standard.

3.10.2.1 Reactive Chemical Incidents Investigated by the CSB after the Reactive Hazard Study

After the publication of the CSB Reactive Hazard Study, the CSB investigated an additional six reactive process incidents between 2002 and 2019 in which the chemicals involved were not covered by the OSHA PSM and EPA RMP regulations. Those incidents are summarized below:

- **First Chemical Corporation reactive explosion (October 13, 2002).** Steam caused mononitrotoluene (MNT) in a distillation tower to decompose and explode. The force of the explosion blew off the upper 35 feet of the tower and sent tons of debris flying up to a mile away. One piece of the tower punctured a storage tank approximately 500 feet away that contained more than 100,000 gallons of MNT, igniting a fire that burned for about three hours. Another piece of debris, weighing six tons, narrowly missed hitting a crude oil tank at an adjacent refinery. A third fragment struck a pipe rack directly above a tank containing 500,000 pounds of toxic anhydrous ammonia, but the tank was spared. Three workers were injured [26]. MNT is not covered by either the OSHA PSM or the EPA RMP regulations.
- **T2 Laboratories Inc. reactive chemical explosion (December 19, 2007).** A runaway exothermic reaction occurred during a batch operation producing methylcyclopentadienyl manganese tricarbonyl (MCMT), due to a loss of cooling. The reactor burst and the reactor contents ignited, creating an explosion equivalent to 1,400 pounds of TNT. Four employees were killed, the facility was destroyed, and 32 people were injured—including 4 employees and 28 members of the public. Debris from the reactor was found up to one mile away [27]. The chemicals involved in the incident are not covered by either the OSHA PSM or the EPA RMP regulations.
- **Airgas nitrous oxide explosion (August 28, 2016).** The CSB determined that a pump likely lost prime or ran dry during a nitrous oxide transfer, causing a temperature increase that likely initiated a nitrous oxide decomposition reaction, causing an explosion. One worker was killed [28]. Nitrous oxide is not covered by either the OSHA PSM or EPA RMP regulations.
- **MGPI Processing Inc. gas leak (October 21, 2016).** During a chemical delivery to a processing plant, sulfuric acid was inadvertently charged to a tank containing sodium hypochlorite. These chemicals reacted to produce a gas cloud containing chlorine gas and other compounds. Four MGPI employees, the chemical delivery driver, and over 140 community members sought medical attention after exposure to the toxic gas cloud [29]. Neither sulfuric acid nor sodium hypochlorite is covered by the OSHA PSM or EPA RMP regulations. Although chlorine is covered by both regulations because it was a reaction product, it did not trigger coverage by these regulations.
- **Midland Resource Recovery explosions (May 24, 2017, and June 20, 2017).** Reactive, unstable chemicals exploded when workers tried to drain uncharacterized, chemically treated liquid from natural gas odorizer equipment. Two workers were killed, and one worker was severely injured [30]. The chemicals involved in the explosions are not covered by the OSHA PSM and EPA RMP regulations.
- **AB Specialty chemical reaction, explosion, and fire (May 3, 2019).** This incident is the subject of this report. The chemicals involved in the incident are not covered by the OSHA PSM and EPA RMP regulations.

3.10.3 Need for Coverage of Reactive Chemical Hazards in the PSM and RMP Regulations

Reactive chemical incidents at chemical processing facilities continue to occur, at times with serious consequences. The CSB concludes that improved coverage of reactive chemicals by the OSHA PSM and EPA RMP regulations would help prevent future highly hazardous chemical reactivity incidents. Despite CSB issuing recommendations to OSHA and EPA to cover reactive hazards and repeatedly reiterating them in other investigation reports, they have not been implemented;^a neither OSHA nor the EPA has improved the PSM or RMP standards to increase coverage of reactive chemicals.

Illustrating the lack of adequate regulatory requirements governing this facility, all of the OSHA citations issued to AB Specialty after the incident related only to controlling ignition sources [31]—there was no other relevant regulation-required topic area that OSHA could cite. And significantly, in 2013 and 2014, respectively, both OSHA and the EPA published requests for information (RFIs) for public input on potential changes to the PSM and RMP regulations, including expanding coverage requirements for reactivity hazards [32], [33]. OSHA's RFI even stated that "OSHA has long been aware of the need to update the PSM Standard to address hazards associated with reactive chemicals" [32]. The CSB responded to the RFIs, strongly encouraging both OSHA and the EPA to expand their regulations to cover reactivity hazards [34], [35]. Neither agency, however, has implemented changes to cover reactivity hazards.

The CSB concludes that both the OSHA PSM and EPA RMP regulations should be amended to cover reactive hazards that could have catastrophic consequences. The CSB reiterates a recommendation to OSHA from the CSB Reactive Hazard Study to amend the PSM Standard, 29 CFR 1910.119, to achieve more comprehensive control of reactive hazards that could have catastrophic consequences. The CSB also reiterates a recommendation to EPA from the CSB Reactive Hazard Study to revise the Accidental Release Prevention Requirements, 40 CFR 68, to explicitly cover catastrophic reactive hazards that have the potential to seriously impact the public, including those resulting from self-reactive chemicals and combinations of chemicals and process-specific conditions. Take into account the recommendations of this report to OSHA on reactive hazard coverage. Seek congressional authority if necessary to amend the regulation.

4 AB Specialty Post-Incident Actions

Since the incident, AB Specialty communicated to the CSB that it has hired a full-time environmental health and safety (EHS) professional with experience in reactivity safety management and comprehensive EHS management to, among other things, evaluate and implement the CSB's recommendations. AB Specialty has also utilized an outside firm to conduct certain reactivity analyses. In March 2021, AB Specialty achieved ISO 45001 occupational health and safety management systems certification.

^a These recommendations are listed as "Open—Unacceptable Response / No Response Received" on the CSB website [25].

5 Conclusions

5.1 Findings

1. Weather was not a factor in the outcome of this incident.
2. There is sufficient evidence to determine that the combination of three chemicals—XL 10, TD 6/12 Blend, and 10% KOH—caused the chemical reaction leading to an explosion at AB Specialty on May 3, 2019.
3. Operator 1 added 10% KOH to the tank with XL 10 and TD 6/12 Blend, which reacted to produce hydrogen gas that subsequently ignited to cause the explosion.
4. The batch ticket did not include 10% KOH, and 10% KOH was not intended to be introduced to the batch at this point in the process.
5. The process upset produced hydrogen gas, though secondary reactions and associated reaction products were also possible, but were not considered causal to the explosion.
6. Operator 1 was an experienced operator who had previously performed batch operations at AB Specialty.
7. Because Operator 1 was fatally injured in the incident, the CSB investigation team could not obtain his account of the events leading to the incident. However, based on interviews with surviving personnel, the CSB investigation team concluded that Operator 1 did not know what had caused the process upset.
8. Numerous proximate safety gaps could have caused or contributed to the introduction of XL 10, TD 6/12 Blend, and 10% KOH in the quantities required to produce the reaction and subsequent explosion, including deficiencies in the methods AB Specialty stored and handled incompatible materials—such as allowing incompatible materials to be stored near each other in nearly identical blue 55-gallon drums, and failures with AB Specialty’s procedural controls—including operator and supervisor non-adherence to the company’s double initial procedure.
9. There is insufficient evidence to determine the degree to which any one company-level gap or failure contributed to the introduction of 10% KOH to the batch process. Rather, this incident demonstrates there were multiple safety gaps leading to the incident, and all should be corrected to prevent future similar incidents.
10. AB Specialty’s technical service request process did not and was not intended to assess the hazards of performing a process operation or to establish safeguards to reduce risk.
11. AB Specialty did not take sufficient action to improve its hazard analysis program after finding that a lack of a comprehensive hazard analysis contributed to its 2014 drum explosion.
12. AB Specialty did not perform a thorough hazard analysis of the EM 652 batch process despite known associated hazards and likelihood for the product and individual chemical component(s) to produce hydrogen.

13. Due to the lack of an effective hazard analysis program, AB Specialty did not identify the hazards associated with (1) storing reactive chemicals in similar containers, (2) the practice of allowing incompatible materials to be stored near each other, (3) the ventilation system and batch tank design, (4) the lack of a gas detection system, or (5) its insufficient emergency preparedness.
14. Using public resources such as the Chemical Reactivity Worksheet to identify reactive hazards is a way companies can gather process safety information (PSI) for use in process hazard analyses (PHAs) to identify process hazards and establish safeguards to protect from those hazards. Gathering PSI and performing PHAs are elements of a process safety management system.
15. All chemicals that could be added to a batch must be listed on the batch ticket. During PHAs, this practice will provide the opportunity for individuals who are knowledgeable of the reactivity hazard to identify ways to prevent hazardous chemical reactions.
16. Up to eleven nearly identical drums containing incompatible chemicals were in the immediate process area at the start of the second batch.
17. AB Specialty's lack of procedures likely led to incompatible 10% KOH and XL 10 remaining in the emulsions area after their use in the first batch, contributing to the mixing of these two chemicals on the night of the incident.
18. Once the drum bung caps were removed, the drums that stored 10% KOH and XL 10 looked nearly identical.
19. The similar appearance of the XL 10 and 10% KOH drums likely contributed to Operator 1 adding the incorrect chemical to the EM 652 batch process.
20. In batch operations that rely on operators to gather and mix chemicals, it is critical that batch processing facilities reduce the risk of human error by making it easy to do the job right and hard to do the job wrong.
21. As a result of the tank having an open hatch-type lid and no vent pipe to vent gases to a safe location, the hydrogen gas produced during the incident vented directly into the production building, where workers were located.
22. The ventilation system, which included a manually operated air mover designed to introduce outside air to the building and was positioned near the location where EM 652 was being manufactured, may have helped distribute the hydrogen in the production building and mix it with air, creating a large and explosive gas cloud.
23. An alternative ventilation design, such as local exhaust ventilation or an extraction system, in which building air discharge fans and vents are located in the process area could have vented released hazardous gases to a safe location, and in this case could have reduced the severity of the explosion.
24. The lack of a system to detect hydrogen gas and automatically activate an alarm contributed to personnel remaining inside the production building between the start of the hydrogen release and the time of ignition, thereby contributing to the severity of the event.

