REMFI Case 1

Thermal Cycling–Induced Fatigue in Brazed Aluminum Heat Exchangers (BAHX)

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Incident Overview

In June 2016, an explosion and fire occurred at the Enterprise Pascagoula gas processing facility in Moss Point, Mississippi. The incident caused extensive damage and resulted in prolonged operational downtime. A detailed investigation completed by early 2019 determined that the initiating failure mechanism was thermal cycling–induced fatigue within brazed aluminum heat exchangers (BAHX) used in the facility's process systems.

The investigation concluded that repeated temperature fluctuations during normal operation progressively degraded internal aluminum joints within the heat exchanger core. Over time, fatigue cracks formed, allowing process gas to escape. Under appropriate conditions, the leaked gas ignited, leading to fire and system shutdown. The failure sequence followed a consistent pattern observed in similar incidents: cyclic thermal loading caused fatigue damage, cracks propagated, leakage occurred, and combustion followed.

System Background: Brazed Aluminum Heat Exchangers

Brazed aluminum heat exchangers are widely used in cryogenic and gas processing applications due to their high thermal efficiency, compact size, and favorable strength-to-weight ratio. These exchangers consist of thin aluminum plates, fins, and headers bonded together through brazing, forming a rigid, monolithic structure.

While this construction enables efficient heat transfer, it also introduces vulnerability under cyclic thermal loading. Because brazed joints restrict relative motion between components, thermal expansion and contraction generate internal stresses that cannot be easily relieved. Over repeated cycles, these stresses accumulate and can lead to fatigue damage.

Primary Failure Mechanism: Thermal Cycling–Induced Fatigue

Thermal fatigue occurs when a material experiences repeated temperature changes while being mechanically constrained. As temperature fluctuates, materials attempt to expand or contract.

When this movement is restricted, cyclic stresses develop even in the absence of external mechanical loading.

In BAHX units, temperature distribution is inherently nonuniform. Plates, fins, and joints heat and cool at different rates, particularly during startups, shutdowns, and transient operating conditions. These mismatches create localized thermal gradients that concentrate stress at brazed joints, bends, and perimeter regions. Research on low-cycle thermal fatigue shows that even moderate temperature swings can initiate fatigue damage when cycling is frequent and constraint is high.

Repeated thermal cycling causes small plastic deformations to accumulate at high-strain locations. Over time, this leads to crack initiation, typically at brazed joints or geometric discontinuities. Once initiated, cracks propagate incrementally with each subsequent thermal cycle. Studies of aluminum heat exchangers and similar structures show that fatigue life is often governed by the magnitude of thermal gradients, the rate of temperature change, and the number of cycles rather than peak temperature alone.

Crack Development and Leakage Behavior

Fatigue cracks in BAHX systems can manifest in several forms. Surface cracks may remain small for extended periods before becoming detectable through leakage. More critically, cracks can form between internal layers of the exchanger core, creating hidden leakage paths that allow fluid to migrate between regions intended to remain isolated.

Internal layer separation is particularly dangerous because it often produces no immediate external indication of failure. Conventional leak detection methods may fail to identify damage until shortly before catastrophic failure. Experimental and field studies have shown that such internal leakage pathways are a common feature in thermally fatigued brazed aluminum exchangers.

As cracks widen under continued cycling, leakage rates increase. In the Pascagoula incident, escaping process gas eventually encountered ignition sources, resulting in fire. The progression from microscopic crack initiation to system-level failure aligns closely with fatigue behavior documented in both aerospace and energy-sector heat exchanger studies.

Contributing Factors

Although thermal cycling–induced fatigue was the root cause of failure, several contributing factors accelerated damage accumulation and increased failure severity.

Frequent startups and shutdowns introduced repeated thermal transients, increasing the number of stress cycles experienced by the exchanger. Rapid heating and cooling rates amplified thermal gradients within the rigid brazed structure. In addition, actual operating conditions often exceeded idealized design assumptions, exposing the system to a greater cumulative fatigue load than anticipated.

Monitoring limitations also played a role. Fatigue damage does not always produce early, easily detectable warning signs. Internal crack growth and interlayer leakage can remain undetected until shortly before failure. Industry guidance on fatigue management emphasizes that reliance solely on leak detection is insufficient for constrained, multilayer systems subjected to thermal cycling.

Detection and Monitoring Implications

Effective detection of thermal fatigue requires monitoring strategies that reflect actual stress drivers rather than only absolute temperature values. Temperature gradients, rate of change, and cycling frequency are critical indicators of fatigue damage accumulation.

Modern approaches increasingly rely on high-resolution temperature data, embedded sensing technologies, and predictive indicators to identify abnormal thermal patterns. However, monitoring systems must be properly aligned with exchanger geometry and known high-strain regions to be effective. Fitness-for-service standards emphasize the importance of combining operational data with structural assessment when evaluating fatigue risk.

Operational discipline remains a key factor. Monitoring improvements are most effective when paired with stable operating practices that minimize unnecessary thermal cycling and rapid transients.

Mitigation Strategies

Operational Measures

Reducing the magnitude and frequency of temperature swings can significantly slow fatigue accumulation. Maintaining stable operating regimes and avoiding unnecessary startups and shutdowns reduces the total number of damaging thermal cycles experienced by the exchanger.

Monitoring and Data Practices

High-resolution historical data enables trend analysis and root-cause investigation. Alerts should focus on abnormal thermal patterns and rates of change rather than fixed temperature thresholds alone. Predictive maintenance strategies are most effective when monitoring reflects real operating conditions.

Mechanical Inspection and Design

Inspection efforts should prioritize brazed joints, attachment points, mounts, and other high-strain regions. Repeated fatigue-related leaks often indicate the need for redesign, component replacement, or tighter operational constraints rather than repeated localized repairs.

Risk-based fatigue management frameworks recommend combining inspection data, operational history, and analytical assessment to identify vulnerable regions before failure occurs.

Transferable Engineering Lessons

Thermal fatigue is a system-level phenomenon rather than a single-component issue. High-performance operation often introduces sharper thermal transients, making heat management a critical reliability concern.

Preventing repeat failures requires controlling cycle frequency, temperature range, and rate of change while improving early-stage damage detection. Engineering decisions should be informed by observed operating patterns and validated fatigue behavior rather than idealized assumptions.

Conclusion

Thermal cycling can progressively damage brazed aluminum heat exchangers until fatigue cracks form and leakage occurs, sometimes without clear early warning signs. Preventing recurrence depends on limiting damaging temperature transients, improving monitoring near critical regions, and implementing stronger mechanical or operational interventions when fatigue indicators persist. This case highlights the importance of treating thermal fatigue as a central reliability concern in energy-system heat exchanger design and operation.

References

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