Improving Plant Performance and Stability with Turbine Inlet Air Chilling

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Gas turbines are a universal fixture within the oil and gas industry, used widely for both power generation and mechanical drive applications. Within the LNG sector, mechanical drive gas turbines have been the preferred driver for refrigeration compression in liquefaction. In LNG facilities, production is dependent on the capacity of the refrigeration compression which is determined by the output of the gas turbine.

Ambient temperature has a significant impact on the performance of gas turbines. The power output of the gas turbine is dependent on the mass of air that is compressed, combusted and expanded through the turbine. A gas turbine is a fixed volumetric flow machine, and therefore the turbine's inlet air density proportionally impacts power output. As the air temperature rises, yielding a lower air density, mass flow decreases and thus power output is reduced. LNG plants located in climates where ambient temperature exceeds the turbine's ISO-rated inlet air design point can experience degraded performance and unpredictable power output. In many cases, it can even turn the gas turbine into a production bottleneck.

TURBINE OUTPUT RELATIVE TO AMBIENT TEMPERATURE

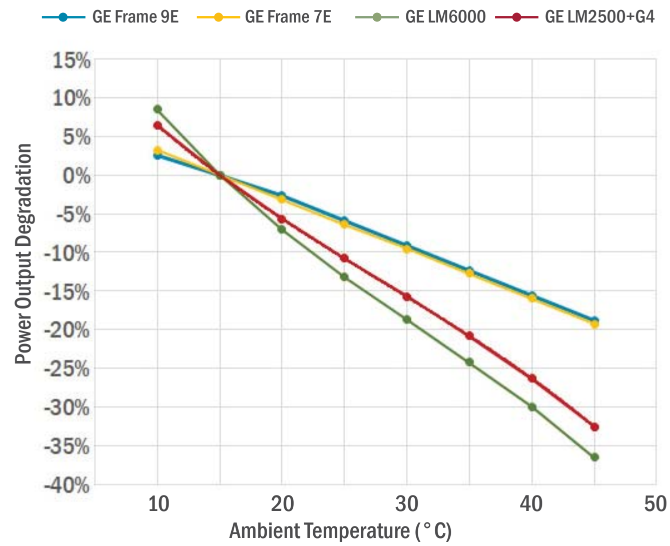


Figure 1: This graph depicts normalized power output versus ambient temperature for typical gas turbines used in LNG plants.

TURBINE TYPES AND OUTPUT DEGRADATION Gas turbines used for mechanical drive fall into two categories: heavy-duty and aeroderivative. Early LNG production facilities used small heavy-duty Frame 5 engines. As plant capacities grew, larger heavy-duty engines such as the 6B, 7E and 9E were employed. In the mid-2000s, aeroderivative gas turbines, derived from aircraft engine technology, were introduced for mechanical drive configurations and are characterized by higher pressures ratios. However, this higher pressure ratio results in greater degradation of output when ambient temperature is higher.

Figure 1 illustrates the relationship of output versus ambient temperature for several gas turbine models in the LNG industry. As ambient air temperature rises, the percentage of output that is lost is more pronounced in the higher pressure ratio aeroderivative turbines versus the heavy-duty units. Output degradation for most gas turbines ranges from 0.5%–1% per degree Celsius temperature rise with the aeroderivatives falling in the higher end of this range.

REMOVING AMBIENT CONDITIONS AS A FACTOR OF OUTPUT The ambient design point selection for an LNG plant can be the most important design decision short of selecting the process technology and driver type (gas turbine or electric motor).

As an alternative to designing around the inherent variability of output of the gas turbine, some operators have elected to employ a technology that has been widely used within the power generation industry for many years. By chilling the inlet air to the gas turbine, output variability can be eliminated, allowing the turbine to maintain consistent, predictable capacity. The most reliable method of chilling the inlet air is a mechanical refrigeration process that passes chilled water through a coil placed in the inlet air stream of the gas turbine. **Turbine inlet air chilling (TIAC)** is a low-risk, proven technology that does not require any modifications to the turbine yet can increase output by over 30% relative to ISO conditions.

