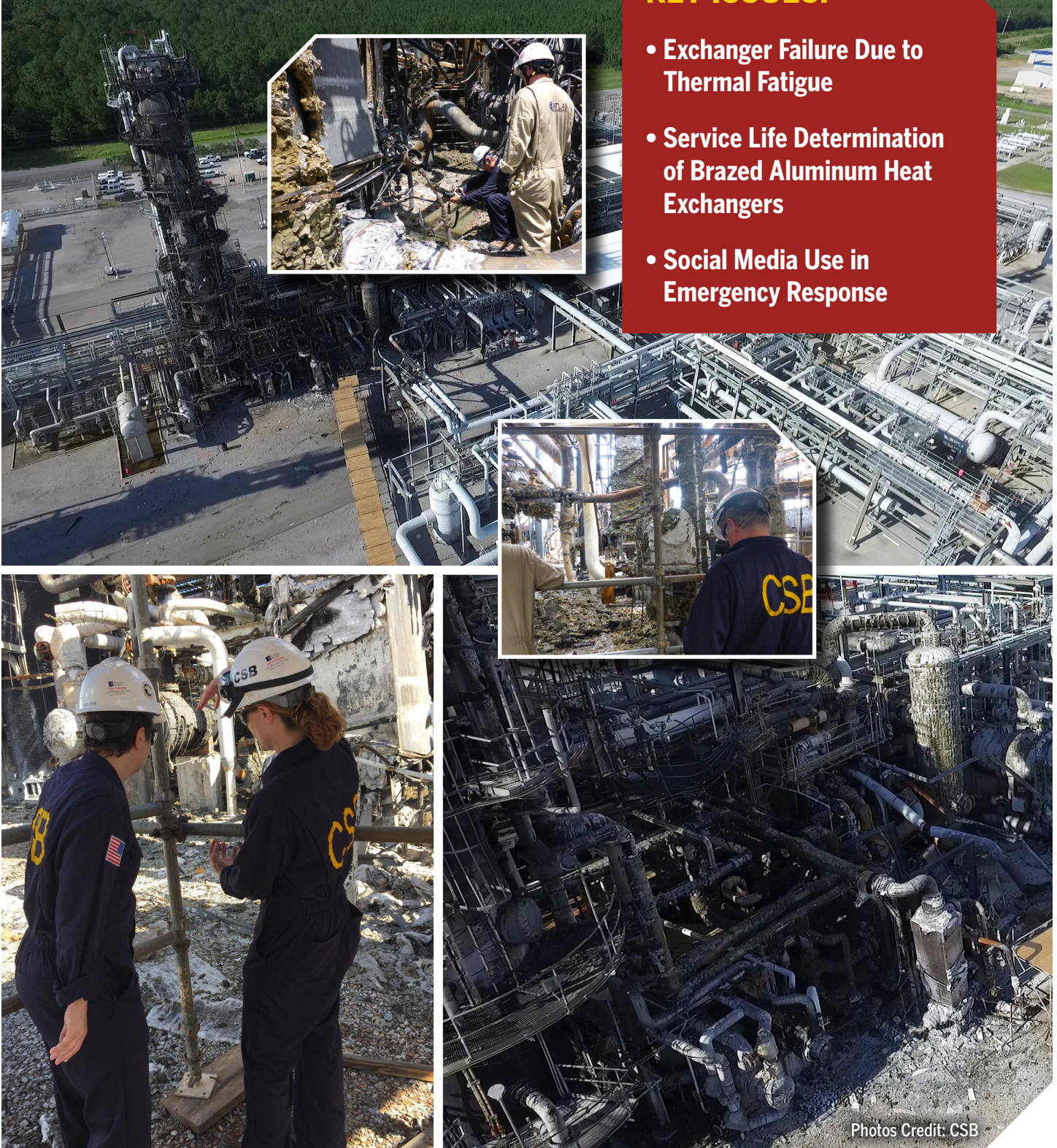


Case Study

Published: February 13, 2019

KEY ISSUES:

- Exchanger Failure Due to Thermal Fatigue
- Service Life Determination of Brazed Aluminum Heat Exchangers
- Social Media Use in Emergency Response





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Acronyms and Abbreviations

ACSR	A-Train cold side reboiler	LOC	loss of containment
AIChE	American Institute of Chemical Engineers	MOC	management-of-change
ALPEMA	Brazed Aluminium Plate-Fin Heat Exchanger Manufacturer's Association	NFPA	National Fire Protection Association
ANSI	American National Standards Institute	NGLs	natural gas liquids
API	American Petroleum Institute	OSHA	Occupational Safety and Health Administration
AWSR	A-Train warm side reboiler	PFD	Pascagoula Fire Department
BAHX	brazed aluminum heat exchanger	PGP	Pascagoula Gas Plant
bpd	barrels per day	PHA	process hazard analysis
Btu	British thermal unit	psi	pounds per square inch
CSB	U.S. Chemical Safety Board	psig	pounds per square inch gauge
DCS	distributed control system	PSM	process safety management
EPA	U.S. Environmental Protection Agency	RAGAGEPs	recognized and generally accepted good engineering practices
ESD	emergency shut down	RMP	Risk Management Plan
LBB	leak-before-break	ROC	rate of change
LEPC	local emergency planning committee		

1.0 Executive Summary

Sometime before 11:22 p.m. on June 27, 2016, a major loss of containment (LOC) resulted in the release of methane, ethane, propane, and several other hydrocarbons at the Enterprise Products Pascagoula Gas Plant (PGP)¹ in Pascagoula, Mississippi. The hydrocarbons ignited, initiating a series of fires and explosions, which ultimately shut down the site for almost six months. Two workers were on the night shift when the incident occurred and were uninjured. Had the event happened during the day, when a larger number of personnel were working amid the process line, the consequences could have been much worse. Enterprise Products (Enterprise) incurred \$10.4 million of expense due to fire response activities and another non-cash loss of \$7.1 million as a consequence of this incident.²

Although no off-site property damage was reported, many nearby residents chose to evacuate. After the incident, members of a local community organization expressed concern to the CSB that some residents did not know how to respond. They felt uninformed and ill equipped to know if they were in harm's way.

The probable cause of this incident was the failure of a brazed aluminum heat exchanger (BAHX) due to thermal fatigue.³ The absence of a reliable process to ensure the mechanical integrity of the heat exchanger contributed to the catastrophic failure of the equipment.

Thermal fatigue, as a damage mechanism, commonly forms small cracks in BAHXs. These small cracks can develop into hydrocarbon leaks that typically can be repaired with minimal expense or consequence before a major LOC occurs.⁴ Yet the June 2016 PGP incident, as well as four other BAHX failure events (also discussed in this report), illustrate that the reliance on a leak-before-failure assumption is not sufficient. Instead, operators of midstream gas plants need to assess and manage the risk of sudden and catastrophic BAHX rupture scenarios where thermal fatigue plays a contributing role.

To minimize thermal fatigue in BAHXs, various industry guidance documents recommend limits for maximum cyclic temperature fluctuations during operation and rates of cooling or heating during start-up and shutdown. Yet a number of midstream gas plant operators have reported that these limits and rates may not be realistic, indicating that further dialogue between equipment manufacturers and operators would be beneficial. The desire by midstream gas plant operators to keep process data confidential, in conjunction with the "low frequency, high consequence" nature of catastrophic failure of BAHXs, has hindered industry-wide examination and learnings as they relate to BAHX life expectancy.

This report aims to share the thermal fluctuation data and repair history of the BAHXs at PGP, summarize industry guidance on BAHX operation, and document previous BAHX incidents, to trigger a meaningful dialogue between BAHX manufacturers, gas processors, and repair technicians. The findings and analysis of this investigation can contribute to improved BAHX guidance and safe use.

Furthermore, this report examines an opportunity to address the need for a more robust and engaged community alert network—one that includes social media and the ability to expand opportunities to interact with the community throughout an incident.

As a result of this investigation, the CSB makes safety recommendations to the American Petroleum Institute, GPA Midstream Association, and the Jackson County (Mississippi) Local Emergency Planning Committee.

1 Before the incident, BP and Enterprise shared ownership of the plant. BP had 60 percent interest and controlled the operation of the plant. In March 2016 Enterprise acquired BP's interest, and it assumed operatorship on June 1, 2016.

2 The non-cash loss in 2016 was attributable to assets damaged in the fire. This amount represented the net book value of assets at the time of the incident. Enterprise Products Partners LP, Annual Report (Form 10-K), December 31, 2016, p F-12, <http://phx.corporate-ir.net/External.File?item=UGFyZW50SUQ9NiYxMzU4fENoaWxkSUQ9MzY4Mjk-wfFR5cGU9MQ==&t=1> (accessed April 12, 2018).

3 The aluminum parts of a BAHX are closely and tightly connected. As the exchanger is heated or cooled, the parts expand or contract together. If the parts change temperatures at sufficiently different rates, the expansion and contraction can be disproportionate. This increases stresses on the connections within the BAHX as the aluminum parts push against and pull apart from each other. Over time, this process "fatigues" the metal, weakening it and ultimately causing cracks.

4 Historical exchanger repairs at the plant were in the range of \$60,000–\$150,000.

2.0 Background

The Pascagoula Gas Plant (PGP) (**Figure 1**) employs 30 people. It was built in 1998/1999 with Amoco Production Company (60 percent) and Shell Midstream Enterprises Inc. (40 percent) as the original partners. In 1998, BP acquired Amoco, and in mid-1999, Enterprise Products Partners LP (Enterprise) acquired Shell's interest, but BP maintained operation of the plant. In March 2016, Enterprise purchased the remaining 60 percent interest in PGP, and it assumed operatorship on June 1, 2016.⁵

The plant receives raw natural gas via a pipeline from Gulf of Mexico deepwater oil wells and separates the material into two products: natural gas liquids,⁶ which serve as a feedstock to the chemical industry, and a natural gas fuel stream, primarily composed of methane. A cryogenic⁷ separation process is used at the plant. A key piece of equipment used in the process is a brazed aluminum heat exchanger (BAHX), which allows for the transfer of heat between different process streams while keeping the streams separate.

More than 500 gas processing facilities operate across the country,⁸ and cryogenic separation using BAHXs is common. For example, Enterprise owns or jointly owns 26 midstream gas plants, most of which are cryogenic processes equipped with BAHXs.



Figure 1. Drone image of the facility depicting fire damage incurred at the plant.

PGP is covered under the Occupational Safety and Health Administration's (OSHA's) Process Safety Management standard, 29 C.F.R. §1910.119,⁹ and the Environmental Protection Agency's Risk Management Plan rule, 40 C.F.R. §68.

2.1 Incident Synopsis

During the night of June 27, 2016, the two personnel on duty at PGP—a control board operator and an outside operator¹⁰—were stopping

5 Enterprise Products Partners LP, Quarterly Report (Form 10-Q), September 30, 2016, p 12, <http://services.corporate-ir.net/SEC/Document.Service?id=P3Vybd1hSFlwYOR-vdkwyRndhUzUwWlc1cmQybDZZWEprTG10dmJTOWtiM2R1Ykc5aFpDNXdhSEEVVdOMGFxOXVQVkJFUmlacGNHRm5aVDB4TVRJeE1qTXIPQ1p6ZFdkemFXUTIOVGM9Jn-R5cGU9MiZmbjJFbnRlcnByaXNlUHJvZHVjdHNOYXJObmVyc0wucGRm> (accessed May 8, 2017). When Enterprise took over operatorship, PGP was the only midstream gas processing facility in the United States under BP's majority ownership.

6 "Natural gas liquids are those hydrocarbons liquefied at the surface in the field facilities or in gas process plants. Natural gas liquids include ethane, propane, butanes, and natural gasoline." Gas Processors Suppliers Association. *Engineering Data Book—FPS English Units*, 14th ed.; Tulsa, OK, 2017; Vol. 1, p 1-6. <https://gpsamidstreamsuppliers.org/gpsa-databook> (accessed July 10, 2018).

7 A cryogenic plant is "a gas processing plant which is capable of producing natural gas liquid products, including ethane, at very low operating temperatures, usually below minus 50°F." Gas Processors Suppliers Association. *Engineering Data Book—FPS English Units*, 14th ed.; Tulsa, OK, 2017; Vol. 1, p 1-4. <https://gpsamidstreamsuppliers.org/gpsa-databook> (accessed July 10, 2018).

8 U.S. Department of Energy. Natural Gas Annual Respondent Query System, https://www.eia.gov/cfapps/ngqs/ngqs.cfm?f_report=RP9&f_sortby=&f_items=&f_year_start=&f_year_end=&f_show_compid=&f_fullscreen (accessed May 16, 2017).

9 The PGP site had no history of OSHA citations up until the June 27, 2016, incident. OSHA, U.S. Department of Labor. Inspection Detail, Inspection 1159519.015, Report ID 0419400, closed March 17, 2017, https://www.osha.gov/pls/imis/establishment.inspection_detail?id=1159519.015 (accessed July 10, 2018).

10 Board operators monitor the plant's computer system and adjust valve positions and set points to maintain safe operations. Duties of an outside operator include making rounds of the plant to conduct safety checks, issuing maintenance permits (e.g., for hot work), and performing manual manipulations of equipment as required by various procedures.

production of natural gas liquids due to pipeline problems downstream of the facility. Although this was a non-routine activity,¹¹ the control board operator had experience conducting the procedure. The operators initiated the necessary steps from the control room,¹² when, at 11:22 p.m., a sudden explosion and fire occurred. No abnormal alarms or other indicators warned the two PGP personnel of any problems. Within a minute of the initial explosion, the operators activated the emergency shut down systems at the plant and sheltered in the control room.

Over the course of the incident, the site experienced 13 different ruptures of piping and equipment. The CSB concludes that the first loss of containment most likely originated at a BAHX when it lost core integrity due to accumulated thermal fatigue.¹³

The BAHX of interest was part of A-Train, one of three process lines (A, B, and C) at PGP.¹⁴ The rupture released flammable hydrocarbon into the process area in and around a variety of potential ignition sources. After ignition, emergency systems depressurized the plant and sent much of the process fluids to a flare,¹⁵ but the rupture also caused a portion of A-Train's contents to continue to feed the fire, which



Figure 2. A comparison of the B-Train (top, shown in mirror image to match A-Train) and A-Train (bottom) process areas after the night of the incident.

11 Operations can be divided into routine and non-routine activities. Routine activities are normal day-to-day operations. Non-routine activities can be further subdivided into three categories. *Expected non-routine activities* would be operations such as start-ups or shutdowns that are developed as part of normal procedures and included as a part of unit operating guidelines. *Preplanned non-routine activities* are "bookshelf" activities such as on-line maintenance that are developed ahead of need and set aside for use on an as-needed, irregular basis. *Unplanned non-routine activities*, also called abnormal activities, would include unique circumstances such as troubleshooting activities, and are developed at the time of need. The procedures for curtailing NGL production were preplanned and written, but used only on a non-routine basis when required.

Center for Chemical Process Safety. *Guidelines for Writing Effective Operating and Maintenance Procedures*; John Wiley & Sons: Hoboken, NJ, 1996; pp 46, 108.

Ostrowski, S. W.; Keim, K. A HAZOP Methodology for Transient Operations. Presented at 11th Annual Symposium, Mary Kay O'Connor Process Safety Center, College Station, TX, October 28-29, 2008.

12 The control room is the operations center where the computer system used to control plant operation is located.

13 The core of an exchanger is composed of layers of parting sheets, fins, and end bars. A header is a chamber that evenly distributes fluid coming into or leaving the exchanger and is welded onto the core. See Section 2.2 for a more detailed description of a BAHX. Thermal fatigue is described in Section 2.3.

14 A- and B-Trains are cryogenic separation process lines. C-Train utilizes similar equipment to A- and B-Trains except that it does not have a turboexpander or demethanizer and operates at warmer temperatures than the other two process lines. See Appendix B for further details on the A-Train process.

15 Plants like PGP use flares to dispose of flammable gas in the event of an emergency by burning it in a safe and controlled manner.

intensified several times over approximately the next 35 minutes as additional piping and equipment failed. Equipment, piping, and vessels in the A-Train process area were extensively damaged (**Figure 2**).

The first of several local fire departments was dispatched to the scene approximately four minutes after the initial explosion. Jackson County Emergency Services,¹⁶ in conjunction with the responding fire departments and PGP management personnel, decided the appropriate course of action would be to allow the fire to burn itself out. The last fire was extinguished by approximately 6:00 p.m. the next day, and emergency response officially ended on the morning of June 29. Enterprise reported that 104,000 pounds of total emissions were released on June 27, 2016; most of the released hydrocarbon was burned off by the ensuing fires and flares.

The site was shut down for almost six months, and Enterprise incurred \$10.4 million of expense due to fire response activities and another non-cash loss of \$7.1 million as a consequence of this incident.¹⁷

2.2 Brazed Aluminum Heat Exchangers

In general, heat exchangers allow for the transfer of heat between different process streams while keeping the streams separate. In a BAHX, fluids are distributed through alternating “layers” made up of aluminum parting sheets and corrugated fins that are sealed along the edges with side bars (**Figure 3**). The layers in a BAHX are collectively called the *BAHX core*, and the outermost layers are bound by aluminum cap sheets that are thicker than the parting sheets. The attachment plates¹⁸ are welded onto the cap sheets; they provide a welding base for the inlet and outlet headers as well as the support legs.¹⁹

The heat from a warmer fluid is transferred to a cooler fluid across the parting sheet and through fins, which help conduct heat to the bulk fluids (**Figure 4**). A layer’s length dictates how much heat is transferred by controlling the time that the colder and warmer fluids are in contact with each other through the parting sheet

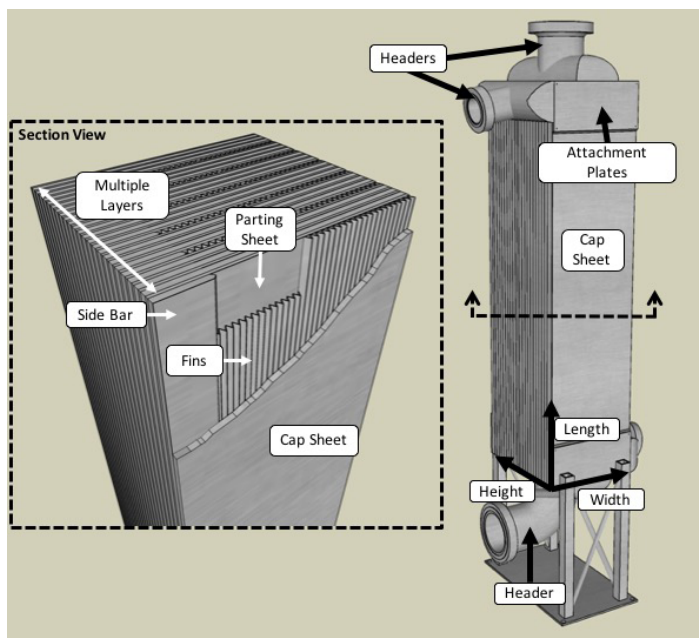


Figure 3. An exchanger core comprises many layers, consisting of a sheet of corrugated fins joined between two thin aluminum parting sheets. The outermost parting sheets are called cap sheets. The edges are sealed with side bars. BAHX length, width, and height are based on the position of the exchanger during its manufacture.

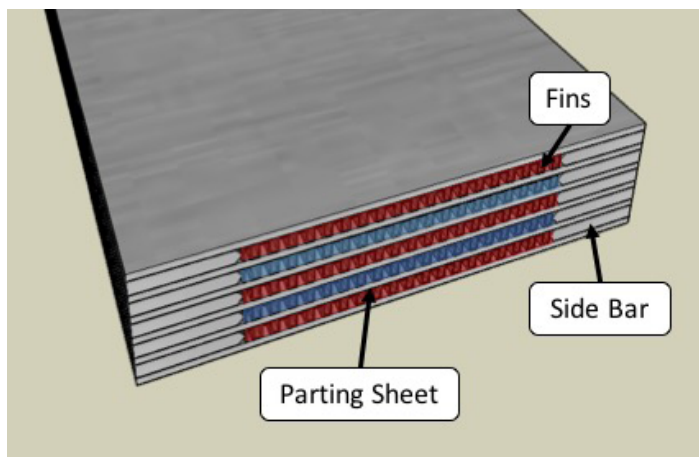


Figure 4. Process streams are distributed through alternating layers, where the warmer stream (red) transfers heat to the cooler stream (blue) across the parting sheet, which acts as a barrier between the streams. The fin matrix also aids in heat transfer.

¹⁶ Jackson County Emergency Services “acts as a coordinating agency during times of emergency or disaster.” Jackson County, Mississippi. Office of Emergency Services, <https://www.co.jackson.ms.us/224/Office-of-Emergency-Services> (accessed May 24, 2017).

¹⁷ The non-cash loss in 2016 was attributable to assets damaged in the fire. This amount represented the net book value of assets at the time of the incident. Enterprise Products Partners LP, Annual Report (Form 10-K), December 31, 2016; p F-12, <http://phx.corporate-ir.net/External.File?item=UGFyZW50SUQ9NjYxMzU4fENoaWxkSUQ9MzY4Mjk-wfFR5cGU9MQ==&t=1> (accessed April 12, 2018).

¹⁸ The space between the attachment plate and cap sheet is not intended to contain process fluid or hold pressure. To relieve any pressure that may develop underneath the attachment plate, weep holes are drilled into each corner.

¹⁹ Brazed Aluminium Plate-Fin Heat Exchanger Manufacturer’s Association (ALPEMA). *The Standards of the Brazed Aluminium Plate-Fin Heat Exchanger Manufacturer’s Association*, 3rd ed.; 2010 with amendments May 2012; p 44. <http://www.alpema.org/standards.html> (accessed July 10, 2018).

and fins. Increasing the number of layers (height) or their width increases the amount of hydrocarbons that can flow through the exchanger.

Critical to the structural integrity of the core are the brazed fin connections to the cap/parting sheet (**Figure 5**).²⁰ When a layer is pressurized, the fins and braze joints hold the layers together, acting like a truss²¹ on a bridge, counteracting the fluid forces on the parting and cap sheets.

Choosing the appropriate exchanger for an application requires an assessment of the risks and an understanding of exchangers' design limitations. The benefits of a BAHX include highly efficient heat transfer with a compact size that can accommodate many different process streams, and the simplification of a plant's heat exchanger network.²² Disadvantages of choosing a BAHX include a sensitivity to two-phase²³ flow distribution, susceptibility of small flow passages to plugging, vulnerability to chemical attacks by mercury, and exposure to fluctuating thermal stresses.²⁴ Fluctuating thermal stress can lead to thermal fatigue, and this damage mechanism is the focus of this case study.

2.3 Introduction to Thermal Fatigue in a BAHX

When a material is stressed by pushing, pulling, or twisting, it can change shape or deform.²⁵ If the material has a different shape when the force is removed, the stress exceeded the material's *yield strength*. If the stress is below a material's yield strength, the material returns to its original shape when the force is removed.²⁶ Yet, when a material experiences stresses below its yield strength repeatedly, it can become fatigued and form small cracks that can worsen as further stress cycles occur.

The parts of a BAHX (fin matrix, parting sheet, side bars, etc.) are tightly connected, each with different thicknesses. The thicker aluminum parts change temperature more slowly than the thinner ones, and if the rates are sufficiently different, the expansion and contraction can be disproportionate. This puts high stresses on the connec-

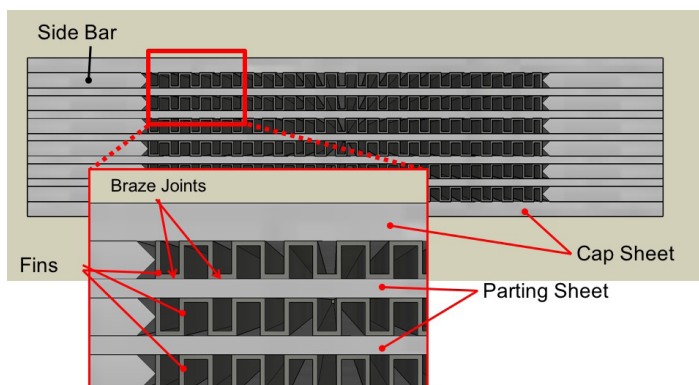


Figure 5. Diagram depicting a view looking down the length of a BAHX core. Pressure from the process fluids applies a force to the fins of the BAHX. The fin arrangement behaves like a bridge truss, distributing the force across the width of the pass.

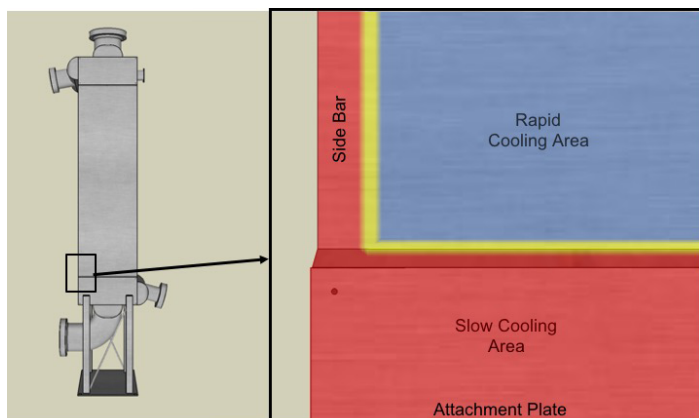


Figure 6. One area of high thermal stress in a BAHX is at the side bar/attachment plate/cap sheet junction. The thicker pieces of aluminum—the side bar and attachment plate (red)—change temperature at a slower rate than the thinner cap sheet (blue). Adding and removing thermal stresses where these pieces join (yellow) can eventually cause thermal fatigue cracks to form.

20 The manufacturer of this exchanger uses a process called *brazing*. Several hundred layers of aluminum sheets coated with a lower-melting-point metal (i.e., the braze material) are stacked to create the core and then placed in a vacuum furnace. As the core is heated, the braze material melts and bonds the fin matrices, side bars, and parting/cap sheets into one unit.

21 A truss is a structural framework of interconnected beams typically arranged in a triangle pattern.

22 BAHXs are just one of several exchanger types. Another design is the shell-and-tube heat exchanger; while common in refineries and gas processing plants, it also has benefits and drawbacks in its design.

23 A two-phase fluid consists of both liquid and vapor components. Under certain conditions flow can become erratic (see Section 5.3.3).

24 Swain, R. D.; Miller, A. C. Aluminum Plate-Fin Heat Exchanger Thermal Fatigue Study. Presented at American Institute of Chemical Engineers (AIChE) Spring National Meeting, Chicago, IL, March 14–17, 2011; AIChE Paper Number 38c.

25 In general, the background overview of metal fatigue in this section was taken from “Ductility,” a chapter by F. C. Campbell in *Fatigue and Fracture: Understanding the Basics*, 1st ed.; ASM International: Novelty, OH, 2012; §2.1.1.

26 Imagine pulling a Slinky apart a few inches and releasing it. If it returns to its original shape, it has been only elastically deformed. If, instead, the Slinky is stretched across a large distance and does not return to its original shape, an inelastic or permanent deformation has occurred.

tions within the BAHX as the aluminum parts push into and pull apart from each other (**Figure 6**).²⁷ Over time, this pushing and pulling fatigues the metal and creates thermal fatigue cracks that can allow process fluids to leak into the atmosphere or between adjacent layers within the exchanger.

Thermal fatigue can also affect the fin matrix in a BAHX when it accumulates to the point that the braze joints between the fins and the parting/cap sheet weaken and fail. This causes the forces on adjacent joints to increase. If the joints are unable to sustain the added load, they may fail as well, causing a chain reaction that ends with a sudden rupture of the exchanger.²⁸ Consequently, when the fin matrix is compromised by thermal fatigue, the pressure necessary to rupture a BAHX layer may be less than its original design pressure.

The manufacturer of the BAHX involved in this incident, Chart Industries (Chart), has stated that “the vast majority of BAHXs that experience thermal stress cracking ... will exhibit small leaks that can be detected and repaired in the field.”²⁹ Yet, as demonstrated by the PGP incident as well as others identified in this report (Section 4.4), the gradual weakening of the BAHX structure can also result in a sudden and significant rupture. Operators need to assess and manage the risk of sudden BAHX rupture scenarios where thermal fatigue plays a contributing role.

Damage from thermal stresses can also result from a single large event, a phenomenon called thermal shock. An everyday example of thermal shock occurs when warm water is poured over an ice cube just taken from the freezer.^a A rapid transfer of heat to the surface of the ice causes the outside of the ice cube to contract.^b The heat does not pass quickly to the interior of the ice cube, so the interior does not contract at the same rate. This creates thermal stresses between the outside and inside of the cube that result in its cracking.

The thickness of the material matters. It is easier to create thermal stresses in thicker materials. Thus, when ice is thinner it heats more uniformly, and the temperature difference across it does not create sufficient thermal stresses to crack it.

a Heselton, K. E. *Boiler Operator's Handbook*, 2nd ed.; Fairmont Press: Lilburn, GA, 2014; p 431. Available at <http://app.knovel.com/hotlink/toc/id:kpBOHE0001/boiler-operators-handbook/boiler-operators-handbook>.

b Unlike metal, ice contracts when it is heated.

27 Peaslee, R. L. Thermal Fatigue and High-Temperature Brazements. *Welding Journal* **1960**, 39 (1), 29–33.

28 Imagine there is a series of five fin-to-parting sheet braze joints, and the middle joint fails. The joints adjacent to the one that failed are subject to the forces originally shared by three joints. These joints have been in the same environment as the failed joint, so they are similarly weakened. The additional load caused by the center joint failure now ruptures the next two. The situation continues. Now the remaining two braze joints are under the load meant to be shared by five, and they rupture. This type of sequential failure can lead to a rapid separation of the fins-to-parting sheet structure over a large area of a layer.

29 The full passage is as follows: “Fortunately, the vast majority of BAHXs that experience thermal stress cracking, either from high-cycle fatigue or from low-cycle thermal shock events, will exhibit small leaks that can be detected and repaired in the field.” *BAHX Product Bulletin*, Issue 1; Chart Energy & Chemicals Inc., April 2016; p 5. <http://files.chartindustries.com/BAHXProductBulletin.pdf> (accessed April 2017).

3.0 The Incident³⁰

PGP processes raw natural gas it receives via the Destin pipeline from offshore production platforms in the Gulf of Mexico (**Figure 7**).³¹ After processing, three products leave the plant: (1) a liquid referred to as *natural gas condensate*,³² (2) lighter natural gas,³³ consisting mainly of methane; and (3) heavier hydrocarbons generally known as natural gas liquids (NGLs). Natural gas, also called *residue gas* because it is what remains from the recovery of the NGLs, is sold as fuel. NGLs, on the other hand, have a higher market value as feedstocks for the manufacture of plastics and other chemicals.³⁴ Once the residue gas has been separated, PGP sends it back into the Destin pipeline³⁵ and the NGLs into the Tri-States NGL pipeline,³⁶ where both products are transported to distribution points or other processing plants. A full process description appears in Appendix B.

On the night of June 27, 2016, PGP was operating A-Train, one of its cryogenic process lines. The board operator was in the control room, a blast-resistant module without windows.³⁷ An outside plant operator was in and out of the control room as needed during the shift.

Around 10:30 p.m., the outside operator was observing the board operator (for training purposes) when Tri-States called to request that the plant curtail by about half the amount of NGL product it was sending to the pipeline; Tri-States was attempting to

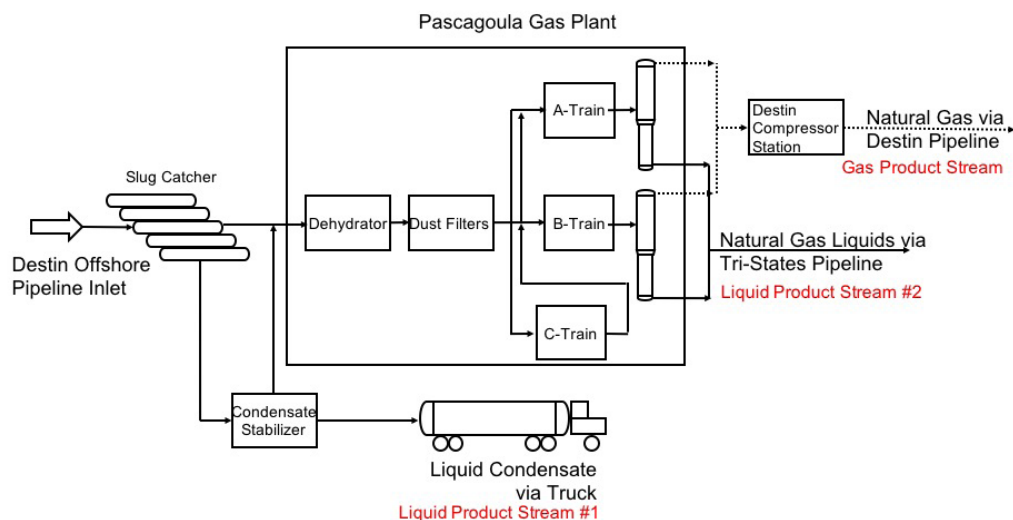


Figure 7. Simplified process overview for PGP. The first liquid product stream is trucked off site and the second is sent through the Tri-States pipeline. PGP sends the gas product stream through the Destin pipeline. A full process description and details on equipment depicted in the figure are in Appendix B.

