

Conference & Exhibition
14-17 September 2026
Bangkok, Thailand

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Freeport LNG Debottlenecking

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Abstract

As global LNG demand continues to grow and capital costs increase, operators are focusing on maximizing production from existing assets rather than relying solely on greenfield developments.

Freeport LNG (FLNG) operates a large-scale LNG export facility on Quintana Island, Texas. Originally developed as an import terminal and commissioned in 2008, the facility was later converted to an export terminal following the expansion of U.S. shale gas production.

Liquefaction operations began in 2019 with the startup of Train 1, followed by Trains 2 and 3 in 2020. Each Train was designed for a nominal capacity of approximately 5.1 MTPA, resulting in a total installed capacity of approximately 15.3 MTPA.

The facility exported its first LNG cargo on September 23, 2019, when the LNG Jurojin departed the terminal carrying approximately 150,000 m³ of LNG.



Figure 1: LNG Jurojin loading the first LNG cargo from the Freeport LNG Liquefaction Project

The facility employs an integrated configuration consisting of three Pretreatment Facility (PTF) trains, with common facilities at the PTF inlet and outlet, and three liquefaction trains along with common liquefaction facilities to those trains (LQF). This architecture enables independent train operation while leveraging shared infrastructure, supporting operational flexibility and reliability. The use of electric motor-driven compressors further enhances efficiency, reduces carbon intensity, improves equipment availability, delivers superior performance in hot-weather conditions, and lowers lifecycle maintenance costs.

Since commissioning, FLNG has leveraged this multi-train configuration to support continuous optimization and incremental capacity expansion. In response to increasing market demand, the facility has implemented debottlenecking initiatives to increase throughput beyond nameplate capacity through targeted modifications and system-wide improvements.

This paper presents the debottlenecking program implemented across the three existing pretreatment and liquefaction trains to increase production while maintaining compliance with process safety, regulatory, and asset integrity requirements.

1.0 Introduction

The LNG industry has entered a phase in which maximizing production from existing infrastructure is increasingly important. Brownfield optimization and debottlenecking initiatives offer opportunities to increase throughput while minimizing capital investment, permitting complexity, and execution risk.

FLNG is pursuing an increase in production capacity at its facility in Freeport, Texas, targeting a rundown rate of 5.7 MTPA, approximately 12% above design nameplate capacity. To support this objective, FLNG and Kiewit performed a comprehensive evaluation of the existing PTF and LQF facilities to assess the impact of the proposed capacity increase on process equipment, piping, instrumentation, and control systems, electrical systems and process safety safeguards.

The assessment identified facility constraints and evaluated mitigation measures necessary to support higher production rates while maintaining safe, reliable, and flexible operation.

This paper summarizes the multidisciplinary findings and recommended modifications required to achieve the targeted capacity increase. A consistent set of assumptions was established as the basis for bottleneck evaluations, and separate process models were developed for the PTF and LQF under low, average, and high ambient temperature conditions.

2. Industry Context for LNG Debottlenecking

Debottlenecking existing LNG facilities offers significant advantages over developing new liquefaction capacity through either greenfield projects or brownfield train expansions. The primary benefit is the substantially lower capital investment required to achieve incremental production increases.

Published studies indicate that the capital cost of new LNG liquefaction facilities typically ranges from approximately US$1,200 to more than US$2,200 per tonne per annum (TPA) of installed LNG capacity, depending on project size, location, infrastructure requirements, labor productivity, and market conditions (Raj et al., 2016; Zhang et al., 2020). In contrast, debottlenecking projects leverage existing process units, utilities, storage tanks, marine facilities, and supporting infrastructure, resulting in significantly lower capital investment requirements. Debottlenecking can also reduce project schedules, permitting requirements, construction risk, and environmental impacts.

Despite these advantages, LNG facilities are highly integrated thermodynamic systems in which incremental increases in throughput may introduce constraints throughout the process. Capacity increases can affect compressor operating margins, refrigeration cycle balance, heat exchanger performance, hydraulic pressure losses, flare capacity, utility consumption, control system performance, and electrical loading. Successful debottlenecking therefore requires a comprehensive facility-wide assessment to identify limiting constraints and verify that increased production can be achieved without compromising safety, operability, or long-term reliability.

3. Facility Overview

FLNG's integrated liquefaction facility includes pretreatment systems, liquefaction systems, refrigeration compressors, cryogenic heat exchangers, flare systems, utilities, and electrical distribution infrastructure. The debottlenecking assessment evaluated Trains 1, 2, and 3 under low, average, and high ambient operating conditions to identify seasonal bottlenecks and hidden operational constraints.