TIAC APPLICATION FOR LNG FACILITIES For LNG plants, TIAC systems using mechanical chilling can be a cost-effective method of optimizing liquefaction and stabilizing production. When chosen early in the project design phase, the use of TIAC can also aid in the selection of compressors for liquefaction. Often times, compressors are required to operate across a broad range of power inputs because as ambient temperature changes, so does gas turbine output. By using TIAC to maintain a constant inlet air temperature, gas turbine performance becomes more predictable, thus allowing the refrigeration compressors to operate efficiently in a fixed power band.

Figure 2 shows NASA's global temperature forecast in relation to existing LNG production facility locations. This notional depiction illustrates large portions of the globe that experience warm and hot conditions (represented in orange and red) that exceed ISO conditions. As can be seen, the majority of the current LNG facilities are located within these regions and are subject to significant turbine output degradation.

Unlike power generation facilities that may respond only to seasonal peaking demand, augmentation for liquefaction facilities typically runs 24 hours a day, seven days a week throughout the year. **Figure 3** and **Figure 4** demonstrate the annual recoverable output for two common LNG gas turbines in U.S. and Persian Gulf coast conditions.

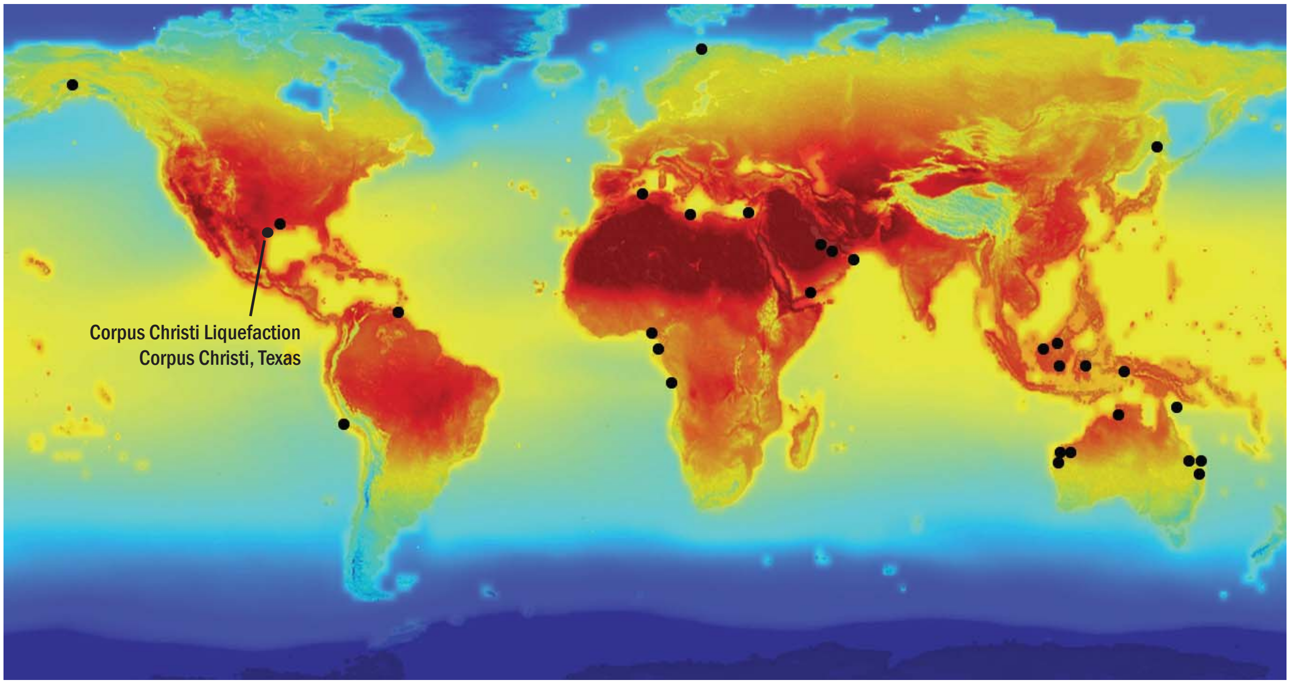


Figure 2: The majority of the world's LNG production facilities are located in warm and hot climates, as depicted here in a NASA map of global temperature forecast through 2100. Because turbine output is dependent upon ambient temperature, most LNG facilities could benefit from turbine inlet air chilling. Image source: www.nasa.gov.