³⁰ A visual representation of the CSB investigation's findings and causal factors of this incident is available in Appendix A.

³² Natural gas product that is transported throughout the U.S. pipeline system has to meet quality standards so that it does not cause operational problems or damage or rupture pipelines; these include having certain specific gravities, pressures, Btu (heat) content range, and levels of non-hydrocarbon contaminants (e.g., water and hydrogen sulfide). Energy Information Administration, Office of Oil and Gas. *Natural Gas Processing: The Crucial Link between Natural Gas Production and Its Transportation to the Market*; Washington, DC, January 2006. https://www.eia.gov/naturalgas/archive/feature_articles/2006/ngprocess/ngprocess.pdf (accessed May 25, 2017).

PGP has a design capacity of 1.5 billion cubic feet per day of raw gas and up to 50,000 barrels per day (bpd) of NGLs. At the time of the incident, throughput was about 500 million standard cubic feet per day of raw gas and 16,000–18,000 bpd of NGLs. The plant used to run at a higher capacity, but the maturity of the offshore field from which it receives raw gas and government restrictions imposed in the Gulf of Mexico reduced its throughput.

³² Natural gas condensate is "a mixture of hydrocarbons, mostly pentanes and heavier, extracted from natural gas, which meets vapor and pressure, end point, and other specifications for natural gasoline as adopted by GPA Midstream." Gas Processors Suppliers Association, *Engineering Data Book—FPS English Units*, 14th ed.; Tulsa, OK, 2017; Vol. 1, p 1-6. <https://gpsamidstreamsuppliers.org/gpsa-databook> (accessed July 10, 2018).

³³ Natural gas is a "gaseous form of petroleum ... consisting predominately of mixtures of hydrocarbon gases. The most common component is methane." Gas Processors Suppliers Association, *Engineering Data Book—FPS English Units*, 14th ed.; Tulsa, OK, 2017; Vol. 1, p 1-6. <https://gpsamidstreamsuppliers.org/gpsa-databook> (accessed July 10, 2018).

³⁴ U.S. Energy Information Administration. High Value of Liquids Drives U.S. Producers to Target Wet Natural Gas Resources. *Today in Energy* (blog), May 8, 2014. <https://www.eia.gov/todayinenergy/detail.php?id=16191> (accessed June 7, 2018).

³⁵ American Midstream Partners LP assumed operatorship of the Destin pipeline at the end of 2016 (<https://markets.businessinsider.com/news/stocks/american-midstream-announces-drop-down-of-destin-pipeline-interests-bolstering-deepwater-gulf-of-mexico-position-1006160289>, accessed October 28, 2018). Before that, BP was owner (http://www.bp.com/en_us/bp-us/what-we-do/bp-pipelines/our-pipelines-and-terminals/destin-pipeline.html, accessed May 25, 2017).

³⁶ Enterprise is a partial owner and the operator of the Tri-States NGL pipeline; at the time of the June 2016 incident, BP was the operator of the pipeline and shared ownership of the pipeline with Enterprise. See also <http://www.enterpriseproducts.com/operations/ngl-pipelines-services/ngl-pipelines> (accessed May 25, 2017).

³⁷ Blast-resistant modules (BRMs) were installed onsite in 2010 to move administrative and engineering personnel away from areas that could be affected by potential fires and explosions. In 2012, operations personnel and the control room were also moved into a BRM.

remedy some operational difficulties it was experiencing downstream of PGP. In response, the board operator reduced flow to the TriStates pipeline. NGL storage bullets at the PGP site allow operators some flexibility to accumulate product until full flow to the TriStates pipeline is reestablished, but storage capacity is limited. As a result, when operators are faced with a curtailment, they also typically reduce the NGL production rate.³⁸ About 20 minutes after the initial call, Tri-States called back to say all flow to the pipeline would have to stop because a lightning strike had shut down its operations.

Because of the limited storage capacity onsite, the operators needed to shut down NGL production completely to comply with Tri-States' request. As part of the normal shutdown procedure, the board operator asked that the outside operator manually light a burner on the hot oil furnace in the unit to add heat to the demethanizer column.³⁹ The additional heat causes more NGLs to vaporize and leave with the residue gas stream, rather than condense as a bottom product to be sent to the storage bullets. Once the NGL bullets were full, any remaining flow of NGLs from the bottom of the demethanizer would be lost through controlled burning in one of the plant's flare systems.⁴⁰ Surveillance video indicates the operator arrived at the hot oil furnace at 11:00 p.m. and left a minute later. After returning from the furnace, the board operator provided tutoring on the written shutdown procedure to the outside operator in what they each described as a normal conversation with "no alarms, no nothing," right up until they heard a "really loud boom."⁴¹ The initial explosion occurred at 11:22 p.m.; it was captured in surveillance footage and coincided with various instrument failures and temperature spikes.

Upon hearing the "boom" sound, the outside operator left the control room to see what was happening in the unit (**Figure 8**) and immediately radioed back to say the plant should be shut down.

The plant has two emergency shut-down (ESD) systems, ESD 1000 and ESD 9900, built into the process for operators to initiate manually. ESD 1000 blocks all the gas and liquid flows into and out of the plant and shuts down some equipment, but does not depressurize the plant. ESD 9900 goes a step further and vents the gas in a predetermined sequence by sending most of it to the flares and releasing the

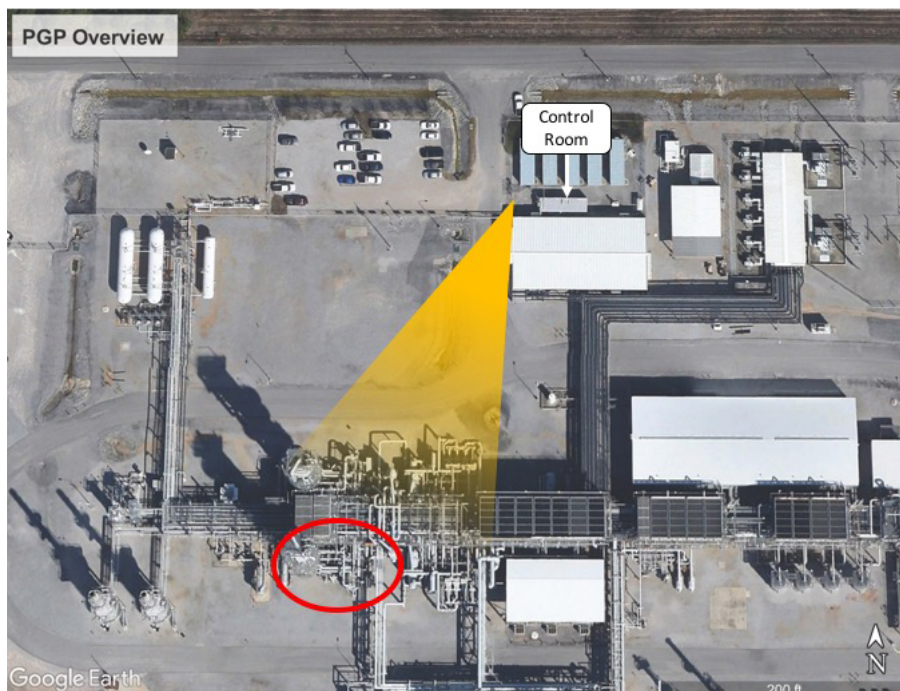


Figure 8. Field of view (yellow) for the operators from their vantage point, located just outside the control room and just inside the access control fencing, from which they assessed the magnitude of the incident (circle).

38 Operators told the CSB it was not uncommon to receive such a request. In fact, operators anticipate and sometimes plan for them. For example, the Tri-States pipeline asked the same board operator on duty the night of June 27 to curtail flow for about two hours on June 25. On June 26, anticipating another potential curtailment, the operator pumped extra product into the pipeline in order to preemptively lower the bullet levels to maximize available storage space. Normal bullet level set points are 28 percent, with a low-level alarm set at 18 percent because bullet pumps shut off at 14 percent. On June 25 when the operator began the shift, the levels were around 30 percent until the operator adjusted them to around 18 percent. Ultimately, Tri-States did not ask the operator to curtail flow on June 26.

39 See Appendix B for process description, which includes an explanation of the demethanizer column.

40 Plants like PGP use flares to dispose of unwanted flammable gas by burning it in a safe and controlled manner.

41 In interviews, both operators referred to the lack of alarms before the incident. A review of the event log shows that there were numerous alarms going off all night, but these were expected and acknowledged by the operators due to the curtailment and shutdown activities taking place.



Figure 9. Photograph taken at the intersection of Stennis Boulevard and Old Mobile Avenue, a major thoroughfare running adjacent to the PGP property line. (Credit: Pascagoula Fire Department)

rest to the atmosphere.⁴² The board operator initiated ESD 1000 about a minute after the initial explosion, and then, after conferring with the outside operator about the severity of the event, hit the ESD 9900 button—23 seconds after initiating ESD 1000.

Within two minutes of hitting the ESD 9900 button, the board operator called the plant operations supervisor at home to brief him on the event and, consistent with PGP emergency response procedures, requested that he come to the plant to assume the role of incident commander (IC) for PGP and manage the emergency response.⁴³ The plant operations supervisor then immediately called 9-1-1. After arriving onsite, he held the IC position until the plant manager assumed it when he arrived.

After calling the plant supervisor, the board operator noticed that a vent on the top of the B-Train demethanizer column had caught fire (**Figure 9**).⁴⁴ This concerned the operator because the vent is not designed to catch fire, so the operator chose to reset the 9900 system at 11:33 p.m. After seeing the flames go out, the operator reinitiated the 9900 at 11:45 p.m. This time, gas started to vent from the top of the demethanizer column without igniting.

Emergency responders from the Pascagoula Fire Department were the first to arrive on scene at 11:30 p.m., setting up a checkpoint at the nearest major intersection from the PGP site and redirecting traffic. Two volunteer fire departments, Escatawpa and Forts Lake/

PGP’s emergency response plan was to vent fuel to the flare or vent to atmosphere and to let any existing fire burn until it self-extinguished. The “let it burn” philosophy was established as a means to minimize the likelihood of a vapor cloud explosion that could extend outside the property line. That is, the purposeful release and flaring of hydrocarbon was chosen to burn off the flammable material before a vapor cloud could form, travel outside the boundaries of the PGP property, and then find an ignition source.



Figure 10. Water monitor being set up by emergency responders to cool equipment. (Credit: Pascagoula Fire Department)

42 Sending demethanizer fluids (at -130°F) to the flare would expose the carbon steel flare piping to temperatures of less than -50°F and potentially create low-temperature brittle fracture hazards. To mitigate the hazard, new 3-inch vent valves were added to the demethanizer column in 2010 to allow venting to atmosphere during an ESD. BP completed a dispersion model of the vented products to evaluate possible fire and explosion concerns during actuation of the 9900, but none were identified. The CSB did not evaluate the adequacy of the modeling.

43 The PGP Incident Management Plan identifies that an IC will be identified to complete initial internal and external notifications. See Chapter 7.0 for further discussion on the emergency response unified command.

44 When either B-Train or A-Train is not operating, the unit is shut down but kept pressurized. When the 9900 ESD button was hit, both A- and B-Trains began to depressurize and vent hydrocarbons from their respective demethanizer columns.

Franklin Creek, also responded. Jackson County Emergency Services⁴⁵ set up a unified command and led the efforts.⁴⁶ The emergency responders, in conjunction with PGP management personnel, decided the appropriate course of action would be to allow the fire to burn itself out, while cooling equipment where feasible.

Emergency responders also determined that the residential population and property would not be physically harmed by the event, and thus did not initiate a reverse 9-1-1 call, relying instead upon the local media outlets and social media to keep the public informed. The sound of the explosions and sight of the fires alarmed community members adjacent to PGP, and some chose to evacuate. (For further details on the emergency response activities, see Chapter 7.)

The fire began to diminish around midnight. At approximately 1:00 a.m., emergency responders approached the process area to conduct reconnaissance because they were concerned about potential structural failures that could lead to additional problems. No fixed fire monitors⁴⁷ were in the plant to provide water for cooling. Instead, emergency responders returned around 2:30 a.m. to set up unmanned fire monitors to cool vessels and equipment near the fire (**Figure 10**).

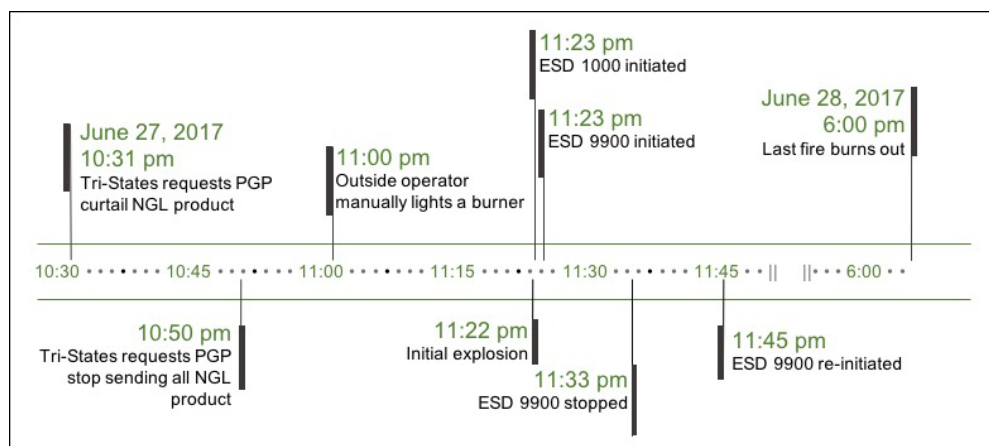


Figure 11. Simplified timeline of events on June 27–28, 2016.

The monitors were operational until the following day, when the fire finally burned out around 6:00 p.m. Emergency responders discontinued safety and fire watch operations on the morning of June 29. The timeline in **Figure 11** summarizes the events of June 27–28.

3.1 OSHA Activities at PGP

The PGP site had no previous record of inspections or citations from the Occupational Safety and Health Administration (OSHA). OSHA conducted

a post-incident inspection of PGP after the June 2016 loss of containment, resulting in three citations, two of which were classified as serious.⁴⁸ In settlement agreements, the serious violations were dropped. PGP was subsequently fined \$7,126 for not ensuring that the site retained documentation associated with all process hazard analyses, updates, and revalidations for each process covered by OSHA's Process Safety Management (PSM) standard, as well as ordered to resolve process hazard analysis recommendations for the life of the process.⁴⁹

⁴⁵ Jackson County Emergency Services “acts as a coordinating agency during times of emergency or disaster.” Jackson County, Mississippi. Office of Emergency Services, <https://www.co.jackson.ms.us/224/Office-of-Emergency-Services> (accessed May 24, 2017).

⁴⁶ The incident command system is designed “to enable effective and efficient domestic incident management by integrating a combination of facilities, equipment, personnel, procedures, and communications operating within a common organizational structure.” When multiple jurisdictions are involved, a unified command intends to allow the groups “to work together effectively without affecting individual agency authority, responsibility, or accountability.” Federal Emergency Management Agency. *ICS Review Material: Incident Command System Training*; May 2008. <https://training.fema.gov/emiweb/is/icsresource/assets/reviewmaterials.pdf> (accessed June 8, 2018).

⁴⁷ A fire monitor is a piece of equipment used to throw large streams of water on equipment from long distances.

⁴⁸ Occupational Safety and Health Administration, U.S. Department of Labor. Inspection Detail, Inspection 1159519.015, Report ID 0419400, closed March 17, 2017, https://www.osha.gov/pls/imis/establishment.inspection_detail?id=1159519.015 (accessed July 10, 2018).

⁴⁹ Process hazard analysis is one of 14 program elements required as part of a company's process safety management plan for processes covered under OSHA's PSM standard, 29 C.F.R. §1910.119.

The original two serious violations, of 29 C.F.R. §1910.119(e)(5) and 29 C.F.R. §1910.119(e)(7), pertained, respectively, to the prompt response to and resolution of the process hazard analyses' recommendations, and the documentation of those efforts. The other violation was for 29 C.F.R. §1910.119(l)(1), the establishment and implementation of written procedures to manage changes to process chemicals, technology, equipment, and procedures, as well as changes to facilities that affect a PSM-covered process.

4.0 Initiating Event and Likely Failure Scenario

The CSB investigation finds that the probable cause of this incident was the failure of a brazed aluminum heat exchanger (BAHX) due to thermal fatigue. The absence of a reliable process to ensure the mechanical integrity of the heat exchanger contributed to the catastrophic failure of the equipment. This chapter discusses the initial failure point and the most likely failure scenario identified by the CSB.

4.1 Initial Failure Point and Likely Damage Mechanism

The CSB concludes that the first loss of containment most likely originated at a BAHX slightly before 11:21 p.m., when the BAHX lost core integrity. The CSB used distributed control system (DCS) data,⁵⁰ the event log,⁵¹ physical evidence, surveillance footage from a nearby industrial facility, and witness testimony to reconstruct the event and identify initial and subsequent failure locations.

DCS data and event log entries indicate that the first sensors to detect a process change or to stop transmitting were on a BAHX known as the A-Train cold side reboiler (ACSR):⁵²

- Metal temperature sensors affixed to the outside of the ACSR stopped transmitting between 11:20 and 11:21 p.m.
- Differential pressure for the two passes in the ACSR fell to nearly zero, starting between 11:21 and 11:22 p.m.
- Temperature and pressure sensors on equipment near the ACSR either stopped transmitting or detected large temperature increases after 11:23 p.m.
- Surveillance video shows that after the initial explosion, the ensuing fire intensified several times over approximately 35 minutes.

The CSB used these indicators to determine the progression of equipment failures as the event unfolded. For more detail, see Appendix C.

Post-incident examination of the ACSR revealed three major breaches: the partial loss of a cap sheet⁵³ along with portions of several layers in the exchanger core, and two holes in the B-inlet header (Figure 12 and Figure 13). The CSB concludes that the partial loss of the north cap sheet was the most likely initial failure point, and the other breaches were a consequence of the ensuing fires. Details of this analysis are in Section 4.3.

⁵⁰ DCS is a general term for a computer system that receives operational data and is used to control various aspects of plant operations.

⁵¹ Event logs are journals of the control system; they record discrete information such as alarm conditions, equipment set point changes, and control system status messages.

⁵² For more detail on the cold side reboiler, see the process description in Appendix B.

⁵³ This cap sheet is on the north-facing side of the exchanger.

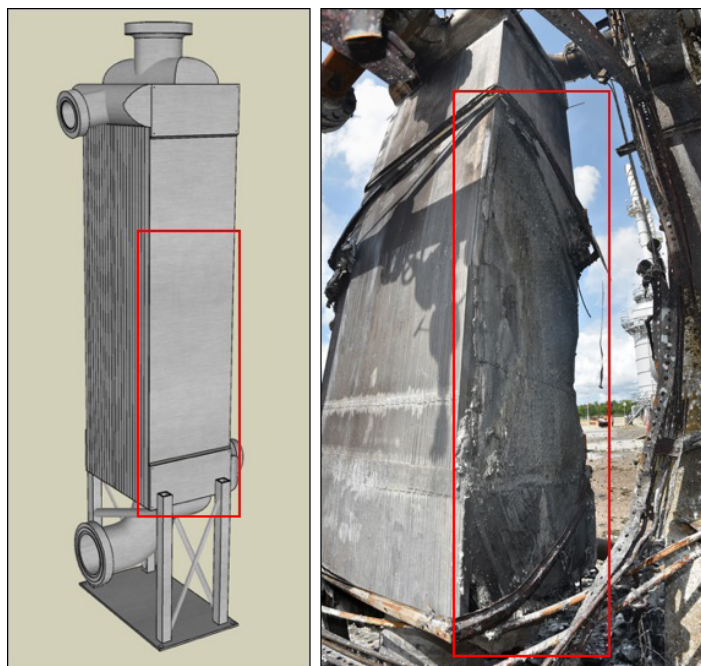


Figure 12. Diagram (left) and post-incident photograph of the ACSR (right). The red box highlights the location of the initial failure, where the partial loss of the north cap sheet along with portions of several layers occurred.

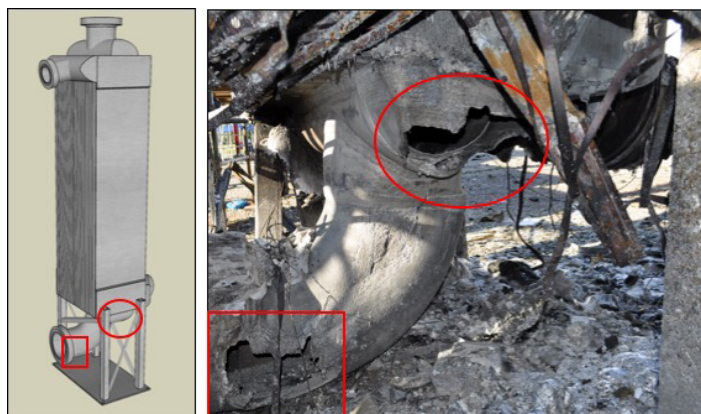


Figure 13. Diagram (left) and post-incident photograph of the ACSR (right) identifying two breaches. The red circle highlights the breach of the header. The red box shows a breach on piping connected to the header. Results of a visual field examination ruled out the latter breach as the initial failure location.

A post-incident laboratory examination of the exchanger revealed clear evidence of service-related thermal fatigue at several locations (Appendix D). Based on this metallurgical examination, as well as process data and physical evidence, the CSB concludes that this damage mechanism likely led to the failure of the ACSR through thermal fatigue cracking, which allowed process fluids in active passes, or layers, to leak into blocked passes,⁵⁴ and weakened braze joints between fins and parting sheets. Available evidence eliminated several other well-known potential damage mechanisms (Table 1).

Table 1. Potential damage mechanisms that could lead to BAHX failures.⁵⁵

Damage Mechanisms	Analysis	Contributing Cause?
Over-pressurization of the active layers of the BAHX core or its headers due to process upset	For the ACSR, the maximum allowable working pressure ^a for the A and B passes, respectively, are 1,200 and 570 pounds per square inch gauge (psig). A review of the DCS data indicates that in the hour leading up to the incident, there were no large increases in pressure. It is unlikely the exchanger exceeded the maximum allowable working pressure (1,200 psig for A pass and 570 for B pass), with the highest readings at less than 1,050 psig for A pass and 480 psig for B pass (see Section 2.2 for BAHX configuration).	No
Water accumulation and ice formation ^b	A dedicated process unit to remove any moisture in the feed to the cryogenic unit was operating normally. PGP has moisture analyzers in the process to indicate high amounts of water, but none of them alarmed in the 24 hours before the incident.	No
Thermal shock ^c	Analysis of the DCS data on the night of the incident does not indicate thermal shock. All temperature changes were slow, around 3°F/min, peaking at 6°F/min.	No
Weakening of the fin matrix as a result of corrosion ^d	As recently as September 2015, headers from the ACSR were removed and inspected. None of the repair reports by either PGP employees or the repair technicians noted any signs of corrosion.	No
Mercury embrittlement	Post-incident tests performed on the two BAHXs on B-Train, which operated under conditions similar to those on A-Train, discovered only trace amounts of mercury. Additionally, metallurgical testing of the ACSR found no evidence of embrittlement.	No
Thermal fatigue	Analysis of the operational history of the ACSR, repair records, historical process data, and a post-incident laboratory examination of the exchanger reveal evidence of service-related thermal fatigue in several areas within the core of the exchanger. Section 4.3 provides details of this analysis.	Yes

a Maximum allowable working pressure is the maximum pressure permissible at the top of a vessel in its normal operating position at operating temperature. American Society of Mechanical Engineers. Rules for Construction of Pressure Vessels. In *ASME Boiler and Pressure Vessel Code*; New York, 2013; §VIII, Div. 1, UG-98(b).

b As water freezes, it expands and can generate sufficient forces to break metal. See previous CSB report for an example: *Final Investigation Report: Valero Refinery Propane Fire, Sunray, TX, February 16, 2007*; Report No. 2007-05-I-TX; Washington, DC, 2008. <https://www.csb.gov/valero-refinery-propane-fire/> (accessed October 26, 2018).

c Thermal shock is the term for exposure to thermal gradients that are likely to cause heat exchanger failure after relatively few occurrences. BAHX Product Bulletin, Issue 1; Chart Energy & Chemicals Inc., April 2016; p 15. <http://files.chartindustries.com/BAHXProductBulletin.pdf> (accessed April 2017).

d Corrosion is a destructive chemical reaction involving on parts of the exchanger. Typical sources are chlorides, acids/bases, amines, cleaning agents, and mercury. BAHX Product Bulletin, Issue 1; Chart Energy & Chemicals Inc., April 2016; p 9. <http://files.chartindustries.com/BAHXProductBulletin.pdf> (accessed April 2017).

54 A blocked pass, or blocked layer, of a BAHX has been welded closed as part of a repair. In contrast, a “dummy layer” is purposely blocked during construction as part of the BAHX’s design.

55 Several potential damage mechanisms are also discussed in BAHX Product Bulletin, Issue 1; Chart Energy & Chemicals Inc., April 2016; p 5. <http://files.chartindustries.com/BAHXProductBulletin.pdf> (accessed April 2017).

4.2 Configuration of the BAHX of Interest

The ACSR had two process streams running through it (**Figure 14**). The warm stream consisted of feed gas (the A pass), while the cooler, liquid stream came from a demethanizer column (the B pass). As depicted in **Figure 15**, the exchanger comprised 99 layers stacked so that the A and B passes formed a BAB pattern. Weep holes were drilled in all four corners of each attachment plate to relieve any pressure that may develop underneath it. The maximum allowable working pressure for the A passes was 1,200 pounds per square inch (psig), and 570 psig for B passes.

4.3 Most Likely Failure Scenario

The ACSR most likely failed as a result of process fluids leaking into outer layers of the exchanger due to thermal fatigue damage. These outer layers were blocked, with no relief venting, after a previous repair for thermal fatigue-induced cracking. They became over-pressurized and catastrophically ruptured.

The key causal factors necessary for a failure of the cap sheet are (1) the existence of blocked layers within the exchanger, (2) the development of thermal fatigue cracks in the parting sheet adjacent to the blocked layers, (3) the separation of at least one layer from the core of the exchanger, (4) the expansion of the accumulated fluid in the blocked layer due to heating, and (5) the absence of venting or draining to allow the accumulated fluid to readily escape from the blocked layer. The circumstances, evidence, and assumptions for each key factor of this scenario are summarized below.

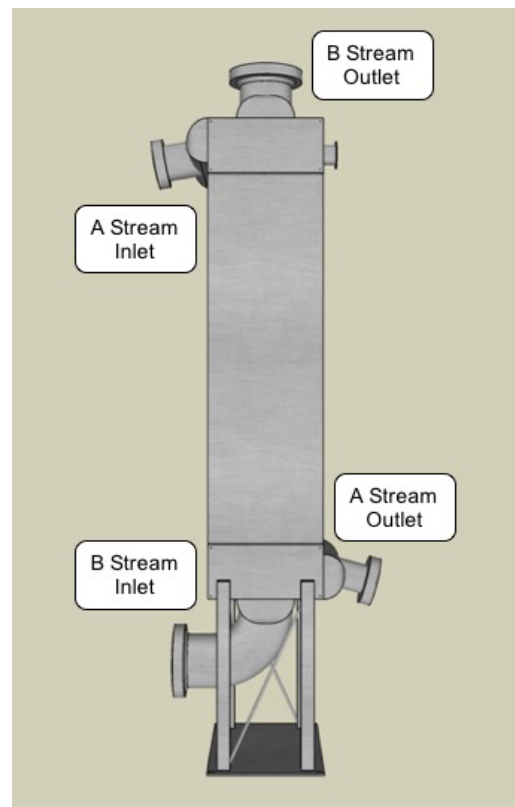


Figure 14. Side view of the ACSR.

The existence of blocked layers on the two outmost passes within the exchanger.

In September 2015, HETSCO, a third-party service provider,⁵⁶ repaired two interpass leaks⁵⁷ in the outermost A layers (98 and 2) of the ACSR.⁵⁸ As depicted in **Figure 15**, leaks into layers 98 and 2 could have originated from either flanking layer. The repair blocked the four outermost layers (99, 98, 2, and 1) from the process by welding shut their inlet and outlet openings, and left layers 97 and 3 open to the process.

During the ACSR repair to block the layers, workers drilled holes into the side bars to allow gases produced during welding to vent. According to welding procedures, workers also used this vent pathway to test the new welds for any other leaks; however, no documentation confirms that any leak test was performed after the layers were blocked. An example of open side bar holes from a non-PGP exchanger being repaired is shown in **Figure 16**.

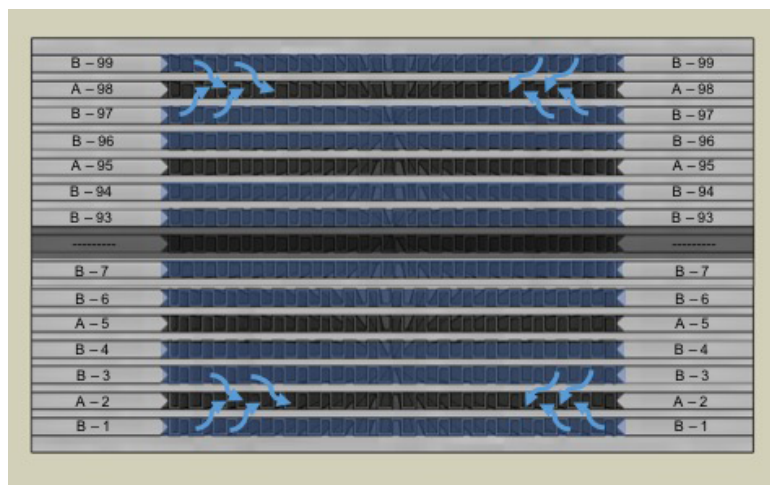


Figure 15. Interpass leaks were detected by pressurizing the B pass layers (blue) of the exchanger and monitoring for leak indicators in the A layers. Leaks into layers 2 and 98 were detected (blue arrows), possibly coming from either layer 1 or layer 3 and either layer 97 or layer 99, respectively.

⁵⁶ HETSCO provides specialty welding, construction, and fabrication services, including BAHX repairs, to natural gas processing and petrochemical industries. In January 2017, HETSCO was acquired by Chart Lifecycle Inc., a subsidiary of Chart Industries. Chart Announces Acquisition of HETSCO. *GlobeNewswire*, January 7, 2017. <https://globenews-wire.com/news-release/2017/01/17/906183/0/en/Chart-announces-acquisition-of-HETSCO.html> (accessed January 7, 2017).

⁵⁷ An interpass leak is a crack between two adjoining layers of a BAHX that allows the fluid from one pass to leak into the other pass. No leaking to the environment occurs with interpass leaks.

⁵⁸ The interpass leaks had previously been identified in 2014. See Section 6.2.1 and Appendix G for more detail on the leaks and repairs.