25. There are numerous gas detection technologies, each with advantages and disadvantages. Not all gas detection technologies will work with all materials (e.g., hydrogen gas, silicone, etc.).
26. Facilities must communicate the planned application and operating environment with the gas detector manufacturer to help ensure the correct sensor technology is selected, properly installed, and adequately maintained.
27. AB Specialty should identify and install a hydrogen gas detection and alarm system, and associated preventive maintenance program, that is effective in AB Specialty's unique production environment.
28. Without gas detectors and alarms alerting of the hazardous conditions, or effective training, the workers did not realize the necessity to evacuate.
29. For chemicals that could experience hazardous chemical reactions, companies need to ensure that workers have the appropriate resources—such as through technology and training—to recognize the signs of an adverse reaction and to respond appropriately.
30. The occurrence of the May 3 incident indicates that AB Specialty's double initial procedure program did not prevent a wrong material from being added to the tank.
31. Numerous safety gaps could have caused or contributed to the mixing of the incompatible chemicals, including insufficient guidance for operators and supervisors for all phases necessary to prevent known catastrophic chemical reactions; insufficient or incomplete training for operators and supervisors on the existing procedures; insufficient training on the potential for hydrogen to be produced with XL 10; and insufficient reinforcement of strictly adhering to all procedures.
32. Applying the hierarchy of controls at the design phase is the best opportunity to ensure that process hazards are properly analyzed and risks are effectively reduced, before the design is implemented in the field.
33. After the design phase, when construction is complete and the process is operating, process safety management system elements such as PHAs are important opportunities to apply the hierarchy of controls to further reduce risk throughout the life of a process.
34. AB Specialty knew that the EM 652 process and the individual ingredient, XL 10, could produce hydrogen gas.
35. It is reasonable to assume that AB Specialty knew that hydrogen gas is colorless, lacks olfactory indications, and is flammable in air at concentrations between a lower explosive limit of 4 volume percent and an upper explosive limit of 75 volume percent.
36. AB Specialty had a weak process safety culture.
37. Implementing the process safety culture guidance in CCPS's *Guidelines for Risk Based Process Safety* can help AB Specialty improve its process safety culture.
38. Effective safety management systems that address process safety are critical to prevent future reactive chemical incidents.

39. Safety at the Waukegan, Illinois AB Specialty facility would improve from an established safety management system that addresses process safety at the AB Specialty Waukegan, Illinois facility.
40. In the absence of a standard addressing a specific hazard, AB Specialty was still responsible for creating a workplace that was safe for its employees and protecting them from hazards, pursuant to OSHA's General Duty Clause.
41. AB Specialty did not perform an effective process hazard analysis.
42. An effective process hazard analysis could have identified the hazards discussed in this report, including hazards associated with (1) mixing of incompatible chemicals, (2) storing incompatible materials in the emulsions area in similar drums, (3) batch tanks that were not equipped to vent hazardous gases to a safe location, and (4) a ventilation system that could disperse flammable gases throughout the production building. The process hazard analysis could also have identified corrective actions to control these hazards and could have identified the need for a hydrogen detection and alert system.
43. AB Specialty is not covered by process safety management regulations requiring a process hazard analysis be conducted.
44. The OSHA PSM Standard has significant gaps in coverage of reactive hazards because it is based on a limited list of individual chemicals with inherently reactive properties.
45. NFPA instability ratings are insufficient as the sole basis for determining coverage of reactive hazards in the OSHA PSM Standard.
46. The EPA RMP has significant gaps in coverage of reactive hazards.
47. Using lists of chemicals is an inadequate approach for regulatory coverage of reactive hazards. Improving reactive hazard management requires that both regulators and industry address the hazards from combinations of chemicals and process-specific conditions rather than focus exclusively on the inherent properties of individual chemicals.
48. Improved coverage of reactive chemicals by the OSHA PSM and EPA RMP regulations would help prevent future highly hazardous chemical reactivity incidents.
49. Both the OSHA PSM and EPA RMP regulations should be amended to cover reactive hazards that could have catastrophic consequences.

5.2 Cause

The CSB determined that the cause of the incident were deficiencies in AB Specialty's operations, policies, and practices including its hazard analysis program, methods used to store and handle incompatible materials, its double initial procedure program, process safety culture weaknesses, and the lack of a safety management system addressing process safety. These deficiencies led to an operator mixing incompatible chemicals, causing a reaction that produced hydrogen gas, which released and ignited in the AB Specialty production building. Contributing to the severity of the incident were AB Specialty's batch equipment and ventilation system design, the lack of a gas detection and alarm system, and ineffective emergency preparedness.

6 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:

6.1 Previously Issued Recommendations Reiterated in This Report

6.1.1 Occupational Safety and Health Administration (OSHA)

2001-01-H-R1

Amend the Process Safety Management Standard (PSM), 29 CFR 1910.119, to achieve more comprehensive control of reactive hazards that could have catastrophic consequences.

- Broaden the application to cover reactive hazards resulting from process-specific conditions and combinations of chemicals. Additionally, broaden coverage of hazards from self-reactive chemicals. In expanding PSM coverage, use objective criteria. Consider criteria such as the North American Industry Classification System (NAICS), a reactive hazard classification system (e.g., based on heat of reaction or toxic gas evolution), incident history, or catastrophic potential.
- In the compilation of process safety information, require that multiple sources of information be sufficiently consulted to understand and control potential reactive hazards. Useful sources include:
 - Literature surveys (e.g., *Bretherick's Handbook of Reactive Chemical Hazards*, *Sax's Dangerous Properties of Industrial Materials*)
 - Information developed from computerized tools (e.g., ASTM's CHETAH, [CCPS]'s The Chemical Reactivity Worksheet)
 - Chemical reactivity test data produced by employers or obtained from other sources (e.g., differential scanning calorimetry, thermogravimetric analysis, accelerating rate calorimetry)
 - Relevant incident reports from the plant, the corporation, industry, and government
 - Chemical Abstracts Service
- Augment the process hazard analysis (PHA) element to explicitly require an evaluation of reactive hazards. In revising this element, evaluate the need to consider relevant factors, such as:
 - Rate and quantity of heat or gas generated
 - Maximum operating temperature to avoid decomposition
 - Thermal stability of reactants, reaction mixtures, byproducts, waste streams, and products

- Effect of variables such as charging rates, catalyst addition, and possible contaminants
- Understanding the consequences of runaway reactions or toxic gas evolution

6.1.2 Environmental Protection Agency (EPA)

2001-01-H-R3

Revise the Accidental Release Prevention Requirements, 40 CFR 68, to explicitly cover catastrophic reactive hazards that have the potential to seriously impact the public, including those resulting from self-reactive chemicals and combinations of chemicals and process-specific conditions. Take into account the recommendations of this report to OSHA on reactive hazard coverage. Seek congressional authority if necessary to amend the regulation.

6.2 Recommendation to AB Specialty Silicones, LLC

2019-03-I-IL-R1

Develop hazardous gas detection and alarm programs and associated procedures based on manufacturer specifications, current codes, standards, and industry good practice guidance, for all hazardous gases that could be released near workers, including hydrogen. The program must address proper installation, calibration, inspection, maintenance, training, and routine operations. Ensure such hazardous gas detection and alarm systems are functional at all times.

2019-03-I-IL-R2

Establish a safety management system that addresses process safety at the AB Specialty Waukegan, Illinois facility. Include in that system elements recommended in industry guidance publications, including Center for Chemical Process Safety (CCPS) publications *Guidelines for Risk Based Process Safety* and *Guidelines for Implementing Process Safety Management*.

2019-03-I-IL-R3

Incorporate into operations and activities at AB Specialty the specific elements recommended in CCPS's *Essential Practices for Managing Chemical Reactivity Hazards*, which are:

1. Put into place a system to manage chemical reactivity hazards
2. Collect reactivity hazard information
3. Identify chemical reactivity hazards
4. Test for chemical reactivity
5. Assess chemical reactivity risks
6. Identify and implement process controls and risk management options

7. Document chemical reactivity risks and management decisions
8. Communicate and train on chemical reactivity hazards
9. Investigate chemical reactivity incidents
10. Review, audit, manage change in, and improve hazard management practices and programs

7 Key Lessons for the Industry

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

1. Companies should make manual operations easy to do right and hard to do wrong. This can be accomplished through systematically evaluating manual operations, identifying potential opportunities for those operations to be performed incorrectly, and then establishing safeguards and controls that help minimize the potential for errors.
2. Using public resources such as the Chemical Reactivity Worksheet to identify reactive hazards is a way companies can gather process safety information relating to hazards of materials. Companies must then conduct effective process hazard analyses to identify process hazards and establish safeguards to protect from those hazards.
3. Companies that handle reactive or incompatible chemicals should establish methods and safeguards to prevent the wrong mixing of those chemicals. Safeguards can include storing incompatible materials in dissimilar containers, storing incompatible materials in different areas at the facility, and using bar coding systems to verify chemicals before mixing, among other practices.
4. Equipment that handles materials with the potential to develop hazardous gases should be vented to a safe location, away from personnel and away from structures that could confine the hazardous gases.
5. Companies that handle hazardous materials inside buildings should design ventilation systems such that the ventilation discharge is positioned to remove hazardous materials from the building, rather than using a design that allows incoming air to disperse hazardous materials throughout the building.
6. Companies that handle hazardous materials need to ensure that facilities are equipped to detect and alert employees of a hazardous material release—through means such as gas detectors and alarms—and that personnel are trained on how to recognize and respond to hazardous material releases.
7. Double initial procedures should not be used as a sole safeguard to prevent mixing of incompatible materials.
8. Chemical processing facilities should assess and strengthen process safety culture to help prevent catastrophic chemical incidents by following industry best practice guidance, including guidance published by the Center for Chemical process Safety.

9. Companies that handle reactive chemicals need to establish a robust process safety management system to identify, evaluate, and control reactive and process hazards. Many industry guidance documents have been published on developing such systems, including *Essential Practices for Managing Chemical Reactivity Hazards*, *Guidelines for Risk Based Process Safety*, and *Guidelines for Implementing Process Safety Management*, all from the Center for Chemical Process Safety.