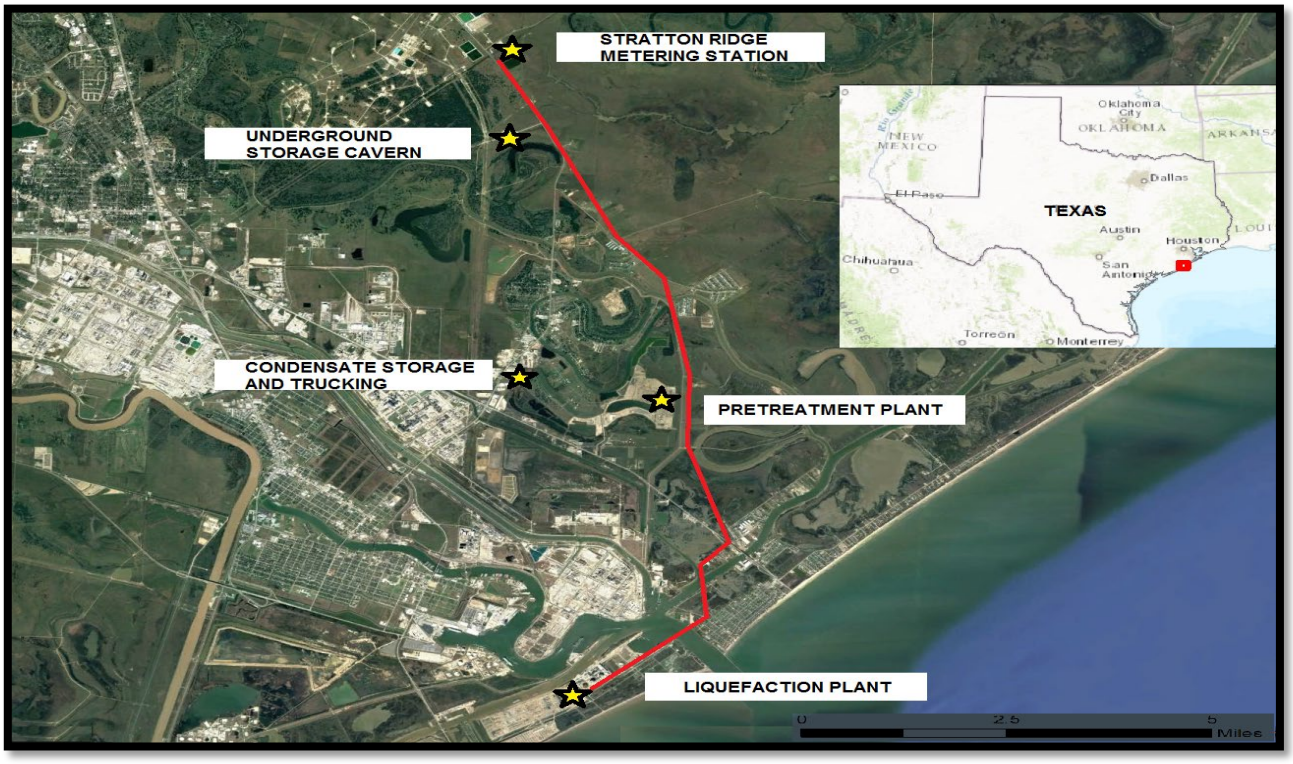


Figure 2: Overview of LNG Facility

4. Engineering Methodology

A structured, multidisciplinary evaluation framework was applied to assess facility operability under elevated throughput conditions. The methodology integrated process simulation, hydraulic analysis, equipment performance evaluation, instrumentation integrity assessment, and relief system validation to establish a consistent basis for debottlenecking recommendations.

Steady-state process simulation models were calibrated against operating data to establish a validated base case. These models were then used to evaluate increased throughput conditions across a range of operating scenarios, including average and high ambient temperatures. Key variables such as refrigerant circulation rates, compressor suction and discharge conditions, and temperature profiles were systematically varied to assess sensitivities and identify limiting constraints.

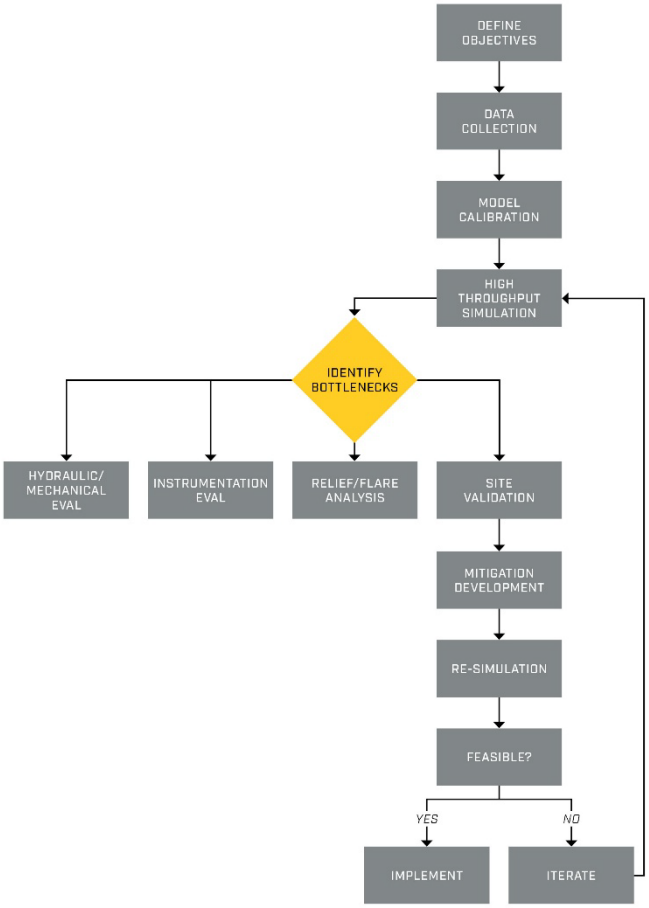


Figure 3: Engineering Process Flow

Hydraulic analyses included detailed pressure-drop calculations and screening evaluations. Line-by-line assessments incorporated frictional losses and local losses associated with fittings, valves, and equipment. Vapor and multiphase flow regimes were explicitly considered to capture compressibility effects and resulting changes in pressure profiles. Velocity checks were performed against recommended limits to evaluate erosion risk, noise generation, and susceptibility to flow-induced vibration.

Mechanical and equipment assessments focused on identifying both capacity constraints and operability risks. Compressor performance was evaluated against vendor curves to determine proximity to surge, stonewall, and maximum power limits. Heat exchanger and air-cooler

performance were reviewed to confirm thermal-duty capability under increased loads. Control-valve capacity was assessed using control valve requirements derived from updated process conditions.

Instrumentation and control systems were evaluated from both measurement accuracy and mechanical integrity perspectives. Focus was placed on inline components exposed to elevated velocities, where increased dynamic loading could affect long-term reliability.

Pressure-relief and flare-system analyses were performed using updated process conditions to verify compliance with design and safety requirements. This included revalidation of governing relief scenarios, backpressure assessments, and screening for vibration risks in discharge piping.

The integration of these analyses ensured that identified constraints were evaluated within a system-wide context, enabling the development of targeted and prioritized mitigation strategies.

5. Process Simulation Findings

The evaluation identified high ambient temperatures as the controlling operating scenario for several systems. Process simulation results showed that achievable throughput is strongly influenced by thermal constraints, particularly within the PTF and associated air-cooling systems.

In the FLNG design, pipeline gas is pressurized by a booster compressor before entering the AGRU. At elevated ambient temperatures, reduced heat transfer in upstream air-cooled exchangers results in higher process temperatures entering the AGRU. This creates a cascading effect in which elevated sweet-gas temperatures leaving the amine contactor reduce the cooling capacity available upstream of the dehydration system, limiting water removal under the original feed-gas composition assumptions. However, reconciliation with field operating data indicated lower CO_2 concentrations than assumed in the original design basis, improving throughput capability. These results underscore the importance of validating simulation models against actual operating conditions.

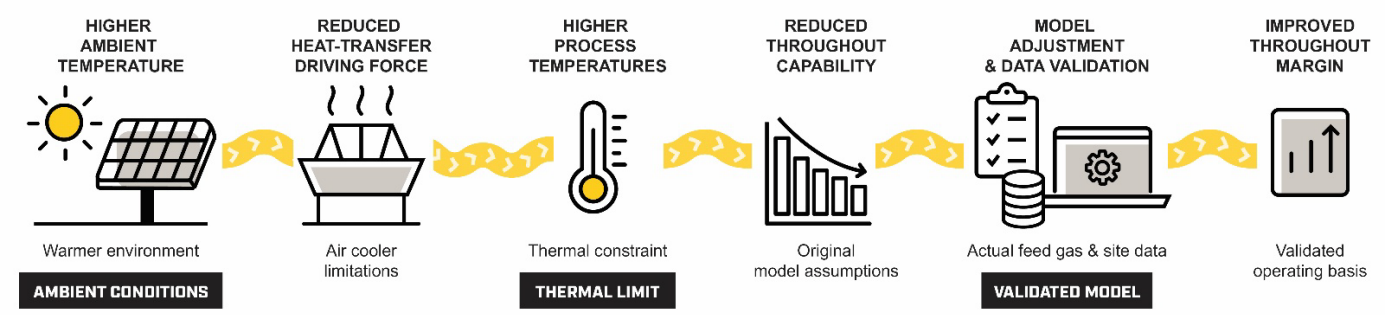


Figure 4: Process Simulation Flow

Within the liquefaction system, major rotating equipment demonstrated the ability to operate at increased flow rates without exceeding design constraints, although operating margins were reduced. Refrigerant compressors required additional power and operated closer to performance limits, requiring careful consideration of operating and control strategies.