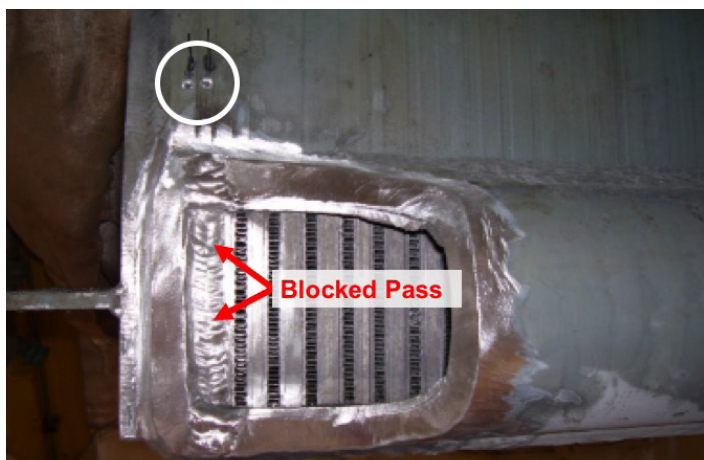


Figure 16. Example of vent holes (white circle) drilled into a BAHX that was in the process of having passes blocked off (red arrow). This image does not depict any exchangers on PGP property. (Credit: Willard, *Field Repair of Brazed Aluminum Plate-Fin Heat Exchangers*, p 7)⁵⁹

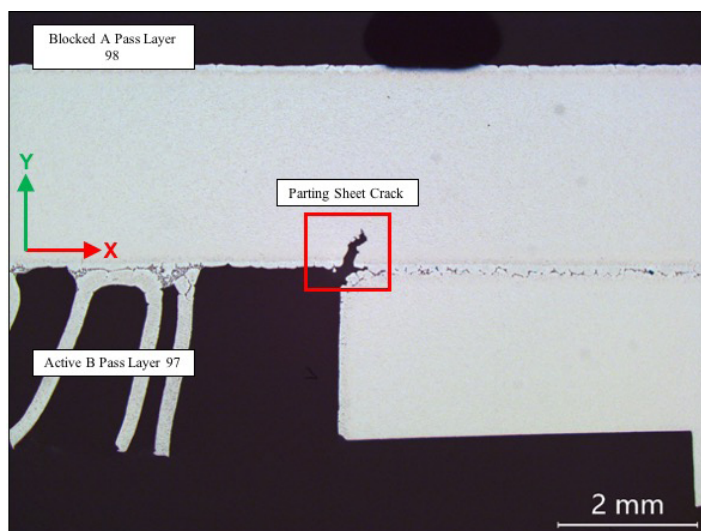


Figure 17. Metallurgical examination revealed a crack in the parting sheet between layer 97 and layer 98. The crack did not extend the full thickness of the parting sheet, but it is an indication that thermal fatigue existed in the parting sheet. Through-wall cracks may have existed in other areas of the parting sheet that were not examined or were destroyed by the ensuing fires.

At some point between the September 2015 repair and the June 2016 incident, the vent holes for the blocked layers were welded closed.⁶⁰ The ACSR was returned to service and operated for 205 days before the incident occurred.⁶¹ Without open vent holes, the blocked layers had no means to relieve pressure should hydrocarbons leak into one of them through a thermal fatigue-induced crack.

After the repair of the exchanger in September 2015, process fluids may have leaked into the blocked layers (98 and 99) of the ACSR through thermal fatigue-generated interpass cracks between layers 97 and 98. On the night of the incident, when the operator warmed up the unit, the increase in temperature of the exchanger would have caused trapped hydrocarbons within the blocked layers to expand due to thermal expansion. Eventually, the pressure in the blocked layers was sufficient to overcome the strength of the braze joints, potentially weakened by thermal fatigue between the aluminum sheets and the fin matrix, and the exchanger ruptured when the cap sheet and blocked layers separated from the core.

Thermal fatigue and cracks in the parting sheet adjacent to the blocked layers. A post-incident analysis of the exchanger identified numerous thermal fatigue cracks on the exchanger and, more specifically, one in the parting sheet between a nonblocked B layer (97) and an adjacent blocked A layer (98) (**Figure 17**).

Figure 17 shows a thermal fatigue crack identified in the exchanger post-incident. The crack was located in an area most susceptible to thermal fatigue damage, next to the sidebar. The crack is visible on the surface of the parting sheet between the active B pass layer 97 and the blocked A pass layer 98. The crack did not extend the full width (y-direction) of the parting sheet, but it is an indication that a thermal fatigue crack existed in the parting sheet between the active and inactive layers. It is possible that the crack in **Figure 17** is just a small portion of a larger crack, or part of a series of cracks, extending the length (into and out of the page) of the parting sheet, which at some point(s) could fully extend through the width of the parting sheet in the y-direction. However, this could not be verified due to the extent of the fire damage.

59 Willard, S. *Field Repair of Brazed Aluminum Plate-Fin Heat Exchangers*. Presented at 94th GPA Midstream Annual Convention, San Antonio, TX, April 12–15, 2015; print copy from GPA Midstream, p 7.

60 The CSB was not able to locate any documentation about when the holes were welded closed. The BAHX was covered with insulation after installation in the unit. This insulation required removal for any subsequent welding activity.

61 This was not continuous operation. The exchanger was in service from October 10, 2015, to March 10, 2016, and then was again in service from May 6, 2016, until the day of the incident.

Assuming this crack extended through the width (y-direction) of the parting sheet somewhere along the length of the parting sheet, it would have allowed fluids to leak from the active B pass into the adjacent blocked-off layer(s). The development of such a crack could have happened one of two ways. The crack shown in **Figure 17** may have been present at the time of the 2015 repair and—not yet being a through-wall crack—passed a leak test, but later developed into a through-wall crack somewhere along its length within the 205 days of operation leading up to the June 2016 incident. This is plausible since fatigue cracks take time to develop. Alternatively, it is possible the crack in **Figure 17** was the interpass leak (at a location somewhere along the length of the parting sheet) that prompted the blocking of layers in September 2015, but the leak was not fully remediated during that repair. The 2015 repair procedures stipulate that after welding close passes 98 and 99, technicians were to pressurize layer 98 to determine if any leaks were present through the parting sheet between layers 98 and 97 (**Figure 18**). No documentation confirms that this test was conducted; therefore, the possibility of an interpass leak existing between layers 98 and 97 at the time of the 2015 repair cannot be ruled out.

Separation of at least one layer from the exchanger core. CSB post-incident observations reveal that the north cap sheet and the parting sheet between layers 98 and 99 separated from the core of the exchanger. The core of a BAHX is able to absorb large amounts of heat from a fire; however, when layer 99 and the north cap sheet separated, there was less material to absorb the heat. The thinner aluminum portion of layer 99, the lower portion of the cap sheet, and the bottom attachment plate melted and fell away. Physical evidence supports this event.

First, investigators found the lower portion of the cap sheet, with the bottom attachment plate attached to it, on the ground near the exchangers (**Figure 19**, bottom right). The attachment plate was in the down position (i.e., the attachment plate was on the ground and covered by the cap sheet) and showed only partial melting and heat damage. The attachment plate on the top of the same cap sheet, however, showed extensive melting, indicating that it was exposed to the effects of the fire longer. The bottom attachment plate likely fell off the exchanger very early in the incident, before the fire could melt and damage it.

Second, while approximately two-thirds of the north cap sheet and sections of several layers were no longer attached to the lower portion of the exchanger, there was no significant melting of the remaining exchanger core, and the end of the remaining cap sheet had an edge that appears to have pulled away from the core

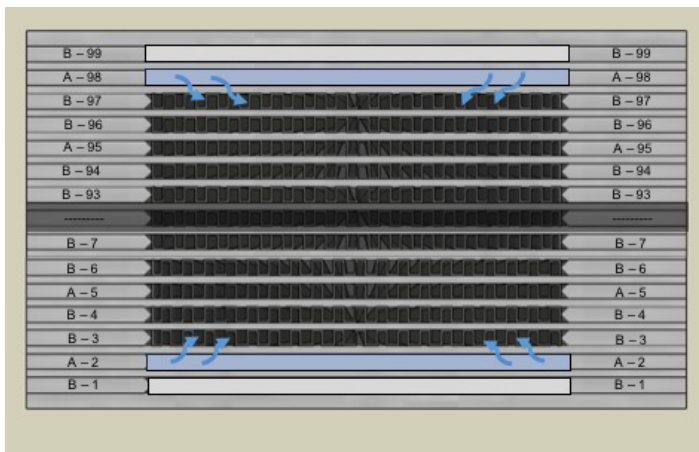


Figure 18. To repair the leaks into layers 2 and 98, workers welded closed layers 99 and 98 as well as layers 1 and 2. Repair documentation states that after welding the four passes closed, workers planned to pressurize the blocked A pass layer 98 (blue) and monitor for leaks into B pass layer 97 (arrows). No records show that workers completed this test to confirm that interpass cracks did not exist between layers 98 and 97.

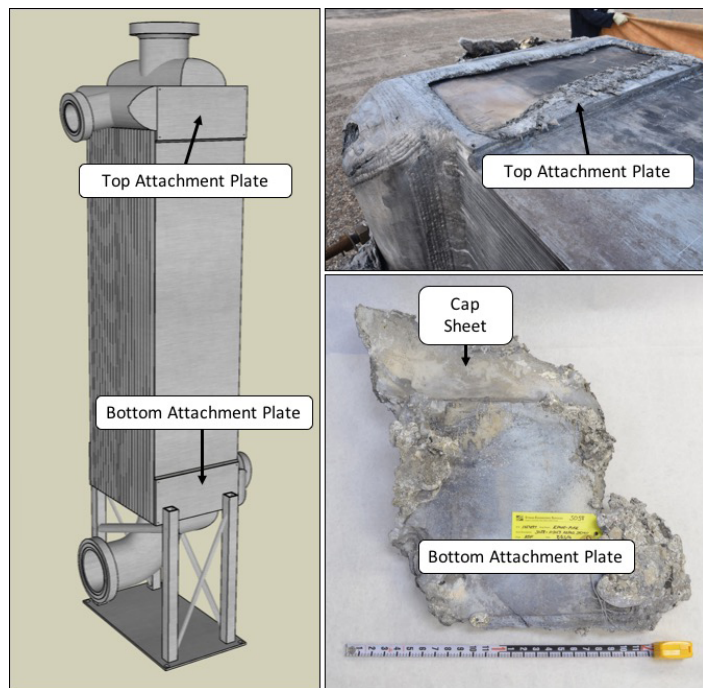


Figure 19. Depiction of the ACSR (left) and two post-incident photos. A portion of the bottom attachment plate and north cap sheet that was found on the ground near the exchanger post-incident (bottom right) shows far less fire damage than the top attachment plate (top right), suggesting that it was not exposed to the effects of the fire as directly as other portions of the exchanger, implying that it fell from the exchanger early during the event.

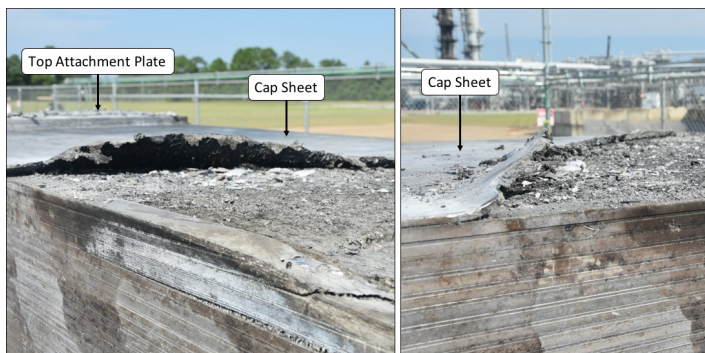


Figure 20. Two post-incident images depicting the remaining north cap sheet attached to the ACSR core. The bottom edge of the cap sheet that remains curls away from the core.

(Figure 20). This physical appearance has similarities to other cap sheet failures (see Section 4.4).

Third, post-incident metallurgical examinations documented a bulge that originated in layer 95 (Figure 21). The fin matrices in layers 93, 94, 96, and 97 were compressed; however, the fin matrix in layer 98 was not. Furthermore, the bulge projected beyond the plane of the side and end bars, which indicates that the north cap sheet, attachment plate, and parting sheet between layers 98 and 99 detached from the core before the bulge occurred. Thermal expansion, to the point of rupture, of leaked process fluids in layer 98 could explain the detachment of the cap sheet and parting sheet, followed by a secondary over-pressurization event that created the bulge later in the incident.



Figure 21. Bulge observed in the ACSR that affected layers 95 through 99 (left). The bulge is on the northeast bottom corner of the exchanger in the area of the missing cap sheet and attachment plate (red box, right). Also shown in the image on the right is the place where the cap sheet is missing from the exchanger.

Thermal expansion of the accumulated fluid in the blocked layer due to heating of the A-Train process. The CSB completed thermal expansion calculations to estimate possible pressures in the unvented, inactive A layer if leaked process fluids were warmed.⁶² Assuming the composition of the leaked process fluids matched what the exchanger was originally designed to process, the maximum calculated pressure would be 705 psig⁶³ (detailed in Appendix E). The maximum allowable working pressure for an A pass is 1,200 psig, so for this particular assumption, the integrity of the pass would have had to degrade to such an extent that it failed at a lower pressure than this maximum. This would not be the first time the strength of a fin matrix was potentially compromised by thermal fatigue and contributed to a catastrophic failure at operating pressures (see Section 4.4). Furthermore, while no method is available to accurately calculate the hydrocarbon composition in the B pass during the incident, samplings of the feed gas taken before the incident reveal that its composition was different than it was when the unit was built. This fact suggests that the liquid in the B pass during the incident would also have differed from the original design composition. Thus, the assumption used to calculate the maximum pressure could be conservative.

No vent or drain to allow the accumulated fluid to readily escape from the blocked layer. The CSB noted that the blocked-off layers had no relief protection. Post-incident examination confirmed that vent holes had been welded closed. The lower photograph in Figure 22 shows a cross-section of holes that had been drilled into the side bar of one of the blocked layers during repairs for the interpass leaks with weld metal over the holes.

⁶² Thermal expansion is the increase in volume of a given mass of a solid, liquid, or gas as it is heated to a higher temperature.

⁶³ The calculations, documented in Appendix E, are highly dependent on the composition of the leaked fluids.

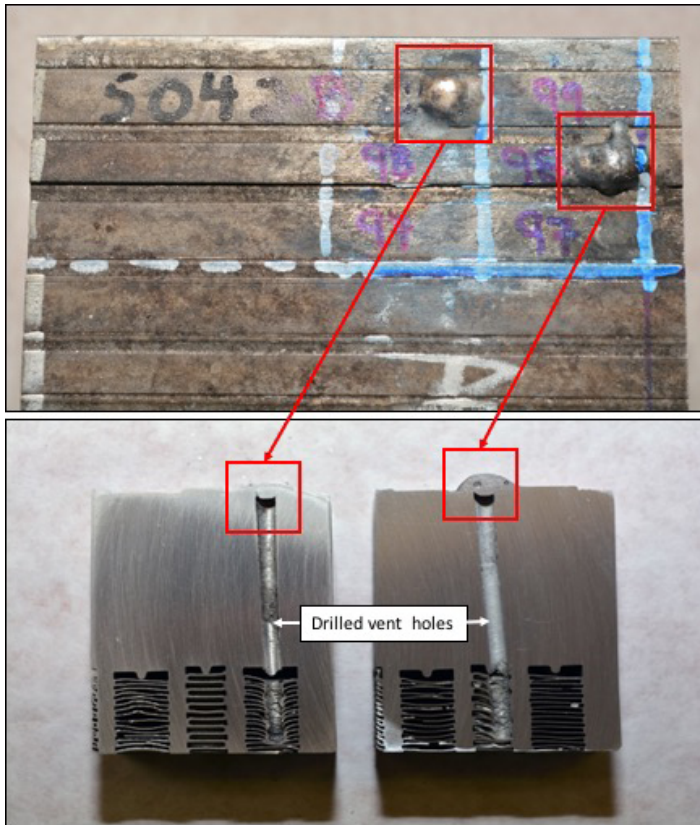


Figure 22. Image of the blocked vent holes. The CSB observed welds on the outside of the exchanger (top). Cross-section of the drilled holes (bottom).

The CSB considered alternative failure scenarios (Appendix F). Ultimately, the Agency could not completely rule out these alternatives, yet sufficient supporting evidence was lacking to deem them as likely as the cap sheet failure scenario.

4.4 Thermal Fatigue Events Elsewhere

Beyond the PGP explosion and fire, thermal fatigue has been suspected of playing a role in BAHX core ruptures and cap sheet detachments in at least three separate incidents.

In May 2015, a ConocoPhillips gas plant BAHX that had been installed in 1994/1995, and repaired in 1998 and 2000, ruptured and released hydrocarbons to the atmosphere. The cap sheet of this exchanger bulged from the core after a failure of the braze joint between the fins and a cap sheet (**Figure 23**). Chart conducted an examination of the exchanger. Based on its visual inspection, discussions with site personnel, and a review of past operating data, Chart concluded that thermal fatigue was the most likely cause of the failure. Similarities between the ConocoPhillips BAHX and PGP's ACSR are apparent. **Figure 23** depicts the lower section of the cap sheet, where it is still attached to the core of the exchanger. The cap sheet curls away from the core (red square), which is similar to the curling of the remaining top portion of the cap sheet on PGP's ACSR. In this case, the ConocoPhillips BAHX aluminum cap sheet was not subjected to fire.

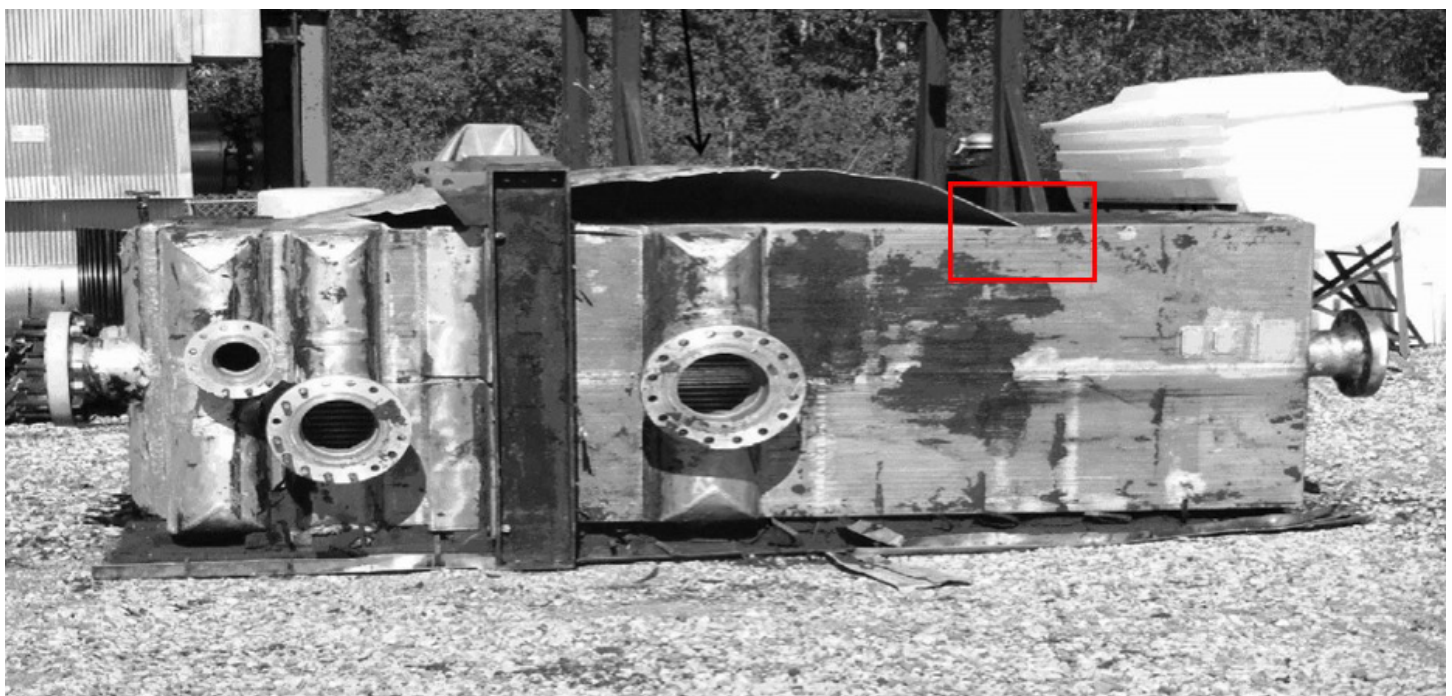


Figure 23. A ruptured BAHX from a ConocoPhillips gas plant in 2015. The red box shows the similarities between the separation of the cap sheet in this incident and the failure scenario described in Section 4.3. (Credit: Chart Industries)

In August 2012, after 17 years of service, a BAHX manufactured by Chart ruptured at Enterprise's Chaco gas plant (**Figure 24**). Before the incident, the exchanger had experienced interpass leaks, but not external ones. An Enterprise-commissioned metallurgical evaluation of the exchanger concluded that a mechanical overload caused the brazed joints to fail, but it did not identify the initiation site of the failure; Chart suspected that thermal fatigue played a role.⁶⁴ Metallurgical testing on this exchanger did not identify any thermal fatigue. However, only one small sample was analyzed from an area that may have been far away from the initiation point and thus less likely to represent an area subjected to thermal fatigue.

In 2006, a BAHX at another gas plant ruptured and one of the cap sheets separated from the core, from top to bottom. After examining the exchanger, Chart indicated that it could not be certain of the failure mechanism, but noted severe fin cracking and pointed to thermal fatigue as the likely cause.⁶⁵

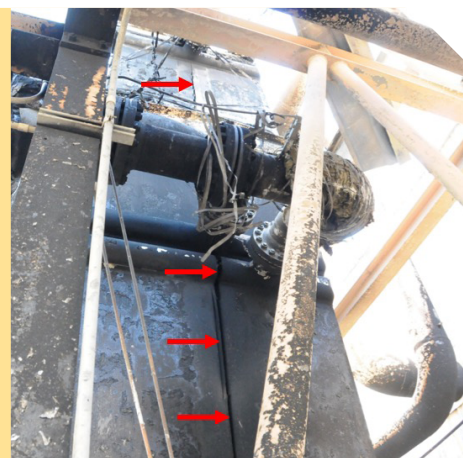
While the non-PGP incidents described here demonstrate that other plants have also experienced major losses of containment due to the failure of a BAHX, the PGP event illustrates some of the potential



Figure 24. Ruptured cold side reboiler at Enterprise's Chaco gas plant, showing the exchanger still covered in insulation. (Credit: Chart Industries)

Different Design, Similar Failure Mechanism

In April 2014, a BAHX failure occurred in a process unit at an Opal, Wyoming, gas processing plant, which had been in operation since 1999 and was owned by Williams Field Services LLC (Williams).^a The exchanger that failed had two cores welded to one another. While this design is different from the single-core PGP exchanger, there is some similarity in the potential failure scenario due to a suspected leak of process fluids into the enclosed area after the intermodal space between the two cores pressurized. Nearly the entire core-to-core weld seam cracked (red arrows).



After the exchanger failed, hydrocarbons were released, and a fire ensued. No one was injured, but the process train containing the BAHX was rendered temporarily inoperable. The post-incident metallurgical analysis ruled out several potential failure modes,^b noting that while direct evidence of thermal fatigue was not found, it could not be eliminated as a probable cause.

^a The Williams Companies Inc. was the ultimate parent of Williams Field Services LLC. Williams is an energy infrastructure company headquartered in Tulsa, Oklahoma. Founded in 1908, Williams owns interests in natural gas and natural gas liquids pipeline and processing facilities throughout North America and conducts most of its operations through subsidiary companies.

A Williams Olefins plant in Geismar, Louisiana, was the focus of a CSB case study for a June 13, 2013, shell-and-tube exchanger rupture that killed two employees. The CSB initially deployed at the site of the Opal incident for a wider review of Williams's corporate oversight in connection with its Williams Geismar investigation, but ultimately did not publish a report on the Opal incident. CSB. *Williams Geismar Olefins Plant Reboiler Rupture and Fire, Geismar, Louisiana, June 13, 2013*; Report No. 2013-03-I-LA; Washington, DC, October 2016. <https://www.csb.gov/williams-olefins-plant-explosion-and-fire/> (accessed October 26, 2017).

^b The post-incident metallurgical analysis included pipe loads, over-pressurization, freezing of water, external corrosion or damage, incorrect materials, internal corrosion, and vibration/mechanical fatigue.

⁶⁴ Again, the CSB notes that mechanical overload can be a consequence of the chain effect described in Section 2.3, whereby the initial fin failure(s) can lead to an unsustainable load on nearby fins. Also, the Chaco plant had documented flow instabilities into the exchanger that failed.

⁶⁵ An independent metallurgical report noted that the examined fractures indicated a mechanical overload and that evidence of thermal fatigue was not found. The report highlighted, however, that further examination would be "prudent" to determine whether evidence for initiation was present in another section of the rupture. The CSB could not determine whether Chart conducted further examination. The CSB also notes that mechanical overload can be a consequence of the chain effect whereby a failure of fins leads to an unsustainable load on nearby fins (Section 2.3).

financial consequences if the hydrocarbons find an ignition source. The fire response activities resulted in \$10.4 million of expense, and the six-month shutdown of the plant and loss of assets led to a combined non-cash loss of \$7.1 million.⁶⁶ Notably, there was potential for much graver human losses, as the time of day when the June 2016 event occurred reduced the number of employees present.

5.0 Thermal Fatigue in BAHXs at the Pascagoula Gas Plant

Thermal stress can lead to thermal fatigue cracking. It is one of the most common causes of leaks in brazed aluminum heat exchangers (BAHXs). As indicated in **Figure 25**, in 17 years of operation, HETSCO repaired four BAHXs nine different times at PGP. Each time, BP suspected that thermal fatigue cracking caused the leaks. Process data for the life-span of the exchangers shows that the BAHXs were repeatedly subjected to temperature changes that exceeded industry-recommended practices.⁶⁷ Both external plant conditions and internal operational practices caused these temperature fluctuations.

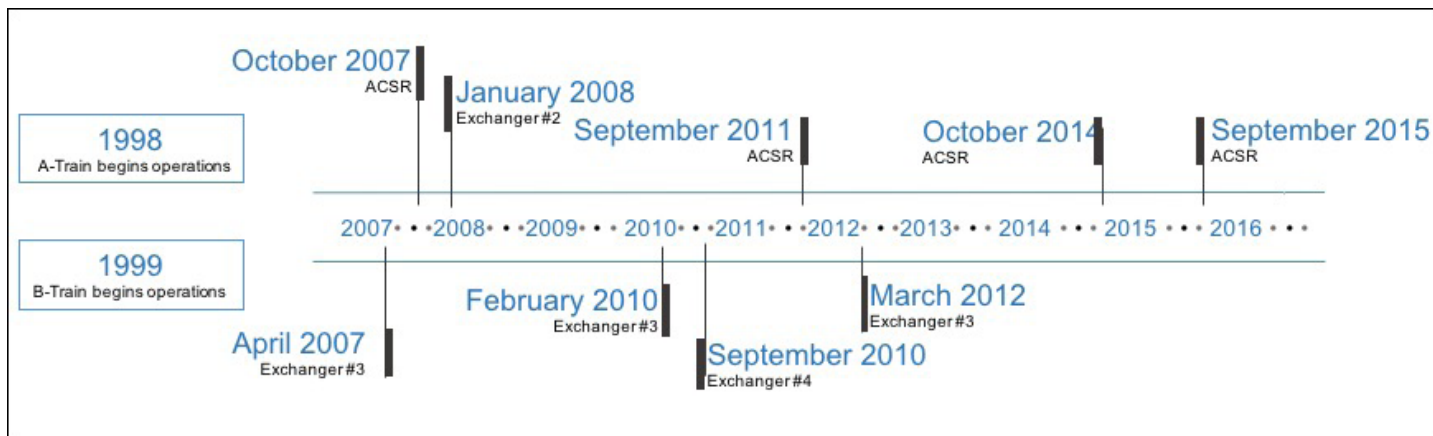


Figure 25. Timeline of hydrocarbon leaks to atmosphere from four BAHXs at PGP.⁷¹

Chart, the manufacturer of the BAHXs used at PGP, informs its customers that “the majority of BAHXs are retired from service due to leaks, and the majority of leaks are caused by some form of thermal stress damage.” Chart stipulates that “the vast majority of BAHXs that experience thermal stress cracking ... will exhibit small leaks that can be detected and repaired in the field.”⁶⁹ Chart observes that “there is no reliable way to directly measure fatigue damage before it results in a leak.”⁷⁰ PGP’s experience mirrored Chart’s description: it identified leaks, safely shut down process trains, and repaired the exchangers with no major health or safety impacts. Generally, this leak-before-break (LBB) approach⁷¹ assumes that a through-wall crack in the exchanger will develop and the resulting leak will be detected before a catastrophic failure happens.⁷² Yet the June 2016 event (Section 4.3) and other BAHX incidents (Section 4.4) illustrate that sudden catastrophic failure can happen.

This chapter summarizes (1) the recommended BAHX operational guidelines; (2) their significant differences in recommended practices; (3) the importance of reviewing an exchanger’s operational data, a practice described in some—but not all—of the guidance documents; (4) the likelihood of PGP’s BAHX’s exposure to thermal fatigue-inducing process conditions; and (5) the value to industry if companies share operational data to better predict thermal fatigue.

⁶⁶ The non-cash loss in 2016 was attributable to assets damaged in the fire. This amount represented the net book value of assets at the time of the incident. Enterprise Products Partners LP, Annual Report (Form 10-K), December 31, 2016; p F-12, <http://phx.corporate-ir.net/External.File?item=UGFyZW50SUQ9NjYxMzU4fENoaWxkSUQ9MzY4Mjk-wfFR5cGU9MQ==&t=1> (accessed April 12, 2018).

⁶⁷ See Section 5.5 for review of ACSR process data.

⁶⁸ ACSR = A-Train cold side reboiler (the BAHX that failed). Exchanger #2 was also called the A-Train warm side reboiler (AWSR); Exchanger #3, the B-Train cold side reboiler (BCSR); and Exchanger #4, the B-Train warm side reboiler (BWSR). For details on the role of these exchangers in the process, see Appendix B.

⁶⁹ *BAHX Product Bulletin*, Issue 1; Chart Energy & Chemicals Inc., April 2016, p 5. <http://files.chartindustries.com/BAHXProductBulletin.pdf> (accessed April 2017).

⁷⁰ *BAHX Product Bulletin*, Issue 1; Chart Energy & Chemicals Inc., April 2016, p 13. <http://files.chartindustries.com/BAHXProductBulletin.pdf> (accessed April 2017).

⁷¹ The LBB approach is discussed further in Section 6.2.3.

⁷² American Petroleum Institute. *Fitness-for-Service*; API 579-1; Washington, DC, June 2016; §9.5.2.1.

5.1 Recognized and Generally Accepted Good Engineering Practices

In 1992 the Occupational Safety and Health Administration (OSHA) adopted 29 C.F.R. §1910.119, Process Safety Management of Highly Hazardous Chemicals (known as the PSM standard). The PSM standard states, “the employer shall document that equipment complies with recognized and generally accepted good engineering practices [RAGAGEPs].”⁷³ OSHA describes RAGAGEPs as “engineering, operation, or maintenance activities based on established codes, standards, published technical reports or recommended practices ... or a similar document. RAGAGEPs detail generally approved ways to perform specific engineering, inspection or mechanical integrity activities, such as fabricating a vessel, inspecting a storage tank, or servicing a relief valve.”⁷⁴ OSHA directs that all PSM-covered equipment shall comply with RAGAGEP guidelines or follow manufacturer recommendations, including the frequency of inspections and tests.⁷⁵

Table 2 describes the four industry associations that provide RAGAGEP guidance for the construction and operation of BAHXs relevant to the PGP incident. Not included in the table, but mentioned throughout this chapter where relevant, are the BAHX manufacturer’s recommended operational practices.⁷⁶

Table 2. Industry associations that provide RAGAGEP guidance for the construction and operation of BAHXs.

Industry Association	Guidance/Standard	Description
Aluminium Plate-Fin Heat Exchanger Manufacturer’s Association (ALPEMA)	<i>The Standards of the Brazed Aluminium Plate-Fin Heat Exchanger Manufacturer’s Association</i> , 3rd ed. (2010 with amendments May 2012) ^a	Membership in this group is for manufacturers of BAHXs over 5,000 kg used primarily in cryogenic applications. As of April 2017, ALPEMA had five members: Chart Energy & Chemicals Inc., Fives Cryo, Kobe Steel Ltd., Linde AG, and Sumitomo Precision Products Co. Ltd. ^b
Gas Processing Association Midstream (GPA Midstream)	<i>GPA Technical Bulletin: Brazed Aluminum Heat Exchangers</i> , GPA-TB-M-001 (September 2015) ^c	GPA Midstream has nearly 100 corporate members that collect and process natural gas into salable pipeline gas. GPA Midstream generates standards and testing methods, and manages a cooperative research program to support the midstream oil and gas sector. ^d Enterprise is a member and BP was a member at the time of the June 2016 event.
Gas Processing Suppliers Association Midstream (GPSA)	<i>Engineering Data Book—FPS English Units</i> , 14th ed., Vols. I & II (revised 2017) ^e	GPSA is an organization of over 500 companies that provide service to the midstream gas processing industry. GPSA issues the <i>GPSA Engineering Data Book</i> , which provides engineering and design guidance for a multitude of equipment used in midstream gas processing. ^f Chart and HETSCO are members.
American Petroleum Institute (API)	<i>Plate Heat Exchangers for General Refinery Services, Part 2: Brazed Aluminum Plate-Fin Heat Exchangers</i> , 1st ed., ANSI/API Standard 662 (February 2006, reaffirmed February 2011) ^g	API has more than 625 corporate members and represents all aspects of America’s oil and natural gas industry: producers, refiners, suppliers, marketers, pipeline operators, and marine transporters, as well as service and supply companies that support all segments of the industry. API develops equipment and operating standards, conducts research, and provides certification and training programs. ^h BP is a member.

a <http://www.alpema.org/standards.html> (accessed July 10, 2018).

b <http://www.alpema.org/members.html> (accessed April 17, 2017).

c <https://gpamidstream.org/publications/item/?id=4165> (accessed July 10, 2018).

d <https://gpamidstream.org/about/who-we-are> (accessed June 19, 2018).

e <https://gpsamidstreamsuppliers.org/gpsa-databook> (accessed July 10, 2018).

f <https://gpsamidstreamsuppliers.org/about/who-we-are> (accessed June 19, 2018).

g https://www.api.org/~media/Files/Publications/2018_Catalog/2018_Pubs_Catalog_final_sm.pdf (accessed October 28, 2018).

h <http://www.api.org/about> (accessed April 30, 2017).