8 References

- [1] AB Specialty Silicones, "About," [Online]. Available: <https://www.andisil.com/#>. [Accessed 24 October 2019].
- [2] Global Silicones Council, "Materials Handling Guide: Hydrogen-Bonded Silicon Compounds," July 2016. [Online]. Available: <https://globalsilicones.org/wp-content/uploads/2020/10/Global-SiH-Manual.pdf>. [Accessed 9 September 2021].
- [3] International Electrotechnical Commission (IEC), *IEC 60079-29-2; Explosive Atmospheres - Part 29-2: Gas Detectors*, London: IEC, 2015.
- [4] A. Bahadori, *Hazardous Area Classification in Petroleum and Chemical Plants: A Guide to Mitigating Risk*, Boca Raton: Taylor & Francis Group, 2014.
- [5] General Monitors, "Fundamentals of Combustible Gas Detection," [Online]. Available: <http://s7d9.scene7.com/is/content/minesafetyappliances/Combustible%20Gas%20Detection%20White%20Paper>. [Accessed 2 June 2020].
- [6] U.S. Food & Drug Administration, "Good Manufacturing Practice (GMP) Guidelines/Inspection Checklist for Cosmetics," [Online]. Available: <https://www.fda.gov/cosmetics/cosmetics-guidance-documents/good-manufacturing-practice-gmp-guidelinesinspection-checklist-cosmetics>. [Accessed 20 January 2021].
- [7] Weather Underground, "Waukegan, IL Weather History," 3 May 2019. [Online]. Available: <https://www.wunderground.com/history/daily/us/il/waukegan/KUGN/date/2019-5-3>. [Accessed 29 April 2021].
- [8] Center for Chemical Process Safety (CCPS), "Chemical Reactivity Worksheet," 2 July 2019. [Online]. Available: <https://www.aiche.org/ccps/resources/chemical-reactivity-worksheet>. [Accessed 15 October 2020].
- [9] CCPS and American Institute of Chemical Engineers (AIChE), *Guidelines for Safe Storage and Handling of Reactive Materials*, Hoboken, NJ: Wiley & Sons, 1995.
- [10] A. Ness and R. Gibson, Rohm and Haas, "Handling Chemicals in Small Containers," in *American Institute of Chemical Engineers 2005 Spring National Meeting, 39th Annual Loss Prevention Symposium*, Atlanta, 2005.
- [11] Center for Chemical Process Safety / AIChE, *Guidelines for Process Safety in Batch Reaction Systems*, New York: American Institute of Chemical Engineers, 1999.
- [12] Seggerman, B, "Addressing Process Safety Challenges in Batch Tolling," in *AIChE 13th Global Congress on Process Safety*, San Antonio, 2017.
- [13] Dow Corning, "Safe Handling of Silicon Hydride Containing Polysiloxanes," 2018. [Online]. Available: <https://www.dow.com/content/dam/dcc/documents/en-us/tech-art/24/24-07/24-711-01-safe-handling-of-sih.pdf?iframe=true>. [Accessed 10 September 2020].
- [14] D. Nolan, *Handbook of Fire and Explosion Protection Engineering Principles of Oil, Gas, Chemical, and Related Facilities* (4th Edition), Houston: Gulf Professional Publishing, 2018.
- [15] Z. Yunusa, N. Hamidon, A. Kaiser and Z. Awang, "Gas Sensors: A Review, Sensors & Transducers," 2014. [Online]. Available: <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.434.3310&rep=rep1&type=pdf>. [Accessed 8 July 2020].
- [16] CCPS, *Inherently Safer Chemical Processes: A Life Cycle Approach*, 2nd ed., New York, NY: CCPS, 2009.
- [17] Center for Chemical Process Safety / American Institute of Chemical Engineers, *Conduct of Operations and Operational Discipline - For Improving Process Safety in Industry*, New Jersey: John Wiley & Sons, 2011.
- [18] CCPS, *Guidelines for Risk Based Process Safety*, Hoboken, NJ: John Wiley & Sons, 2007.
- [19] CCPS, *Essential Practices for Managing Chemical Reactivity Hazards*, New York: AIChE, 2003.
- [20] U.S. Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health (NIOSH), "NIOSH Pocket Guide to Chemical Hazards," [Online]. Available: <https://www.cdc.gov/niosh/npg/default.html>. [Accessed 15 October 2020].
- [21] United States Department of Labor Occupational Safety and Health Administration, "U.S. Department of Labor Issues \$1,591,176 in Penalties To AB Specialty Silicones After 4 Fatalities in Illinois Plant Explosion," 25 October 2019. [Online]. Available: <https://www.osha.gov/news/newsreleases/region5/10252019>. [Accessed 13 September 2021].

- [22] United States Department of Labor Occupational Safety and Health Administration, "Citation and Notification of Penalty-Inspection No: 1398632," 24 October 2019. [Online]. Available: <https://www.dol.gov/sites/dolgov/files/OPA/newsreleases/2019/10/osha20191849.pdf>. [Accessed 13 September 2021].
- [23] U.S. Occupational Safety and Health Administration (OSHA), "Process Safety Management (Information Booklet). OSHA 3132," 2000. [Online]. Available: <https://www.osha.gov/Publications/osha3132.html#problem>. [Accessed 2020 24 November].
- [24] U.S. Chemical Safety and Hazard Investigation Board (CSB), "Hazard Investigation: Improving Reactive Hazard Management. Report No. 2001-01-H," 2002. [Online]. Available: <https://www.csb.gov/improving-reactive-hazard-management/>. [Accessed 5 February 2021].
- [25] CSB, "Recommendations: Improving Reactive Hazard Management (24 Recommendations)," [Online]. Available: https://www.csb.gov/recommendations/?F_InvestigationId=3553. [Accessed 23 October 2020].
- [26] CSB, "First Chemical Corp. Reactive Chemical Explosion," 15 October 2003. [Online]. Available: <https://www.csb.gov/first-chemical-corp-reactive-chemical-explosion/>. [Accessed 23 October 2020].
- [27] CSB, "T2 Laboratories Inc. Reactive Chemical Explosion," 15 September 2009. [Online]. Available: <https://www.csb.gov/t2-laboratories-inc-reactive-chemical-explosion/>. [Accessed 23 October 2020].
- [28] CSB, "Nitrous Oxide Explosion - Airgas (Air Liquide)," 20 April 2017. [Online]. Available: <https://www.csb.gov/airgas-facility-fatal-explosion-/>. [Accessed 2 December 2020].
- [29] U.S. Chemical Safety Board, "Key Lessons for Preventing Inadvertent Mixing During Chemical Unloading Operations," 3 January 2018. [Online]. Available: <https://www.csb.gov/mgpi-processing-inc-toxic-chemical-release-/>. [Accessed 13 November 2020].
- [30] CSB, "Midland Resource Recovery Explosion," 17 December 2019. [Online]. Available: <https://www.csb.gov/midland-resource-recovery-explosion-/>. [Accessed 23 October 2020].
- [31] OSHA, "Citation and Notification of Penalty, Inspection Number 1398632," 24 October 2019. [Online]. Available: <https://www.dol.gov/sites/dolgov/files/OPA/newsreleases/2019/10/osha20191849.pdf>. [Accessed 16 November 2020].
- [32] OSHA, "Request for Information (OSHA-2013-0020)," 9 December 2013. [Online]. Available: <https://www.regulations.gov/document?D=OSHA-2013-0020-0001>. [Accessed 16 November 2020].
- [33] U.S. Environmental Protection Agency (EPA), "Request for Information (Document 2014-18037)," 31 July 2014. [Online]. Available: <https://www.federalregister.gov/documents/2014/07/31/2014-18037/accidental-release-prevention-requirements-risk-management-programs-under-the-clean-air-act-section>. [Accessed 16 November 2020].
- [34] R. Moure-Eraso, "CSB Letter in Response to Docket No. OSHA-2013-0020," 31 March 2014. [Online]. Available: https://www.csb.gov/assets/1/6/csb_rficommments1.pdf. [Accessed 16 November 2020].
- [35] R. Moure-Eraso, "CSB Response to Docket No. EPA-HQ-OEM-2014-0328," 29 October 2014. [Online]. Available: https://www.csb.gov/assets/1/6/epa_rfi2.pdf. [Accessed 16 November 2020].
- [36] E. Rochow, An Introduction to the Chemistry of the Silicones.
- [37] Gelest, "(25-35% METHYLHYDROSILOXANE) - DIMETHYLSILOXANE COPOLYMER, TRIMETHYLSILOXANE TERMINATED, Reduced Volatility, 25-35 cSt," [Online]. Available: <https://www.gelest.com/product/HMS-301R/>. [Accessed 10 September 2020].
- [38] U.S. Chemical Safety Board, "Board Order 22: Recommendations Program," [Online]. Available: https://www.csb.gov/assets/record/csb_board_order_022_final_20161.pdf.
- [39] U.S. Chemical Safety Board (USCSB), "Board Order 40: Investigation Program," [Online]. Available: https://www.csb.gov/assets/record/board_order_040_approved_2_14_17.pdf.
- [40] D. Ganguli and M. Ganguli, "Emulsions: A General Introduction," in *Inorganic Particle Synthesis via Macro and Microemulsions*, Boston, Springer, 2003, p. 1.
- [41] W. Bridges and T. Clark, "LOPA and Human Reliability - Human Errors and Human IPLs (Updated)," in *American Institute of Chemical Engineers, 2011 Spring Meeting, 7th Global Congress on Process Safety*, Chicago, 2011.
- [42] United States Department of Labor Occupational Safety and Health Administration, "Severe Violator Enforcement Program (SVEP) Directive: CPL 02-00-149," 8 June 2010. [Online]. Available: <https://www.osha.gov/enforcement/directives/cpl-02-00-149>. [Accessed 13 September 2021].

Appendix A—EM 652 Process Operations

Figure A-1 is a process schematic illustrating the equipment AB Specialty used to manufacture EM 652.

The first raw ingredient added into the Thick Phase Tank was XL 10. After adding multiple drums of XL 10, operators started the agitators. Subsequently, more ingredients were added and mixed into the Thick Phase Tank. Operators would then have to visually observe the materials in the tank to determine whether the process was ready to continue to the next step. While the Thick Phase Tank ran, water was added to the Water Phase Tank. When the process was completed in the Thick Phase Tank, the product would turn from a liquid to a stiff gel. Meanwhile, the water in the Water Phase Tank was circulating through a mixing chamber.

The stiff gel would be pumped from the Thick Phase Tank to a mechanical shearing device. This material was processed through the mechanical shearing device and into the mixing chamber with water from the Water Phase Tank, creating the right consistency in the product, which is like that of milk. The material from the mixing chamber was then fed into the Water Phase Tank. When the product was in the water phase, AB Specialty employees conducted several tests to ensure product quality. These tests were conducted by a QA chemist. Depending on the results of these analytical tests, AB Specialty employees might adjust the pH to bring the product into specification. Once the product is determined to be within specification, the operators are given approval to package. After the final product is packaged, an operator or supervisor will verify the completeness of the batch ticket documentation before it is turned over for administrative processing.