Air-cooler performance emerged as a secondary throughput constraint. Increased process duty combined with fixed heat transfer surface area resulted in higher outlet temperatures that affected both upstream and downstream process conditions. In several cases, fan capacity and motor power limitations restricted achievable heat rejection, indicating targeted upgrades may be required to maintain thermal balance.

Importantly, the simulations confirmed that the facility could operate at increased throughput without exceeding design pressure or temperature limits. The results indicate that operational constraints are driven primarily by localized thermal and equipment limitations rather than system-wide design restrictions.

6. Refrigeration Compressor Performance

All main refrigerant compressors could operate at debottlenecked conditions with increased speed and power demand. However, the propane compressor string approached choke conditions at elevated throughput, reducing operating flexibility. Additional evaluations identified torque-limit constraints associated with motor control logic rather than actual motor capability, demonstrating that control systems and instrumentation logic can become hidden production bottlenecks.



Figure 5: Refrigeration Compressor driven by 76.5 MW motor

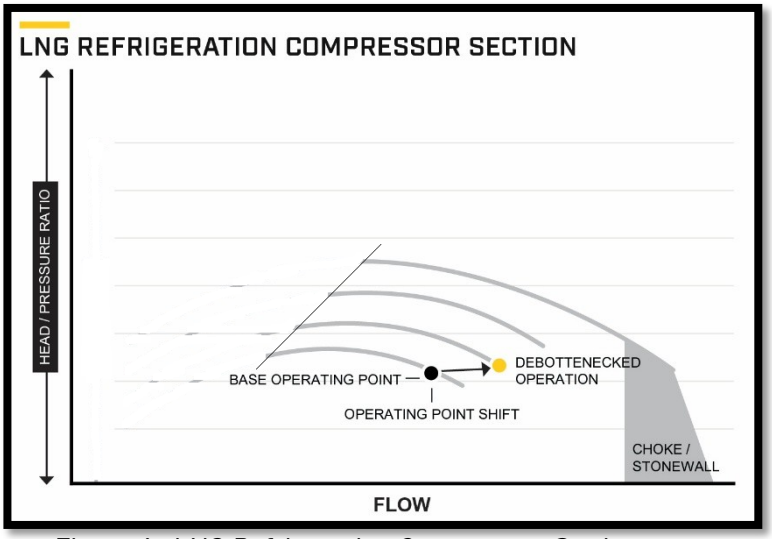


Figure 6: LNG Refrigeration Compressor Station

As flow through the piping system increases, pressure losses increase, reducing liquefaction pressure and efficiency. The resulting decrease in efficiency increases refrigeration power demand and compressor loading. To mitigate these effects, Freeport LNG re-wheeled selected compressors to utilize available motor margin and increase feed-gas pressure, improving liquefaction efficiency and supporting higher production rates.

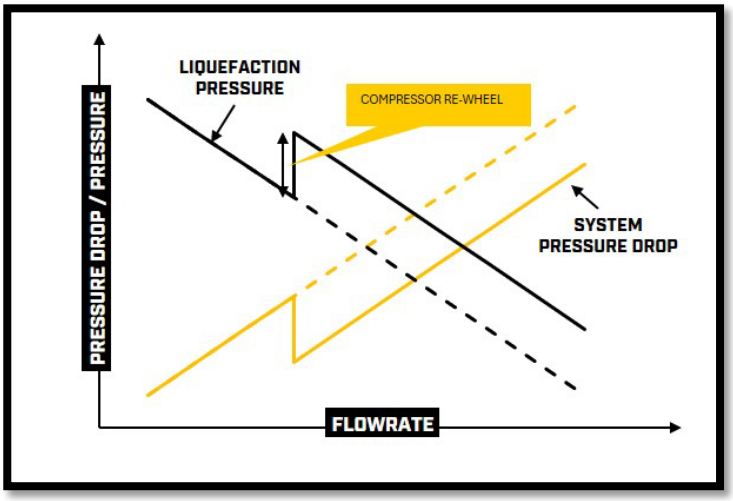


Figure 7: Impact of Feed Gas Flow Rate on System Pressure Drop, Liquefaction Pressure

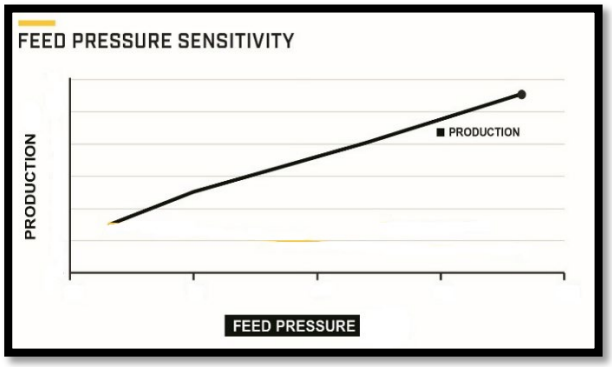


Figure 8: Impact of Feed Gas Pressure on LNG Production and Specific Power

7. Air-Cooled Heat Exchanger Limitations

Air-cooled heat exchangers (ACHEs) were identified as one of the primary constraints limiting LNG production during periods of elevated ambient temperatures. In liquefaction facilities employing propane and mixed-refrigerant cycles, ACHEs provide the primary means of rejecting compression heat to the atmosphere. As ambient temperatures increase, the temperature between the process fluid and cooling air decreases, resulting in higher refrigerant condensing temperatures and compressor discharge pressures. These effects increase compressor power consumption, reduce refrigeration cycle efficiency, and ultimately limit liquefaction capacity. Consequently, ACHE performance often becomes the controlling bottleneck during summer operation, particularly in regions experiencing prolonged periods of high ambient temperatures.

A comprehensive thermal sensitivity analysis was performed using a calibrated process simulation model to quantify the impact of ambient conditions, fan performance, and hot-air recirculation on overall plant throughput. Multiple operating scenarios were evaluated, including degraded fan performance, reduced airflow, wind-induced recirculation, and elevated ACHE inlet air temperatures representative of peak summer conditions. The analysis demonstrated that relatively small increases in cooling-air inlet temperature produced disproportionate reductions in refrigeration system capacity, confirming that air-side heat transfer performance represented one of the most influential variables affecting LNG production. Comparison of simulation results with plant operating data further revealed measurable discrepancies between predicted and

actual heat exchanger performance, emphasizing the importance of field validation and model calibration. These efforts identified localized airflow deficiencies and equipment degradation that could not be adequately represented using design data alone.