73 29 C.F.R. §1910.119(d)(3)(ii).

74 OSHA. *Petroleum Refinery Process Safety Management National Emphasis Program*; Instruction CPL 03-00-0100; August 18, 2009. <https://www.osha.gov/enforcement/directives/cpl-03-00-010> (accessed June 15, 2018).

75 OSHA. *OSHA Standard Interpretation Letter: Recognized and Generally Accepted Good Engineering Practices in Process Safety Management Enforcement*; Standard Number 1910.119; May 11, 2016. <https://www.osha.gov/laws-regs/standardinterpretations/2016-05-11-0> (accessed June 14, 2018).

76 *BAHX Product Bulletin*, Issue 1; Chart Energy & Chemicals Inc., April 2016. <http://files.chartindustries.com/BAHXProductBulletin.pdf> (accessed July 10, 2018).

A noteworthy distinction surfaces in the various sources of guidance: the API standard is the only one listed in **Table 2** that was generated under the American National Standards Institute (ANSI) rules of development of voluntary consensus.^a ANSI does not generate any standards on its own; it simply sets up certain rules, accredits multiple organizations to develop standards if they follow those rules, implements some measures to ensure that the rules are followed, and provides a mechanism for dispute resolution about adherence to the rules. ANSI historically designed these mechanisms to develop commercial standards for products. Furthermore, the ANSI concept of “balance” in a committee typically meant the inclusion of diverse members of an industry so that no single firm or commercial interest could dominate the standard in its favor. For example, many ANSI standards strive to ensure a balance among different producers and users of a given product on committees attempting to standardize the product. Although API 662 is an ANSI standard, the CSB notes that only about 20 percent of GPA Midstream’s members are also members of API.^b This means midstream operator interests may not be fully represented in the API standard.

API 662, Part 2, is being replaced by API 668, *Brazed Aluminum Plate-Fin Heat Exchangers for General Refinery Services*, which was in the final development stage when the CSB prepared this report for publication. Publication of API 668 is expected in late 2018.

a <https://www.ansi.org> (accessed June 26, 2018).

b Enterprise, the current operator of PGP, falls in line with the majority of its midstream counterparts; it is a member of GPA Midstream but not API.

Despite important differences in the BAHX industry guidance (**Table 2**), a company may achieve compliance with RAGAGEP requirements for safe BAHX operation by choosing to follow any one of these guidance documents. Consequently, midstream operators could reach conflicting conclusions about their BAHX thermal fatigue risks.

Some gas processing companies, including Enterprise, indicate that the recommended guidelines can be difficult to achieve, even with engineering controls in place, particularly during process upsets. For instance, in a 2012 American Institute of Chemical Engineers (AIChE)⁷⁷ meeting, a metallurgist observed that “brazed aluminum heat exchangers are not immune to process upset conditions”⁷⁸ and “because of the number of transients plants will experience through start-ups, shutdowns, and trips... in principle you would be subjecting [the exchangers] to thermal fatigue conditions.”⁷⁹

Determining the practicality of the operating guidelines presented in this chapter is beyond the scope of this report, but the perception that they may not be practical during gas processing operations warrants further examination and requires conversation between operating companies and manufacturers.

5.2 Recommended BAHX Heating and Cooling Rates

ALPEMA, GPA Midstream, and API describe recommended heating and cooling rates of a BAHX to prevent thermal fatigue, as does the manufacturer, Chart. They give similar heating and cooling guidance, stating that the temperature rate of change (ROC), during either cooling or heating, should be less than 3.6°F (2°C)/min, not to exceed 108°F (60°C) in an hour during start-up and shutdown. The guidance generally recommends that cyclic temperature fluctuations during normal operation be limited to less than ±1.8°F (1°C) (**Table 3**).⁸⁰

77 AIChE is an organization for chemical engineering professionals, with more than 50,000 members from over 100 countries. <https://www.aiche.org/> (accessed May 2, 2017).

78 Oulton, D. J.; Koppenhoefer, K. C. The Application of Finite Element Analysis to the Remaining Life Assessment of Ageing Cold Boxes. Presented at AIChE Spring National Meeting, Houston, TX, April 1–5, 2012; AIChE Paper Number 97f, p 4.

79 Oulton, D. J.; Koppenhoefer, K. C. The Application of Finite Element Analysis to the Remaining Life Assessment of Ageing Cold Boxes. Presented at AIChE Spring National Meeting, Houston, TX, April 1–5, 2012; AIChE Paper Number 97f (video recording), 1:50.

Transients in this context are large temperature swings occurring over short time frames. See Section 5.2 for current industry guidelines on acceptable rates of temperature change.

Trips are unexpected shutdowns or process upsets like those described in Sections 5.3.1 through 5.3.3.

80 The guidance generally recommends that the temperature difference between adjacent streams be limited to less than 50°F (28°C). The stream temperature difference would indirectly contribute to the total number of minutes exceeding temperature ROCs referenced in industry guidance documents.

Table 3. Recommended operating windows from industry guidance documents.

	ALPEMA ^a	Chart ^b	GPA Midstream ^c	API 662 ^d
ROC of no more than 3.6°F (2°C)/min during start-up or shutdown	Yes	Yes	Yes	Yes
Total temperature change of no more than 108°F (60°C) in an hour	Yes	Yes	Yes	No
Cyclic or frequently repeated ROCs limited to 1.8°F (1°C)/min	Yes	Yes	Yes	No

a *The Standards of the Brazed Aluminium Plate-Fin Heat Exchanger Manufacturer's Association*, 3rd ed.; 2010 with amendments May 2012. <http://www.alpema.org/standards.html> (accessed July 10, 2018).

b *Installation, Operation, and Maintenance Manual for Chart Brazed Aluminum Heat Exchangers (BAHX) and Core-in-Kettle® Assemblies*; Chart Energy & Chemicals Inc.: La Crosse, WI, October 2017. <http://files.chartindustries.com/BAHX-IOM.pdf> (accessed July 5, 2017).

c *GPA Technical Bulletin: Brazed Aluminum Heat Exchangers*; GPA-TB-M-001; Tulsa, OK; September 2015. <https://gpamidstream.org/publications/item/?id=4165> (accessed July 10, 2018).

d *API. Plate Heat Exchangers for General Refinery Services, Part 2: Brazed Aluminum Plate-Fin Heat Exchangers*, 1st ed.; ANSI/API Standard 662; Washington, DC, February 2006, reaffirmed February 2011. https://www.api.org/~media/Files/Publications/2018_Catalog/2018_Pubs_Catalog_final_sm.pdf.

ALPEMA and Chart explicitly state that exceeding the recommended ROCs listed in **Table 3** can create thermal stresses sufficient to cause BAHX failures. However, the CSB was unable to determine any technical basis to assess the validity of the recommended ROCs. GPA Midstream discusses BAHX failures, but the API guidance does not mention potential failures (**Table 4**). Industry may benefit from incorporation of such information into API's BAHX guidance.

Table 4. BAHX operating guidance language addressing thermal stresses.

ALPEMA	<p>"... thermally induced loads produce stresses which must be maintained within permissible limits to prevent component damage or failure."</p> <p>"If the local metal temperature differences are large, the combined thermally-induced stresses and other stresses from imposed loads can exceed the yield stress and possibly the ultimate stress⁸¹ of the material."</p> <p>"Temperature differences between adjacent parts of a heat exchanger, having the potential to produce significant thermal stresses, can arise from unsteady operating conditions [and] can generate cyclic stresses exceeding the yield strength, and failure by fatigue may result."^a</p>
Chart	<p>"If the local metal temperature differences are large, the margin for thermal stress can be exceeded and the combined thermal and mechanical stress can exceed the yield strength and possibly the ultimate strength of the material. Stresses at or above the ultimate strength subject the BAHX to failure after only one event. Stresses below ultimate strength can result in failure if applied repeatedly. The number of cycles an exchanger can withstand before failure depends on the stress amplitude and history."^b</p>
GPA Mid-stream	<p>"The gas processing industry experienced failures of some of brazed aluminum heat exchangers (BAHX), both minor and catastrophic. The Gas Processors Association (GPA Midstream) Board directed [a] sub-committee ... to identify recommendations to minimize future failures."^c</p> <p>"Endeavor to operate according to ALPEMA and API standards at steady-state and transient conditions to minimize excursions and cycles." Referring to ALPEMA recommendations, this document highlights the need for controlling exchanger temperatures to allow for "gradual dimensional adjustments" and prevent "thermal shocks."^d</p>
API 662	Does not address thermal stress.

a *The Standards of the Brazed Aluminium Plate-Fin Heat Exchanger Manufacturer's Association*, 3rd ed.; 2010 with amendments May 2012; p 59. <http://www.alpema.org/standards.html> (accessed July 10, 2018).

b *Installation, Operation, and Maintenance Manual for Chart Brazed Aluminum Heat Exchangers (BAHX) and Core-in-Kettle® Assemblies*; Chart Energy & Chemicals Inc.: La Crosse, WI, October 2017, p 35. <http://files.chartindustries.com/BAHX-IOM.pdf> (accessed July 5, 2017).

c *GPA Technical Bulletin: Brazed Aluminum Heat Exchangers*; GPA-TB-M-001; Tulsa, OK; September 2015; p 1. <https://gpamidstream.org/publications/item/?id=4165> (accessed July 10, 2018).

d *GPA Technical Bulletin: Brazed Aluminum Heat Exchangers*; GPA-TB-M-001; Tulsa, OK; September 2015; pp 8-9. <https://gpamidstream.org/publications/item/?id=4165> (accessed July 10, 2018).

81 The "ultimate stress" is also called the tensile stress of a material and is the maximum amount of stress a material can sustain before it fails.

5.3 PGP's Thermal-Fatiguing Process Conditions

As a midstream gas processing plant, PGP was subjected to conditions that challenged smooth operation. Upstream and downstream activities impacted the site, often in unpredictable ways, requiring PGP to reduce or completely stop production. These external activities, as well as process changes made by the facility itself, led to process upsets. PGP made several improvements to optimize its gas processing operation and manage both the internal and external challenges. The improvements used administrative controls, such as procedural changes, and engineering controls, such as shutting down or replacing the equipment causing the upsets. The challenges also subjected the BAHXs to conditions conducive to thermal fatigue damage, where significant and sometimes rapid temperature fluctuations of the hydrocarbons circulating through the process often exceeded the recommended operational guidance of the BAHXs at the site.

5.3.1 Upstream Influences and Downstream Orders to Curtail or Stop Production

Any process upset that disturbs the flow or composition of the hydrocarbons entering or leaving PGP could cause temperature swings in the BAHXs. PGP operators describe being “at the mercy of [the plant’s] inlet and outlet” because the offshore suppliers sending raw gas to PGP and the pipelines receiving PGP’s products could modify composition, temperature, pressures, and flows with very little warning.

For instance, offshore platforms go on- and offline, affecting the feed volume and inlet pipeline pressures. Also, changes to the composition, impurities, and temperatures of the feed could decrease the efficiency of the plant. To optimize efficiency, plant personnel would adjust equipment parameters within the site, which in turn affected process conditions for the BAHXs. Variable conditions generally made it difficult to write a single procedure for personnel to follow.

On the night of the incident, PGP was responding first to a curtailment and then to a complete shut-in of natural gas liquids because the Tri-States pipeline could not take the product. Curtailments at the plant have typically occurred a few times per month. Shut-ins were less common, occurring several times a year.⁸² Over the years, PGP refined its written preplanned, non-routine curtailment and shut-in procedures to mitigate the magnitude of resulting temperature changes that occurred in the exchangers.

5.3.2 Compressor Shutdowns

By original design, PGP would increase the pressure of the residue gas feeding the Destin pipeline by using dedicated compressors within the plant. When the Destin pipeline received this residue gas, it further boosted the pressure as needed for the distribution system, using a different set of compressors. Residue gas from PGP drove the turbines for the Destin pipeline compressors. If gas rates were too low, the turbines would suddenly shut down, allowing operators only a few minutes to shut PGP down, which would result in rapid temperature increases within the BAHXs. Plant personnel estimated this could happen up to six times a month, but the compressors shut down six times on one particularly difficult weekend. Subsequently, sometime in the year before the incident, PGP modified its process to prevent further upsets and bypassed the Destin compressors. Instead, PGP ran its own compressors to meet the distribution pressure requirement of the Destin pipeline.

5.3.3 Erratic Flow

While external conditions were conducive to thermal fatigue damage on the exchangers, situations also occurred in which PGP operations caused potentially damaging erratic flows and temperatures.

The A-Train cold side reboiler (ACSR) is a thermosiphon reboiler, where liquid material from the demethanizer column moving through the B pass of the reboilers is partially vaporized before exiting as a liquid-vapor mixture.⁸³ Driving flow through the reboilers is the difference in density between 100 percent liquid in the inlet and a mixture of liquid and vapor in the outlet. The pressure created by the denser liquid pushes the lighter mixture out of the top of the reboiler and back into the demethanizer column. The higher the percentage of vapor in the outlet, the larger the density differential, and the faster the flow rate (and vice versa). During various process changes, such

⁸² Curtailments and shutins by Tri-States affect not only PGP but also the other two gas processing plants feeding into the pipeline.

⁸³ Kern, D. Q., *Process Heat Transfer*; McGraw Hill: New York, 1950; pp 458–459.

as start-up, shutdown, or production rate modifications, the boiling regime inside the exchanger can also change, leading to a fluctuating pressure differential across each pass of the exchanger. These changes can cause conditions within the B pass to become unstable; rapid, localized temperature fluctuations can occur. Portions of the B pass layers can oscillate between liquid (which transfers heat quickly) and vapor (which transfers heat slowly). Consequently, the metal exposed to alternating “slugs” of vapor and liquid can quickly oscillate between heating up and cooling down.⁸⁴ Erratic flows can thermally stress an exchanger, even when differences in the stream temperatures remain close to recommended industry guidelines.⁸⁵

The CSB reviewed differential pressure data for the ACSR during a month when A-Train was in operation and not experiencing any start-ups or shutdowns. The differential pressure for the B pass and the B outlet stream temperature are plotted in **Figure 26**. As indicated on the plot, the typical differential pressure for the ACSR B pass is approximately 3 psi. Yet the differential pressure often becomes erratic and oscillates between 2.0 and 5.5 psi. The recommended ROC limits from API and the other industry guidance documents listed in **Table 2** are also indicated on the plot. An unstable differential pressure typically coincides with an exceedance of the recommended ROC fluctuations, but not always.

Comparison of B Outlet ROC to B Pass Pressure Differential

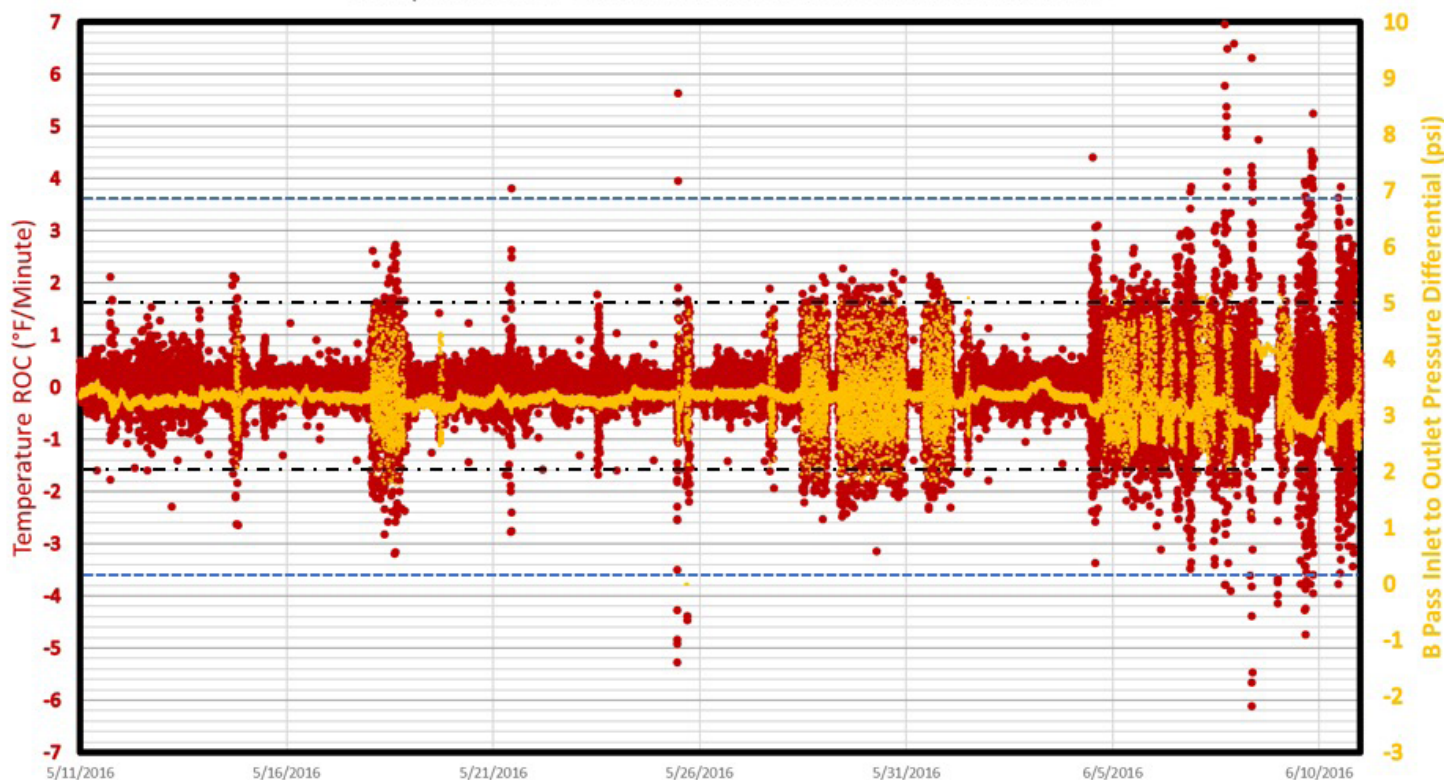


Figure 26. ACSR process stream temperature ROC data for B pass outlet (red) and B pass differential pressure data (yellow). The black dot-dashed lines indicate the maximum temperature ROC for steady-state operations, as recommended by industry guidance of ALPEMA, Chart, and GPA Midstream. The blue dashed lines indicate API guidance for temperature ROC.

⁸⁴ In a BAHX, the vertical liquid-vapor flow regime can have several different patterns. When the fraction of vapor is low, vapor bubbles are uniformly dispersed through the liquid. As the fraction of vapor increases, “slug flow” through the exchanger can develop, whereby large bubbles are separated by slugs of liquid. If the flow rate through the exchanger is increased, these large bubbles can become unstable and break through the liquid slugs, creating a more chaotic slug flow. Chart generally refers to this phenomenon as *unstable boiling* in its literature; see *Installation, Operation, and Maintenance Manual for Chart Brazed Aluminum Plate-Fin Heat Exchangers (BAHX) and Core-in-Kettle® Assemblies*; Chart Energy & Chemicals Inc., October 2017. <http://files.chartindustries.com/BAHX-IOM.pdf> (accessed October 26, 2018).

Similar changes in the type of vapor-liquid flow occur in the pipes connecting the reboiler outlet to the demethanizer, and the resulting changes in the pipes can also affect what happens in the reboiler. For a more general introduction to vertical flow regimes, see Thome, J. I. Two-Phase Flow Patterns and Flow Pattern Maps (slide presentation). Laboratory of Heat and Mass Transfer, Swiss Federal Institute of Technology Lausanne. http://lcm.epfl.ch/files/content/sites/lcm/files/shared/import/migration/COURSES/TwoPhaseFlowsAndHeatTransfer/lectures/Chapter_12.pdf (accessed May 1, 2017).

⁸⁵ See Section 5.2 for a description of industry guidelines regarding heating and cooling rates.

According to API temperature ROC guidelines, most of the temperature fluctuations shown in **Figure 26** are within the recommended operating conditions, which could imply that the exchanger is not operating under thermal-fatiguing conditions. According to the other guidelines listed in **Table 2**, the ROC fluctuations are either within the recommended limits of 1.8°F (1°C)/min, or close to them. Regardless, the fluctuating differential pressure evinces that whenever the flow becomes erratic, the potential for localized metal temperature differences puts the exchanger at risk for thermal fatigue.

During its life-span, the ACSR was subjected to all three operational conditions that induce thermal fatigue.

5.4 Industry Thermal Fatigue Monitoring Guidance

Industry guidelines provide recommendations for the operation of BAHXs to minimize the effects of thermal stress damage (see Sections 5.1 and 5.2). Yet the CSB found that none of these guidelines give criteria for using current and historical process data to assess the potential for thermal fatigue risks associated with BAHXs. (**Table 5** demonstrates the extent to which the guidelines suggest use of operational data for monitoring BAHXs.) This lack of industry guidance suggests that fitness-for-service decisions at midstream gas plants across the country are based on other factors and that one company's internal approach, and the subsequent quality of its BAHX service decisions, may vary greatly from that of its industry counterparts.

Table 5. Recommended process data inspections.

ALPEMA	"A record of all relevant data should be kept for each individual start-up. This will be required in the event of problems developing later in the life of the heat exchanger." ^a
Chart	"An operating log should be kept to record normal operation procedures, any plant upsets, shutdowns, and any other operating conditions. It is critical the operating data be monitored to ensure operation is within the ... stated guidelines." ^b
GPA Mid-stream	"Develop and maintain the ability to archive and review operating data (seconds to a maximum of one minute) to trend transient behavior and to predict possible leak or catastrophic core failure." ^c
API 662	Does not address process data inspections.

^a *The Standards of the Braze Aluminum Plate-Fin Heat Exchanger Manufacturer's Association*, 3rd ed.; 2010 with amendments May 2012; p 30. <http://www.alpema.org/standards.html> (accessed July 10, 2018).

^b *Installation, Operation, and Maintenance Manual for Chart Braze Aluminum Heat Exchangers (BAHX) and Core-in-Kettle® Assemblies*; Chart Energy & Chemicals Inc.: La Crosse, WI, October 2017; p 35. <http://files.chartindustries.com/BAHX-IOM.pdf> (accessed July 5, 2017).

^c *GPA Technical Bulletin: Braze Aluminum Heat Exchangers*; GPA-TB-M-001; Tulsa, OK; September 2015; pp 8–9. <https://gpamidstream.org/publications/item/?id=4165> (accessed July 10, 2018).

The CSB identified two methods a company could use to quantify the damage caused by thermal stress on BAHXs: predictive thermal stress modeling and comparison of operational process data with the industry guidance ROC recommendations.

With predictive thermal stress modeling, a company can use various approaches to analyze the thermal stresses an exchanger might experience under specific operating conditions, such as a fast start-up or an unexpected shutdown.⁸⁶ Such modeling predicts areas of high thermal stress and the number of such temperature cycles before a failure might be expected. The "cycles to failure" measure is not an absolute value but a measure of high thermal stress relative to other, comparative operational conditions. For instance, a company could compare the predicted cycles to failure for a BAHX under fast start-up versus slow start-up to assess the relative risk.

⁸⁶ Examples of such modeling include these:

Oulton, D. J.; Koppenhoefer, K. C. The Application of Finite Element Analysis to the Remaining Life Assessment of Ageing Cold Boxes. Presented at AIChE Spring National Meeting, Houston, TX, April 1–5, 2012; AIChE Paper Number 97f.

Carter, P.; Carter, T. J.; Viljoen, A. Failure Analysis and Life Prediction of a Large, Complex Plate Fin Heat Exchanger. *Engineering Failure Analysis* 1996, 3 (1), 29–43.

Comparing operational process data with the industry guidance ROC recommendations is laden with challenges. According to the standards, the rate of cooling or heating a BAHX should be limited to is less than 3.6°F (2°C)/min during start-up and shutdown, and 1.8°F (1°C)/min during normal operation (**Table 3**). Yet industry guidance recommendations for BAHX operation say little about how excursions outside of these recommendations impact a BAHX's fitness for service. Unanswered are questions such as how much more effect a 100°C/min temperature ROC has on a BAHX than does a 5°C/min ROC, and whether any amount of time outside of the recommended operating conditions is tolerable. Further, the guidance does not draw comparisons between theoretical thermal stress models and actual historical conditions experienced by BAHXs. In other words, real-world comparisons with the recommended operational parameters are missing from the available guidelines.

Additionally, the guidelines do not cite the technical basis for the ROC recommendations or provide empirical data to support the identified operational parameters.⁸⁷ Without such data, the CSB has little basis to assess the feasibility and achievability of the ROC recommendations or to compare the operational practices at PGP with those at other sites. In an effort to begin closing this informational gap, the CSB compares its review of PGP's historical process data for the ACSR with recommended industry guidelines in three primary ways:

1. Drawing comparisons between the total number of minutes of BAHX operation above the recommended ROC guidelines and the development of leaks (Section 5.5)
2. Quantifying the magnitude of the BAHX's stream temperature excursions (Section 5.5)
3. Drawing comparisons between BAHX operational conditions and both metal temperatures and stream temperatures (Section 5.6)

By comparing the PGP process data with the recommendations in industry guidelines, the CSB aims to encourage more industry data sharing of BAHX operational conditions and failures, and to offer a baseline set of data to initiate this data-sharing process.

5.5 Operating Conditions Can Gradually Manifest into Thermal Fatigue Failures

The CSB calculated temperature ROC measurements for the inlet and outlet stream temperatures for the 17-year operational history of the ACSR.⁸⁸ The plot in **Figure 27** demonstrates that a plant can have many thermal excursions in a year with no exchanger failure, but the historical thermal fatigue effects will remain and can later manifest themselves. The CSB analyzed the data without filtering out normal operations or start-ups and shutdowns. Some industry guidance recommends that ROC for normal operations not exceed 1.8°F (1°C)/min. Thus, the data presented here should be used only as a starting point for discussion, and additional work is needed to more accurately analyze the use of historical process data to determine potential risks of thermal fatigue cracking.

The first leak on this exchanger occurred in 2007, followed by leaks in 2011, 2014, and 2015. Leaks do not necessarily occur at the time of, or even just after, the years with the greatest number of minutes above the recommended guidelines. For instance, between the 2014 and 2015 leaks, the recommended ROC guidelines were exceeded for fewer than 4,000 minutes for the ACSR B inlet, while the leaks in 2007 and 2011 occurred after almost 260,000 and 115,000 minutes, respectively. This data reflects accumulated thermal fatigue damage over the lifetime of the exchanger. Leak repairs can fix thermal fatigue damage only in very localized areas. Such localized repairs do not reverse thermal fatigue damage accumulated on other parts of the exchanger that have not yet resulted in a leak. Consequently, as an exchanger accumulates thermal fatigue damage from temperature swings, leaks are expected to occur more frequently. For this reason, while operators can help minimize real-time thermal stresses through procedural controls, managing thermal fatigue risks also requires a historical perspective because current operator actions and observations cannot erase past thermal damage.

⁸⁷ This may be in part because the equipment manufacturers doing the thermal stress modeling do not have access to the data unless operators provide it to them.

⁸⁸ Data were provided to the CSB in varying intervals of 15 seconds (e.g., 15, 45, and 60 seconds). The rate-of-change was calculated for at least one minute of operational data. If a time interval between the points was greater than one minute, the average rate of temperature change per minute was used. The CSB did not attempt to remove extraneous points, such as those that might occur during startup, shutdown or calibration periods on the transmitters.

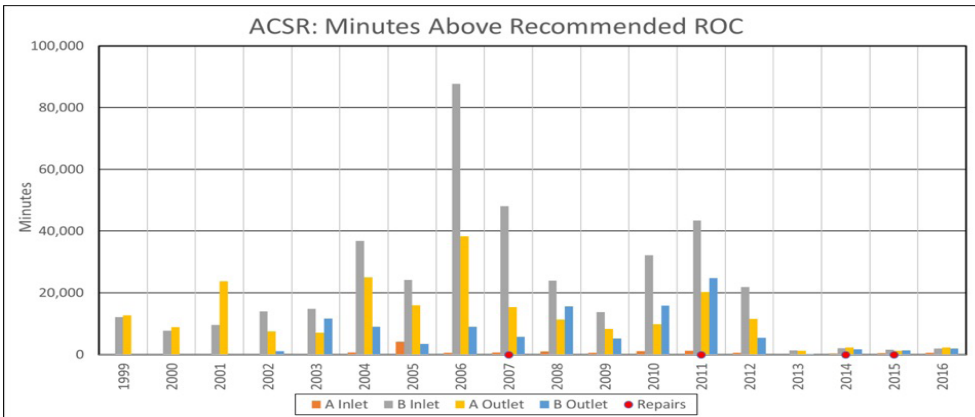


Figure 27. Total minutes per year that the inlet and outlet stream temperatures of the ACSR were greater than the industry-recommended ROC guidelines of 1.8°F/min. Red dots indicate years when cracks that resulted in leaks which were repaired.

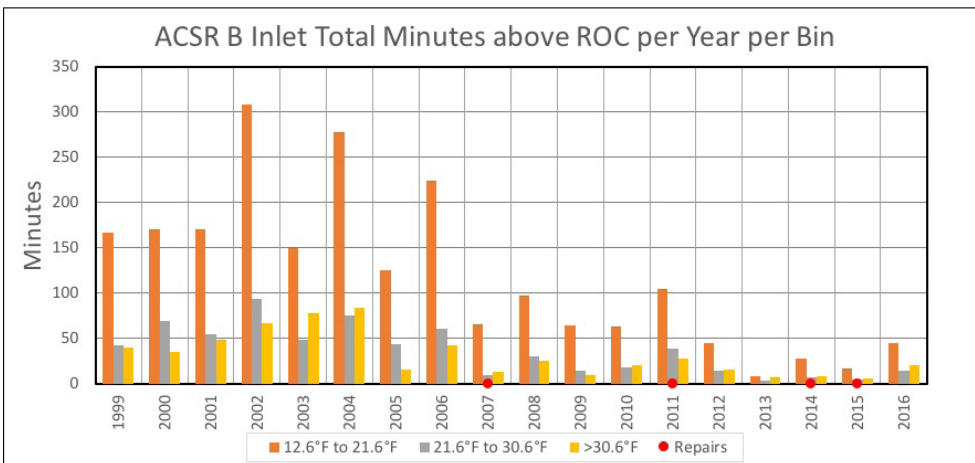
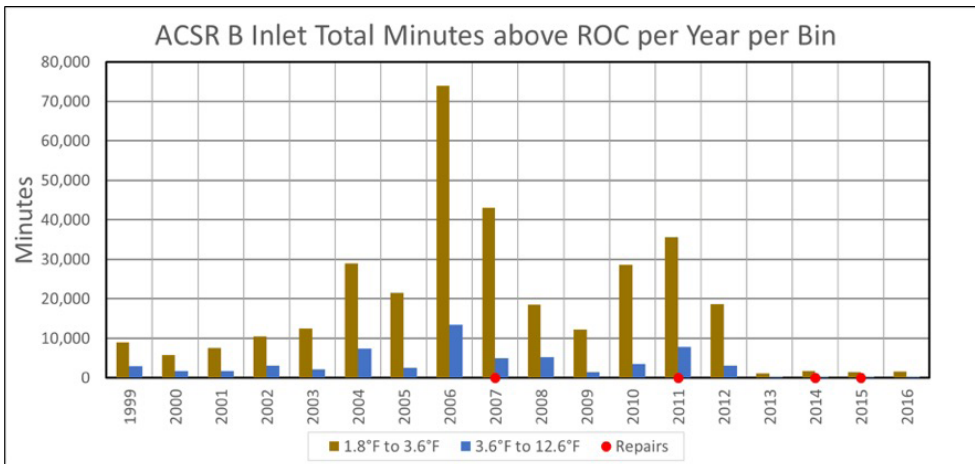


Figure 28. ROC in temperature categorized into five temperature ranges, split between two graphs, to illustrate the magnitude of stream temperature changes for the ACSR over its life-span. The bottom graph shows the bins with an ROC greater than 12.6°F/min. Note that there the scale for the Y axis on each graph is different.