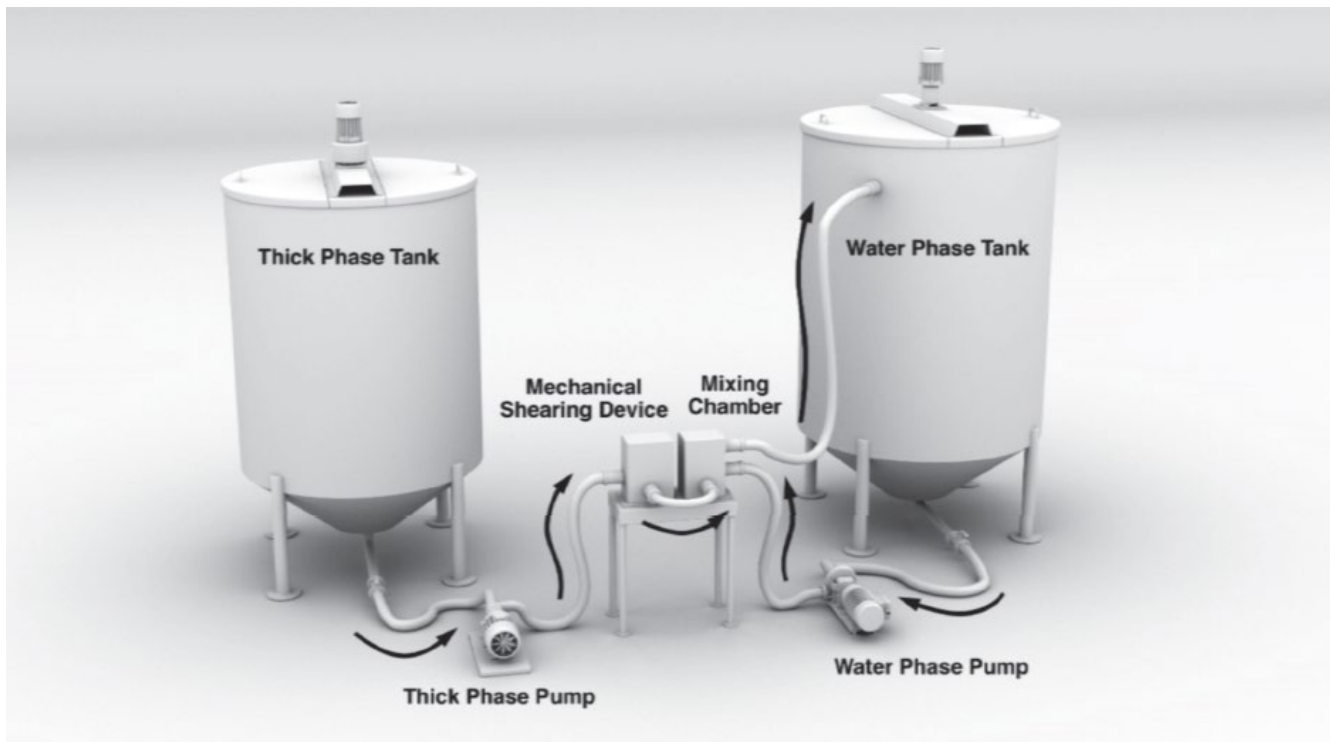


Figure A-1. Process schematic of the EM 652 batch process equipment. (Credit: CSB)

Appendix B—Hydrogen Generation Calculations

Chemical reactivity tests (**Appendix C**) found that a mixture of XL 10, TD 6/12 Blend, and a solution of 10 percent potassium hydroxide in water (10% KOH) produced both a flammable gas—hydrogen—and foaming consistent with witness observations from the day of the incident. The CSB-commissioned blast analysis (**Appendix D**) found that the ignition of a flammable gas cloud containing 41–42 pounds of hydrogen could have produced the blast damage observed at the AB Specialty facility. This appendix examines the reaction between XL 10, the 10% KOH solution, and TD 6/12 Blend, and calculates the theoretical maximum amount of hydrogen that could be produced from the quantities of these chemicals known to be in the emulsions area at the time of the incident.

XL 10 is a methylhydrogensiloxane dimethylsiloxane copolymer. The structure of this molecule, which has repeating methylhydrogensiloxane and dimethylsiloxane units, is shown in **Figure B-1**, with the silicon hydride (SiH) bond highlighted. The SiH bond in the copolymer has an “extreme chemical reactivity” with various chemicals, including bases and water [13].

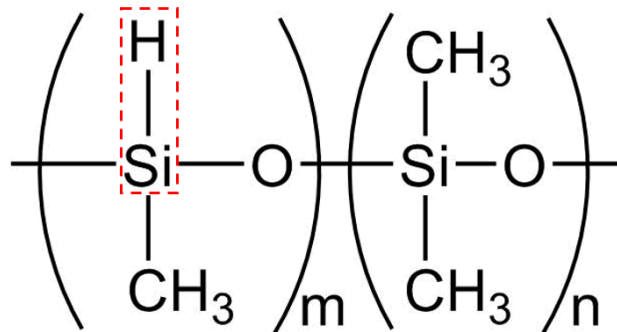


Figure B-1. Structure of the methylhydrogensiloxane dimethylsiloxane copolymer (the AB Specialty Silicones product commercially known as XL 10). (Credit: Gelest [37] with modifications by the CSB)

The KOH solution used by AB Specialty contained 10% KOH and 90% water. When 10% KOH, an aqueous base, contacts molecules with SiH bonds, the KOH catalyzes a reaction between the SiH and water, which produces hydrogen [36, p. 6]. This reaction is shown in **Figure B-2**.

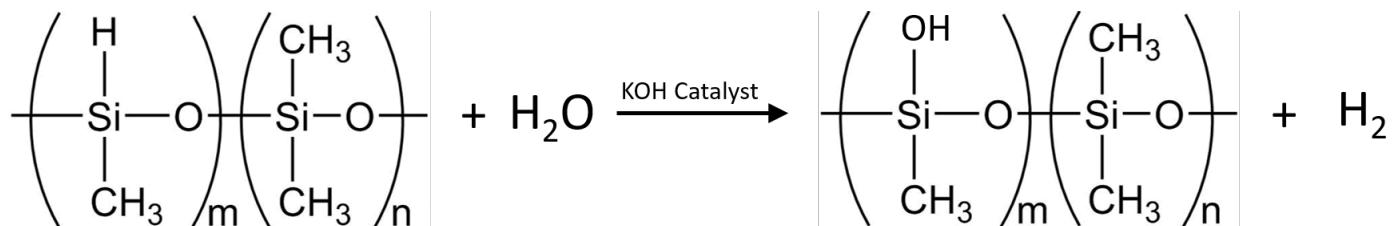


Figure B-2. Reaction between molecule with SiH bond and water in presence of KOH catalyst. (Credit: CSB, based on image from Gelest [37])

Theoretical Hydrogen Generation Calculations

This section details the calculations used by the CSB to determine the maximum amount of hydrogen that could be produced from a reaction involving XL 10, 10% KOH solution, and TD 6/12 Blend, using the quantities present at the time of the AB Specialty incident.

Defined Conditions	Quantity	Source
Weight of XL 10 in production vessel	3,348 lb	EM 652 batch ticket and XL 10 drums (one empty and one partially full) found post-incident indicate that all of the required XL 10 was charged to the batch process vessel.
Weight of TD 6/12 Blend in production vessel	468 lb	EM 652 batch ticket and witness statement that the operator was in the first steps of the EM 652 production (TD 6/12 Blend charge is second step). TD 6/12 Blend totes were damaged by the fire, and confirmation of the amount used in the batch is not possible.
Weight of 10% KOH solution in emulsions area	396 lb	CSB calculation based on inventory and KOH usage in first batch
Water content in TD 6/12 Blend	10 wt % (avg)	TD 6/12 Blend info sheet
SiH content in XL 10	$\frac{7.55 \text{ mmol SiH}}{\text{g XL10}}$ (avg)	AB Specialty product information for XL 10
Moles H ₂ produced per mole of SiH reacted	$\frac{1 \text{ mol H}_2}{1 \text{ mol SiH}}$	Reaction illustrated in Figure B-2
Moles H ₂ produced per mole of water reacted	$\frac{1 \text{ mol H}_2}{1 \text{ mol H}_2\text{O}}$	Reaction illustrated in Figure B-2
Molecular weight H ₂	$2.016 \frac{\text{g}}{\text{mol}}$	Known
Molecular weight H ₂ O	$18.02 \frac{\text{g}}{\text{mol}}$	Known

Determination of maximum amount of hydrogen that could be produced from quantity of XL 10

$$\begin{aligned}
 & 3,348 \text{ lbs XL10} * \frac{453.59 \text{ g XL10}}{1 \text{ lb XL10}} * \frac{7.55 \text{ mmol SiH}}{\text{g XL10}} * \frac{1 \text{ mol SiH}}{1,000 \text{ mmol SiH}} * \frac{1 \text{ mol H}_2}{1 \text{ mol SiH}} * \frac{2.016 \text{ g H}_2}{\text{mol H}_2} \\
 & \quad * \frac{1 \text{ lb H}_2}{453.59 \text{ g H}_2} \\
 & \qquad \qquad \qquad = 50.96 \text{ lbs H}_2
 \end{aligned}$$

Determination of maximum amount of hydrogen that could be produced from quantity of water**Determination of maximum amount of water in batch vessel**

$$(396 \text{ lb KOH Solution} * .90) + (468 \text{ lb TD6/12} * .10) = 403.2 \text{ lb H}_2\text{O}$$

Determination of maximum amount of hydrogen produced from water content

$$\begin{aligned}
 & 403.2 \text{ lb H}_2\text{O} * \frac{453.59 \text{ g H}_2\text{O}}{1 \text{ lb H}_2\text{O}} * \frac{1 \text{ mol H}_2\text{O}}{18.02 \text{ g H}_2\text{O}} * \frac{1 \text{ mol H}_2}{1 \text{ mol H}_2\text{O}} * \frac{2.016 \text{ g H}_2}{1 \text{ mol H}_2} * \frac{1 \text{ lb H}_2}{453.59 \text{ g H}_2} \\
 & \qquad \qquad \qquad = 45.11 \text{ lbs H}_2
 \end{aligned}$$

Conclusion

As shown above, water content was the limiting reactant in the production vessel for the reaction between SiH and water, catalyzed by KOH. The vessel contents could theoretically produce about 45 pounds of hydrogen. This supports the blast analysis (**Appendix D**), which determined that a flammable gas cloud containing about 41–42 pounds of hydrogen could cause the observed blast damage.