Currently, there are three LNG facilities in the world that use TIAC. These systems are based on a propane refrigerant and screw compressor design. The remainder of this paper will introduce an alternative TIAC system that offers a number of advantages in regards to design, operation, installation and safety. This system is currently in the process of commissioning at Cheniere Energy's liquefaction facility near Corpus Christi, Texas.

USE OF TIAC AT CORPUS CHRISTI LIQUEFACTION FACILITY Owned and operated by Corpus Christi Liquefaction, a subsidiary of Cheniere Energy, the facility utilizes Conoco Philips Optimized Cascade® process technology. The first three trains are designed for an expected aggregate nominal production capacity of 13.5 mtpa of LNG. Each train employs six GE LM2500+G4 DLE aeroderivative gas turbines for a total of 18 turbines.

In June 2015, Stellar Energy was awarded a contract by Bechtel Oil, Gas, and Chemicals, Inc. to design and supply a TIAC system for the Corpus Christi facility. Stellar Energy assessed the design parameters of ambient design condition, turbine inlet temperature and site footprint, and designed a custom modular, air-cooled TIAC system that uses centrifugal compressors and a non-flammable hydrofluoro-olefin (HFO) refrigerant to provide a constant 7.2°C (45°F) inlet temperature to the turbines. This TIAC system is capable of producing 36,900 total tons of refrigeration. **Figure 5** illustrates the projected benefit of augmentation at Corpus Christi.

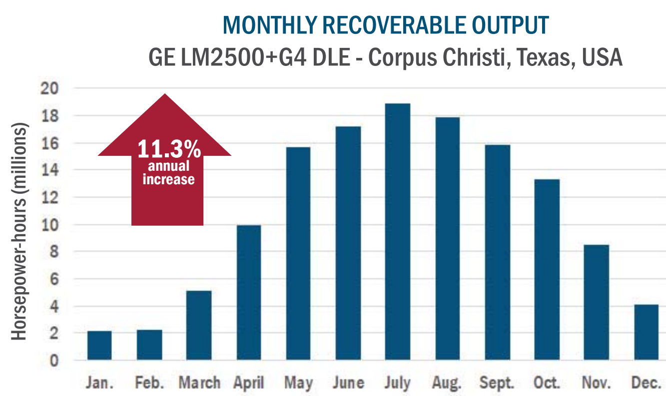


Figure 3: With an inlet temperature of 7.2°C (45°F), the Corpus Christi Liquefaction facility will see an 11.3% annual increase in horsepower-hours. Calculations are based on local Corpus Christi weather data.

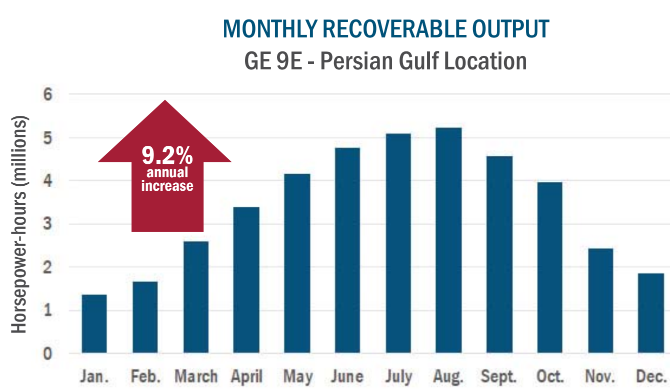


Figure 4: Similarly here, an inlet temperature of 15°C (59°F) will result in a recovery of 9.2% annual horsepower-hours. Calculations are based on Ras Laffan weather data.