To illustrate the magnitude of the ROCs the ACSR saw over its history, **Figure 28** displays the unit's historical data in five different temperature ranges, 1.8°F–3.6°F/min, 3.6°F–12.6°F/min, 12.6°F–21.6°F/min, 21.6°F–30.6°F/min, and greater than 30.6°F/min. As the graphs in **Figure 28** demonstrate, most minutes exceeding the recommended ROC of 1.8°F/min fall into the first two bins, 1.8°F–3.6°F/min and 3.6°F–12.6°F/min. The total minutes in the larger bins (above 12.6°F/min) are several orders of magnitude smaller. The CSB chose the temperature ranges, but further granularity may also be useful, for example, for the 1.8°F–12.6°F/min bins, where most of the minutes exceeding temperature ROCs fall. It is difficult to infer the accumulated fatigue damage on a BAHX based on this data because industry guidance does not provide any baseline data for plants to compare with their records.

5.6 Temperature Sensor Location

PGP began to collect metal temperatures after conducting its 2010 root cause report investigating BAHX leaks at the plant (Section 6.1). The plots in **Figure 29** indicate the percentage of time the ACSR exceeded the industry-recommended temperature ROC guidelines while operating from January 1, 2011, to June 27, 2016, for both the stream and the metal temperatures.⁸⁹

The stream temperature data indicates that the ACSR operated above the ROC recommended by industry guidelines for more than 10 percent of its operational time over several years (**Figure 29**). This is quite different from the data recorded by the metal sensors, where the ROCs

⁸⁹ To normalize the data, the total number of minutes of ROC above 1.8°F/min was divided by the total number of minutes the exchanger was operating each year. Only six years of data are provided because the metal temperature sensors were installed in 2010.

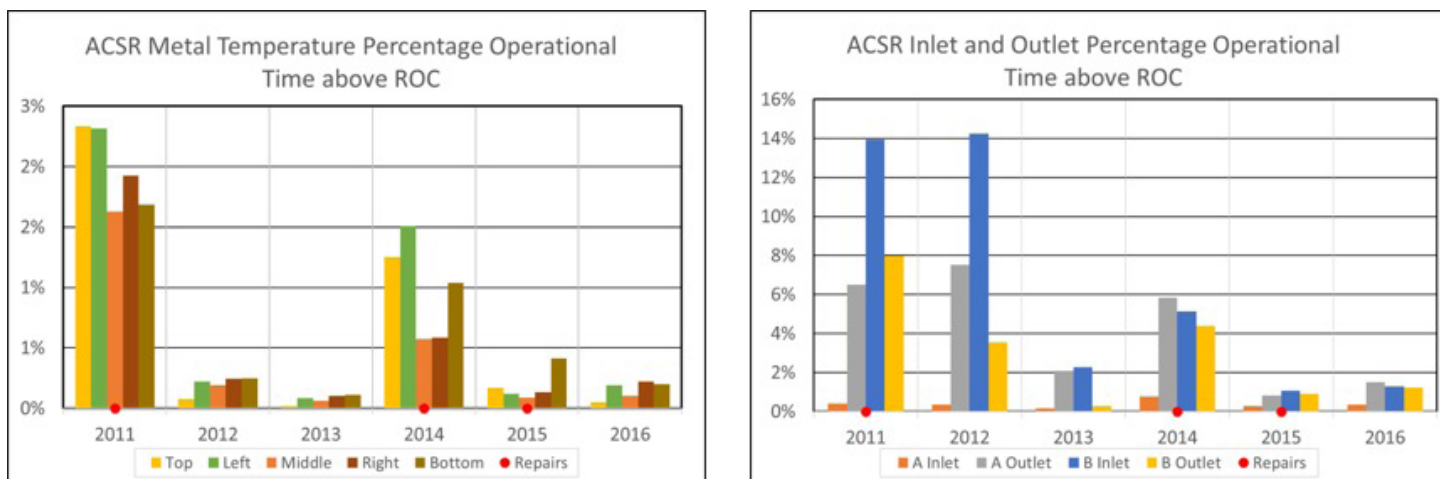


Figure 29. ROC data from January 1, 2011, to June 27, 2016, normalized to the A-Train run time for the inlet, outlet, and metal temperatures of the ACSR. ROCs calculated from the metal temperatures are about 10 times less than those for the stream temperatures.

are about four times less than those for the stream temperatures. For example, in 2011, ROC exceedances for the metal sensors occurred between 2 and 3 percent of the time, while inlet and outlet stream ROCs exceeded industry recommendations up to 14 percent of the operating time.

PGP alarmed the metal temperature sensors, but not the stream temperature sensors, to alert operators to temperature problems in the exchangers. As the data in **Figure 29** indicates, if gas plant personnel monitor for thermal stresses using metal temperatures, then they could be misled to believe that their responses to the operational conditions are sufficient in minimizing thermal fatigue damage in their exchangers.

HETSCO and Chart both indicated that the use of metal temperature sensors like those used at PGP is uncommon but not unique.⁹⁰ Chart also reported to the CSB that it does not install metal temperature sensors on the exchangers it sells unless they are requested by the customer. Normally, Chart would expect a company to look at stream temperatures to monitor for potential thermal stresses in an exchanger. Despite these perspectives, the CSB notes that industry guidelines differ on where to measure the temperature on an exchanger. Chart and GPA Midstream specifically recommend monitoring the inlet and outlet stream temperatures, while ALPEMA and API reference both stream temperatures and “metal” temperatures. ALPEMA does not offer further detail, but API indicates that “suitable metal-temperature indicating devices” should be used to monitor the exchanger’s temperature.⁹¹ Clarification from these groups could provide insight on this aspect of thermal fatigue management.

5.7 Lack of Industry Data Sharing

Enterprise committee members who helped produce the GPA Midstream guidance document reported that, while the committee did have some exchanger failure data to analyze, there were times when the data was not shared for confidentiality or proprietary reasons. As a safety agency focusing on future accident prevention, the CSB has previously discussed the conflict that sometimes arises between safety and confidentiality protections, and the resultant challenges companies may face in sharing near-miss and incident data.⁹² Companies fear that lessons learned will result in a punitive response from the regulator, which creates a chilling effect. So, instead of sharing incident details, companies tend to protect incident investigation documents under attorney-client privilege.

90 HETSCO personnel participated in the root cause investigation that resulted in the placement of the metal temperature sensors. See Section 6.1.

91 API. *Plate Heat Exchangers for General Refinery Services, Part 2: Brazed Aluminum Plate-Fin Heat Exchangers*, 1st ed.; ANSI/API Standard 662; Washington, DC, February 2006, reaffirmed February 2011; p 6. https://www.api.org/~media/Files/Publications/2018_Catalog/2018_Pubs_Catalog_final_sm.pdf.

92 CSB. *Drilling Rig Explosion and Fire at the Macondo Well, April 20, 2010*; Report No. 2010-10-I-OS; Washington, DC, April 2016; p 127. https://www.csb.gov/assets/1/20/macondo_vol3_final_20160527.pdf?15658 (accessed October 26, 2018).

Around the time of the incident, Enterprise began pursuing independent research of BAHX failures. Enterprise's stated goal was to analyze process data to better understand thermal fatigue, with hopes of producing tools to estimate the extent of thermal fatigue damage and of better predicting BAHX life-spans. For example, rapid temperature changes and flow instabilities have been identified as damage mechanisms, but neither has been quantified (e.g., frequency or magnitude) in industry guidance. Enterprise solicited grant proposals from various universities to study and address these and other BAHX factors in an effort to expand available resources and expertise on BAHX issues. However, at the beginning of 2018, GPA Midstream started its own effort by establishing a BAHX research committee. The committee had objectives similar to those of Enterprise's efforts. Thus Enterprise, in order to contribute to the new research, opted to merge its work with GPA Midstream's research effort by sharing BAHX data and sample specimens for metallurgical testing. GPA Midstream's research, meanwhile, ran into similar data-sharing challenges. Many midstream gas companies opted not to provide data to the GPA Midstream research effort because of various proprietary and confidentiality concerns.

In addition, companies may monitor and record different types of process data. This lack of standardization in the data can make it challenging to compare the effects of temperature ROCs with thermal fatigue damage on the exchangers.

Not sharing data has its own cost. Catastrophic failures like the June 2016 event are generally not expected. PGP had nine minor exchanger leaks before that event, but these exchanger failures occurred in a gradual procession, slow enough to be detected before they turned into catastrophic releases. This scenario demonstrates a faulty risk perception, since both the incident at PGP and the previous incidents described in Section 4.4 demonstrate the possibility that thermal fatigue can result in catastrophic ruptures with serious consequences.

Industry data sharing can lead to industry safety improvements. In 1997, the Federal Aviation Administration established the Commercial Aviation Safety Team (CAST).^a CAST's goal is to increase public safety and reduce fatality risk in commercial air travel by analyzing voluntarily submitted safety and flight data. Over 99 percent of U.S. commercial operators provide data to the Aviation Safety Information Analysis and Sharing System.^b CAST analyzes and reports on this data to understand the underlying contributing factors in aviation accidents and develop mitigating strategies.^c In 2008, 10 years after establishing CAST, the fatality risk in commercial air travel had reportedly been reduced by 83 percent. If a data-sharing model such as this one could be implemented to collect specific BAHX process data, subsequent analysis may yield lessons that could assist companies in both reducing the number of thermal events and estimating the life-span of their BAHXs.

a CAST. History, http://www.cast-safety.org/apex/f?p=102:1:14588173069465::NO::P1_X:history (accessed August 15, 2018).

b CAST. Fact Sheet—Aviation Safety Information Analysis and Sharing Program, December 29, 2017, https://www.faa.gov/news/fact_sheets/news_story.cfm?newsId=22454 (accessed August 15, 2018).

c CAST. Organization and Procedures, http://www.cast-safety.org/apex/f?p=102:1:14588173069465::NO::P1_X:organization (accessed August 15, 2018).

6.0 Process Safety Management at PGP

BP had operational control of PGP for almost its entire existence up to the time of the June 2016 event. The transition from BP to Enterprise operatorship resulted in a change in corporate engineering support teams, but not in onsite plant operations. For the most part, the personnel and operational procedures were the same on June 27 as they had been before Enterprise's full acquisition of the site.

In 1992, the Occupational Safety and Health Administration (OSHA) adopted 29 C.F.R. §1910.119, Process Safety Management of Highly Hazardous Chemicals (the PSM standard). As a PSM-covered facility, the PGP site is required to establish and maintain a management program that addresses 14 process safety elements. This chapter discusses 3 of those elements as they relate to the safe operation of BAHXs at the site: hazard assessment, mechanical integrity, and management of change.

6.1 Hazard Assessment and Evolving Perception of Thermal Fatigue Risk at PGP

A review of various plant documents (e.g., process hazard analysis revalidations, purchase inquiries, investigation reports) from throughout the site's existence and varied owners demonstrates that the perceived risks associated with thermal stress to the exchangers evolved over time and, at one point, expanded to include thermal fatigue cracking. Eventually, in step with the plant's experience, site management and personnel focused their assessment of the BAHX hazards on relatively minor safety/health concerns and financial costs for repairing thermal fatigue cracks.

Amoco assembled a team to perform the first process hazard analysis (PHA) for PGP in 1997, before construction of the plant.⁹³ In line with regulatory requirements, the PHA identified, evaluated, and proposed controls for process hazards at the plant, which included potential thermal shock to the plant's BAHXs. The PHA team categorized thermal shock as of "marginal" severity, identifying it as potentially causing minor injuries to workers through the release of a small amount of process fluids. The team did not expect the hazard to have a public impact and anticipated only minor damage and downtime. Amoco assumed the likelihood of thermal shock to be once every 50 years and labeled it as a "medium priority," for which the company recommended that "serious and appropriate actions should be taken." In response, the PHA team⁹⁴ recommended developing procedures for the BAHXs' various operating modes (e.g. start-up, shutdown) to minimize the likelihood of thermal shock events.

When the first BAHX leak occurred in 2007, PGP chose to modify its operating procedures to reduce temperature swings during start-ups. After a second leak the same year, PGP again modified procedures, specifically instructing that the rate of temperature change not exceed 5°F/min. It is unclear why the procedural change exceeded the recommended operating practices of 3.6°F/min (start-up and shutdown) or 1.8°F/min (normal operations).⁹⁵

Citing previous BAHX leaks, the September 2009 PHA revalidation identified thermal fatigue cracking and the release of hydrocarbons as a "high impact health/safety incident" with the potential to cause (1) "permanent partial disability(ies)," (2) "several non-permanent injuries or health impacts," and (3) "days away from work." As a consequence, the PHA team recommended evaluating the replacement of the BAHXs with a different exchanger design.

After another BAHX leak in 2010, PGP assembled a team that included BP personnel and HETSCO repair technicians to determine the root cause of the recurring leaks. Corrective actions from that investigation did not suggest evaluating BAHX replacement, but rather

93 Facilities that process a threshold quantity of hazardous materials, such as PGP, are required to conduct a PHA per 29 C.F.R. §1910.119(e)(1). Per 29 C.F.R. §1910.119(e)(6), the PHA must be revalidated at least every five years to assure the analysis remains consistent with the current process.

94 As described in the PHA report, the team members were selected "because of their detailed knowledge of the process and plant design, and operations at similar Amoco facilities."

95 The rationale supporting the decision was not described in the incident report documenting the change. The Braze Aluminum Plate-Fin Heat Exchanger Manufacturer's Association (ALPEMA) recommended a shutdown and start-up temperature change rate of less than or equal to 3.6°F (2°C)/min. ALPEMA. *The Standards of the Braze Aluminum Plate-Fin Heat Exchanger Manufacturer's Association*, 3rd ed.; 2010 with amendments May 2012; §§4.9.1, 4.9.3, 8.1. <http://www.alpema.org/standards.html> (accessed July 10, 2018). Chart's guidance at the time recommended a smaller ROC, less than or equal to 1.8°F (1°C)/min. Start-up, Operation, and Shut Down. In *Chart Heat Exchangers User's Manual: Installation, Operation, and Maintenance Instruction for Chart Braze Aluminum Plate-Fin Heat Exchangers, Core-in-Kettle, and Transition Joints*; Chart Energy & Chemicals Inc.: La Crosse, WI, 2002; §III C. Current Chart guidance matches the 3.6°F (2°C)/min recommended by ALPEMA.

It is not entirely clear from BP corporate standards whether it deemed the BAHX appropriate for service at PGP, particularly in 2012 when it considered replacement of the A-Train cold side reboiler (ACSR). BP Group Practice GP-26-10, *Guidance on Practice for Heat Exchangers*, recommends BAHXs for cryogenic service, which was the service of A-Train at PGP. However, in the same document, BP advises against using BAHXs in a service that experiences fluctuations in temperature or contains two-phase fluids. The reboilers in A-Train were subjected to both of these conditions. The standard requires the documentation of inherently safer design principles in selecting a replacement exchanger, yet BP superseded the recommendation to replace the exchanger with a subsequent recommendation to insert temperature sensors for improved monitoring.

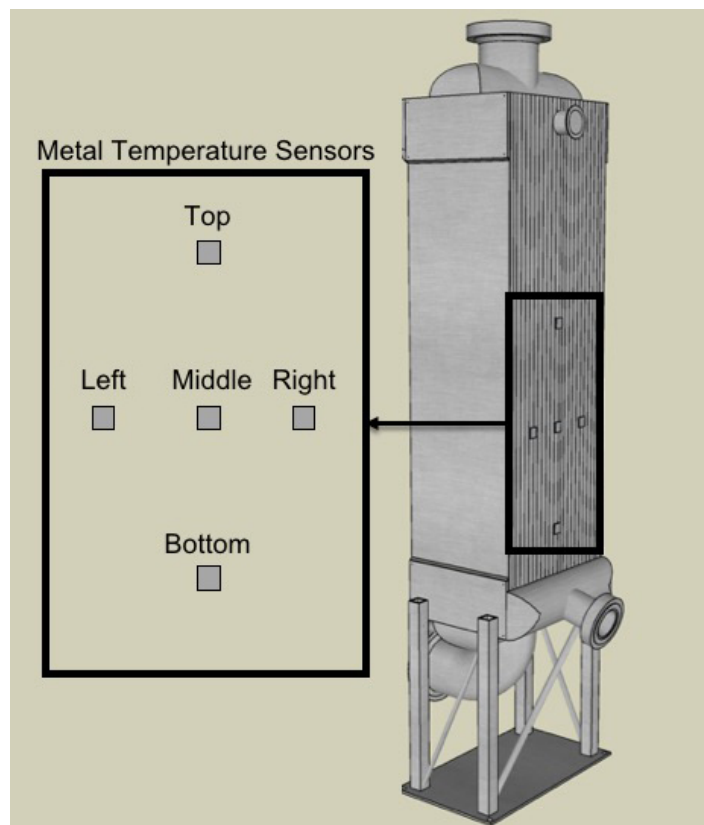


Figure 30. Location of the metal temperature sensors installed on the side bars of the ACSR.

recommended installing metal temperature sensors on the exchangers and making more procedural modifications (**Figure 30**).⁹⁶ This time, the procedure modifications cited industry guidance to control the rate of temperature change on the exchanger core to less than 3.5°F/min (2°C/min). According to BP’s root cause report, the metal temperature sensors “will give accurate readings to help prevent thermal stresses and allow operations to accurately adjust procedures as needed.” Management-of-change (MOC) documentation indicates that BP added rate-of-change (ROC) alarms to alert operators when either the positive or negative ROCs of the metal temperature sensors exceeded 1.9°F/min, and identified 3.6°F/min as a safe upper limit. At the time of the incident, however, the CSB determined that the set point for the metal temperature sensor alarms was actually 14.25°F/min. PGP did not provide the CSB with MOC documentation detailing the origin and justification of this set point.

Another leak occurred toward the end of 2010 in a different exchanger. In response, a BP engineer reviewed 30 days of data from the inlet and outlet temperature sensors for each exchanger pass, as opposed to the metal temperature sensors, and emailed his observations to the operations team.⁹⁷ No other action items were generated in response to the leak. HETSCO repaired the leak, and PGP put the exchanger back into service.

Repair documentation indicates that another leak occurred in 2011, but no incident report was created that tracked any corrective actions in response to the leak. In 2012, BP again explored the replacement of BAHXs and evaluated other manufacturers’ BAHX designs as well.⁹⁸ One of these manufacturers, Linde,⁹⁹ incorporates as part of its exchanger design “dummy layers,” outermost layers that are purposely blocked so that process fluids cannot enter them.¹⁰⁰ In a request for quote sent to Chart and Linde, BP stated that

⁹⁶ The CSB interviewed BP personnel involved in the root cause investigation in an effort to understand how BP made the sensor decision, but workers indicated they did not recall details beyond what appears in the report.

⁹⁷ The email noted that temperature deviations occur most often when the flow is changing in the exchanger, and the most severe temperature deviations occur when the plant shuts down or starts up too quickly. The email also noted that a high quantity of lower-magnitude excursions can also lead to failures.

⁹⁸ BP also explored replacing BAHXs with shell-and-tube exchangers.

⁹⁹ http://www.linde-engineering.com/en/plant_components/plate_fin_heat_exchangers/index.html (accessed May 2, 2017).

¹⁰⁰ Linde uses dummy layers in its design to facilitate welding headers to the brazed structure. These dummy layers have vent holes drilled into them to allow any potential trapped hydrocarbons to escape to atmosphere. Section 6.2 discusses the vent holes in more detail.

external plant conditions were causing temperature swings and provided exemplar process data that showed thermal cycling.¹⁰¹ BP also asked each manufacturer to describe the relative benefit of its design. Contrasting the Linde design to its own, Chart indicated to BP that it did not design BAHXs with dummy layers because exchangers so designed were no less susceptible to thermal stress failures than those without such layers, and the dummy layers posed a safety risk. Chart suggested that inter-stream leaks into blocked layers could occur, and that if the blocked layer “becomes pressurized it can fail catastrophically if venting through the tiny relief holes does not occur.”

In 2012, BP began the solicitation process with Linde after evaluating various quotes. Emails indicate that the BP project manager needed to create a “business case” for using the Linde design with dummy layers, since BP’s standard for the selection and design of heat exchangers stated that blocked passes should not be used because of an increased risk of thermal stress;¹⁰² the use of *should* instead of *shall* in BP’s standard implies that not using dummy layers is the recommended, but not mandatory, practice.¹⁰³ Emails further indicate that one of the primary concerns with using dummy layers was not over-pressurization but leak detection. Ultimately, BP did not purchase new exchangers.

The 2013 PHA revalidation no longer identified health and safety consequences associated with the exchangers. Instead, the listed potential consequences mirrored the plant’s experiences with leaks: (1) minor loss of gas containment due to hairline leaks (non-recordable quality), (2) operational upsets and loss of production time, and (3) historical exchanger repairs in the range of \$60,000–\$150,000—finance and numerical impact only. The potential for severe injuries, death, or significant financial losses was not identified. The safeguards for minimizing BAHX damage identified in the PHA were metal temperature sensors, operator intervention, and operating procedures.

By 2015, the BAHXs had been in service for approximately 15 years, and BP laid out a plan to change them out within 3 years to “ensure equipment integrity.” Justification for the plan stated that “cyclical operation causes small cracks on heat exchangers. Rapid cooling or heating of the brazed aluminum heat exchangers has the potential to create small cracks around support pads. Small cracks result in weeps of gas out. Potential for personnel injury is minor. Cost associated with repairs and downtime. Repair costs vary from \$80 thousand onsite to \$100 thousand offsite.”

In sum, over the years between the first documented BAHX hydrocarbon leak and the June 2016 loss of containment (LOC), PGP risk perception focused on minor leaks and financial consequences of repair.

6.2 Mechanical Integrity at PGP

Within the PSM standard, 1910.119(j), Mechanical Integrity, states, “the employer shall document that equipment complies with recognized and generally accepted good engineering practices [RAGAGEPs]”¹⁰⁴ and “inspection and testing procedures shall [also] follow [RAGAGEPs],” and that the frequency shall be consistent with the manufacturers’ recommendations and “more frequently if determined to be necessary by prior operating experience.”¹⁰⁵ All PSM-covered equipment, the standard says, shall comply with RAGAGEP guidelines or follow manufacturer recommendations, including the frequency of inspections and tests.¹⁰⁶

¹⁰¹ The request for quote indicates that BP was interested in improving exchanger design to better withstand these process conditions and assumed the process upsets would occur 5 to 10 times a year. In the exemplar data, which was for the ACSR, the rate of temperature change (°F/min) for the various inlets and outlets peaked at 30°F/min (A outlet), 3°F/min (A inlet), 48°F/min (B outlet), and 73°F/min (B inlet).

¹⁰² The standard further indicated that “there have been failures localised to dummy passages as they react differently to process changes relative to active passages and solid parts of BAHX.”

¹⁰³ See general discussion by OSHA of using *should* and *shall* in the section titled “‘Shall’ and ‘Should’ in RAGAGEP” at <https://www.osha.gov/laws-regs/standardinterpretations/2016-05-11-0> (accessed June 24, 2018), and the American Petroleum Institute’s definitions for *shall* (denotes a minimum requirement in order to conform to the standard) and *should* (denotes a recommendation or that which is advised but not required in order to conform to the standard) in its *Procedures for Standards Development*; Washington, DC, April 2016; section titled “Definitions.”

¹⁰⁴ 29 C.F.R. §1910.119(d)(3)(ii).

¹⁰⁵ 29 C.F.R. §§1910.119(j)(4)(ii)–(iii).

¹⁰⁶ OSHA. *OSHA Standard Interpretation Letter: Recognized and Generally Accepted Good Engineering Practices in Process Safety Management Enforcement*; Standard Number 1910.119; Washington, DC; May 11, 2016. <https://www.osha.gov/laws-regs/standardinterpretations/2016-05-11-0> (accessed June 14, 2018).

Table 2 in Chapter 5 describes the four different industry associations that provide RAGAGEP guidance for the construction and operation of BAHXs relevant to the PGP incident.¹⁰⁷ Additionally, Chart publishes recommended operational practices for its BAHXs.¹⁰⁸

Mechanical integrity is a broad safety management category covering inspection and maintenance (preventive and reactive) for the safe operation of PSM-covered equipment.

While most of the industry guidance discussed in Section 5.2 (other than API 662) tells operators to complete repairs to leaking BAHXs as soon as possible, no guidance explains how many repairs a BAHX can undergo before its integrity is jeopardized. Only Chart's product bulletin mentions, "there is no way to reverse damage accumulation due to thermal fatigue."¹⁰⁹ This statement implies only that repairs do not fix the root of the problem and instead, industry must control and manage the potential for thermal fatigue.

6.2.1 Leak and Repair History of the ACSR

Beginning in 2007, leaks occurred on four different BAHXs at PGP on nine occasions. None of the leaks resulted in major health or safety impacts, and the affected exchangers were successfully repaired and put back into service. (See Appendix G for more detail on the repairs.)

The 17-year-old ACSR had the largest history of repairs. On four occasions, beginning in 2007, operators detected flammable hydrocarbon leaks from the exchanger to the atmosphere. Each time, the plant shut down, the exchanger was removed from service, and HETSCO¹¹⁰ repaired the cracks,¹¹¹ most recently in September 2015.

Overall, before June 27, 2016, PGP's approach to the mechanical integrity of its BAHXs was leak detection and repair. Furthermore, workers had a perception that other plants dealt with BAHXs in much the same way. As one PGP worker told the CSB, technicians regularly traveled around the country repairing exchangers: "Over the course of a five-day week, they may be in three states. That's what they do ... That's just the way life is." Ultimately, BP accepted leaks as something that it could address efficiently, and it did not document concerns that the leaks could progress to a sudden, catastrophic failure.

6.2.2 2015 ACSR Repair

This section describes the MOC documentation for blocking layers in the ACSR, but the CSB was not provided sufficient information to analyze why PGP did not address potential over-pressurization hazards associated with blocked layers. The CSB was informed that other BAHX owners besides PGP have also requested that vent holes be welded closed, implying that over-pressurization hazards extend beyond the exchanger at PGP.

BP explored blocking the outermost passes when it first detected an interpass leak in the ACSR in 2014. BP notes from a 2014 meeting

107 Braze Aluminium Plate-Fin Heat Exchanger Manufacturer's Association (ALPEMA). *The Standards of the Braze Aluminium Plate-Fin Heat Exchanger Manufacturer's Association*, 3rd ed.; 2010 with amendments May 2012. <http://www.alpea.org/standards.html> (accessed July 10, 2018).

GPA Midstream. *GPA Technical Bulletin: Braze Aluminum Heat Exchangers*; GPA-TB-M-001; Tulsa, OK; September 2015. <https://gpamidstream.org/publications/item/?id=4165> (accessed July 10, 2018).

American Petroleum Institute. *Plate Heat Exchangers for General Refinery Services*; ANSI/API Standard 662; Washington, DC, February 2006, reaffirmed February 2011. https://www.api.org/~media/Files/Publications/2018_Catalog/2018_Pubs_Catalog_final_sm.pdf.

Gas Processors Suppliers Association. *Engineering Data Book—FPS English Units*, 14th ed.; Tulsa, OK, 2017; Vol. 1. <https://gpsamidstreamsuppliers.org/gpsa-databook> (accessed July 10, 2018).

108 *BAHX Product Bulletin*, Issue 1; Chart Energy & Chemicals Inc.; April 2016. <http://files.chartindustries.com/BAHXProductBulletin.pdf> (accessed July 10, 2018).

109 *BAHX Product Bulletin*, Issue 1; Chart Energy & Chemicals Inc., April 2016, p 5. <http://files.chartindustries.com/BAHXProductBulletin.pdf> (accessed April 2017).

110 HETSCO provides specialty welding, construction, and fabrication services, including BAHX repairs, to natural gas processing and petrochemical industries. In January 2017, HETSCO was acquired by Chart Lifecycle Inc., a subsidiary of Chart Industries. Chart Announces Acquisition of HETSCO. *GlobeNewswire*, January 7, 2017. <https://globenews-wire.com/news-release/2017/01/17/906183/0/en/Chart-announces-acquisition-of-HETSCO.html> (accessed January 7, 2017).

111 Leaks to atmosphere were identified in 2007, 2011, 2014, and 2015. To repair the reboilers, technicians ground out the crack, the welds around the crack, and the cap sheet/side bar if necessary. After grinding, technicians welded over the ground-out area to rebuild the material lost during the grinding. See Appendix G for more details. Inspecting such vessels for any previous welds is possible. The telltale characteristic of a weld repair is additional weld passes that appear as different "bands" in the metal.

with HETSCO indicate that BP asked if HETSCO's other clients had success reducing thermal stresses when passes were blocked and if Chart would approve the alterations. The answer to both questions was yes. The leak was perceived to pose only a contamination threat, not an over-pressurization hazard.¹¹²

After operating for a few more months, in 2015, the ACSR developed a new external leak, and BP decided to address the interpass leak discovered in 2014 while fixing the external one. An October 2015 MOC form indicates that four layers would be blocked, two on each side of the ACSR (numbers 1, 2, 98, and 99). Just as in 2014, the MOC justification indicates that HETSCO recommended the alteration to reduce the potential for thermal stresses that could lead to further exchanger leaks to atmosphere (**Figure 31**). The MOC documentation also indicates that the blocking of passes was in accordance with BP engineering and industry standards, and that Chart would provide a new data sheet calculating the reduced capacity to exchange heat.

Neither BP nor Enterprise provided the "what-if" hazard review¹¹³ with the MOC documentation, so the CSB could not determine which engineering standards BP assessed, how it assessed them, or whether it considered the over-pressurization of the blocked passes a potential hazard.¹¹⁴

Industry guidance by both the American Petroleum Institute (API) and the Aluminium Plate-Fin Heat Exchanger Manufacturer's Association (ALPEMA) indicates that inactive areas, including blocked and/or dummy layers at the top and bottom of exchangers, shall be vented, but protected from the ingress of dust and water.¹¹⁵ As discussed in Section 4.3, the vent holes created during repair work were found welded closed during post-incident metallurgical analysis, contrary to accepted industry standards.¹¹⁶ The CSB learned

Since 1999, the CSB has issued 24 recommendations to 14 entities that address MOC^a practices. Several other CSB investigations describe MOC learnings but did not result in formal CSB recommendations.^b The CSB continues to identify managing changes safely as one of the biggest challenges facing high-hazard work environments—whether changes are to the operating environment, systems, procedures, equipment, or the organization itself.

- a MOC or *management of change* is defined as "a management system to identify, review, and approve all modifications to equipment, procedures, raw materials, and processing conditions, other than replacement in kind, prior to implementation to help ensure that changes to processes are properly analyzed (for example, for potential adverse impacts), documented, and communicated to employees affected." Center for Chemical Process Safety (CCPS). CCPS Process Safety Glossary, <https://www.aiche.org/ccps/resources/glossary> (accessed June 20, 2018).
- b For example, see the following two documents: CSB. *Investigation Report: Drilling Rig Explosion and Fire at the Macondo Well, Volume 3: Deepwater Horizon Rig, Mississippi Canyon 252, Gulf of Mexico, April 20, 2010*; Report No. 2010-10-I-OS, April 2016, p 102. <https://www.csb.gov/file.aspx?DocumentId=5992> (accessed June 15, 2018). CSB. *Case Study: Texas Tech University Laboratory Explosion, January 7, 2010*; Report No. 2010-05-I-TX; October 2011, pp 12-13. <https://www.csb.gov/texas-tech-university-chemistry-lab-explosion/> (accessed October 25, 2018).

112 BP documentation indicates that the leaks were not fixed at that time because contamination between the two process streams was not a concern. During the ensuing year, thermal fatigue cracking continued to develop, evidenced by the 2015 leak to atmosphere; presumably, the interpass cracks could have grown as well in this same time frame.

113 A "what-if" hazard review is a documented method that uses a checklist or other broad risk categories to help brainstorm potential hazards.