Appendix C—Chemical Reactivity Experiments and Results

Chemical reactivity experiments were conducted to help determine if there was an unintended addition of a substance during the EM 652 production on May 3, 2019. Below are the results of the chemical reactivity experiments.

Chemical Reactivity Experiments

Objectives

EM 652 had been fabricated prior to May 3, 2019 without the effects observed on the day of the incident (foaming, fog, heat, etc.). [...] A hypothesis was developed that the unintended addition of a substance (or a mix-up) occurred during the production process on May 3, 2019 that resulted in the rapid generation of hydrogen. To further evaluate that hypothesis, material reactivity tests were conducted. Based on the interviews with ABSS employees, known materials located at the [production] location, photographs and drone footage, known behavior of XL 10 in certain situations and the procedure for making EM 652 itself, it was concluded that there were three potential reagents available that could have caused the incident:

- 10% potassium hydroxide (KOH) in water by weight
- 85% phosphoric acid (H₃PO₄) in water by weight
- Glacial acetic acid (HAc)

[The firm's] testing focused on introducing these three materials at different stages of the EM 652 production process [...]. To summarize, the [first] steps for producing ... EM 652 included:

1. Addition of XL 10 and TD 6/12 [Blend] to [the batch tank], mix for 30 minutes
2. Mix water, Pel Alc 738, and glacial acetic acid in IBC/tote; add to [batch tank], continue mixing
3. Add 137 Silane, continue mixing

All tests were performed on a small scale, using a maximum of 100 ml (\approx 98 g) of the XL 10 material and adjusting the amount of all other reagents accordingly based on the ratios from the batch sheet. Initial reactivity tests included mixing XL 10 with water, H₃PO₄, and KOH. Further testing included the addition of each material in quantities equal to the amount of glacial acetic acid expected to have been added to the batch and the step during which it was added (during Step 1 or Step 2 as listed above).^a Once the reagent likely to have incited the violent reaction was identified, further tests were conducted to understand the necessary amounts and timing of the addition.

^a Note that these three steps do not reflect the numbered steps from the EM 652 batch sheet.

Experimental Methods

Three unique experimental setups were used; an open setup (**Figure C- 1**) and a closed system setup either using a flow meter or not (**Figure C- 2** and **Figure C- 3**, respectively). Tests were first conducted in the open system, in order to evaluate potential for a violent reaction. They were then run in one of the closed systems. The initial tests with XL 10 were run only in a closed setup.

In the open system, a 500 ml glass jar was used. Reagents were added and mixed using an IKA EURO-STPBS1 overhead mixer at 800 revolutions per minute. Temperature was measured using a thermocouple inserted into the reaction mixture. This work was performed outdoors.

The closed system setup utilized a 1000-ml, 3-necked round bottom flask with 24/40 ground glass joints. XL 10 and TD 6/12 Blend were directly added to the flask and all reagents later in the process were added via addition funnel. Some quantitative tests were performed under flowing nitrogen (N₂) gas at a rate of 50 ml/min to provide an inert atmosphere within the flask. The nitrogen and any gas produced by the reaction were routed through a flow meter with a range of 25 to 250 milliliters per minute (ml/min)^a to indicate the general rate of gas generation. From the flow meter, the gases were routed through a liquid "bubbler" to provide a visual indication of the relative rate of gas generation. This setup is shown in **Figure C- 2**. In the non-quantitative closed system setup, just a liquid "bubbler" was used; the flow meter and nitrogen purge were not used (**Figure C- 3**). In both closed system setups, the reaction mixture was stirred continuously using an egg-shaped magnetic stir bar at a rate of 800 revolutions per minute.

Initial XL 10 reactivity studies (10% KOH, 85% H₃PO₄, glacial acetic acid) were labeled according to the reactive material and the volume relative to the XL 10 used (e.g. H₃PO₄-0.2 corresponds to 100 ml XL 10 and 20 ml 85% H₃PO₄). Later experiments were labeled according to the potentially reactive material and the step during which it was added (e.g. TD-HAc corresponds to glacial acetic acid being added after TD 6/12 Blend was introduced). The "o" designation represents tests conducted in the open system (i.e., o-TD-KOH represents 10% KOH being added after TD 6/12 Blend was added in the open system).

^a Flowmeter employed was an Omega FLDA3224C.

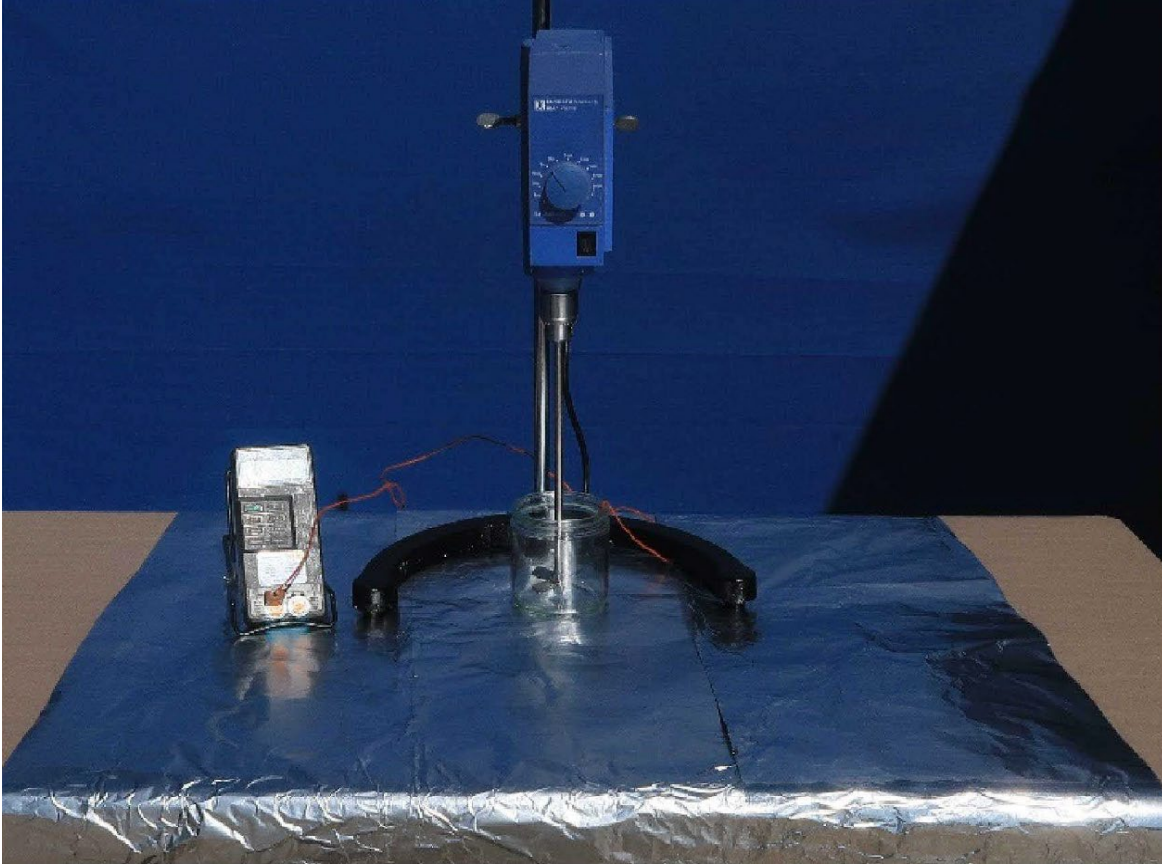


Figure C- 1. Open system experimental setup. (Credit: Crane)



Figure C- 2. Closed system experimental setup – with Nitrogen and Flow Meter. (Credit: Crane)



Figure C- 3. Closed system experimental setup – without Nitrogen and Flow Meter. (Credit: Crane)

Tests conducted include:

- Typical Andisil® EM 652 recipe, as a control (closed setup, without flow rate)
- Andisil® XL 10 Reactivity Studies (closed setup, with flow rate)
 - 100 ml XL 10 mixed with 100 ml water
 - 100 ml XL 10 mixed with 5, 10, 20, and 50 ml 10% KOH
 - 100 ml XL 10 mixed with 20, 50, and 100 ml, 85% H₃PO₄
- Andisil® EM 652 recipe, with addition of unexpected reactive material (open and closed setup, with flow rate)^a
 - 98 g of XL 10 mixed with 13.4 g TD 6/12 Blend for 30 minutes, followed by direct injection of 1.4 g 10% KOH, 85% H₃PO₄, or glacial acetic acid

^a These tests were either stopped after significant gas generation was observed, or until 137 Silane was added. Each step of the process was allowed to react for 30 minutes before the next addition.

- 98 g XL 10 mixed with 13.4 g TD 6/12 Blend for 30 minutes, followed by injection of 4.2 g Pel Alc 738B, 26.3 g water, and 1 .4g 10% KOH, 85% H₃PO₄, or glacial acetic acid mixed together
- Diluted 10% KOH solution (pH dependency)
- Minimum amount of 10% KOH solution necessary to incite reaction
- Timing of 10% KOH addition

Results of Chemical Reactivity Testing

Andisil® EM 652 Recipe

A small-scale experiment was conducted in which the [first] portion of the Andisil® EM 652 batch sheet was followed (i.e. through the addition of Andisil® 137 Silane). The experiment was conducted in a closed system without nitrogen flow as shown in **Figure C- 3**. As a result of the experiment, it was demonstrated that there was no significant temperature increase (other than a few degrees due to some heat from mixing) and there was no gas generation observed.

Andisil® XL 10 Reactivity Studies

XL 10 and Water

When XL 10 was mixed directly with an equal amount of water there was very little reaction observed. The flow of gas generated never exceeded the lower limit for the flowmeter being used (25 ml/min), and very slow bubbling through the bubble meter was observed for only the first approximately three minutes of the test.

XL 10 and Phosphoric Acid

Mixing XL 10 directly with 85% phosphoric acid (H₃PO₄) yielded small amounts of gas. There was no observable gas generation at the beginning of each test. Final flow rates of gas generated are shown in **Table C- 1**. Using 20 percent of the total volume of XL 10 (20 ml), the H₃PO₄ solution appeared to not cause any gas generation. Using 50 and 100 percent, the flow rate of gas generated increased gradually throughout the test until reaching the rates in **Table C- 1**. The flow rate of gas generated was dependent on the volume percent of H₃PO₄ in XL 10 and developed over time.