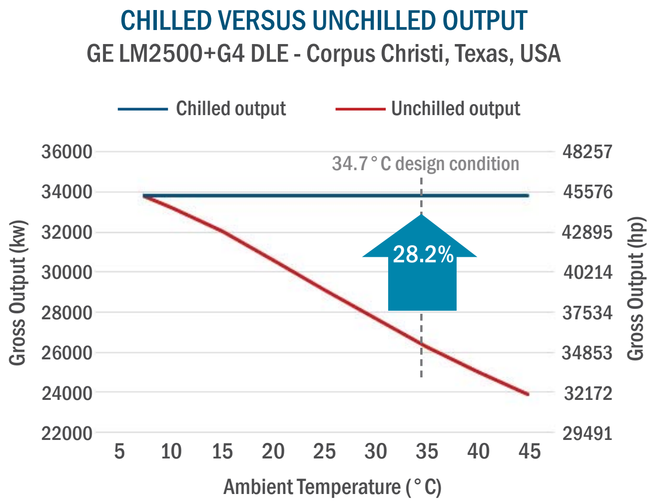


Figure 5: This graph shows the expected increase in output of chilled versus unchilled performance for an LM2500+G4 DLE turbine at a 34.7°C (94.5°F) ambient condition and a chilled inlet temperature of 7.2°C (45°F).

THE DESIGN PROCESS For a mechanical drive, air-cooled LNG plant such as the Corpus Christi facility, the critical weather parameter is the ambient dry bulb temperature because it dictates the heat rejection sizing and driver output. Capacity of a TIAC system that is cooling the turbine inlet air below the dew point is a function of the wet bulb temperature, or the amount of moisture in the air which will be condensed. The result is a cooling capacity requirement driven by wet bulb temperature and a heat rejection performance driven by dry bulb temperature. A weather data analysis of both ambient dry bulb temperature and wet bulb temperature was required to ensure the desired plant performance. In this instance, Stellar Energy was provided an ambient dry bulb design condition of 34.7°C (94.5°F) and wet bulb condition of 26.7°C (80.1°F), with a 36.4°C (97.5°F) dry bulb condition for the heat rejection. A five-year local weather model was developed to validate the selected design point.

The detailed weather analysis also revealed the need for the addition of propylene glycol to the water loops to ensure freeze protection of the heat transfer surfaces as site minimum ambient temperature can drop below 0°C (32°F).

REFRIGERANT SELECTION Hydrocarbons and hydrocarbon mixtures have been the refrigerants of choice for LNG plants for decades. TIAC system refrigerants have evolved since the technology first gained acceptance in the power industry over 20 years ago. Many of the earliest systems relied on ammonia, a natural refrigerant with sufficient efficiency. Early ammonia screw compressor refrigeration systems were viewed as an industrial solution preferred by the power industry. In the 1990s, TIAC technology shifted to centrifugal chillers for most applications. Chlorofluorocarbon and hydrofluorocarbon refrigerants dominated the market except with air-cooled solutions, where ammonia screw compressors remained preferred.

The first projects using TIAC on LNG plants were propane refrigerant-based, air-cooled screw compressor systems in Australia. Prior to these projects, propane had not been used as a refrigerant for TIAC.