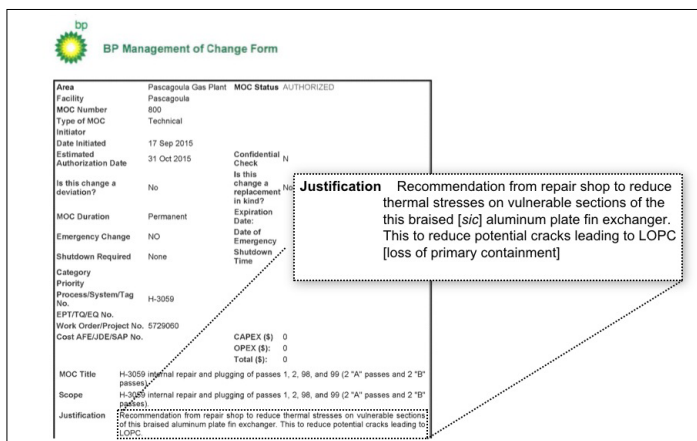
114 The MOC documentation indicates that a "what-if" hazard review was attached to the filed MOC.

115 BP's internal exchanger guidance cited API 662, Part 2, but did not address venting of blocked layers. API. *Plate Heat Exchangers for General Refinery Services, Part 2: Brazed Aluminium Plate-Fin Heat Exchangers*, 1st ed.; ANSI/API Standard 662; Washington, DC, February 2006, reaffirmed February 2011; pp 6, 14. https://www.api.org/~media/Files/Publications/2018_Catalog/2018_Pubs_Catalog_final_sm.pdf.

ALPEMA. *The Standards of the Brazed Aluminium Plate-Fin Heat Exchanger Manufacturer's Association*, 3rd ed.; 2010 with amendments May 2012; pp 21, 30. <http://www.alpema.org/standards.html> (accessed July 10, 2018).

The GPA Midstream technical bulletin goes a step further and warns that blocking vents "may create an unrated pressure vessel with additional hazards to consider." This guidance is specific to an intermodular layer/vent, but the same potential consequence exists for a blocked layer. GPA Midstream. *GPA Technical Bulletin: Brazed Aluminum Heat Exchangers*; GPA-TB-M-001; Tulsa, OK; September 2015; p 5. <https://gpamidstream.org/publications/item/?id=4165> (accessed July 10, 2018).

116 Despite this fact, OSHA did not cite PGP for the lack of venting of the blocked layers.



bp Management of Change Form	
Area	Pascagoula Gas Plant
Facility	Pascagoula
MOC Number	800
Type of MOC	Technical
Initiator	17 Sep 2015
Date Initiated	31 Oct 2015
Estimated Authorization Date	Confidential
MOC Duration	Permanent
Emergency Change	NO
Shutdown Required	None
Category	Priority
Process/System/Tag No.	H-3056
EPI/TO/IEQ No.	Work Order/Project No. 5729000
Cost AFE/DESAP No.	CAPEX (\$): 0
	OPEX (\$): 0
	Total (\$): 0
MOC Title	H-3056 internal repair and plugging of passes 1, 2, 98, and 99 (2 "A" passes and 2 "B" passes)
Scope	H-3056 internal repair and plugging of passes 1, 2, 98, and 99 (2 "A" passes and 2 "B" passes)
Justification	Recommendation from repair shop to reduce thermal stresses on vulnerable sections of this braised aluminum plate fin exchanger. This to reduce potential cracks leading to LOPC

Figure 31. MOC form for repairing and blocking passes on the ACSR.

from HETSCO that PGP is not the only facility using BAHXs in which vent holes made during repairs were sealed. Some HETSCO personnel indicated that in recent years they left the holes open but filled them in with silicone. The silicone protects against ingress of dust and water, yet will break loose in order to relieve process fluids in case the next pass begins leaking into the blocked layer, allowing the layer to vent if it were to become minimally pressurized.¹¹⁷ HETSCO's repair procedures at the time of the repair describe creating the holes, but do not describe what should happen to the holes after the repair is made. As the MOC documentation indicated, Chart provided BP new rating sheets for the PGP exchanger to quantify the reduction in heat transfer that would occur as a result of the blocked layers.

6.2.3 Recommended Thermal Fatigue Inspection Practices

Table 6 summarizes how Chart, ALPEMA, GPA Midstream, and the Gas Processing Suppliers Association Midstream (GPSA) provide guidance on methods to inspect exchangers for damage by detecting active leaks. Chart and ALPEMA also warn operators of possible catastrophic failure if the cracking is not remedied promptly.

Table 6. Industry guidance on methods to inspect exchangers for damage by detecting active leaks during operation.

GPSA	"Internal leaks in a brazed aluminum heat exchanger are generally indicated by a change of purity in any of the fluid streams. External leaks can be determined by sight, smell, audible sounds of leaking fluid, external gas monitoring equipment, or localized cold spots appearing on the external insulation." ^a
GPA Midstream	"Perform leak detection utilizing Forward-Looking Infrared (FLIR) surveys on BAHX reboilers, those in subcooler service, and those configured with inter-modular layers." ^b
ALPEMA	"External leaks will be evident by the appearance of localised freeze spots or vapour clouds on the outer casing of the insulation. In the case of heat exchangers installed in a cold box, an increase in or contamination of the purge gas flowing out of the cold box purge valve will be evident. The smell or sound of the escaping fluid may also be discernible." "WARNING: FAILURE TO RECTIFY LEAKING UNITS MAY RESULT IN PERSONNEL INJURY AND/OR SERIOUS DAMAGE TO THE UNIT AND COMPROMISE THE SAFETY OF THE PLANT." ^c
Chart	"... fatigue will eventually result in leaks if it is allowed to continue to failure. There is no reliable way to directly measure fatigue damage before it results in a leak." "Excessive thermal stress is one of the most prevalent causes of leaks in brazed aluminum heat exchangers." "Fortunately the vast majority of BAHXs that experience thermal stress cracking either from high cycle fatigue or from low cycle thermal shock events will exhibit small leaks that can be detected and repaired in the field." "API 572 (8.2.5) states that: It is important for the owner-user and the inspector to understand that fatigue cracking is likely to cause vessel failure before detection with any NDE [nondestructive examination] methods. Of the fatigue cycles required to produce failure, the vast majority are required to initiate cracking and relatively few cycles are required to propagate the crack to failure." ^d
API 662	Does not provide guidance on inspection methods. ^e

a *Engineering Data Book—FPS English Units*, 14th ed.; Tulsa, OK, 2017; Vol. 1, §9, p 31. <https://gpsamidstreamsuppliers.org/gpsa-databook> (accessed July 10, 2018).

b GPA Midstream. *GPA Technical Bulletin: Brazed Aluminum Heat Exchangers*; GPA-TB-M-001; Tulsa, OK; September 2015; p 10. <https://gpamidstream.org/publications/item/?id=4165> (accessed July 10, 2018).

c *The Standards of the Brazed Aluminium Plate-Fin Heat Exchanger Manufacturer's Association*, 3rd ed.; 2010 with amendments May 2012; § 4.11.1, p 34. <http://www.alpema.org/standards.html> (accessed July 10, 2018).

d While the Chart bulletin references API 572 regarding the inspection of BAHXs for fatigue cracking, the CSB was unable to find this information in the actual standard.

e API 662 provides guidance for inspecting an exchanger during construction, but not during operation. Chart's bulletin lists API RP 579-1, *Fitness-for-Service* (2007), as a useful BAHX reference. See Section 6.2.4.

API RP 579-1 (2007), *Fitness for Service*, referenced in Chart's bulletin, describes the leak-before-break (LBB) approach. The recommended practice states, "fitness-for-service assessments are quantitative engineering evaluations that are performed to demonstrate the structural integrity of an inservice component that may contain a flaw or damage. ... this standard can be used to make run-repair-replace decisions to help determine if pressurized equipment containing flaws that have been identified by inspection can continue to operate safely for some period of time." API 579 generally addresses an LBB analysis. The remaining life of a vessel cannot be determined by the LBB analysis, but rather it is used for "determining an upper bound for a part-through flaw that is growing at an unknown rate." There are several limitations to an LBB methodology; it should not be used unless the leak is readily detectable, the damage

117 The CSB did not do any calculations to determine what size holes in the blocked layers would have been necessary to vent trapped process fluids.

mechanism has a low crack growth rate, the material leaking is not operating in a potentially dangerous condition (such as above the temperature at which a flammable material auto-ignites), and companies have an in-service monitoring program to detect the leaks as they occur. To use the LBB methodology, operators are also required to run engineering calculations showing that the expected size of a leaking crack is less than the longest crack that the equipment can experience before complete failure occurs.

PGP did not conduct any calculations to determine the critical size of a crack required to result in a catastrophic failure of the exchanger, nor is the calculation requirement mentioned in any of the guidance documents listed in **Table 2**.

6.2.4 PGP Inspection Practices for BAHXs

At times PGP workers heard, saw, or smelled process fluids leaking from BAHXs. Sometimes, however, workers were alerted to leaks through secondary indicators, such as ice formation on the outside of the exchanger. Workers typically used a flammable gas detector to verify a suspected leak. After confirmation, operators shut down the affected process line and HETSCO repaired the exchangers.¹¹⁸ In addition to repairing through-wall cracks, HETSCO also repaired visible surface cracks that had not yet begun to leak.¹¹⁹

BP inserted small tubes into the ACSR's weep holes.¹²⁰ The newly installed tubes stuck out of the insulation when the exchanger was reinstalled (**Figure 32**).¹²¹

Operators believed the tubes provided flammable vapors an escape path from the insulation so that workers could use a gas detector near the tube opening to identify a leak early. While this practice might help detect a leak underneath an attachment plate, of the nine repairs made to BAHXs at PGP, only one leak originated beneath an attachment plate. The other leaks were located on the side bars or the cap sheet above the attachment plate.

BP was not alone in using tubes to make leaks easier to detect. The CSB learned in interviews that Enterprise also employed a similar approach at some of its own sites.

6.3 Enterprise BAHX Integrity Management at Other Facilities

Currently, each gas processing company decides whether or when to replace a BAHX. Enterprise operates over 20 midstream gas plant facilities.

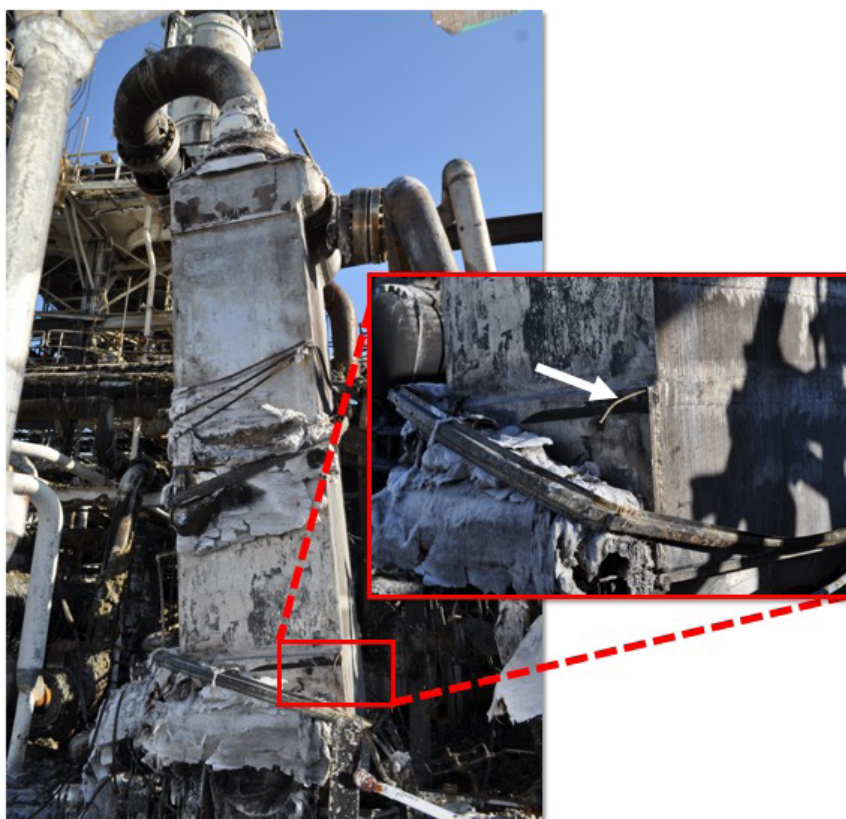


Figure 32. Post-incident image of a tube installed on the ACSR to aid in detecting leaks from the exchanger (white arrow).

118 The decision to repair in field or in HETSCO's repair shop was usually dictated by acceptable downtime. In an emergency, HETSCO will typically travel to the site, but if the company has more time, it will send the exchanger to HETSCO repair facilities.

119 See Section 6.2.1 and Appendix G or more details on the repairs to the BAHXs.

120 Chart drilled weep holes into the corners of the attachment plates during initial construction to relieve any pressure that might have developed underneath it due to process fluids' leaking from a crack.

121 Cryogenic plants like PGP insulate equipment to maintain cold temperatures and prevent moisture from forming damaging ice balls in or on the equipment. While the insulation keeps warm air and moisture away from the equipment, it also can have the effect of trapping gas leaks and inhibiting their detection.

It has relied on internal technical and engineering judgments, in conjunction with available industry guidance, to implement a repair or replacement strategy on the BAHXs at each of its other facilities.

Enterprise aims to maximize the life-span of its BAHXs by using procedural and engineering controls, including

- valves to adjust the process stream flow into the exchanger, along with active monitoring for flow changes, temperature changes, or pressure drops, to control the ROC exceedances;
- distributed control system data monitoring for transient conditions near the BAHX, enabling operators to better respond to possible temperature excursions;
- training of personnel on methods to minimize temperature excursions through their operational control of the unit; and
- automated infrared cameras to improve leak detection.

Other Enterprise facilities still experienced leaks from the company's fleet of BAHXs. When detecting a leak like the ones at PGP, operators responded by shutting down and repairing the unit. However, in some cases Enterprise replaced the exchanger with another BAHX after the first leak. Sometimes the BAHX was repaired and, when a second leak occurred, it was replaced. In one case, when a leak was found on a BAHX, the exchanger was replaced with a stainless-steel shell-and-tube exchanger. Enterprise has also replaced BAHXs that were in service for more than 25 years with no recorded leaks.

Enterprise also began its own data analysis initiative, studying its historical BAHX process data to model LOC incidents, with the aim of better identifying future damaging conditions and refining its repair/replacement decisions.

6.3.1 Enterprise BAHX Mechanical Integrity Initiative

Following several LOC incidents, in 2012 Enterprise published an equipment reliability bulletin. The company followed up this internal bulletin by sending multiple employees to assist GPA Midstream in developing the industry association's technical bulletin. An Enterprise employee led the committee that developed the document, and after completing the technical bulletin, Enterprise implemented many of the guidance's recommendations at its own facilities.

After the production of the GPA Midstream technical bulletin, Enterprise employees began consolidating all of the previous work on BAHXs into one BAHX initiative with the goal of developing the best method to achieve equipment reliability. The goal of the initiative is to provide tools and internal standards for improved operations of BAHXs as well as historical and real-time data analysis to determine potential failure rates and service life predictors for BAHXs. In addition to updating its own BAHX standard and operating procedures, Enterprise's initiative includes developing two data analysis tools:

- *Historical analysis tool*: This tool examines past operating data for a BAHX and calculates the cross-stream temperature differences and ROC measurements, much in the way discussed in Section 5.5. The goal of this tool is to review the data for a possible correlation between stream temperature differences and ROC measurements, and a resulting LOC.
- *Real-time monitoring tool*: Enterprise began recording ROC counts using temperature differential bins to analyze its BAHXs in real time, aiming to use this data as an early indication of the relative health of each exchanger.

These tools provide qualitative criteria to analyze the risk factors that can affect the mechanical integrity of a BAHX, including age of the unit; design; type of process in which it is used; and effect of changing operating conditions and other damage mechanisms, such as mercury embrittlement. Both the historical analysis tool and the real-time monitoring tool are fed into a risk management matrix, which Enterprise uses to determine whether to replace each BAHX.

Enterprise does not appear to be the only company attempting to develop better monitoring and service life predictors for BAHXs. In 2011, Shell produced a document for AIChE describing methods to study how thermal fatigue affects BAHXs and how to limit the effects

of thermal stresses.¹²² This study has similarities to Enterprise's initiative. It presents methods for predicting the life-span of an exchanger by counting the number of transient cycles it has been exposed to and comparing them with the number allowable to calculate an estimated fatigue life. The paper also provides recommendations for companies to develop a replacement strategy before a leak occurs.

Operational data is a key component for studying the effect of thermal fatigue on BAHXs. If more data is available for analysis, the accuracy and reliability of the analysis and conclusions become more robust. Further, if tools like Enterprise's historical analysis and risk management matrix are developed through the cooperation of many groups, industry could better understand the mechanical integrity of BAHXs and effect improved proactive management for preventing leaks or catastrophic failure. It would benefit industry if GPA Midstream worked with its members to compile and analyze historical process data to better understand the operational influences causing thermal fatigue, and then shared the learnings that result from this analysis.

6.4 Hierarchy of Controls and Risk Assessment

The concept of *hierarchy of controls* refers to the ranking of the safety potential of strategies for hazard management from most to least effective.¹²³ Operators who use the hierarchy of controls during the hazard assessment process explore various mitigation methods—administrative, engineering, and procedural—in effect bringing safety benefits to the process and raising awareness of each method's limitations. The intent, therefore, is a more thorough evaluation of the company's risk-based decisions.

Throughout its operational ownership of PGP, BP used administrative controls, modifying its operating procedures and installing temperature ROC alarms, to manage the integrity of its BAHXs. The company did not replace the leaking BAHXs with new ones or switch to another type of exchanger. Not until 2015, after more than nine leaks from the BAHXs at PGP, did BP make plans to replace the first BAHX by 2018. Enterprise used a variety of approaches for the BAHXs at its other facilities, sometimes replacing its exchangers after a single leak, sometimes preemptively before any leak occurred. Despite the mechanical integrity approach taken, the process data from the ACSR shows that both companies struggled to operate the BAHXs within the confines of the RAGAGEP guidance operational parameters during all phases of operations, including start-ups and shutdowns as well as normal operation.

Several gaps in the safety management of the BAHXs at PGP reveal deficiencies in hazard assessment, MOC, and mechanical integrity programs at the site. Furthermore, reliance on temperature sensors, procedures, and operator intervention as safeguards against thermal fatigue does not address the accumulative nature of the damage and overlooks potential engineering controls to prevent fluctuations in BAHXs. The CSB reviewed the process data for the ACSR and available industry guidance on monitoring and evaluating for thermal fatigue damage in BAHXs to demonstrate the need for further data sharing. When assessing operational risks, companies need to fully evaluate the design limitations of the equipment and the system requirements to ensure that the chosen control methods will be effective in the management of the process hazards of their operations. Specifically, as it relates to the June 2016 incident at PGP, operators need to assess and manage the risk of sudden and catastrophic BAHX rupture scenarios in which thermal fatigue plays a contributing role.

122 Swain, R. D.; Miller, A. C. Aluminum Plate-Fin Heat Exchanger Thermal Fatigue Study. Presented at AIChE Spring National Meeting, Chicago, IL, March 14–17, 2011; AIChE Paper Number 38c.

123 For more on the hierarchy of controls, see these sources:

CSB. *Investigation Report: Catastrophic Rupture of Heat Exchanger (Seven Fatalities)*, Tesoro Anacortes Refinery, Anacortes, Washington, April 2, 2010; Report 2010-08-I-WA; Washington, DC, 2014; pp 34–35. http://www.csb.gov/assets/1/7/tesoro_anacortes_2014-may-01.pdf.

OSHA. Hierarchy of Controls (graphic). https://www.osha.gov/dte/grant_materials/fy10/sh-20839-10/hierarchy_of_controls.pdf (accessed October 26, 2018).

7.0 Emergency Response, Community Notification, and the Use of Social Media

In its history, the CSB has investigated a variety of emergency response activities performed as a result of catastrophic chemical incidents. The use of social media by emergency responders to communicate with local residents and businesses has surfaced with more prominence in recent years.¹²⁴ Its ever-increasing growth suggests that it will enhance more traditional notification approaches, such as reverse 9-1-1 calling programs, radio public address alerts, and door-to-door messaging.

While no one at PGP was injured as a result of the incident, and onsite chemical monitoring detected no hydrocarbon traveling beyond the plant's property,¹²⁵ those in the area witnessed dramatic fires and heard the flames blowing like a loud torch, as well as thunderous booms throughout the night as piping and equipment failed. Community members told the CSB that as the incident progressed, "we found out more through Facebook than we did from anything [else]," demonstrating that the Pascagoula Police Department Facebook page was at some level a useful means of communication. Yet it also became a space of speculation that led to public concern: "We get on Facebook and everybody [is] making assumptions of what's going on, so everybody was in a panic not knowing what to do."

This chapter summarizes the emergency response activities, highlights social media as a community notification tool, and identifies opportunities for improvement.

7.1 Emergency Plan and Response

PGP is subject to the Risk Management Plan (RMP) regulations of the U.S. Environmental Protection Agency (EPA).¹²⁶ The RMP rule requires a facility with extremely hazardous substances to develop an RMP report that identifies¹²⁷

- potential effects of a chemical accident,
- steps the facility takes to prevent an accident, and
- emergency response procedures should an accident occur.

The PGP site considered the potential for a vapor cloud explosion. To minimize the potential for a vapor cloud to form, travel outside the boundaries of the PGP property, and then find an ignition source, PGP's emergency response plan was to vent the fuel both to the atmosphere and to flares, and to allow any fires to burn until they self-extinguished. PGP established this "let it burn" philosophy when it designed and built the plant, and its staff and responders generally followed the plan on June 27, 2016.

The first of three local fire departments—the Pascagoula Fire Department (PFD)—was dispatched to the scene at 11:27 p.m.¹²⁸ Arriving at 11:30 p.m., PFD set up a checkpoint at the nearest major intersection to the PGP site.¹²⁹ In concert with local police, the fire departments blocked vehicular traffic and temporarily shut down rail traffic.

¹²⁴ For instance, in CSB's MGPI Processing Inc. investigation, when problems with a community notification system prevented public notification of a chemical release, emergency responders relied on social media and local radio and television to communicate details of the emergency. CSB. *Key Lessons for Preventing Inadvertent Mixing during Chemical Unloading Operations: Chemical Reaction and Release in Atchison, Kansas, October 21, 2016*; Report No. 2017-01-I-KS; Washington, DC, January 2018; p 29. <https://www.csb.gov/file.aspx?DocumentId=6047> (accessed June 15, 2018).

Also, during its investigation of a toxic chemical release at the DuPont Laporte Facility in November 2014, the CSB learned that after the release, at least one DuPont employee checked the Local Emergency Planning Committee's Facebook page before heading to the plant; the CSB does not address social media in its DuPont investigation, but details of the incident can be found at the Agency's website, <https://www.csb.gov/duPont-laporte-facility-toxic-chemical-release/> (accessed June 15, 2018).

¹²⁵ Onsite chemical monitoring conducted for 24 hours, starting at 10:30 a.m. on June 28, 2016, detected no hydrocarbon reaching beyond the plant's property. The CSB is unaware of any chemical monitoring at the PGP boundary conducted between the initial explosion, shortly after 11:20 p.m. on June 27, 2016, and 10:30 a.m. on June 28, 2016.

¹²⁶ 40 C.F.R. §§ 68.150–68.195.

¹²⁷ EPA. Risk Management Plan (RMP) Rule Overview, <https://www.epa.gov/rmp/risk-management-plan-rmp-rule-overview> (accessed June 15, 2018).

¹²⁸ The others included the Forts Lake/Franklin Creek Volunteer Fire Department and the Escatawpa Volunteer Fire Department.

¹²⁹ Also dispatched or held on standby were the fire departments of Forts Lake, Escatawpa, and Moss Point.

The first local responders to the incident encountered “many people” who lived in the general vicinity of the PGP plant self-evacuating westward. A battalion chief described it as people “running down the streets. They were getting in their vehicles, leaving. It was a mass traffic jam, basically, of people trying to exit. ... And then you had the common sightseers that were trying to go the same way we were to get their pictures and their videos and see what’s going on.”

Around 12:00 a.m., PGP management met up with emergency responders who had established a command post¹³⁰ on a nearby highway overpass. Jackson County Emergency Services, with the responding fire departments and PGP management personnel, decided the appropriate course of action would be to continue to cut the feed into the plant (as the operators had initiated) and allow the contained fire to burn itself out, while cooling equipment where feasible. To the responders, it would be “better to have a controlled release burning than an uncontrolled release looking for [an] ignition point somewhere else.” This is in line with PGP’s response approach.

Some sources reported that responders began evacuating the small community between Industrial Road, Chevron Drive, and Stennis Boulevard, north of PGP;¹³¹ however, an official evacuation was not ordered, nor was a shelter-in-place.

Remaining fuel burned out around 6:00 p.m. on June 28, 2016, and units from the Forts Lake Fire Department remained onsite to provide safety and fire watch until released from the incident scene at 8:47 a.m. on June 29, 2016.

Emergency responders told the CSB that the incident closely mirrored tabletop exercises during emergency response planning activities that had been conducted while BP was the operator. Because of this, they felt well prepared to respond that night. Some responders noted, however, an opportunity for communications improvement. The planned emergency response activities stipulate that the plant will participate in the unified command structure, which PGP’s Incident Management Plan describes as a structure that “brings together the incident commanders of each major organization involved in the response operations for joint decision making.”

On the night of the incident, PGP did not assign someone to stay at the command post where the unified command was established. When emergency responders needed information, they had to travel to the plant and seek someone out (**Figure 33**). While plant personnel answered emergency responders’ questions and communicated freely with them when solicited, the lack of a company representative at the command post delayed response decision making, contrary to the requirements of a unified command structure.



Figure 33. Relative positions of the command post and PGP.

¹³⁰ This is the field location, either on scene or nearby, where responsible officials and planning elements from various organizations (e.g., fire departments, government agencies, the company) meet to decide on tactical-level, on-scene actions.

¹³¹ Note that the witness statements appear to be slightly inaccurate. The residential area is north/northeast of the plant; residential properties do not appear to exist east of the plant between Stennis and Chevron. Also, there does not appear to be a Chevron Road, but there is a Chevron Drive that intersects with Highway 90.

7.2 Community Notification during the Incident

First responders relied on several news media outlets on the scene and on social media to communicate information about the incident to the community. The Pascagoula Police Department posted an update on its Facebook page (**Figure 34**) at 11:41 p.m., approximately two minutes after the first responders were notified of the incident and six minutes before the first fire department arrived on scene to assess the situation. The department then posted an update the next day at 1:34 p.m., stating, “every-one is fine and no injuries occurred.”

Unified Command did not initiate the reverse 9-1-1 system called CodeRED®. CodeRED® disseminates “any message regarding the safety, property or welfare of the community. ... These may include AMBER alerts, notifications of hazardous traffic or road conditions, boil water advisories or evacuation notices.”¹³²

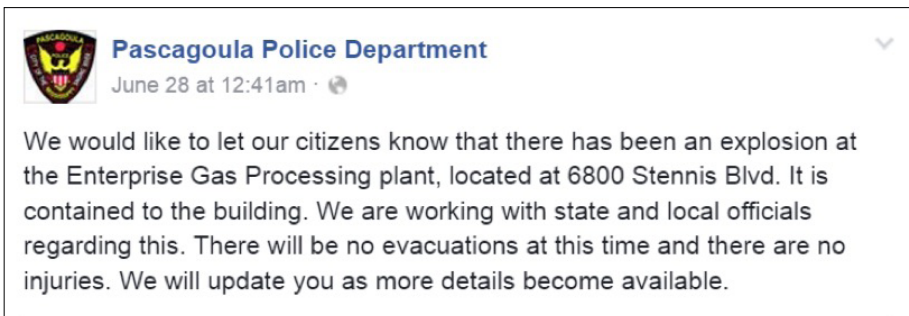


Figure 34. Pascagoula Police Department Facebook post on June 27, 2016, at 11:41 p.m.

Unified command decided not to activate CodeRED® after concluding the following:

- An evacuation was not needed. Responders deduced that the fires and explosion effects would only lessen with time because (1) the incident was contained within the property boundary lines and (2) feed to the site could be blocked off (i.e., there was a limited fuel source).
- It was better to let the sleeping public stay asleep. Responders explained their concern that waking to a reverse 9-1-1 call could cause unnecessary anxiety and potentially result in more traffic as people either self-evacuated or tried to view the scene.
- Communication through several news media outlets and a post on the Pascagoula Police Department’s Facebook page was sufficient.

In discussing the CodeRED® system, emergency responders pointed out an important limitation of the program—unlike landlines, cell phones have to be registered by the user to receive CodeRED® notifications. Emergency responders have initiated campaigns to increase registrations, but they know that not all community members are in the system. They told the CSB, “You have to reach out through Facebook and Twitter.”

7.3 Options and Opportunities for Community Notification

Unified Command decided not to require an official shelter-in-place or evacuation order while the incident was unfolding, but community notification efforts did not alleviate all public concerns. Post-incident, members of a local community organization expressed concern to the CSB that some residents did not know how to respond. They felt uninformed and ill equipped to know if they were in harm’s way. Some community members decided to evacuate; others remained in their residences.

While it may be impossible to eradicate all public concern during a major chemical event, social media provides an opportunity to create a dialogue with the public during an emergency that goes beyond reverse 9-1-1 calls or passive hotline systems that provide a recorded message from emergency response personnel concerning incidents that impact a neighborhood. In a statement before the U.S. Senate, the administrator of the Federal Emergency Management Agency (FEMA) observed, “while YouTube, Facebook and Twitter have different capabilities and audiences, we use each of these tools as a way to facilitate two-way dialogue with the communities we serve.”¹³³

¹³² <https://www.co.jackson.mi.us/215/CodeRED> (accessed June 20, 2017).

¹³³ U.S. Department of Homeland Security. Written Statement of Craig Fugate, Administrator, Federal Emergency Management Agency, before the Senate Committee on Homeland Security and Governmental Affairs, Subcommittee on Disaster Recovery and Intergovernmental Affairs: “Understanding the Power of Social Media as a Communication Tool in the Aftermath of Disasters,” May 4, 2011, <https://www.dhs.gov/news/2011/05/04/written-statement-craig-fugate-administrator-federal-emergency-management-agency> (accessed June 20, 2017).

Establishing such a dialogue could be helpful in situations like the PGP event, during which local citizens took to social media to glean information. As a testament to Facebook's reach, family members of the PGP operators involved in the incident who lived beyond the communities surrounding the plant first learned of the incident from Facebook and then monitored the situation via Facebook posts.

A 2013 report by the Department of Homeland Security (DHS) reviewed how government organizations, news outlets, charity organizations, and community members use social media to share information and collaborate during emergency situations.¹³⁴ The report collated successful methods for implementing social media, some of which are summarized in **Table 7**. Many of these methods encompass engaging the public on social media before an emergency develops, and then responding to the public while the situation is ongoing.

Table 7. Methods for implementing social media in emergency situations.^a

Method	Description
Establish a social media presence	<ul style="list-style-type: none"> Engage with the community in advance through social media and recommend standard hashtags^b
Manage expectations	<ul style="list-style-type: none"> Engage early and often with the public to help set realistic expectations during emergencies Disclose the source, type, and frequency of official emergency communications
Establish a concept of operations	<ul style="list-style-type: none"> Determine how social media will be managed during emergencies Establish training and staffing plans to allocate more resources to social media monitoring during an incident Incorporate social media strategies into emergency management exercises
Actively monitor social media content	<ul style="list-style-type: none"> Monitor conversations on popular social networks Engage with community members by responding to questions and comments, and providing clarification
Evaluate public information	<ul style="list-style-type: none"> Monitor social media channels to assess the manner in which official messages are being received Quickly correct any misperceptions or inaccurate rumors

a Space and Naval Warfare Systems Center Atlantic. *Innovative Uses of Social Media in Emergency Management*; DHS, Science and Technology Directorate: Washington, DC, 2013. https://www.dhs.gov/sites/default/files/publications/Social-Media-EM_0913-508_0.pdf (accessed June 20, 2017).

b As defined in the DHS report, "a hashtag, beginning with the pound sign, is a form of metadata tag used in short messages on microblogging social networking services such as Twitter, and allows grouping of social media messages by topic." Clicking on a hashtag in social media posts will generally display related posts that also mention the hashtag. Space and Naval Warfare Systems Center Atlantic. *Innovative Uses of Social Media in Emergency Management*; DHS, Science and Technology Directorate: Washington, DC, 2013; p 4. https://www.dhs.gov/sites/default/files/publications/Social-Media-EM_0913-508_0.pdf (accessed June 20, 2017).

Effective use of social media is likely the next evolution in the efforts to address community notifications in Jackson County, an issue the CSB has investigated previously. Upon its investigation of a 2002 runaway reaction and explosion at First Chemical Corporation in Pascagoula that launched debris both on and off site, the CSB concluded that the Jackson County public communication system was ineffective.¹³⁵ In that incident, the county issued a shelter-in-place advisory, but the media did not effectively communicate it to local residents. In addition, the county did not provide training or information on sheltering in place to the local community.