Table C- 1. Final flow rate (ml/min) of XL 10 mixed with various amounts of H₃PO₄

Volume of XL 10	Volume of 85% H ₃ PO ₄	Final Flow of Gas Generated
100 ml	20 ml	0 ml/min
100 ml	50 ml	25 ml/min
100 ml	100 ml	50 ml/min

XL 10 and 10% KOH

A different trend was observed when mixing XL 10 directly with 10% KOH. For all volumes of 10% KOH mixed with XL 10, gas generation rate was highest at the beginning of the experiment, shortly after the 10% KOH solution was added, and reduced as time went on, as demonstrated in **Figure C- 4**. Flow rate of gas generated by mixing different volumes of 10% KOH with XL 10 as a function of time. (Credit: Crane). The gas generation was highest when 100 ml of XL 10 was mixed with 50 ml of 10% KOH (KOH-0.5) and decreased with decreasing volumes of KOH.

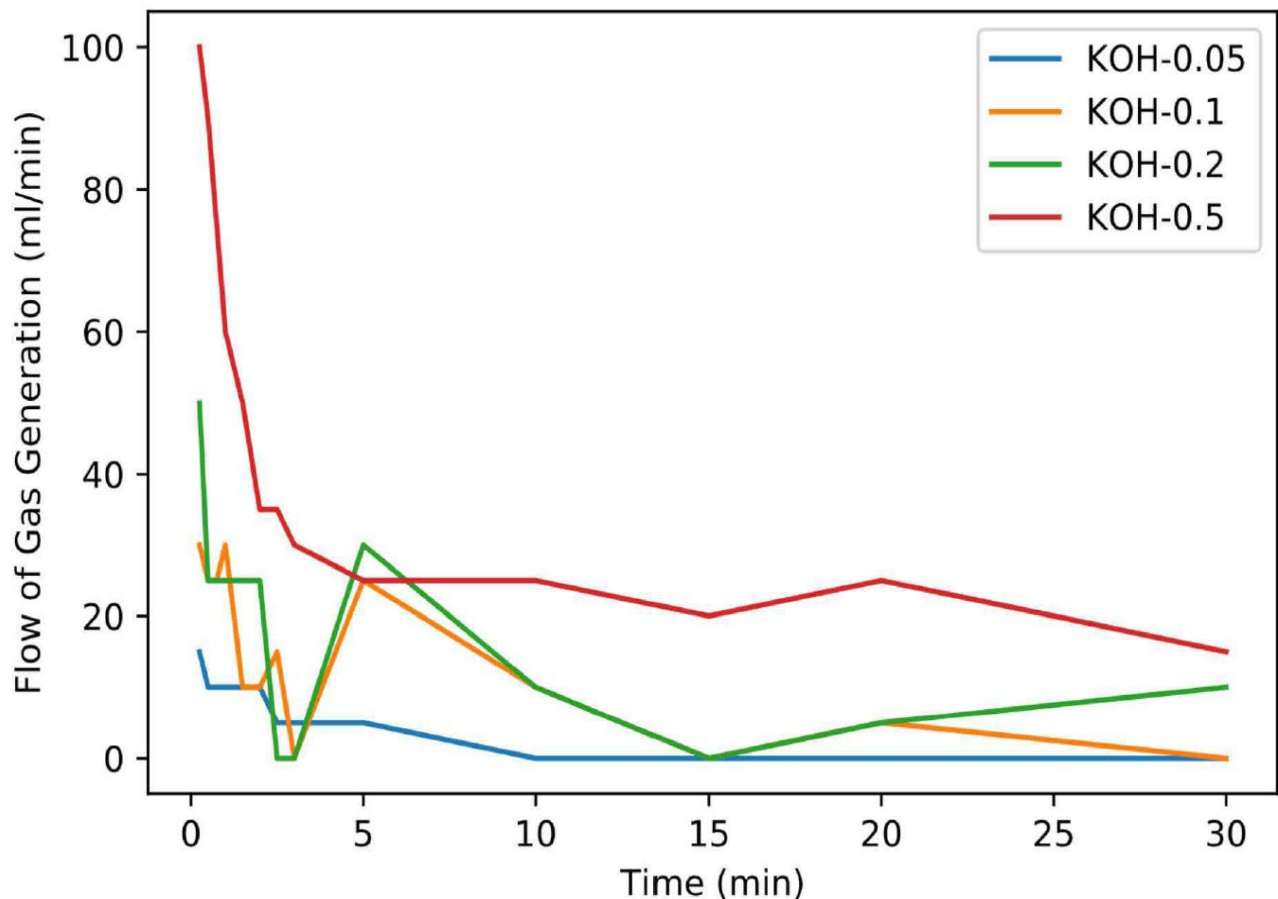


Figure C- 4. Flow rate of gas generated by mixing different volumes of 10% KOH with XL 10 as a function of time. (Credit: Crane)

EM 652 Addition Studies

Results of the testing of the three identified potentially reactive materials in the open system are summarized in **Table C- 2**. Only 10% KOH yielded an observable gas generating reaction when added after the XL 10 and TD 6/12 Blend. In this experiment, the ratio of XL 10 and TD 6/12 [Blend] were the same as indicated on the EM 652 batch sheet; approximately 7.5 to 1 and the amount of 10% KOH added was equivalent to approximately 48-pounds. **Figure C- 5** shows photographs of o-TD-KOH at various points. At 5 seconds before the KOH was added, the XL 10 and TD 6/12 Blend mixture appeared to be a milky white color and was measured to have a temperature of 95.6°F (**Figure C- 5a**). 20 seconds after the KOH was added (**Figure C- 5b**) the mixture turned white and foamy and the temperature increased to 121.2°F. A large bubble can be seen surfacing just right of the

agitator. At 25 seconds after the KOH was added (**Figure C- 5c**), the mixture was overflowing the container and further increased in temperature to 138.0 °F. Five seconds later (**Figure C- 5d**) the foam completely dissipated and the mixture solidified, in what appeared to be a rapid polymerization of the polysiloxane species. The measured temperature was 161.2°F. 50 seconds after the KOH was added (**Figure C- 5e**) the temperature further increased to 242.4°F. Similar results were observed in o-TD-KOH^a in terms of time and temperature of reaction progress.

Table C- 2. Observable gas generation from introducing contaminants at various stages of EM 652 production process in open experimental setup

Test	Reagents	Observable Gas Generation
o-TD-HAc	XL 10, TD 6/12 Blend, Acetic Acid, [Pel Alc 738B + Water], 137 Silane	No
o-PA-HAc	XL 10, TD 6/12 Blend, [Pel Alc 738B + Water+ Acetic Acid], 137 Silane	No
o-TD-H ₃ PO ₄	XL 10, TD 6/12 Blend, 85 % H ₃ PO ₄ in Water, [Pel Alc 738B + Water], 137 Silane	No
o-PA-H ₃ PO ₄	XL 10, TD 6/12 Blend, [Pel Alc 738B + Water + 85 % H ₃ PO ₄ in Water], 137 Silane	No
o-TD-KOH	XL 10, TD 6/12 Blend, 10% KOH	Yes
o-TD-KOH ^a	XL 10, TD 6/12 Blend, 10% KOH	Yes
o-PA-KOH	XL 10, TD 6/12 Blend, [Pel Alc 738B + Water + 10 % KOH], 137 Silane	No
o-PA-KOH ^a	XL 10, TD 6/12 Blend, [Pel Alc 738B + Water + 10 % KOH], 137 Silane	No

^a Note: The "a" designation indicates a repeated experiment.

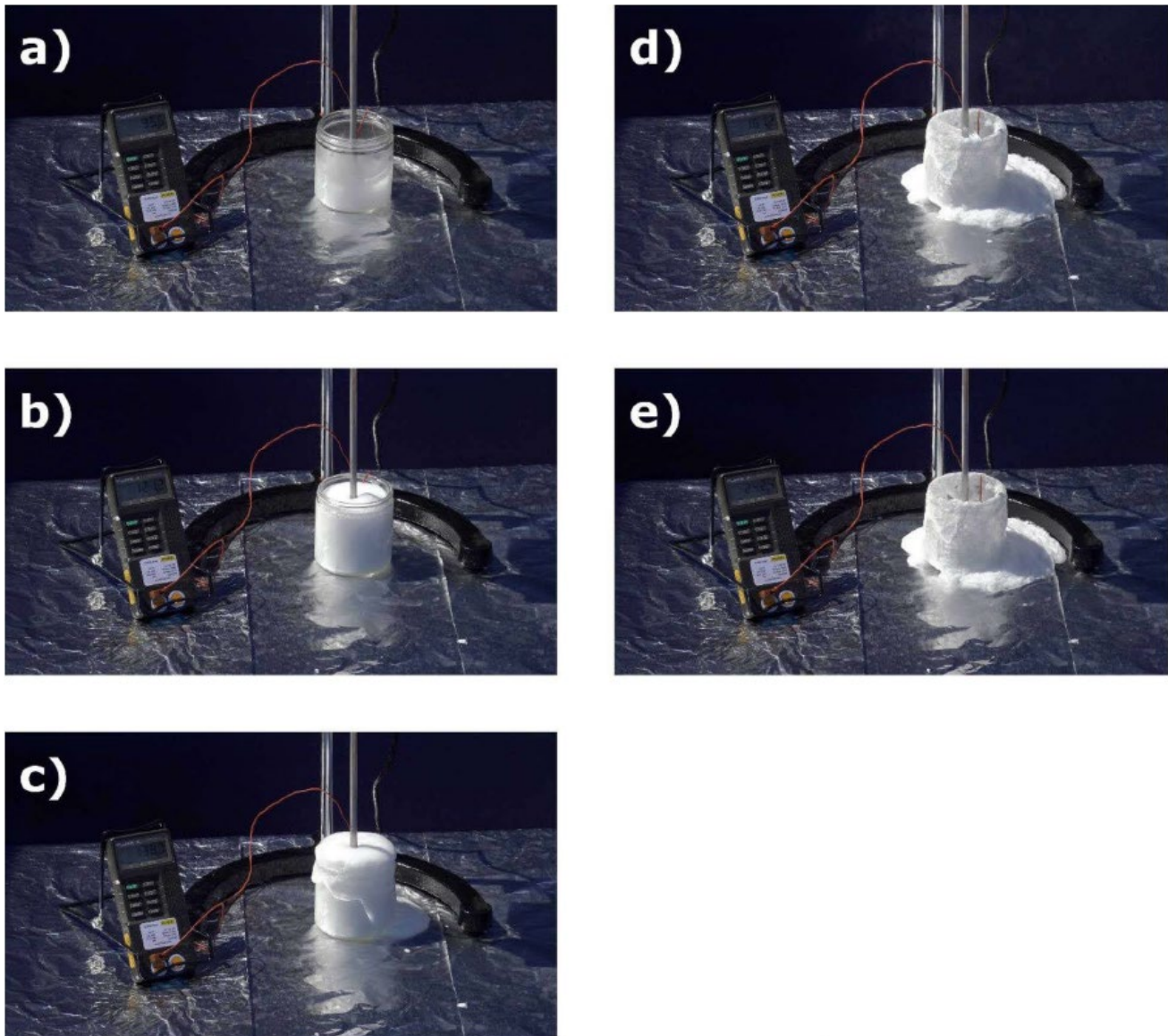


Figure C- 5. Photographs of o-TD-KOH test a) 5 seconds before KOH was added and b) 20 c) 25 d) 30 and e) 50 seconds after KOH was added to XL 10 and TD 6/12 Blend. (Credit: Crane)