Based on these findings, the residue gas compressor aftercoolers were selected as the initial target for a pilot debottlenecking program. These aftercoolers represent a critical component of the liquefaction process because the residue gas temperature entering the liquefaction unit directly influences the refrigeration duty required to achieve LNG production. Lower residue gas temperatures reduce the thermal load imposed on the propane refrigeration system, which is typically the first refrigeration cycle to become capacity-limited during periods of high ambient temperature. Consequently, improving aftercooler performance provides a direct increase in summer LNG production by reducing the burden on the propane compressors.

The pilot program replaced the original aftercooler fan assemblies with 48 high-efficiency, ultra-low-noise fans designed to increase airflow while maintaining acceptable acoustic performance. Performance was evaluated across multiple operating seasons, including airflow, approach temperature, compressor discharge conditions, vibration, power consumption, and plant throughput. The upgraded fans reduced residue gas outlet temperatures, improving refrigeration efficiency and increasing LNG production during high ambient temperature operation.

Figure 9 summarizes the operational improvements achieved following installation of all 48 residue gas compressor aftercoolers.

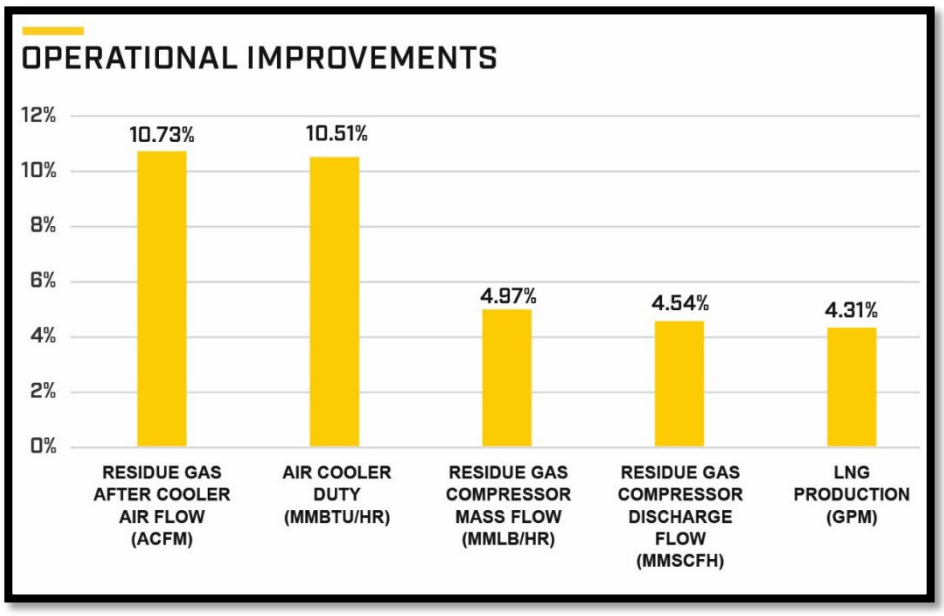


Figure 9: PTF ACHE Revamp operational improvements

Following the successful pilot installation, the upgraded fan design was adopted as the standard configuration for the facility. The upgrade was subsequently expanded to replace 456 ACHE fans throughout the liquefaction plant, significantly increasing heat rejection capacity and improving summer performance, when air-side cooling limitations historically constrained production.

Although the higher-capacity fans provided significant thermal performance improvements, the increased air flow and associated aerodynamic loading introduced additional mechanical stresses on the rotating equipment. To ensure long-term operational reliability, the fan upgrade program incorporated several complementary mechanical improvements. Fan drive shafts were redesigned to improve fatigue resistance under the increased transmitted torque associated with the higher-capacity fans.

An automatic lubrication system was installed to provide continuous, controlled lubricant delivery to critical bearing components. This enhancement improved lubricant film integrity, reduced bearing operating temperatures, minimized wear caused by insufficient lubrication, and extended bearing life under sustained high-load operation. It also reduced routine maintenance requirements and improved fan reliability and availability.

In addition, drive sprockets and power transmission components were manufactured using improved metallurgy and heat-treatment processes to enhance wear resistance and reduce maintenance requirements. Belt alignment procedures, tensioning practices, and vibration monitoring were also refined based on operational experience obtained during the pilot program.

The combined thermal and mechanical optimization program demonstrated that sustainable production gains require both improved heat transfer performance and reliable equipment potation. By integrating detailed process simulation, field performance validation, pilot-scale testing, and reliability-centered mechanical upgrades, the facility successfully increased cooling capacity while maintaining high equipment availability. The implementation of the upgraded fan technology across 456 ACHE fan locations significantly reduced summer production losses attributable to ambient temperature limitations and provided a practical framework for maximizing LNG production from existing liquefaction assets through targeted brownfield modifications.

8. Hydraulic and Piping Evaluations

Detail hydraulic calculations considering pipe routing and fittings extracted from the 3D model were performed to accurately predict pressure losses under increased throughput conditions. The analysis identified increased pressure losses in several piping segments with measurable system impacts. Increased pressure losses in suction piping to rotating equipment reduced suction pressure, impacting compressor performance and operating margin. Similarly, increased backpressure in discharge systems, particularly flare and relief headers, reduces effective capacity of upstream relieving devices.

Flow-induced vibration (FIV) and acoustic-induced vibration (AIV) risks were evaluated using established screening methodologies. High-pressure drop devices such as control valves (CVs) and orifice plates were identified as potential sources of acoustic excitation. Screening parameters including pressure ratio, velocity, and Mach number were used to identify high-risk locations.

Relief and flare discharge piping received particular attention due to the high flow energy present during relieving scenarios. Acoustic energy levels were evaluated to ensure compliance with conservative design criteria.

Overall, the piping system demonstrated sufficient capacity to accommodate increased flow rates. However, targeted mitigation of high-velocity and high-energy locations was required to ensure long-term mechanical integrity and reliability.

9. Instrumentation and Thermowell Challenges

Instrumentation systems were identified as a key constraint area due to both measurement limitations and mechanical integrity concerns under elevated flow conditions.

Thermowell vibration screening was performed using the wake-frequency evaluation methodology of ASME PTC 19.3 TW. The assessment focused on maintaining adequate separation between vortex-shedding frequency and thermowell natural frequency while also evaluating stress under the revised operating conditions.

Thermowells in high-velocity service were particularly susceptible to vortex-induced vibration. Evaluation of vortex-shedding frequencies relative to thermowell natural frequencies indicated that several installations operated near resonance conditions under increased flow rates. This condition can significantly increase cyclic stress and the potential for fatigue failure.

A thermowell may remain susceptible to vibration-induced fatigue even when cyclic stress criteria at inline resonance are satisfied. Therefore, the vortex-shedding frequency should remain sufficiently separated from the thermowell natural frequency to avoid resonance. As illustrated in Figure 10, the excitation frequency is typically maintained below a specified fraction of the natural frequency as an initial screening criterion. If the calculated excitation frequency falls within the resonance avoidance region, additional evaluation at inline resonance conditions is required to confirm acceptability.