Subsequently, the CSB recommended to the Jackson County Board of Supervisors, the Jackson County Emergency Management Agency, and the Jackson County Local Emergency Planning Committee (LEPC) that the following updates be made to the community notification system:¹³⁶

¹³⁴ Space and Naval Warfare Systems Center Atlantic. *Innovative Uses of Social Media in Emergency Management*; DHS, Science and Technology Directorate: Washington, DC, 2013. https://www.dhs.gov/sites/default/files/publications/Social-Media-EM_0913-508_0.pdf (accessed June 20, 2017).

¹³⁵ U.S. Chemical Safety and Hazard Investigation Board. *First Chemical Corporation Explosion and Fire Investigation Report*; No. 2003-01-I-MS; Washington, DC, October 2003.

¹³⁶ In accordance with the Emergency Planning and Community Right-to-Know Act, Jackson County has an LEPC, or local emergency planning committee. The LEPC is meant to serve "as a focal point in the community for information and discussions about hazardous substance emergency planning, and health and environmental risks. Citizens will expect the LEPC to reply to questions about chemical hazards and risk management actions." The Jackson County LEPC meets every other month. Members include all the area industries, first responders, and any interested citizen within Jackson County. The meetings usually have 20-30 attendees. Local citizens started attending about six months before this incident.

- Immediately alert residents in the neighboring Moss Point community when an incident could affect their health and safety.
- Determine when a community response should be initiated.
- Communicate the nature of the incident and the appropriate response by residents.
- Alert residents when the incident is over (i.e., the all-clear has sounded).

Local Communities Integrate Social Media into Their Emergency Response Plans

Kanawha and Putnam Counties in West Virginia and Contra Costa County in California are communities located adjacent to major hazard facilities^a that have integrated social media into their emergency response plans.

The Kanawha Putnam Emergency Planning Committee's (KPEPC's) emergency management plan codifies the use of social media as one of the many mechanisms to notify the public of an emergency during hazardous material incidents.^b Depending on the magnitude of a hazardous material emergency event, the Kanawha County Department of Homeland Security and Emergency Management (KCDHSEM) uses multiple tools to inform the public,^c recognizing, "It is critical that all available public warning methods be utilized in order to reach as many people as possible." At the beginning of an emergency event, KCDHSEM informs the public via Facebook, Twitter, and an app called KC Ready,^d and dedicates emergency personnel to social media outreach. KCDHSEM finds great utility in using social media to correct misinformation during an incident. In addition, since many news organizations follow its Twitter feed, KCDHSEM uses social media to ensure that accurate and relevant information is broadcast expeditiously to the public during an emergency.

Contra Costa County (CCC) has the CCC Hazardous Materials Area Plan (CCC HMAP),^e a well-developed response plan for various hazardous materials emergencies. The CCC HMAP addresses four levels of incident severity with corresponding emergency response protocols. The highest, Level 3, requires notifying both media and the public via the Community Warning System (CWS)^f and social media. Each major hazard facility in CCC must notify the public in its assigned geographic area of the impending public health advisory^g using Facebook, the CWS website, and Twitter. Furthermore, the CWS issues alerts via Facebook and Twitter. According to Randy Sawyer, chief environmental health and hazardous materials officer, "social media is used for everything, especially if it concerns public protection." He goes on to state that social media is an advantage, facilitating expedient and accurate public notification because news media outlets follow the Twitter feed and rebroadcast the alerts. Contra Costa Health Services also has dedicated personnel attend to social media during hazardous material emergencies.

a Major hazard facilities are entities that store, manufacture, or process chemicals and are subject to requirements of the Occupational Health and Safety Administration's Process Safety Management of Highly Hazardous Chemicals ("PSM standard"), 29 C.F.R. § 1910.119, https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=9760 (accessed August 9, 2018), and/or the Environmental Protection Agency's Risk Management Plan rule, 42 § USC 7412(r), <https://www.epa.gov/rmp/risk-management-plan-rmp-rule-overview> (accessed August 9, 2018).

b KPEPC. Functional Annex A03, "Communications," *Kanawha Putnam Emergency Management Plan*, http://www.kpepc.org/shared/content/Page_objects/ahp_docs/FA_A03_Communications.pdf (accessed August 8, 2018).

c These public notification systems include National Oceanic and Atmospheric Administration (NOAA) All Hazards Weather Radio, the Emergency Alert System, digital receivers, outdoor warning siren systems, reverse 9-1-1, paging systems, and public address systems.

d The KC Ready app helps people keep informed on road closures due to weather, use the power company map for electrical outages, access water company information, and obtain information from the West Virginia 511 traffic information system.

e Contra Costa Health Services Hazardous Materials Programs Office. *Contra Costa County Hazardous Material Area Plan*; Martinez, CA, May 2016. <https://cchealth.org/hazmat/pdf/Area-Plan-2016May.pdf> (accessed August 9, 2018).

f "The CWS is a computer-integrated alerting and notification system that incorporates safety sirens, emergency responder pagers, the Emergency Alerting System, and a telephone emergency notification system." The CWS sends out alerts out through social media (i.e., Facebook and Twitter). In addition to these tools, the CWS delivers text messages, makes phone calls, sends email alerts to individuals who register their phones. Contra Costa Health Services, *Hazardous Material Incident Notification Policy*; Martinez, CA, January 22, 2016; p 3. https://cchealth.org/hazmat/pdf/incident_notification_policy.pdf (accessed August 9, 2018).

g Contra Costa Health Services Hazardous Materials Programs Office. *Contra Costa County Hazardous Material Area Plan*; Martinez, CA, May 2016; p 68. <https://cchealth.org/hazmat/pdf/Area-Plan-2016May.pdf> (accessed August 9, 2018).

The CSB noted this recommendation as “closed—acceptable action” on April 15, 2011. Based upon information provided by the Jackson County Emergency Management Agency director at the time, a reverse 9-1-1 system was established in 2006 to send text messages to cell phones as well as to call landlines.

The PGP incident, however, demonstrates an opportunity to address the need for a more robust and engaged LEPC/community alert network—one that includes social media and the ability to dialogue with the community throughout the incident. This notification effort goes beyond relying on media outlets to simply convey information; it seeks to manage community concerns in real time by fostering back-and-forth communication between responders and the public. In this way, for events like PGP’s that did not require an evacuation or shelter-in-place, it allows sleeping community members to remain undisturbed, whereas those awake and concerned have a method not only to obtain information but to clarify whether they should take any further action to remain safe.

In communities like Jackson County, the LEPC may be the appropriate facilitator to encourage dialogue between responders, industry, and the community on the various information-sharing modalities available and the appropriate uses of each. As the methods in **Table 7** indicate, the successful use of social media to manage public concern during an emergency will require planning, ongoing resources, and practice.

8.0 Recommendations

American Petroleum Institute (API)

2016-02-I-MS-R1

Develop a new informational product or incorporate into the next revision of Brazed Aluminum Plate-Fin Heat Exchangers for General Refinery Services 1st ed.; ANSI/API Standard 668 (formerly Standard 662, Part 2), guidance focused on the safe operation, maintenance, and repair of brazed aluminum heat exchangers (BAHX) to advance understanding of thermal fatigue hazards and how to mitigate them.

At a minimum the informational product/incorporated material must include:

- a. Information on the potential for both minor leaks and catastrophic failure as a result of accumulated thermal fatigue (beyond a single cyclic thermal shock event);
- b. Clarification on the optimal placement of BAHX temperature and pressure sensors to effectively monitor the operating conditions for the potential impact of accumulated thermal fatigue on BAHX, including temperature rates of change; and
- c. Clarification on the need to safely vent layers that have been blocked off as part of the repair process for interpass leaks in all BAHX configurations, as well as information describing the consequences when safe venting does not occur.
- d. Should applicable data from CSB Recommendation No. 2016-02-I-MS-R4 (R4) be available prior to finalizing the requirements of this recommendation, then the data from R4 will be considered for inclusion and/or incorporation by reference in the product required by this recommendation. If the decision is made not to include/incorporate by reference the data from R4, then a detailed explanation for the exclusion will be provided.

GPA Midstream Association

2016-02-I-MS-R2

Revise *GPA Technical Bulletin: Brazed Aluminum Heat Exchangers*, or develop a new bulletin, to incorporate the significant lessons learned from this incident, including but not limited to

- a. information on the potential of both minor leaks and catastrophic failure as a result of thermal fatigue;
- b. clarification on the optimal placement of BAHX temperature and pressure sensors to better monitor operating conditions, including temperature rates of change; and
- c. clarification on the need to safely vent layers that have been blocked off after interpass leak repairs, in all BAHX configurations.

2016-02-I-MS-R3

Develop a database for operators to submit BAHX operational data for collaborative industry learning and analysis. Encourage your members to submit pressure and temperature data associated with the entire service life of brazed aluminum heat exchangers as well as the date(s) of leak(s) or failure(s) for each exchanger on which data is being submitted. At a minimum this system should:

- a. provide a way to anonymously input data into the database;
- b. specify the time interval between measurements such that data can be normalized across different exchangers; and
- c. capture the type of service in which the exchanger was operating.

2016-02-I-MS-R4

Using available operational process data of BAHXs in midstream gas plant operation collected in fulfillment of 2016-02-I-MS-R3, continue data analysis efforts to determine what, if any, correlation exists between operational process data and the frequency or timing of thermal fatigue-generated cracking to more accurately predict the service life of a BAHX.

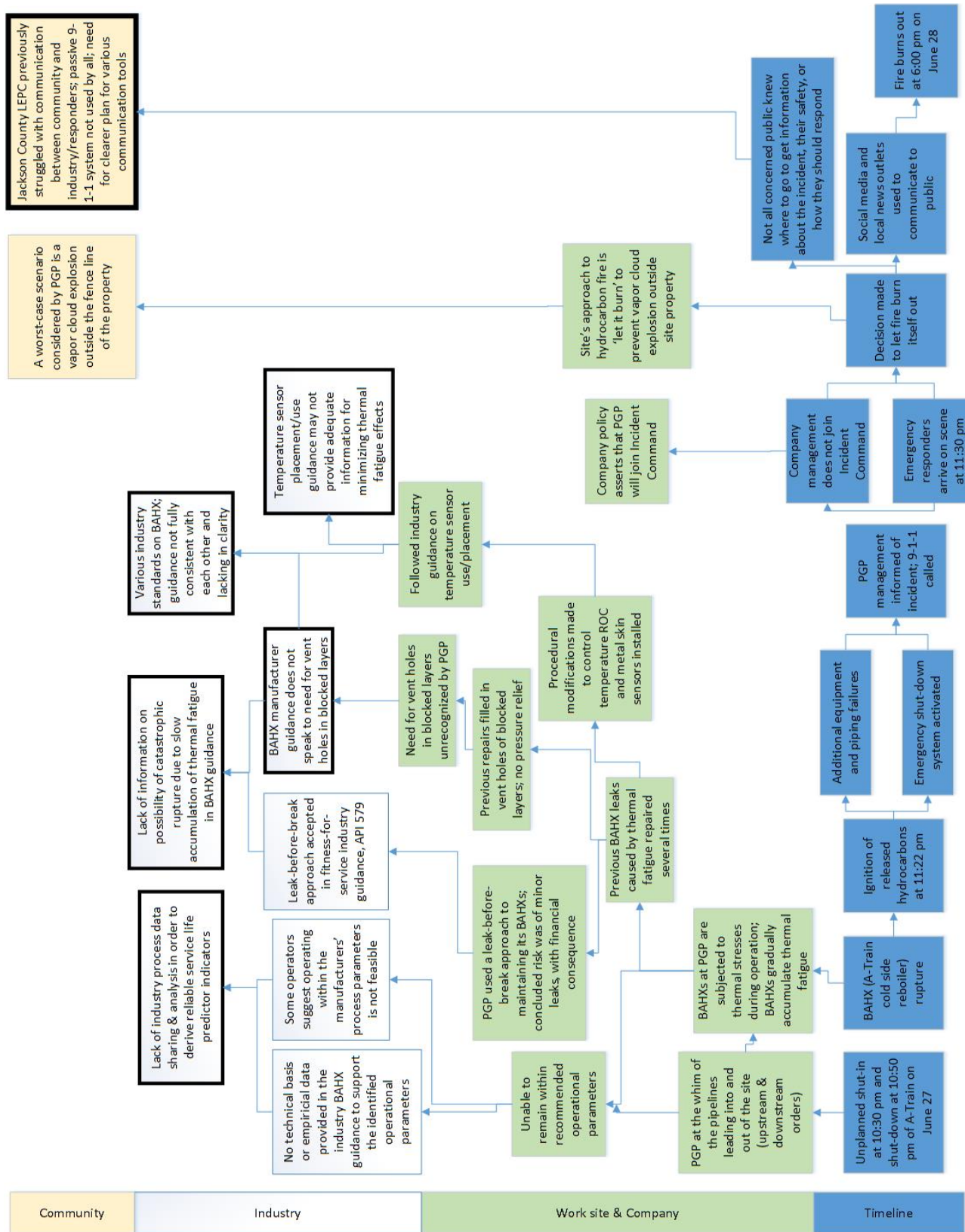
Should predictors be identified, develop and offer to your members industry tools, techniques, or criteria for estimating when thermal fatigue warrants preemptive replacement of a BAHX (e.g., risk assessment tools or damage rate calculations).

Jackson County Local Emergency Planning Committee

2016-02-I-MS-R5

Work with members (industry, emergency response, community) to explicitly define the communication methods for community notification and incident updates (e.g., social media, local news outlets, passive phone system), and the expectations for their use, so that members of the public can efficiently and effectively obtain current safety information. Publish these defined community notification methods and expectations for use on the most appropriate mediums available, such as the Jackson County Emergency Management website, the Jackson County LEPC website, and the social media outlets Jackson County utilizes to disseminate safety information to the community.

Appendix A: Visual Representation of CSB Investigation Findings and Causal Factors of the June 27, 2016, Event¹³⁷



137 The bolded boxes indicate findings and factors that resulted in recommendations.

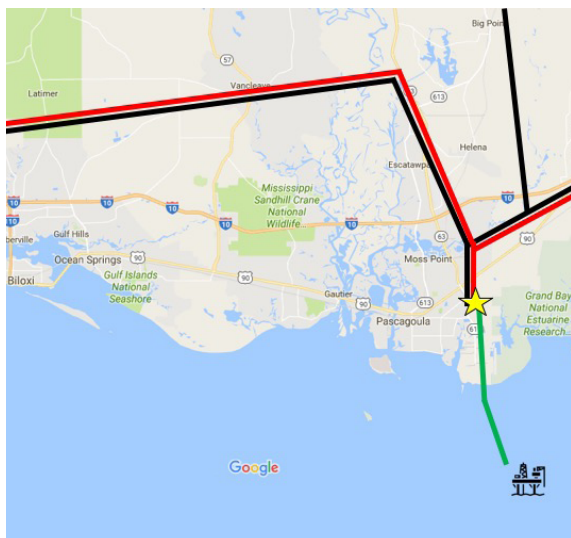


Figure 35. PGP receives raw gas via the offshore Destin (green) pipeline. Natural gas and natural gas liquids leave the plant (star) via the Destin (black) and Tri-States (red) pipelines, respectively. Pipeline locations are approximate.¹³⁸

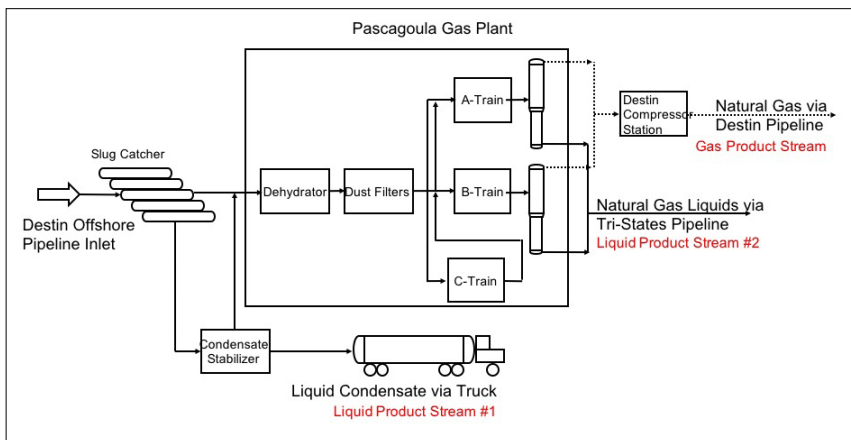


Figure 36. Simplified process overview for PGP. The first liquid product stream is trucked off site and the second is sent through the Tri-States pipeline. The gas product stream is sent through the Destin pipeline.

Appendix B: Process Overview

PGP processes raw natural gas it receives via the Destin pipeline from offshore production platforms in the Gulf of Mexico (Figure 35).¹³⁹

After processing, three product streams leave the plant, one gas and two liquid (Figure 36). PGP produces the first liquid product, natural gas condensate, by simply letting it settle out by gravity through a series of long pipes called a *slug catcher*.¹⁴⁰ The collected liquid is trucked off site for processing and sold as natural gasoline. The plant processes the remaining raw natural gas to separate the lighter natural gas,¹⁴¹ consisting mainly of methane, from heavier hydrocarbons generally known as natural gas liquids (NGLs).¹⁴² Natural gas, also called *residue gas* because it is what remains from the recovery of the NGLs, is sold as fuel. NGLs, on the other hand, have a much higher market value as feedstocks for the manufacture of plastics and other chemicals. Once these elements have been separated, PGP sends the natural gas into the Destin¹⁴³ pipeline and the NGLs into the Tri-States¹⁴⁴ pipeline, where they are transported to distribution points or other processing plants.

¹³⁸ The National Pipeline Mapping System Public Viewer (<https://pvnpm.s.phmsa.dot.gov/PublicViewer/>) was used to help generate this map.

¹³⁹ So that it does not cause operational problems or damage or rupture pipelines, natural gas product that is transported throughout the U.S. pipeline system has to meet quality criteria, including certain specific gravities, pressures, Btu (heat) content range, and levels of non-hydrocarbon contaminants (e.g., water and hydrogen sulfide). Energy Information Administration, Office of Oil and Gas. Natural Gas Processing: The Crucial Link between Natural Gas Production and Its Transportation to Market; January 2006. https://www.eia.gov/naturalgas/archive/feature_articles/2006/ngprocess/ngprocess.pdf (accessed May 25, 2017).

¹⁴⁰ In addition to liquids that settle out from the raw gas when passing through the slug catchers, liquids that gather in the pipeline are also pushed into the slug catcher using a *pig*. *Pigging* is a process of propelling a device (pig) through a pipeline, typically using a gas or liquid propellant.

¹⁴¹ Natural gas is a "gaseous form of petroleum ... consisting predominately of mixtures of hydrocarbon gases. The most common component is methane." Gas Processors Suppliers Association. *Engineering Data Book—FPS English Units*, 14th ed.; Tulsa, OK, 2017; Vol. 1, p 1-6. <https://gpsamidstreamsuppliers.org/gpsa-databook> (accessed July 10, 2018).

¹⁴² "Natural gas liquids are those hydrocarbons liquefied at the surface in the field facilities or in gas process plants. Natural gas liquids include ethane, propane, butanes, and natural gasoline." Gas Processors Suppliers Association. *Engineering Data Book—FPS English Units*, 14th ed.; Tulsa, OK, 2017; Vol. 1, p 1-6. <https://gpsamidstreamsuppliers.org/gpsa-databook> (accessed July 10, 2018).

¹⁴³ American Midstream Partners LP assumed ownership of the Destin pipeline at the beginning of 2017 (<https://markets.businessinsider.com/news/stocks/american-midstream-announces-drop-down-of-destin-pipeline-interests-bolstering-deepwater-gulf-of-mexico-position-1006160289>, accessed October 28, 2018). Before then, BP was the owner (http://www.bp.com/en_us/bp-us/what-we-do/bp-pipelines/our-pipelines-and-terminals/destin-pipeline.html, accessed May 25, 2017).

¹⁴⁴ Enterprise is the owner of the Tri-States pipeline. <http://www.enterpriseproducts.com/operations/ngl-pipelines-services/hgl-pipelines> (accessed May 25, 2017).

PGP has a design capacity of 1.5 billion cubic feet per day of raw gas and up to 50,000 barrels per day (bpd) of NGLs. At the time of the incident, throughput was approximately 500 million standard cubic feet per day of raw gas and 16,000–18,000 bpd of NGLs.¹⁴⁵

Cryogenic Process Description

After the condensate is collected in the slug catcher, the natural gas continues on to a dehydrator and dust collector to remove water and solid particles, preparing it as feed gas for one of the three process trains: A, B, or C.¹⁴⁶ A- and B-Trains are identical, operating below -50 °F to make it easier to separate the NGLs.¹⁴⁷ Several relevant pieces of the equipment that are referenced throughout the appendices of this case study are labeled in **Figure 37**, which shows an image of B-Train.

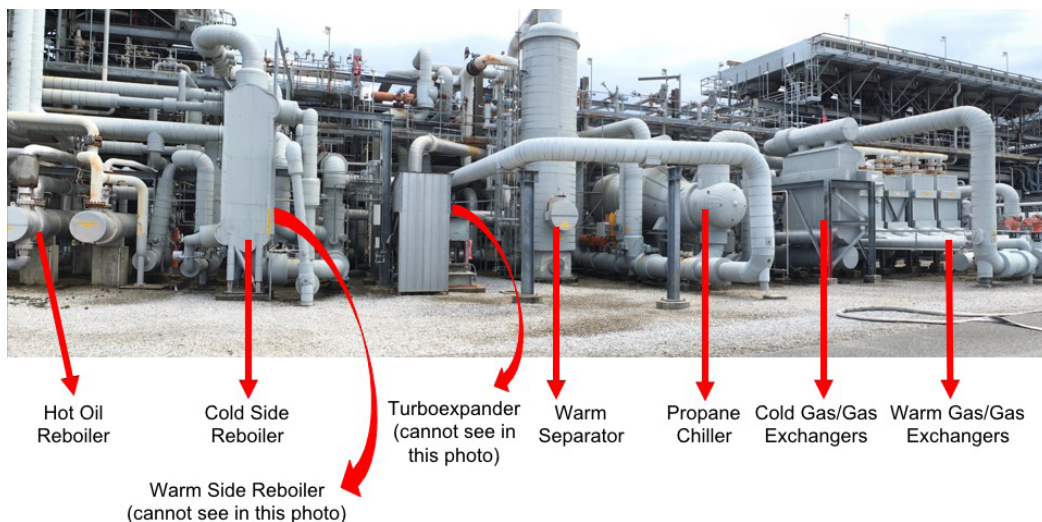


Figure 37. Photograph of B-Train taken after the incident.

PGP uses a low-temperature distillation column,¹⁴⁸ called a *demethanizer*, to separate natural gas from the NGLs (**Figure 38**). The portion of feed gas passed through the warm side reboiler heats material in the demethanizer to effect separation. The feed leaving the warm side reboiler is cooled by a propane chiller before it is recombined with cooled gas leaving the warm gas/gas exchanger. The combined stream is then sent to the warm separator, where liquids and vapors in the feed gas are first separated.

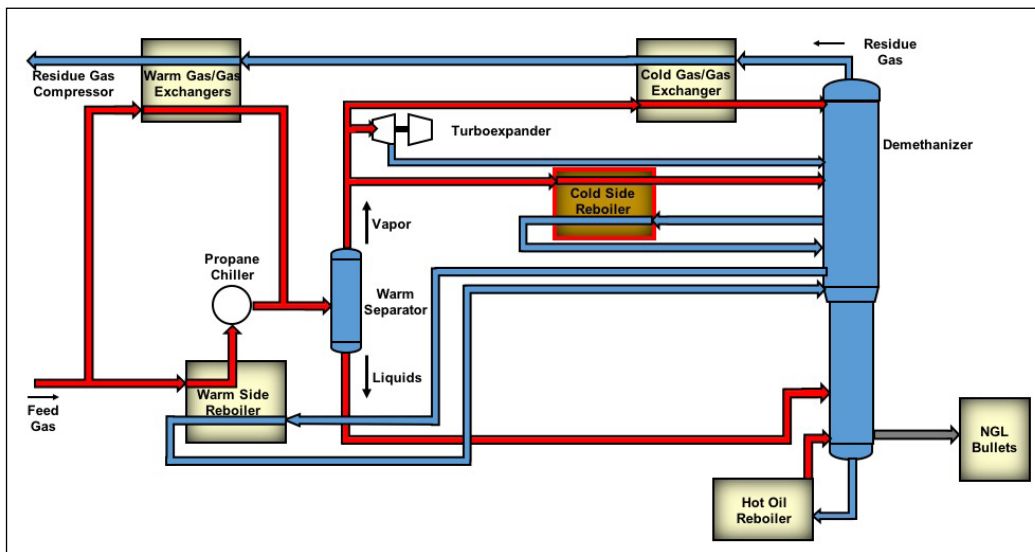


Figure 38. Simplified overview of the cryogenic process. The cold side reboiler (dark orange) is likely the vessel that initially failed. Red arrows indicate the streams that are warmer, blue the cooler streams.

¹⁴⁵ The plant used to run at a higher capacity, but the age of the offshore field from which it receives raw gas and government restrictions imposed in the Gulf of Mexico reduced its throughput.

¹⁴⁶ Water is a concern because it can form ice that could block gas flow in the plant. Also, natural gas has a tendency to form methane hydrates in the presence of water at low temperatures. Methane hydrates are solid or semisolid compounds that can accumulate and block gas flow. Dust can damage equipment utilized later in the process.

¹⁴⁷ Particularly hydrocarbons such as ethane.

¹⁴⁸ Heat is added to a mixture of components in a tall vertical column. Hot vapor rises in the column, where it comes into contact with cooled liquids descending the column. As a result, the more volatile compounds (in this case, methane) progressively increase in concentration up the column. Correspondingly, heavier compounds (NGLs) progressively increase in concentration down the column. Schaschke, C. *A Dictionary of Chemical Engineering*; Oxford University Press: Oxford, UK, 2014; p 111.

Liquids that settle in the warm separator are sent to the bottom of the demethanizer column. Vapor coming from the top of the warm separator splits into three streams:

- One stream passes through a turboexpander,¹⁴⁹ where its temperature is reduced to about -90°F. The turboexpander is a key piece of equipment in A- and B-Trains. It is the most efficient way to refrigerate the gas leaving the warm separator and reach the cryogenic temperatures necessary for the demethanizer separation process to occur, because it also simultaneously performs work by turning a compressor.¹⁵⁰
- Another stream passes through the cold side reboiler to heat material in the demethanizer. The outlets from the turboexpander and the cold side reboiler are combined and their contents fed into the middle of the demethanizer.
- The final stream is cooled and liquefied by the cold gas/gas exchanger and then fed into the top of the demethanizer.¹⁵¹

In addition to the warm and cold side reboilers, the bottom of the demethanizer also utilizes a shell and tube-type hot oil reboiler to supply additional heat for the separation process to occur. Two multi-burner furnaces are used to heat the oil for the reboiler. As needed by heat demand, burners are manually lit or extinguished by an operator.

NGLs are taken from the bottom of the demethanizer, after which they are cooled and stored in two vessels onsite called *bullets*¹⁵² before PGP pumps them into the Tri-States pipeline.

The final methane-rich natural (or residue) gas is taken from the top of the demethanizer column. To conserve energy, it is used in the cold gas/gas exchanger and the warm gas/gas exchanger to cool incoming offshore gas on its way to the demethanizer. Its pressure must exceed the pressure of the gas already in the pipeline to transfer the residue gas into the Destin pipeline. To achieve this, PGP compresses the residue gas in two stages.¹⁵³ The first stage passes through the compressor side of the turboexpander, and the second stage passes through additional compressors called *residue compressors*. Compressing the gas also increases its temperature, so after compression, the gas is cooled before being sent to the Destin pipeline. Another set of compressors, referred to as the Sonat compressors, not operated by PGP, are available to increase the pressure further if needed for the Destin distribution system.

A- and B-Trains were part of the original design of the plant and were commissioned in 1999 after the plant was built. C-Train was added in 2003. C-Train utilizes similar equipment to that of A- and B-Trains except that it does not have a turboexpander or demethanizer and so does not operate at cryogenic temperatures. It effectively ends with a warm separator and as a result, separates fewer NGLs from the natural gas. C-Train cannot be run by itself because separation without the turboexpander or demethanizer is unable to meet customer product requirements. As a result, the gas coming from C-Train is either passed through A- and B-Trains for further separation or, in some cases, subsequently blended with product from A- and B-Trains.¹⁵⁴ C-Train also includes its own dehydration and filter sections. This additional capacity to remove water and particles from the inlet gas increases the plant's capacity to process raw gas.

¹⁴⁹ The turboexpander comprises two ends, an expander and a compressor, each of which performs a different function. In the expander, gas is cooled by being passed across a fan to extract work from it. The momentum of the gas is converted to mechanical energy that spins a common shaft connected to the compressor end. The spinning compressor then boosts the pressure of the residue gas stream leaving the demethanizer column. The compressor end is not depicted in Figure 37.

¹⁵⁰ Gas Processors Suppliers Association. *Engineering Data Book—FPS English Units*, 14th ed.; Tulsa, OK, 2017; Vol. 1, p 16-13. <https://gpsamidstreamsuppliers.org/gpsa-databook> (accessed July 10, 2018).

¹⁵¹ This stream helps to increase the amount of NGLs, specifically ethane, that can be recovered. A source of reflux to condense the ethane vapor must be generated in the demethanizer. When the liquid from this exchanger is introduced back into the demethanizer, it experiences a pressure drop that “flashes” some of the liquid into vapor. The vapor and residual liquid are cooled in the process. Ethane vapor then condenses on the cooled vapor and residual liquid, allowing it to be recovered as part of the NGLs.

¹⁵² A pressure vessel with both ends having a spherical shape.

¹⁵³ The turboexpander that is used to cool the inlet gas is the same piece of equipment that recompresses the gas. The expander part of the turboexpander drops the pressure and temperature of the inlet gas, creating the energy necessary to compress the residue gas.

¹⁵⁴ Natural gas transported by major intrastate and interstate pipelines must meet quality standards, including a maximum Btu, or heat content, per standard cubic foot. Natural gas from C-Train has a higher NGL content than the gas from A- or B-Train, and this results in a higher Btu content. Depending on the relative Btu content and flow rates, blending can sometimes be used to mix C-Train residue gas with A- or B-Train residue gas and still make a product within the required Btu specifications.

Appendix C: Initial Failure Point and Progression of Equipment Failures

The CSB relied on witness testimony, distributed control system (DCS) data, the event log, and surveillance footage from a nearby facility to reconstruct the timeline presented in this report. The time stamps from the sources did not match, so the CSB used various instrument signals and visual clues to determine their relative time shifts.¹⁵⁵ All times in this report have been adjusted to real time, but time stamps in still images taken from the surveillance footage maintain a seven-minute-forward offset. **Figure 39** shows the location of key pieces of equipment in the footage from the night of the incident.

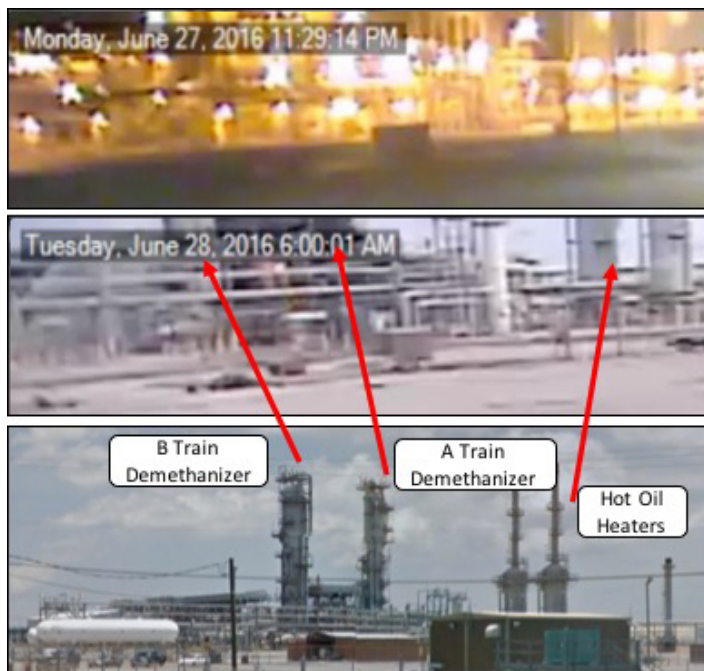


Figure 39. Surveillance camera field of view shown during the night (top) and day (middle). Photo from a nearby roadway showing a wider view of the facility from approximately the same angle as the surveillance footage at PGP on the night of June 27, 2016 (bottom).