To test whether the gas being generated was hydrogen, a Drager-Tube measurement was collected during the o-TD-KOH test. Drager-Tubes are packed with a solid substance that selectively chemically reacts with the gas that is sought to be detected. The solid material changes color according to the concentration of the gas. Tubes sensitive to hydrogen gas with a detection range of 0.2 to 2.0 volume % were used.^a In the presence of hydrogen, the solid material turns from a green yellow color to a turquoise blue. The Drager-Tube used for this measurement alongside an unused one for comparison are shown in **Figure C- 6**. The turquoise color can be clearly seen along the entire length of the tube, signifying that at the point of measurement, hydrogen in air was greater than or equal to 2.0 volume %.

^a Drager Part # 8101511.



Figure C- 6. Hydrogen Dräger-Tube used to qualify hydrogen gas generation from o-TD-KOHa test (above) compared with sealed, unused Dräger-Tube (below). (Credit: Crane)

These tests were repeated in the closed setup while collecting flow rate data. The flow rate of gas generation during the first 10 minutes of each test is shown in **Figure C- 7**. Gas generation was so rapid during the TD-KOH test that it immediately exceeded the maximum capacity of the flowmeter used, was accompanied with vigorous bubbling through the oil bubbler, and an apparent heating, evidenced by what appeared to be the evaporation and re-condensation of water on the sides of the flask (**Figure C- 8**). This rapid gas and heat generation was consistent with the equivalent tests performed in the open experimental setup. The gas generation was so rapid that shortly before 3 minutes into the test, one of the joints popped off the flask.

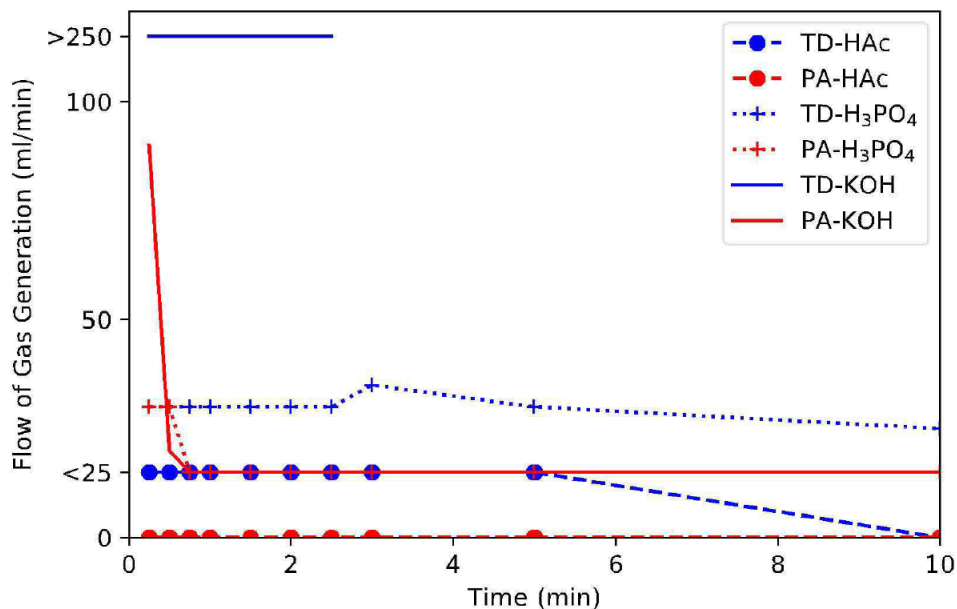


Figure C- 7. Flow rate of gas generated by each test during the first 10 minutes. (Credit: Crane)



Figure C- 8. Photograph of TD-KOH test a few seconds before joint was blown off due to substantial gas generation. (Credit: Crane)

PA-KOH showed a higher initial flow rate than all other tests aside from TD-KOH, but the flow rate quickly dropped to a rate of less than 25 ml/min. A slow, consistent bubbling was observed, so it can be concluded that the flow was greater than 0 ml/min. Both H₃PO₄ tests showed relatively slow, but measurable flow rates of gas generation initially, approximately 30 ml/min. That flow rate persisted for TD-H₃PO₄ but dropped off for PA-H₃PO₄. Tests performed with glacial acetic acid had very low or no flow rate measured throughout the duration of the tests.

Two main trends were observed through the closed system experiments. The relative flow rate of gas generated increased with the strength of the potentially reactive material and decreased with the step of the EM 652 process. The Glacial Acetic Acid (HAc) produced less hydrogen gas than the phosphoric acid (H₃PO₄) which produced less gas than the 10% KOH. Phosphoric acid is a stronger acid than acetic acid, meaning that it more readily donates a hydrogen ion (H⁺) and more readily breaks the Si-H bond. 10% KOH is a base (pH higher than 7), and it is understood that the reactivity of XL 10 increases with increased pH. The increased reactivity with increasing pH could have also explained why less gas was produced when the reactive material was added during the Pel Alc step instead of directly after the TD 6/12 [Blend] step. This relationship was explored through additional experiments as described in the Surfactant Studies section below.

Surfactant Studies

Both TD 6/12 Blend and Pel Alc 738B act as surfactants, improving miscibility of non-polar and polar phases. Thus, it would be expected that both conditions would lead to similar levels of gas generation. However as described above, when the potentially reactive material (HAc, H₃PO₄, KOH) was added during the Pel Alc step, significantly less hydrogen gas was generated than if the material was added just after the TD 6/12 [Blend] step. The hypothesis was developed that the addition of Pel Alc 738B and water to the tank already containing XL 10

and TD 6/12 [Blend] further diluted the effect of 10% KOH on the overall pH. The solution was therefore less basic, leading to a slower rate of hydrogen generation.

The pH of the 10% KOH solution used in the reactivity testing was measured to be 13.96. The pH of the Pel Alc 738B, water, and 10% KOH mixture, on the other hand, was measured to be 12.80. In order to evaluate the hypothesis above that lowering the pH of the solution would reduce the rate of the hydrogen generating reaction, the 10% KOH solution was diluted with water such that its pH was reduced from 13.96 to 12.80. Using this diluted KOH solution, the o-TD-KOH test was repeated (XL 10 + TD 6/12 [Blend], mixed with diluted KOH solution). This condition was mixed for approximately 30 minutes and no visible reaction, nor increase in temperature, was observed. Therefore, the hypothesis that pH influences the strength of the hydrogen generating reaction is supported.

Minimum 10% KOH Amount to Incite Reaction

Since mixing 10% KOH with XL 10 and TD 6/12 Blend was shown to produce a rapid, exothermic reaction and release hydrogen gas, a series of tests was performed to determine the minimum amount of 10% KOH necessary to produce this reaction. Tests were performed by again using the same ratios of XL 10 and TD 6/12 [Blend] indicated in the EM 652 batch sheet and subsequently reducing the amount of 10% KOH added. The amount of 10% KOH added was reduced by half for each test until the violent reaction was no longer observed. Once the point of no reaction was reached, one final test was conducted in which the amount of 10% KOH added was the intermediate point between the two prior tests. The results of those tests are provided in **Table C- 3**.

Table C- 3. Time to decomposition of Andisil® XL 10 and maximum temperature observed by adding decreasing amounts of 10% KOH to XL 10 and TD 6/12 Blend.

Amount of 10% KOH Added (pounds, scaled up) ^a	Time to Rapid Decomposition (min:sec)	Maximum Temperature (°F)
48	0:30	242
24	0:55	189
12	1:52	178
6	N/A	100
9	1:45	170

The minimum amount of 10% KOH required to trigger a strong, exothermic reaction with 3,348 pounds of XL 10 and 468 pounds of TD 6/12 [Blend] was found to be between 6 and 9 pounds, as shown in **Table C- 3**. This was concluded both visually and by temperature. While a full, robust, kinetic study is beyond the scope of the

^a The amount of 10% KOH represented is the amount of 10% KOH that would have to have been added to S2 during the production of the second batch of EM 652 with 3,348 pounds of XL 10 and 468 pounds of TD 6/12 [Blend] being mixed.

work performed as part of [this] investigation, [the] testing does suggest a linear relationship between KOH concentration and reaction rate.

Timing of the Addition of 10% KOH

As described above, when mixed with Andisil® XL 10 and TD 6/12 Blend, 10% KOH was found to cause an exothermic reaction that produced heat, steam, and hydrogen gas. It was observed to result in a foaming mixture that overflowed from the glass jar (see **Figure C- 5**). In order to evaluate whether the order of the addition of these three materials has an impact on the reaction, an additional set of open-system experiments were conducted. In both experiments the ratio of XL 10 and TD 6/12 [Blend] were the same as indicated on the EM 652 batch sheet; approximately 7.5 to 1. The amount of 10% KOH added was equivalent to approximately 48-pounds as also used in the experiments described above.

In the first experiment, XL 10 and TD 6/12 [Blend] were mixed for approximately two minutes before the 10% KOH was added. In the second experiment, the XL 10 and 10% KOH were mixed for approximately two minutes before the TD 6/12 [Blend] was added. In both experiments, the mixture began to generate heat and then foam and then overflowed the glass jar (see **Figure C- 9**). The only significant difference was the time for the reaction to begin to accelerate, attributed to a difference in the ambient temperature at the time of the experiments. This set of experiments was conducted outdoors in October when the ambient temperature was approximately 20°F (11 °C) colder than the first set of experiments conducted in July. This resulted in the reaction taking slightly longer than was observed previously. It was concluded that the addition of 10% KOH before or after the addition of TD 6/12 [Blend] did not impact the nature of the reaction.