With propane as the only refrigerant implemented on LNG TIAC to date, the initial RFQ issued by Bechtel called for a similar propane-based solution for the Corpus Christi plant. Stellar Energy, realizing the opportunity to implement a technological improvement already accepted by the power industry, offered an innovative air-cooled centrifugal chiller-based solution incorporating one of the next generation hydrofluoro-olefin (HFO) refrigerants. This newly developed, inert refrigerant offered the following benefits:

- No flame propagation (see **Figure 6**)
- Low pressure operation
- Near-zero ozone depletion potential (ODP) and global warming potential (GWP) ratings
- Low toxicity
- Comparable efficiency to propane

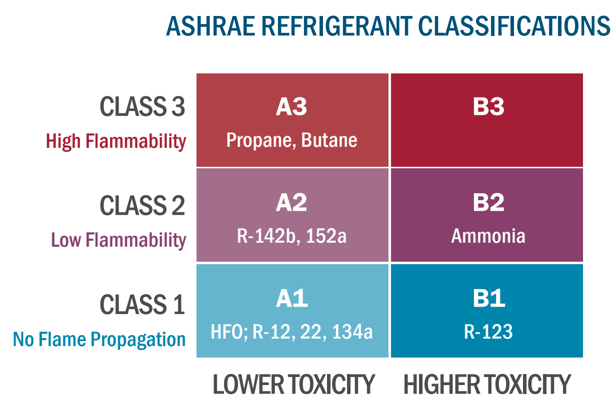


Figure 6: Refrigerant safety classifications are defined by the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE).

EQUIPMENT SELECTION AND DESIGN Centrifugal refrigerant compressors have long been the preferred cooling method for LNG facilities. This has also been the case with TIAC facilities after the industry shifted away from ammonia refrigeration. Stellar Energy's solution for the Corpus Christi Liquefaction project was unique in that it uses centrifugal technology in an air-cooled application. This solution was facilitated by several design decisions:

- Close temperature approach on the condenser heat rejection (radiator field)
- Series evaporators to split the compressor lift
- Low-pressure HFO refrigerant

Using packaged centrifugal chillers in lieu of screw compressors has many advantages. First, in a conventional propane refrigeration cycle, gaseous propane is sent to an air-cooled condenser where it liquefies and drops back into a receiver (see **Figure 7**). In the Corpus Christi design, a secondary coolant (low-concentration glycol solution) is sent through condensers to a radiator field (see **Figure 8**). This eliminates the need to directly condense the primary refrigerant, thus confining it to a much smaller area and reducing refrigerant system charge. Total refrigerant charge for this TIAC system is around 30,000 kg; an air-cooled propane screw compressor solution would demand four to five times more refrigerant.

Second, the HFO refrigerant used in the Corpus Christi design has an ASHRAE classification of A1 (see **Figure 6**), which signifies that the refrigerant has the lowest rating for flammability and toxicity. The decision to use a non-flammable refrigerant in a plant located outside the battery limits dramatically reduced cost and also significantly reduced hazards associated with the equipment running in a classified electrical location.

Third, centrifugal chillers greatly reduce maintenance and operational issues. Although screw compressors are generally capable of producing higher compression ratios than centrifugal compressors, they often have drawbacks with regards to reliability. This is largely due to the fact that they use high-speed, twin-rotor, positive displacement compressors, which place stress on the rotors and bearings and create the need for high lubricating oil circulation rates. Furthermore, this oil can carry over into the refrigerant stream, causing the need for protective measures to prevent the fouling of heat transfer surfaces. In contrast, centrifugal compressors are variable volume machines that have fewer moving parts and are simpler to operate than screw compressors. In addition, the reduced flow and function of the refrigerant oil in a centrifugal compressor eliminates the risk of oil migration.