Figure 40. Surveillance camera field of view shown during the night (top) and day (middle). Photo from a nearby roadway showing a wider view of the facility from approximately the same angle as the surveillance footage at PGP on the night of June 27, 2016 (bottom).

The initial explosion was captured in surveillance footage and coincided with various instrument failures and temperature spikes at 11:22 p.m. (**Figure 40**).

The inlet and outlet process streams on the cold and warm side reboilers are monitored by a differential pressure¹⁵⁶ sensor and eight different temperature sensors. Both reboilers also have five

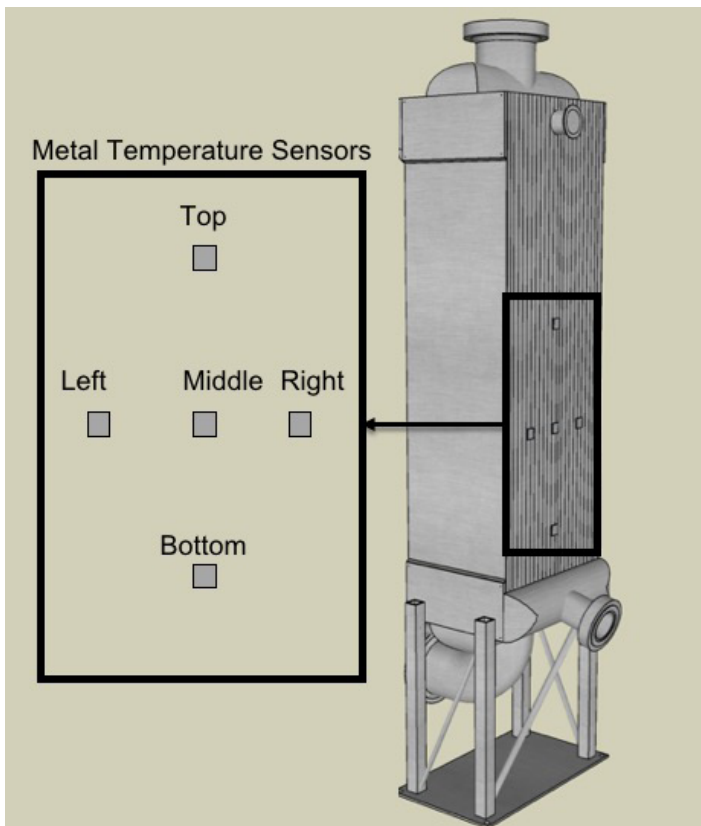


Figure 41. Location of the metal temperature sensors on the cold and warm side reboilers.

¹⁵⁵ Relative to “real time,” the event log clock was 95 seconds behind, the DCS clock was 75 seconds ahead, and the BP surveillance clock was approximately seven minutes ahead. Operators calculated real time during the week of the incident by comparing the times of the DCS and event log with that of a cell phone.

¹⁵⁶ The difference between the pressure of the inlet and the outlet of the stream is affected by factors that can restrict flow, such as blockages, obstacles, the amount of liquid versus vapor in the stream, and friction. The more the flow is restricted by these factors, the greater the pressure differential. See Section 5.3.3 for further discussion on differential pressure in BAHXs at PGP.

temperature sensors to track metal temperatures on the outside of the exchanger (**Figure 41**). The recorded measurements from all of these sensors have been used to establish a sequence of events that identifies the initial failure point and the subsequent progression of equipment failures.

DCS data from temperature and differential pressure sensors suggest that the first loss of containment most likely originated at the cold side reboiler shortly before 11:21pm. First, DCS data indicates that the A-Train cold side reboiler (ACSR) bottom metal temperature sensor stopped transmitting between 11:20 and 11:21 p.m., quickly followed by a cessation of signal transmission from the remaining metal sensors during the next minute (**Figure 42**).

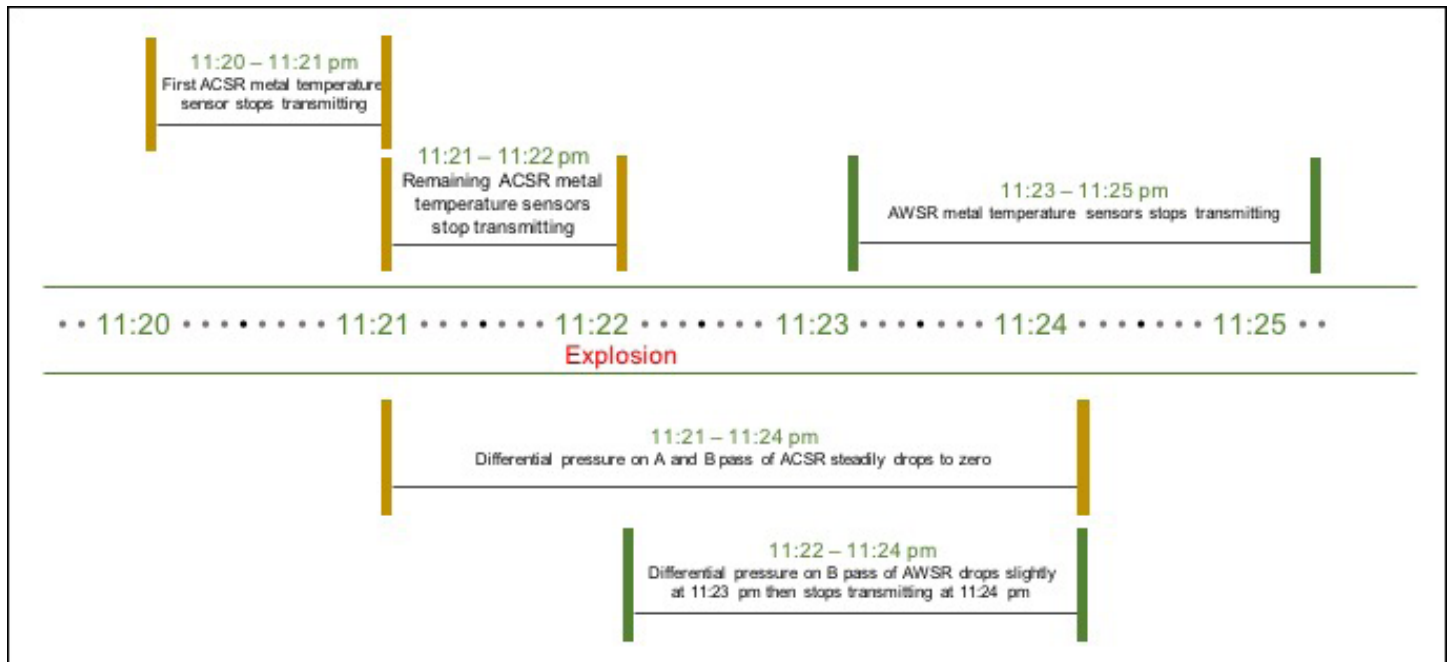


Figure 42. ACSR (gold bars) and A-Train warm side reboiler, or AWSR (green bars) temperature and pressure readings in the minutes before and after the initial incident.

Concurrent with the loss of metal temperature sensor data, the differential pressure of both the A and B passes began dropping between 11:21 p.m. and 11:22 p.m., most likely indicating a rupture of the core that compromised the integrity of both passes simultaneously (**Figure 42**). By 11:24 p.m., the ACSR differential pressure sensor stopped transmitting. During the initial few minutes after the explosion, the differential pressures in the B pass of the other reboiler in the area, the A-Train warm side reboiler (AWSR), showed a steady differential pressure in the B pass until sometime between 11:22 and 11:23 p.m., when the reading dropped slightly, and then the sensor stopped transmitting between 11:23 and 11:24 p.m. (Figure 42).¹⁵⁷ The metal temperature sensors on the AWSR also stopped transmitting between 11:23 and 11:25 p.m. (**Figure 42**). Overall, the process data of the AWSR either did not change significantly from post-explosion values.

157 The A pass differential pressure on the AWSR began dropping at 10:50 p.m., when the operator began making process changes following the curtailment procedures.



Surveillance video shows that after the initial explosion, the ensuing fire intensified several times over a time frame of about 35 minutes (**Figure 43**).

Correspondingly, temperature sensors either stopped transmitting or measured large temperature spikes (**Figure 44**). The first explosion affected sensors in the immediate vicinity of the A-Train cold and warm side reboilers, where a failure in the ACSR would have initially released flammable gas.

After the incident, 12 different breaches were identified in the A-Train equipment, piping, and vessels. The CSB analyzed several of the breaches to determine whether they were the initial point of failure before deciding the ACSR was the most likely initial failure point. Section 4.1 describes the evidence that supports the ACSR as the location of the initial breach.

Figure 43. Surveillance footage of a series of large explosions that occurred after the initial explosion.

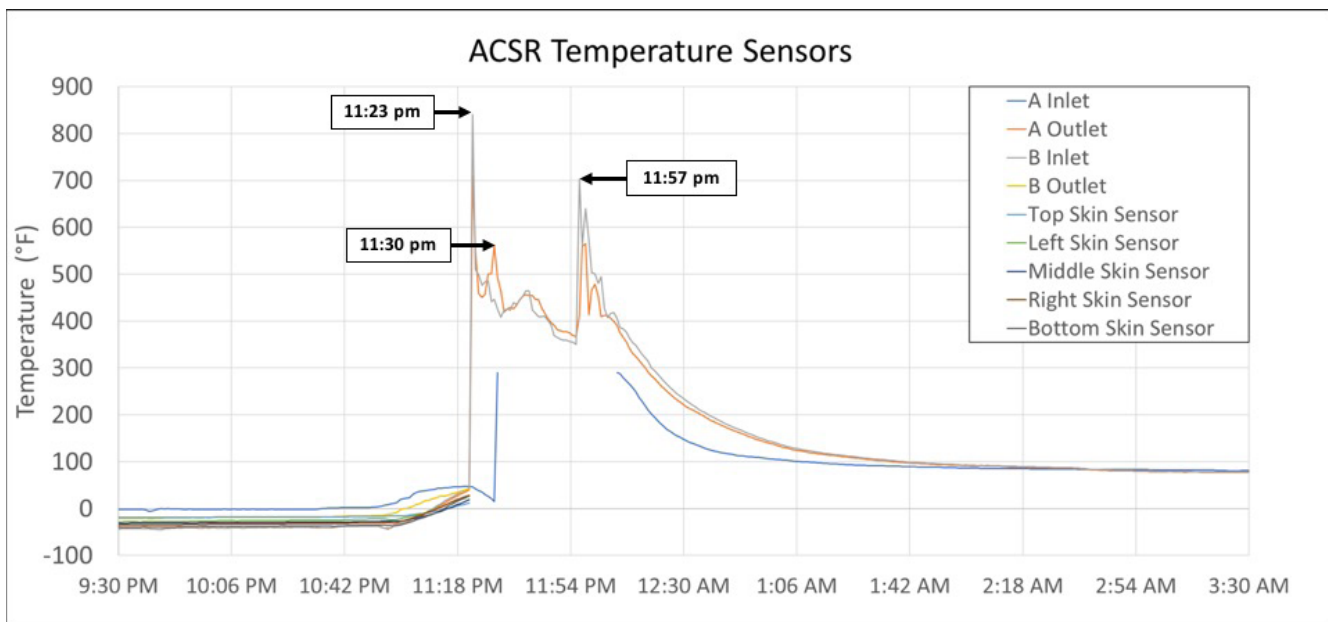


Figure 44. Corresponding temperature data from the ACSR, showing large temperature spikes at the same time as changes in the fire intensity from the security footage.

Appendix D: Post-incident Metallurgical Examination

The CSB commissioned Anamet to perform the metallurgical examination of the A-Train cold side reboiler.

The report is available at: <https://www.csb.gov/enterprise-pascagoula-gas-plant-explosion-and-fire/>.

Appendix E: Pressure Changes Resulting from Thermal Expansion During Curtailment

The CSB commissioned ioMosaic to perform thermal expansion calculations in order to determine the approximate pressure of the blocked-off pass on the A-Train cold side reboiler BAHX in alternative failure scenario #1 (see Appendix F).

The report is available at: <https://www.csb.gov/enterprise-pascagoula-gas-plant-explosion-and-fire/>.

Appendix F: Alternative Failure Scenarios

Failed weld on the A-Train cold side reboiler (ACSR) B-inlet header. The operator of the facility, Enterprise, has proposed an alternative failure scenario. Its analysis considers the initiating event to be a catastrophic failure of repair welds and header material from the B-inlet header. During the September 2015 repair, HETSCO repair technicians reattached sections of the header that had been removed to block off the leaking passes in the core (**Figure 45**). Had this scenario occurred, a large amount of liquid hydrocarbon could have been released and then ignited. Additionally, this breach would have contributed significantly to the fire, since no method existed to isolate the breach from the contents in the demethanizer column.



Figure 45. The B-inlet header on the ACSR is marked for cutting during the September 2015 repair (left, white arrow). The breach found in the B-inlet header post-incident partially followed the new weld (right, white arrow).

Visually, this breach partially runs along the repair weld left after completion of the 2015 repair, as well as through metal from the header where there was no welding.

Metallurgical testing found extensive fire damage on the breach surface, which destroyed any direct evidence that could have more conclusively determined the validity of a weld failure as the initiating event. The CSB notes that aluminum can contain slight differences in its metallic structure, which could affect how it melts in a high-temperature environment. Certain areas of the metal may begin to melt before the rest of the material, both in the weld metal and in the original header metal. This localized melting creates weak points that are susceptible to failure. Such a failure can appear as a fracture surface; however, the metallurgical examination of the other welds in the same area of the breach show early stages of this localized melting. Voids are present in the weld metal; these formed due to the

melting, while the remaining metal is less affected. (In **Figure 46**, the red arrows identify fractures on the weld.) This same type of failure can explain the fractures on the base metal (yellow arrows).

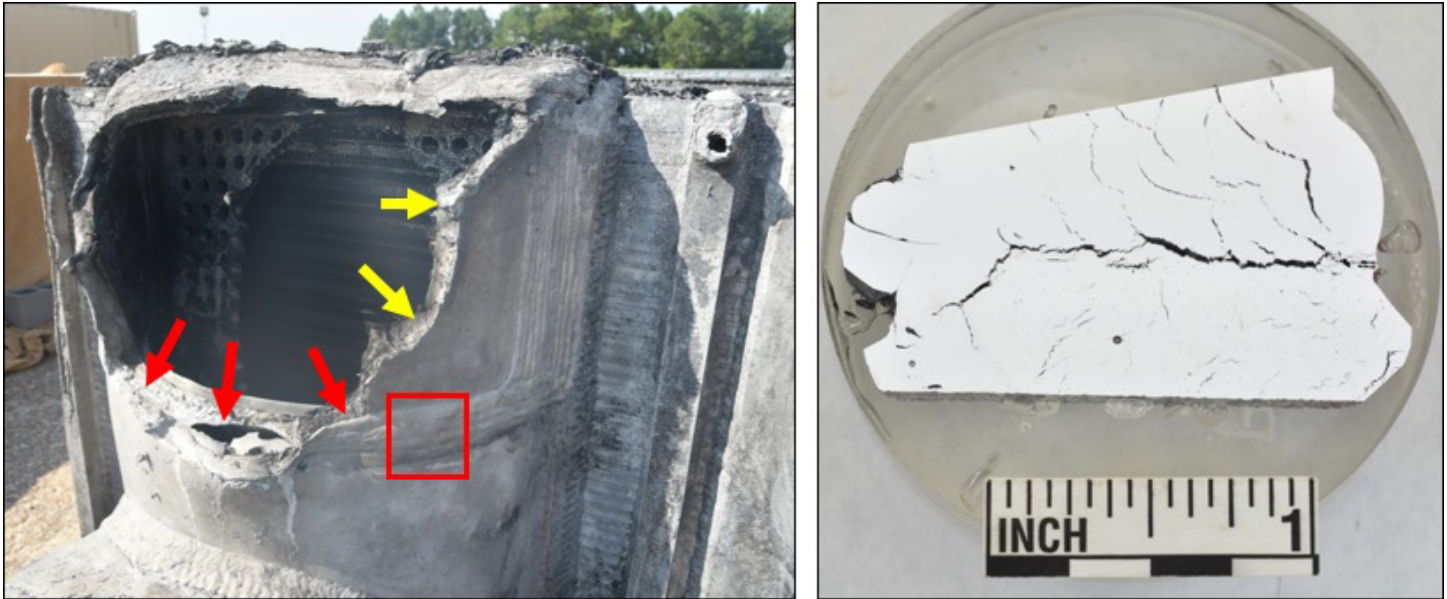


Figure 46. The left image is of the header rupture, showing the fracture surface. The right image is a section of a weld taken from the region identified with the red box in the left image, showing the formation of voids (black lines) due to localized melting of the metal.

Metallurgical testing also examined welds from the same header, but on the opposite side from the breach. This examination revealed small features where the weld was not complete, creating cracklike features. However, the CSB metallurgical examination found no signs of fatigue damage coming from these or any other areas within the weld. Additionally, at the time of the repair, the headers were pressure-tested at a higher pressure than the exchangers' normal operating pressure and did not fail. For the header to fail at normal operating pressure in this scenario, the header failure location would have needed to be weakened by another damage mechanism, yet no evidence of such weakening was found. The absence of fatigue cracking in other parts of the header, in conjunction with evidence of high-temperature, localized melting found near the potential failure surface and the success of the header pressure test after the repair, leads the CSB to conclude that this scenario does not have sufficient supporting evidence to categorize it as the most likely initiating event.

Notably, the repair of this header was required because of leaks resulting from thermal fatigue damage, which necessitated cutting and rewelding of the header. Thus, this scenario also highlights the importance of minimizing thermal fatigue damage.

Gasket failure at the B-inlet flange. The manufacturer of the ACSR, Chart, has proposed the rupture of a gasket on the B-inlet flange as the initiating event, as opposed to any failure of the ACSR itself. Before the incident, the flange would have nearly lined up with a depression in the ground identified during post-incident examination (**Figure 47**). If a gasket failure occurred, it could have resulted in the release of high-pressure liquid or jet fire. Assuming this scenario, the escaping hydrocarbons or a jet fire from the flange created the depression and initiated the other equipment failures.



Figure 47. Post-incident examination of the area revealed a large depression in the ground (left and upper right images). The breach visible in the lower right image lines up with the depression in the ground. Red arrows point out the B-inlet flange.

The CSB also concludes that this scenario is less likely than the cap sheet failure described in this case study. First, if the gasket failed, only the B pass differential pressure would be expected to be affected by the release. Yet DCS data in the minutes around the initiation of the event shows the loss of differential pressure of both the A and B passes of the ACSR within the same minute. Further, **Figure 47** (lower right image) depicts a large breach in the side of the aluminum piping next to the flange, which also could have led to the formation of the large earthen depression with the release of significant quantities of high-pressure hydrocarbon. Using metallurgical testing and field evaluations, the CSB concluded that the intense heat of the fires likely created the breach in the piping.¹⁵⁸

Analysis of the process data, metallurgical testing of the piping breach, and field evaluations lead the CSB to conclude that this scenario does not have sufficient supporting evidence to categorize it as the most likely initiating event.

¹⁵⁸ The CSB concluded that during the fire, but before the breach shown in Figure 47 occurred, the aluminum legs of the exchanger likely melted, resulting in the exchanger's shifting down and to the east. Sometime later, after severe weakening due to fire, the aluminum piping failed, at which time it released hydrocarbons still in the demethanizer column in a manner similar to that of the header breach.

Appendix G: PGP Brazed Aluminum Heat Exchanger Repair History

PGP commissioned HETSCO to repair four PGP brazed aluminum heat exchangers (BAHXs) a total of nine times. Each time HETSCO completed a repair on an exchanger, inspectors completed an examination for additional leaks or cracking on the external surfaces. If damage was found, welders removed the crack and welded the location with aluminum.

Figure 48 illustrates the results of three repair types: (1) internal leaks between two passes would be repaired by welding the leaking passes closed, (2) a leaking side bar would be ground out and then the location would be welded over, and (3) a crack on the cap sheet would be ground out and filled in with weld material.

HETSCO repaired the ACSR four times, most recently in September 2015. A total of 16 defects were fixed. **Figure 49** identifies the location of each repair: five leaks on the side bars (9, 11, 12, 13, 14), nine cracks on the cap sheet (1, 2, 3, 4, 5, 6, 8, 15, 16), one leak on the cap sheet under the attachment plate (7), and two pass sealings on either end of the BAHX (10).

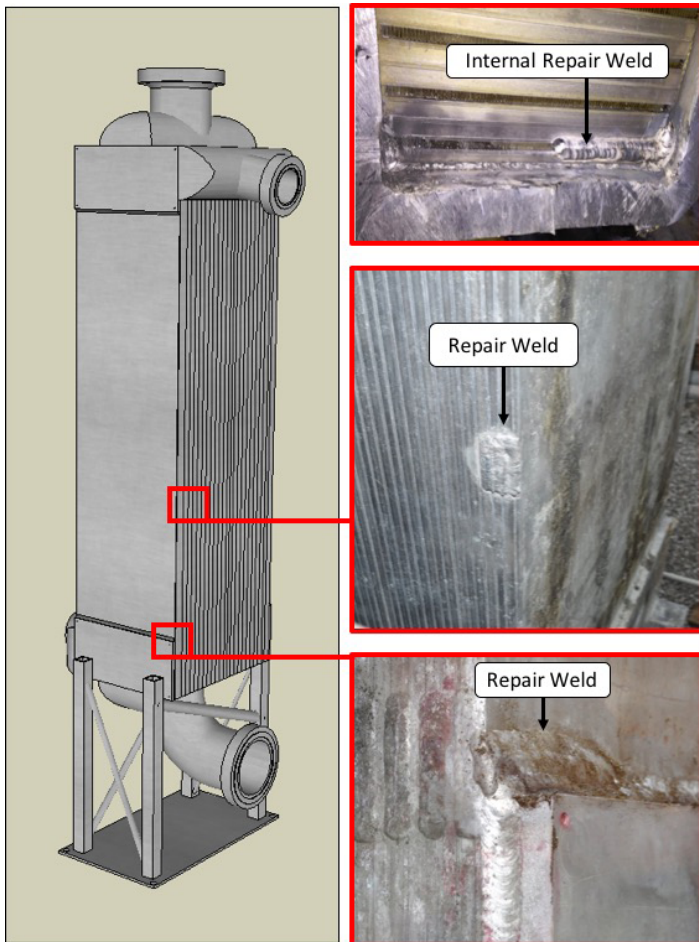


Figure 48. Black arrows point to repair welds: (1) for an internal interpass leak (top left, repair only partially completed in the photograph); (2) side bar repair (bottom left); and (3) cracks on a cap sheet (right).

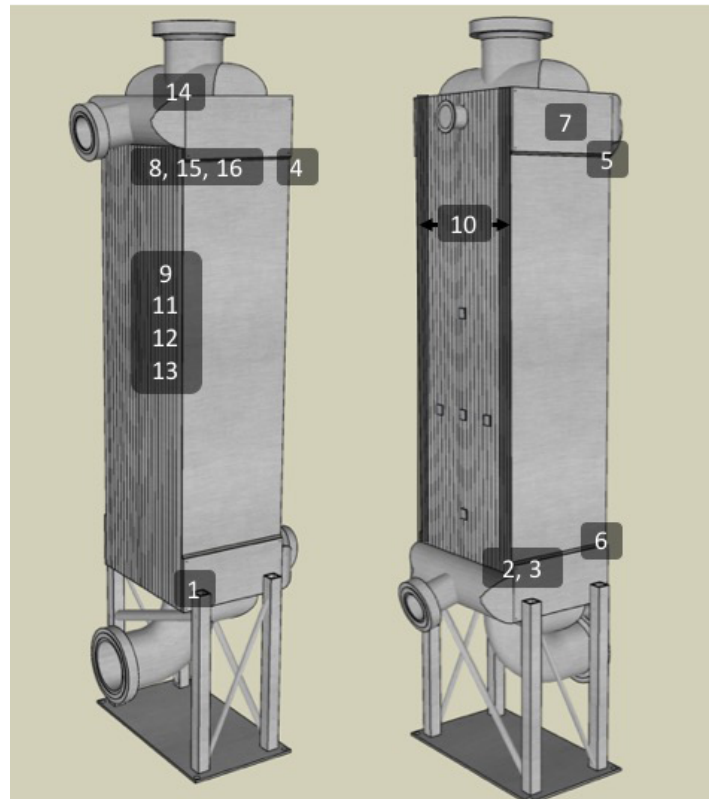


Figure 49. Visual depiction of the repairs on the ACSR. The numbering represents the order in which the leaks or cracks occurred and were repaired.

Table 8. Repair history of the ACSR.

Repair Number	Part	Date	Crack, Loss of Containment (LOC), or Internal	Notes
1	Side bar			
2	Cap sheet	10/16/2007	LOC	
3	Repad			
4	Cap sheet	9/15/2011	LOC	Documentation does not state which crack resulted in the leak that needed repair.
5	Cap sheet			
6	Cap sheet			
7	Cap sheet	10/23/2014	LOC	
8	Cap sheet		LOC	
9	Side bar		LOC	
10	Interpass	9/16/2015	Internal	
11	Side bar		LOC	
12	Side bar		LOC	
13	Side bar		LOC	
14	Side bar		LOC	
15	Cap sheet		LOC	
16	Cap sheet		Crack	

The cold side reboiler on B-Train was taken out of service for repair three times: (1 & 2) two cracks on the cap sheet, and (3) sealing passes 97, 98, and 99 (**Figure 50** and **Table 9**). Other than the known leaks, no other damage was found during any of these three repairs.

Table 9. Repair history of the B-Train cold side reboiler.

Repair Number	Part	Date	Surface, LOC, or Internal
1	Cap sheet	4/12/2007	LOC
2	Cap sheet	2/26/2010	LOC
3	Interpass	3/7/2012	LOC

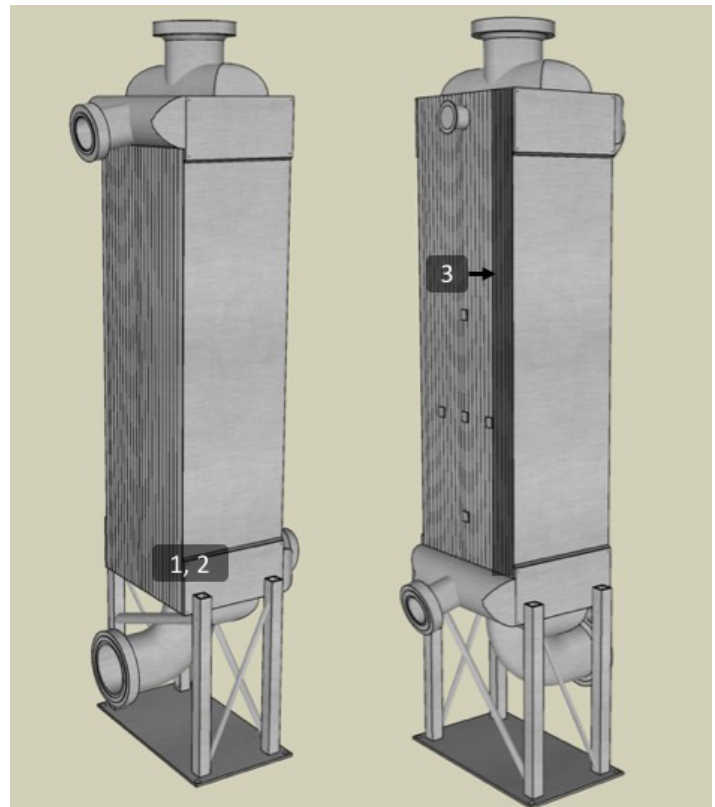


Figure 50. Visual depiction of the repairs on the B-Train cold side reboiler. The numbering also represents the sequential order in which the leaks occurred or were detected.

The A-Train warm side reboiler (AWSR) has only one recorded repair. HETSCO welded all four edges along the joint where the cap sheet and attachment plate meet (**Figure 51** and **Table 10**).

Table 10. Repair history of the AWSR.

Repair Number	Part	Date	Crack, LOC, or Internal
1	Cap sheet	1/8/2008	Crack
2			Crack
3			Crack
4			Crack

The B-Train warm side reboiler has been repaired only once and had the same cap sheet-to-attachment plate crack as the other three reboilers (**Figure 52** and **Table 11**).

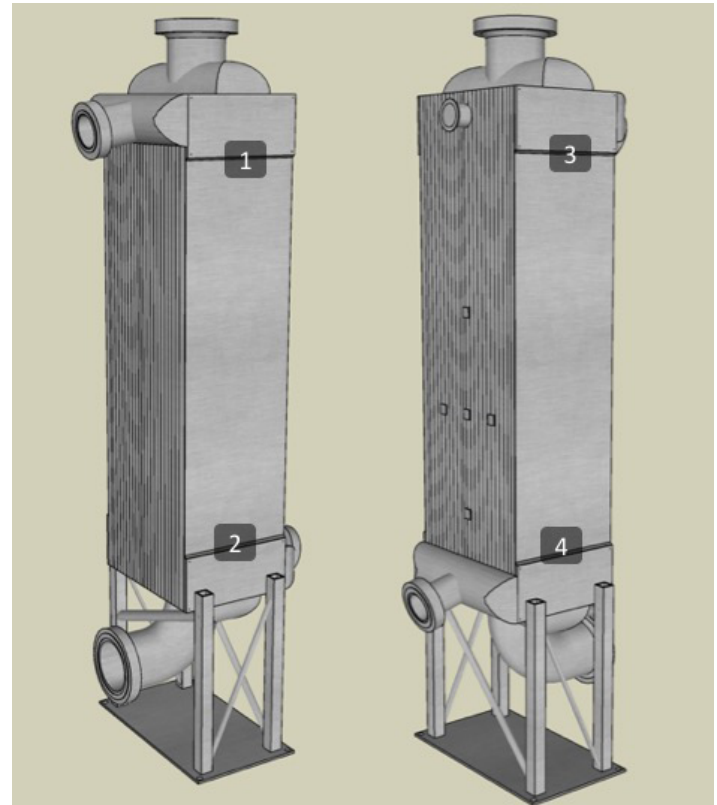


Figure 51. Visual depiction of the repairs on the AWSR. The repair in 2008 covered all four welds where the cap sheet was attached to the attachment plate (1-4).

Table 11. Repair history of the B-Train warm side reboiler.

Repair Number	Part	Date	Crack, LOC, or Internal
1	Cap sheet	9/21/2010	Crack

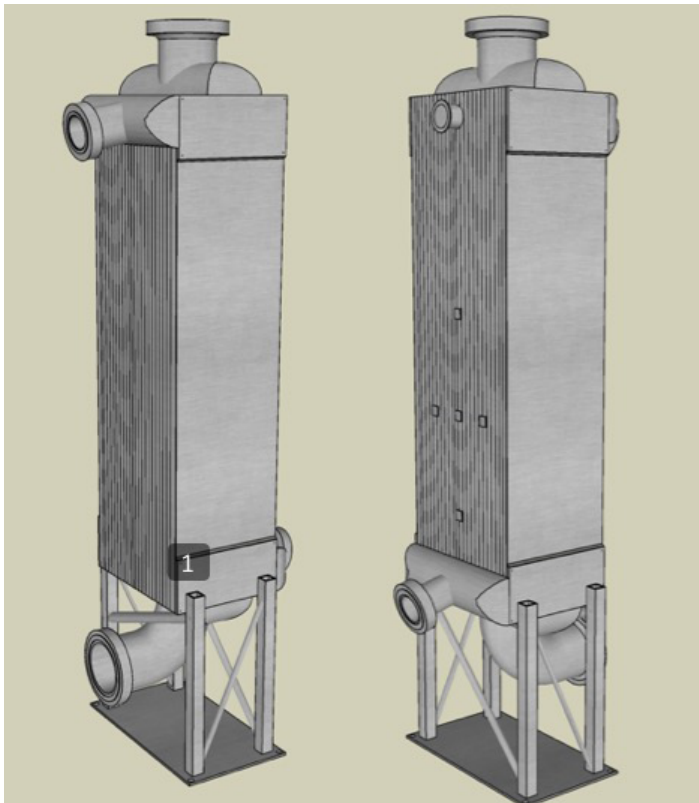


Figure 52. Visual depiction of the repairs on the B-Train warm side reboiler. The crack was repaired in 2010 (1).



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

Kristen Kulinowski, Ph.D.
Interim Executive Authority

Manuel Ehrlich
Member

Richard Engler
Member