In all the experiments with XL 10, TD 6/12 [Blend] and 10% KOH, the temperature of the mixture increased over time. When the mixture reached approximately 120°F (49°C) the rate of the reaction began to increase dramatically as shown in **Figure C- 10**. The blue line represents a condition where 10% KOH was added to a mixture of XL 10 and TD 6/12 [Blend] during the summer when the ambient temperature was higher. The orange line is representative of the same condition but performed during autumn when the ambient temperature was lower. The green curve represents TD 6/12 [Blend] being added to a mixture of XL 10 and 10% KOH. The red line represents all three components being added at the same time. Once the reaction reached approximately 200 to 220°F (93 to 104 °C), the rate of temperature rise began to slow. This slowing can be attributed to either the completion of the reaction due to the consumption of the XL 10, a break in contact with the thermocouple as the foam overflowed (see **Figure C- 5d**), or a combination of both.

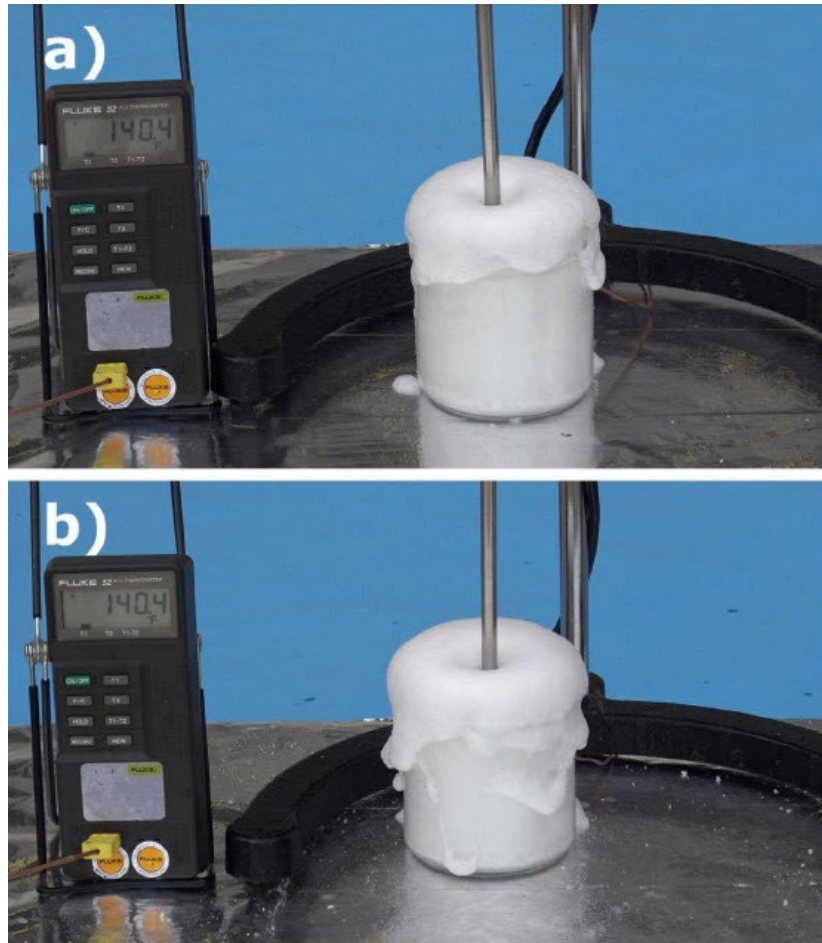


Figure C-9. XL 10, TD 6/12 [Blend], and 10% KOH experiments: (a) 10% KOH added to the XL 10 and TD 6/12 [Blend] mixture, (b) TD 6/12 [Blend] added to the XL 10 and 10% KOH mixture. (Credit: Crane)

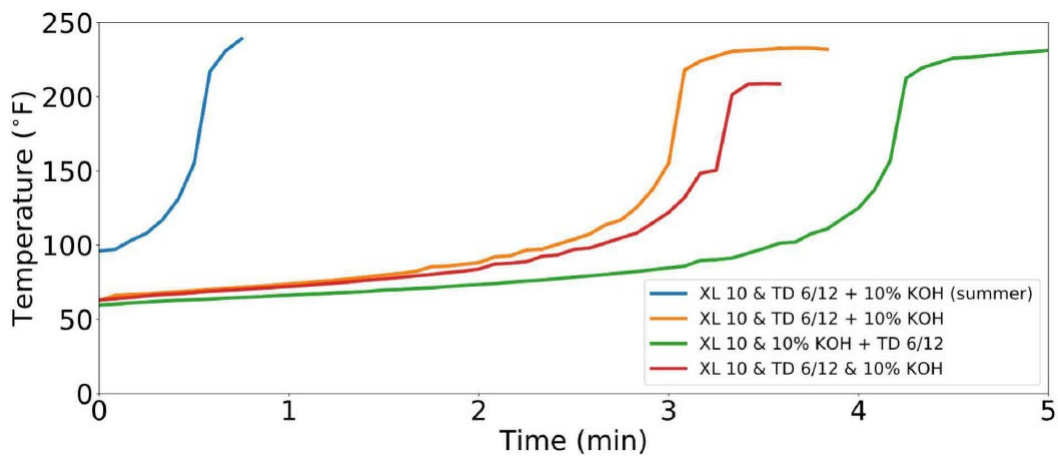


Figure C-10. Temperature versus time for XL 10, TD 6/12 [Blend], and 10% KOH experiments performed in an open setup. (Credit: Crane)

Conclusions from Chemical Reactivity Testing

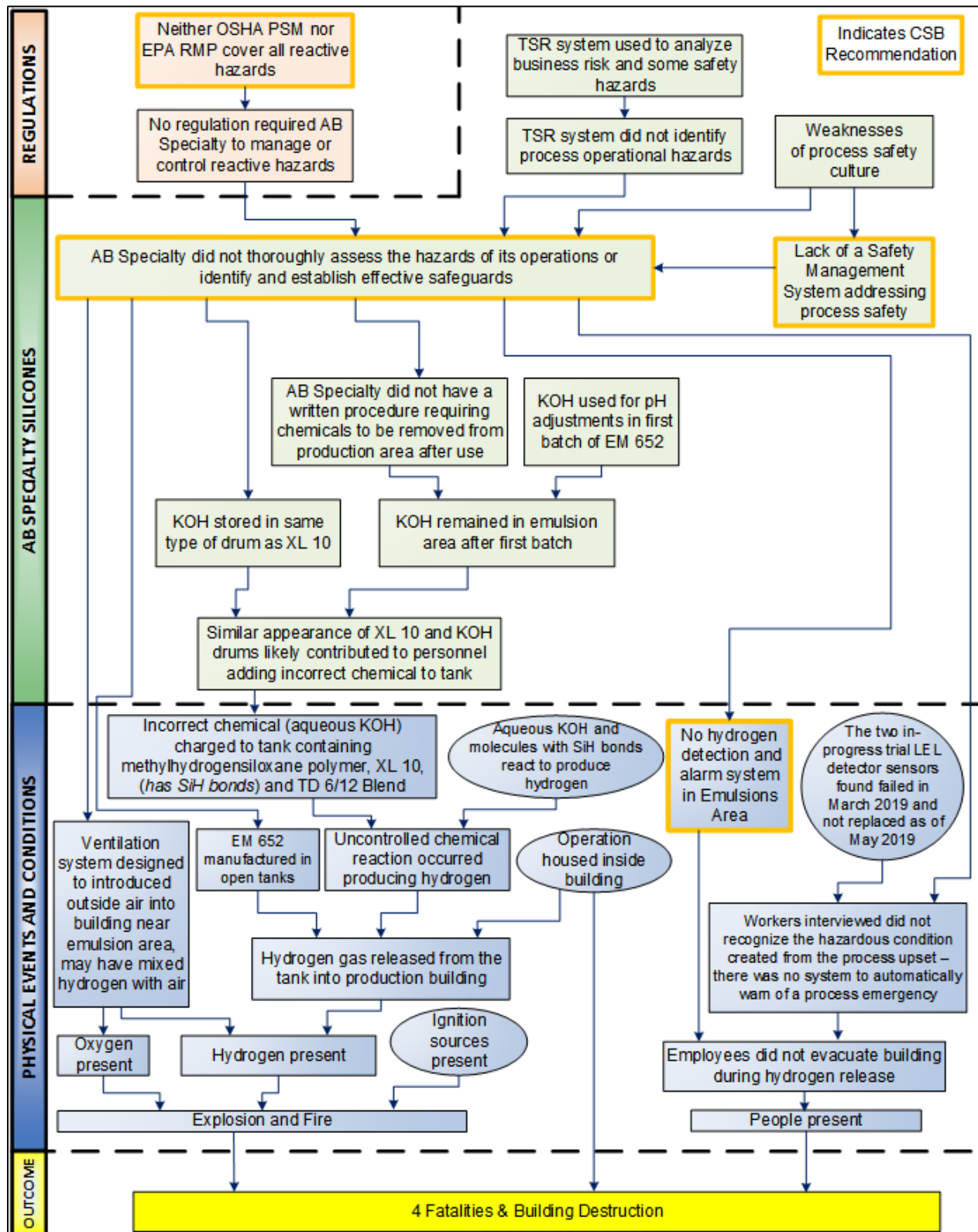
The chemical reactivity tests conducted as a part of this investigation indicated that 10% KOH was the reactive material most capable of causing a violent exothermic reaction in [the batch tank] during EM 652 production. It was likely added before the addition of Pel Alc 738B, water, and glacial acetic acid. It would not have mattered if it was added before the TD 6/12 [Blend] or after. At least 6 to 9 pounds of 10% KOH would have been necessary to incite the reaction.

Appendix D—CSB Blast Analysis

See the CSB blast analysis at www.csb.gov on the AB Specialty Silicones investigation page.

The blast analysis determined that a flammable gas cloud containing about 41–42 pounds of hydrogen could cause the observed blast damage.

Appendix E—Causal Analysis (AcciMap)





**U.S. Chemical Safety
and Hazard Investigation
Board**

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

Katherine A. Lemos, PhD
Chairman and CEO