For thermowells that do not satisfy the resonance avoidance criteria, stress calculations at inline resonance conditions (0.6 fn < fs < 0.8 fn) are required to demonstrate compliance with ASME PTC 19.3 TW.

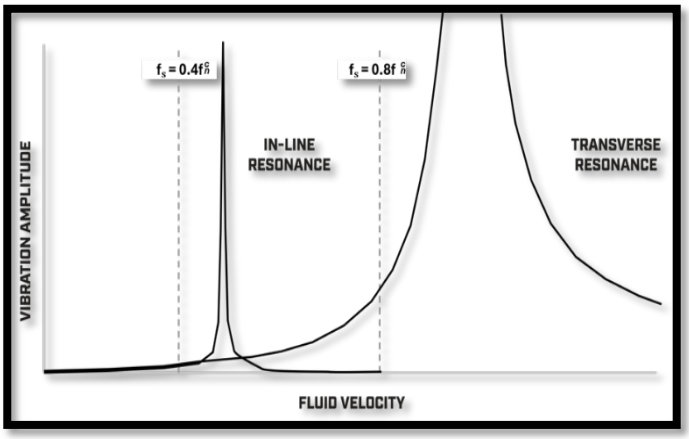


Figure 10: Thermowell Vibration Response for Inline and Transverse Excitation Modes (ASME PTC 19.3 TW)

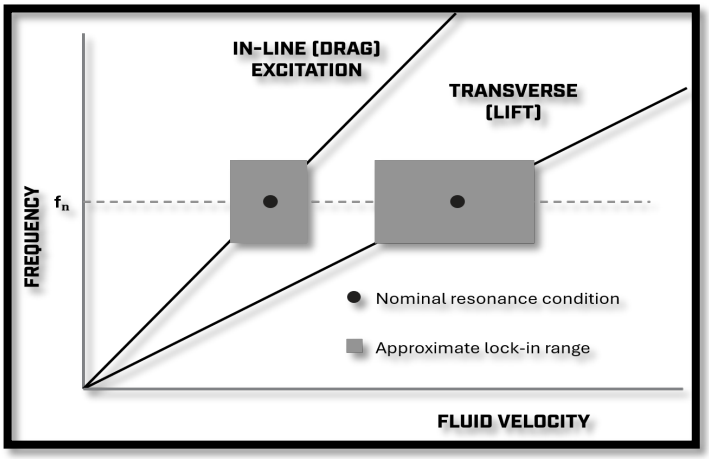


Figure 11: Thermowell Resonance Regions Occurring When Vortex-Shedding Frequency Coincides with the Thermowell Natural Frequency (ASME PTC 19.3 TW)

As illustrated in Figure 11, operation within the shaded lock-in regions may result in inline or transverse resonance when the excitation frequency coincides with the thermowell natural frequency.

Mitigation strategies focused on replacing conventional thermowells with optimized designs incorporating vortex-suppression features, such as helical strakes. These geometries disrupt periodic vortex formation, reducing excitation forces and shifting the dominant excitation

frequency away from resonance. Design validation was performed in accordance with applicable industry standards for thermowell vibration assessment.

However, thermowell replacement may require a unit shutdown and system deinventorying, increasing downtime and potential production losses where adequate isolation is not available. For selected thermowells, additional evaluations, including finite-element analysis and site resonance testing, were performed to validate the screening results and determine whether replacement was necessary.

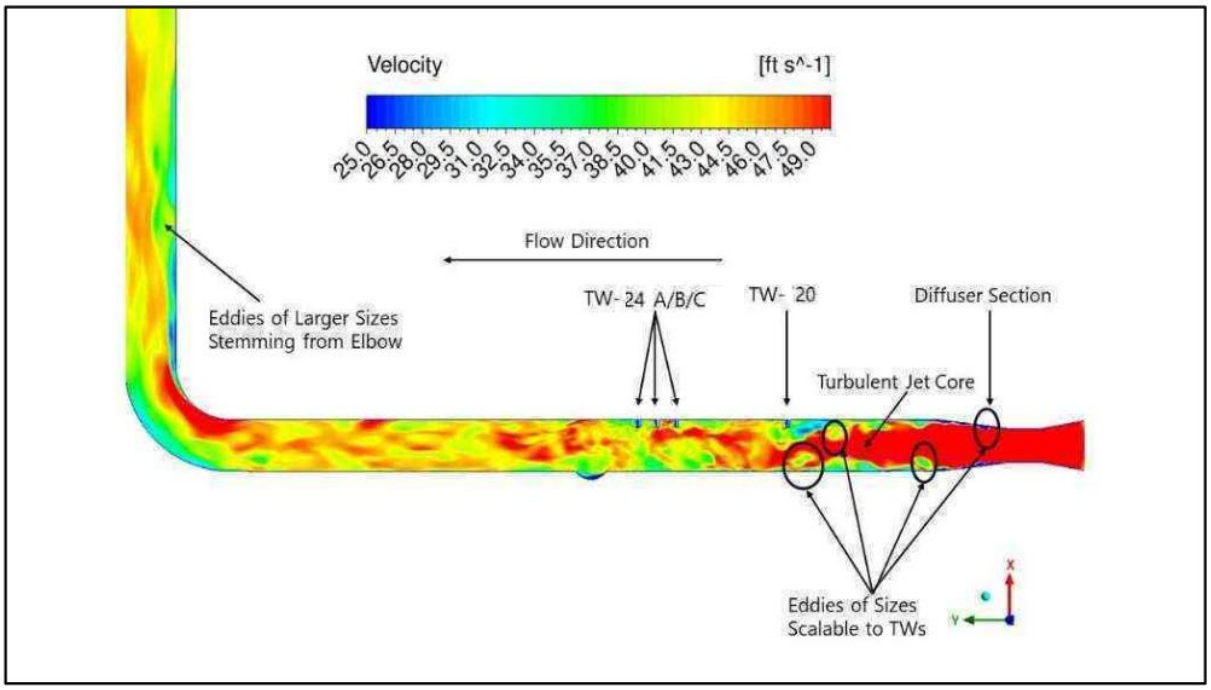


Figure 12: Finite-element Analysis (FEA) analysis of thermowells in series

Flow measurement systems also required modification to maintain measurement accuracy at higher throughput. Differential-pressure flow meters, including orifice plates and venturi meters, were found to exceed their calibrated operating ranges under increased flow conditions. This resulted in reduced measurement resolution and potential inaccuracies in flow indication.

Corrective actions included transmitter re-ranging and, where necessary, modification or replacement of primary measurement elements. These adjustments ensured that flow measurements remained within their optimal operating range and maintained process control reliability.