Finally, Stellar Energy's centrifugal chiller system design provides valuable system redundancy for the plant operator. The three-train TIAC system at the Corpus Christi Liquefaction facility features three parallel stand-alone chiller plants. The three chiller plants share a common

Figure 7: FIELD-ERECTED AIR-COOLED PROPANE TIAC SYSTEM WITH SCREW COMPRESSOR

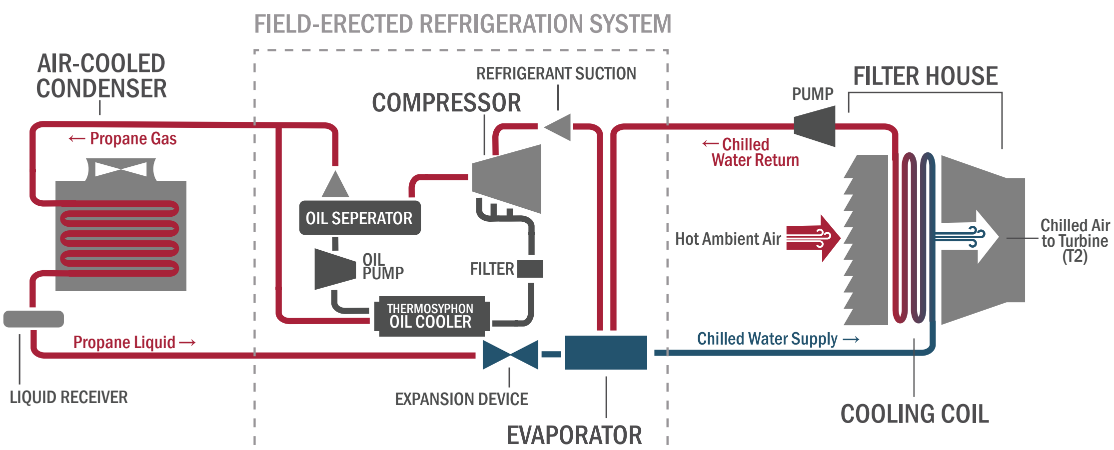
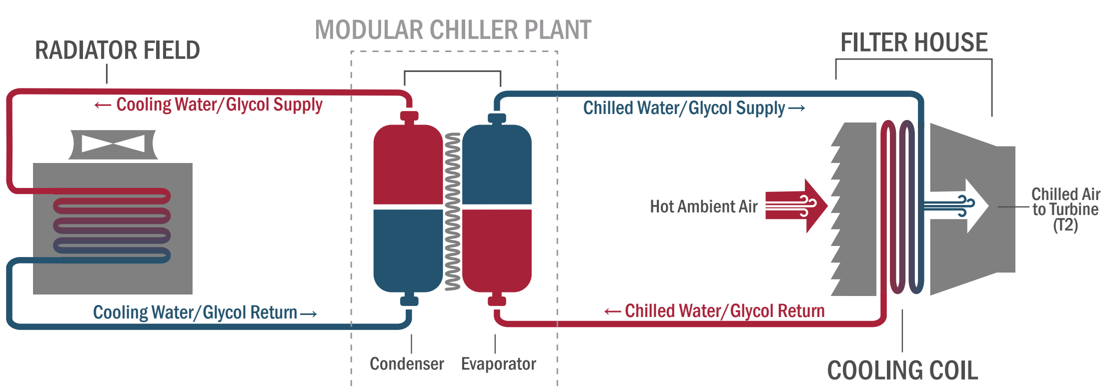
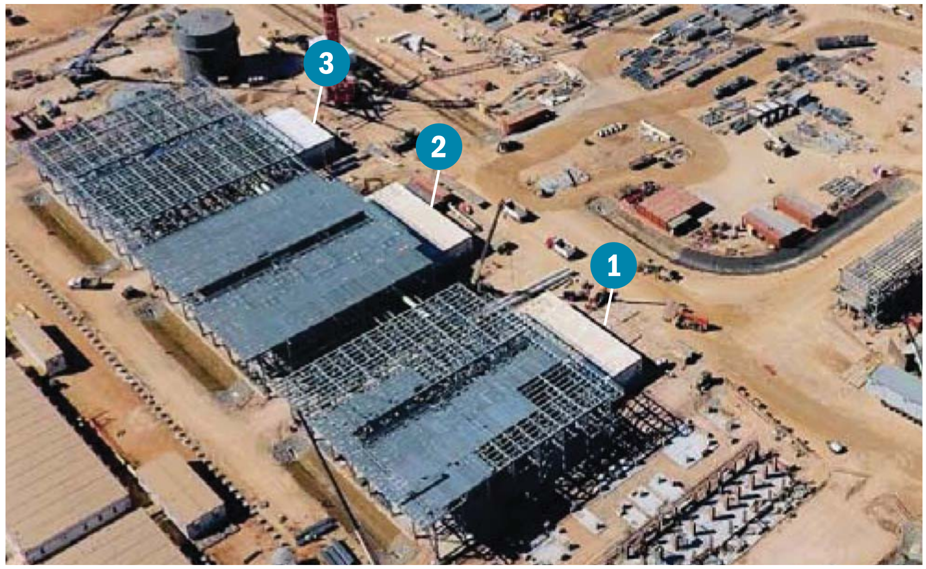