Control valves were evaluated for both capacity and controllability. At higher flow rates, several valves were found to operate near full travel, reducing control range and increasing susceptibility to instability and wear. Required valve coefficients were recalculated, and trim modifications were identified as an effective means of increasing capacity without full valve replacement in most cases.

These findings underscore the importance of evaluating instrumentation and control systems early in debottlenecking studies, as limitations within these systems can directly constrain achievable capacity and impact operational reliability.

10. Pressure Relief and Flare-System Assessment

Relief and flare-system evaluations confirm overall system adequacy while identifying localized capacity and operability considerations under increased throughput conditions.

Relief loads were recalculated for governing scenarios using updated process conditions derived from simulation results. Increased throughput resulted in higher relieving rates, with the most significant impacts observed during blocked-outlet scenarios. On a case-by-case basis, detailed dynamic simulations were performed to confirm calculated relief-load requirements under the revised operating conditions.

The analysis showed that most pressure safety valves (PSVs) retained sufficient relieving capacity; however, select valves were identified as undersized for the updated conditions. In these cases, upgrades to larger effective orifice areas were required to maintain compliance with allowable accumulation limits.

Backpressure analysis indicated increased pressure losses in discharge piping and flare headers due to higher flow rates. While calculated back pressure remained within allowable limits for most devices, reduced operating margins were observed in select cases. Elevated backpressure can reduce effective relieving capacity, making accurate evaluation critical.

Dynamic effects in relief discharge piping were also assessed due to the high-energy nature of relieving flows. AIV screening identified locations where acoustic energy could induce vibration and potential fatigue damage.

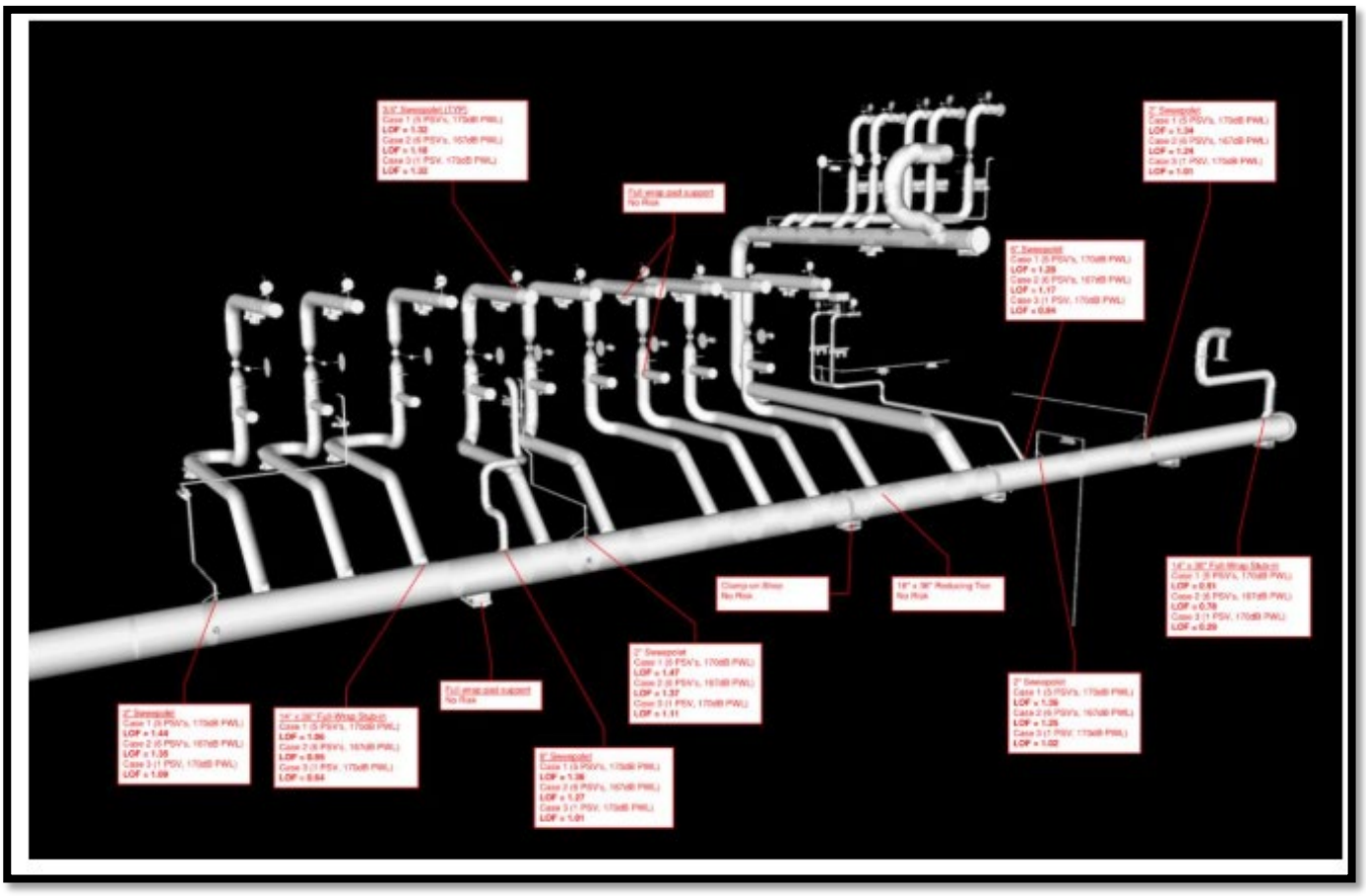


Figure 13: Sample AIV evaluation for multiple PSV discharge scenarios within a common relief header system.

Where screening thresholds were exceeded, additional evaluations, including FEA and computational fluid dynamics (CFD) modeling, were performed to estimate connection fatigue life. In several cases, the analyses confirmed the need for localized reinforcement or design modifications.

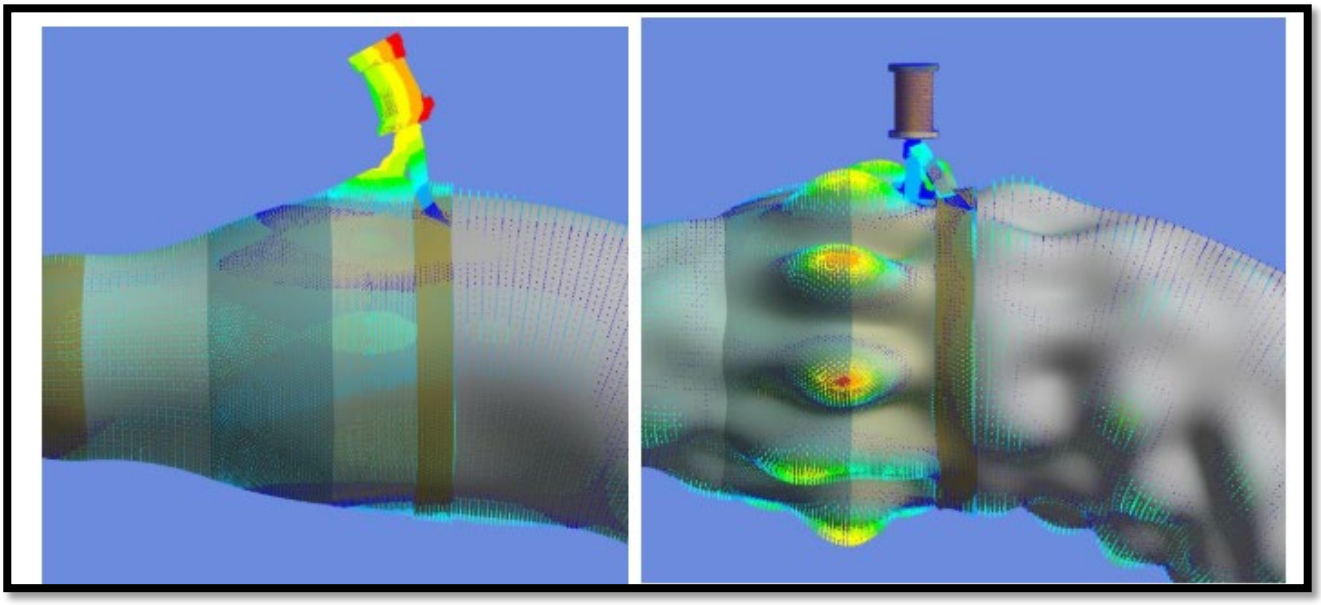


Figure 14: FEA modeling at outlet of PSV for two different peak frequencies

Importantly, the analysis confirmed that the overall flare system did not require major modifications to accommodate the increased loads. Instead, targeted upgrades and mitigation measures were sufficient to address identified constraints.

These results highlight that while relief systems are typically designed conservatively, debottlenecking efforts can reduce available operating margin and expose localized limitations that require careful evaluation and mitigation. The project reinforced that throughput increases must never compromise process safety, flare-system integrity, or mechanical reliability.

12. Operational Lessons Learned

The project demonstrated the importance of reconciling actual plant operating data with historical design assumptions. Successful LNG debottlenecking requires close collaboration among operations, engineering, OEMs, licensors, and maintenance organizations. The evaluation also reinforced that maximizing peak throughput should not come at the expense of long-term operational flexibility and reliability.

One of the key lessons learned from the debottlenecking project was the value of early engineering assessments in identifying process constraints and supporting efficient project

execution. By conducting detailed simulations and equipment evaluations before implementation, the project team was able to develop modifications that effectively addressed capacity limitations without introducing new operational risks.

Effective coordination among engineering, procurement, and construction (EPC) teams was critical to maintaining the project schedule and minimizing delays. A phased execution strategy reduced production disruptions while enabling comprehensive testing and validation of individual modifications. Real-time process monitoring and data analytics also played a key role in optimizing system performance and verifying that modifications performed as intended under increased throughput conditions.

13. Reliability and Integrity Considerations

Long-term reliability was a central consideration throughout the evaluation process. The assessment examined fatigue exposure, vibration susceptibility, compressor operating margins, thermal performance, and electrical system stability. Enhanced monitoring and predictive analytics were identified as important tools for sustaining long-term performance following implementation.

During the project debottleneck evaluation, the hydraulic turbines were identified as a significant contributor to LNG production, particularly during high ambient summer conditions. Process simulations indicated that maintaining the hydraulic turbines in continuous operation could increase LNG production by approximately 4% under these conditions. This gain results from improved hydraulic energy recovery within the LNG expansion process, increasing process efficiency while reducing refrigeration demand on the main refrigerant compressors.

Although the hydraulic turbines were originally incorporated into the facility design to recover expansion energy and improve liquefaction efficiency, historical reliability challenges limited their use. Frequent trips and operational instability led operators to bypass the turbines and operate primarily through the Joule-Thomson (JT) valve. While this approach improved short-term reliability, it reduced process efficiency and constrained maximum production capability, particularly during periods of elevated ambient temperature when compressor capacity became the primary bottleneck.

Recognizing the production opportunity identified during the debottlenecking project evaluation, Freeport LNG initiated a targeted reliability improvement program to restore dependable

hydraulic turbine operation. Rather than modifying the process design, the effort focused on eliminating the operational issues that prevented sustained turbine service.

The improvements consisted of three primary initiatives:

- **Hydraulic turbine standby mode.** A standby operating philosophy was developed to maintain a small continuous flow through the turbine during periods of reduced load.
- **Control logic modifications.** The turbine control strategy was redesigned to improve load sharing between the hydraulic turbine and the LNG JT valve.
- **Operating temperature optimization.** Operating data collected following the logic modifications demonstrated consistently lower LNG temperatures across all three Trains (Figure 15). Lower LNG temperatures improve liquid density and process efficiency while reducing unnecessary flashing through the expansion system. More stable operating temperatures also contribute to improved turbine reliability by reducing thermal excursions and maintaining equipment within its preferred operating envelope.

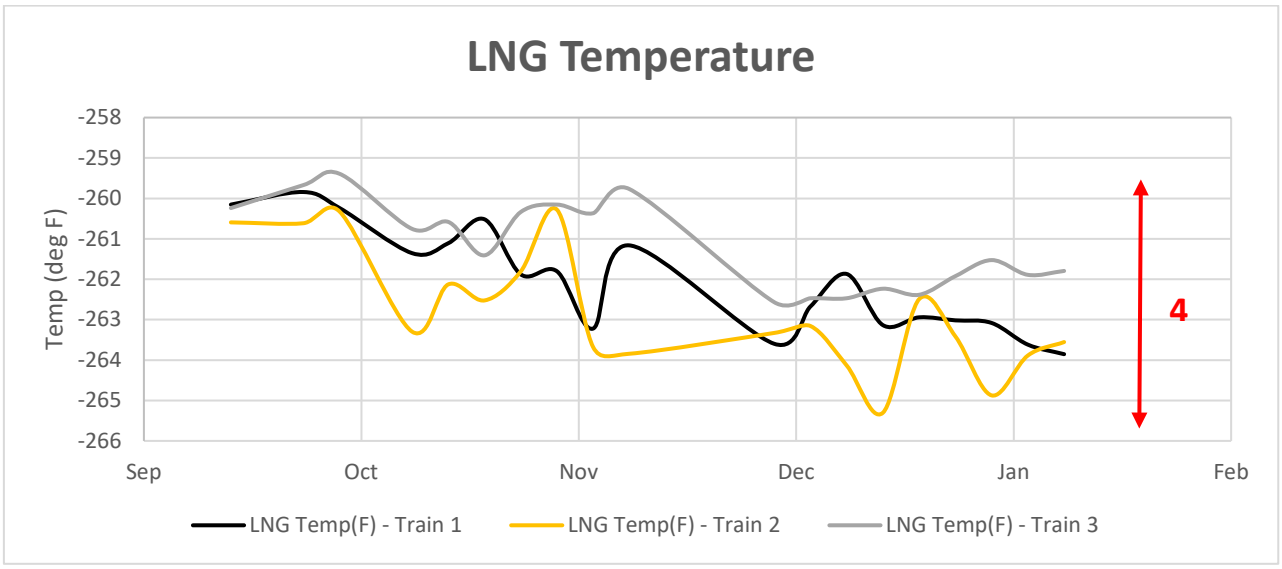


Figure 15: LNG Temperature Improvement Following Hydraulic Turbine Reliability Enhancements

Collectively, these modifications transformed the hydraulic turbine from an intermittently utilized asset into a reliable production contributor. The improvements enabled sustained turbine operation during periods of peak production demand, allowing Freeport LNG to capture the

production benefits identified during the debottlenecking project evaluation without requiring additional capital-intensive equipment upgrades.