Figure 8: MODULAR AIR-COOLED TIAC SYSTEM WITH CENTRIFUGAL CHILLERS



Figures 7 and 8: The diagrams above illustrate the major components of two types of TIAC systems. Stellar Energy's innovative solution features a number of benefits over a propane-based system including modular construction, safety and maintenance and operational considerations.



Pictured, top left: The three chiller plants consist of 18 factory-built modules that were custom-designed, pre-engineered and fabricated in a controlled, ISO-certified environment. Modular fabrication enabled a 50% reduction in construction time. **Bottom left:** Packaged in an enclosed, climate-controlled skid, the modules were pre-piped, wired, tested and shipped to site. **Right:** All three modular chiller plants (labeled in the photo above) were reassembled on site (image source: www.cheniere.com).

header to supply the chilled secondary coolant to the gas turbines. Thus, taking annual weather into consideration, the redundancy feature of this design means that two of the three chiller plants can produce enough continuous tonnage to chill all 18 gas turbines to the design inlet air temperature in excess of 80% of operational hours.

MODULAR CONSTRUCTION Early in the project design phase, Stellar Energy proposed modular, off-site fabrication of the TIAC system instead of a field-erected system. This afforded a number of benefits including reliable access to skilled and experienced manpower, improved fabrication quality, a controlled manufacturing environment and reduced site safety risk. Each of the three separate plants were manufactured in Stellar Energy's ISO-certified fabrication facility as a single multi-module plant. Each unit was fully assembled, wired and tested before being separated into six modules and shipped to site. By manufacturing each plant as a complete unit, the client was assured of seamless reassembly at site. Implementing modular fabrication ultimately allowed Stellar Energy to reduce construction time of the TIAC plants by 50%.

ADDITIONAL BENEFITS In addition to consistent, stable driver output, TIAC can provide additional benefits to LNG plant design engineers and owners. Some of those additional benefits include:

- Recovery of permanent drive degradation or degradation between major maintenance intervals
- Increased driver options (aeroderivative versus heavy-duty, competitive driver pricing, two-shaft engines)
- Lower emissions per unit energy input

CURTIS LOVELACE

Vice President Business Development

Curtis Lovelace has more than 30 years of experience in operations management, project engineering, construction management and product development in the industrial/cryogenic gas, industrial cooling and turbine inlet air chilling industries. With particular focus and extensive experience in turbine inlet air chilling for the power, utilities, oil and gas and LNG markets, Curtis has served as project developer for over 100 completed projects during his 17-year tenure at Stellar Energy, including the largest TIAC system in the United States as well as the first non-propane refrigerated TIAC system in the LNG industry. Prior to Stellar Energy, Curtis worked for Air Products and Chemicals Inc. Curtis holds a Bachelor of Science in Chemical Engineering from the University of Florida and a Master's of Business Administration from the University of North Florida.