This work demonstrates that debottlenecking opportunities are not limited to new equipment installations. Meaningful capacity gains can also be achieved through improvements in equipment reliability, controls, and operating philosophy. In this case, relatively modest control-system enhancements and operational changes enabled consistent utilization of existing equipment, recovering approximately 4% additional production potential during high ambient conditions while improving overall process stability.

14. Project Execution Strategy

Modifications were prioritized based on safety impact, throughput benefit, implementation complexity, and outage requirements. A phased execution strategy was adopted to reduce risk, validate assumptions incrementally, and minimize impacts to ongoing operations. Shutdown planning and multidisciplinary coordination proved essential to successful brownfield implementation.

In 2018, Freeport LNG engaged KBR to perform an initial debottlenecking study prior to startup of the liquefaction facility. The objective was to independently evaluate the design, verify the facility's ability to achieve guaranteed performance, and identify the plant's ultimate production potential through operational optimization, equipment modifications, and selective facility upgrades. The study concluded that the original design could achieve the guaranteed performance established by the CB&I and Zachry Joint Venture (CZJV) EPC contractor.

In 2021, FLNG engaged Kiewit Engineering Group, Inc. to assess the impact of a proposed capacity increase on the existing PTF and LQF. The assessment focused on equipment, piping, instrumentation, controls, and long-term operability under enhanced production conditions. Throughout the evaluation, potential bottlenecks were identified and mitigation measures were developed to support safe and reliable operation at the increased production rate. Emphasis was placed on maintaining compliance with FERC and Pipeline and Hazardous Materials Safety Administration (PHMSA) requirements. The evaluation resulted in the identification and implementation of modifications, including:

- Replacement of the 3 PTF Booster and 3 Residue Gas Compressors bundles
- Thermowell upgrades to withstand increased operating conditions

- PSV modifications to accommodate higher relieving rates
- Control valve trim modifications within both the PTF and LQF systems

In addition to the engineered modifications, several operational improvement initiatives contributed significantly to the overall increase in LNG production capacity. Plant reliability was improved through implementation of a structured root-cause failure analysis (RCFA) program that systematically evaluated unplanned downtime events and identified corrective actions to prevent recurrence. Plant availability was further enhanced by optimizing the frequency and duration of planned maintenance outages, particularly for refrigeration compressors and other major rotating equipment that directly influence liquefaction capacity.

Additional improvements in LNG inventory management, storage utilization, marine loading coordination, and export logistics enabled the facility to accommodate higher LNG production volumes while remaining within the constraints of the existing storage and export infrastructure. Collectively, these initiatives complemented the engineering debottlenecking modifications and demonstrated that sustained capacity increases are achieved through the combined application of reliability engineering, maintenance optimization, operational excellence, and targeted facility improvements.

15. Broader LNG Industry Implications

The FLNG debottlenecking effort demonstrates that meaningful increases in LNG production can be achieved through disciplined engineering analysis and targeted brownfield modifications without the substantial capital investment and extended execution schedules associated with new liquefaction trains. The results highlight the growing importance of digital process modeling, integrated multidisciplinary engineering collaboration, operational data reconciliation, advanced process controls, and reliability-centered optimization in identifying latent production capacity while maintaining compliance with safety and operational requirements.

Beyond the technical benefits, debottlenecking has become increasingly attractive in response to the evolving global LNG market dynamics. Since 2022, disruptions to Russian pipeline gas exports following the Russia–Ukraine conflict have fundamentally reshaped European natural gas markets, driving unprecedented demand for LNG imports and increasing utilization of existing liquefaction facilities worldwide. Europe transitioned from receiving approximately 40% of its natural gas from Russian pipelines prior to the conflict to relying heavily on LNG imports from

the United States, Qatar, Australia, and other exporters (IEA, 2023; GIIGNL, 2024). This shift created a premium for incremental LNG production that could be delivered within months rather than the five to seven years typically required to develop and construct a new liquefaction train.

More recently, geopolitical instability in the Middle East has further reinforced the value of maximizing production from existing assets. Escalating regional tensions involving Iran and Israel have heightened concerns regarding LNG shipments through the Strait of Hormuz, a strategic chokepoint through which approximately one-fifth of global LNG trade passes. While major supply disruptions have largely been avoided, the increased geopolitical risk has highlighted the importance of supply flexibility, production resilience, and geographic diversification among global LNG suppliers.

Economic considerations further strengthen the case for debottlenecking. Debottlenecking frequently provides one of the lowest-cost and fastest methods of increasing LNG production while leveraging existing permitting, utilities, storage, and export infrastructure. As demonstrated by the FLNG project, targeted modifications can unlock meaningful production gains while avoiding the cost, complexity, and schedule risks associated with large-scale expansion projects.

As global LNG demand continues to grow and market uncertainties remain elevated, operators are increasingly viewing debottlenecking not merely as an operational improvement initiative but as a strategic investment. The combination of lower capital intensity, shorter implementation schedules, reduced permitting requirements, and improved asset utilization enables operators to respond more rapidly to market opportunities while enhancing overall supply security.

Consequently, advanced process simulation, digital twins, data analytics, and reliability-based optimization are expected to become integral components of LNG asset management strategies, allowing existing facilities to safely maximize production throughout their operating life.

16. Conclusions

FLNG's multi-train debottlenecking effort demonstrated that sustainable LNG throughput increases require holistic evaluation across process systems, rotating equipment, instrumentation, electrical infrastructure, mechanical integrity, and process safety systems. Many critical bottlenecks were associated not with major equipment, but with supporting systems, controls, and instrumentation. The FLNG project reinforced the importance of integrated

engineering, vendor collaboration, field-data reconciliation, and balanced reliability-focused decision-making to achieve increased production while maintain safe and reliable operation.

References

1. *Kiewit Energy Group, Debottleneck Study Report*
2. *API Standard 617 – Axial and Centrifugal Compressors*
3. *API RP 521 – Pressure-relieving and Depressuring Systems*
4. *GPSA Engineering Data Book*
5. *ASME PTC 19.3 TW – Thermowell Standards*
6. *LNG Industry Best Practices for Brownfield Optimization*