



## **Stress Engineering Challenges in Mega Liquefied Natural Gas Projects: A Comprehensive Framework for Cryogenic System Design and Risk Mitigation**

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### **Article Info:**

**DOI:** 10.22399/ijcesen.4966

**Received :** 03 January 2026

**Revised :** 20 February 2026

**Accepted :** 22 February 2026

### **Keywords**

Cryogenic Stress Engineering,  
Mega LNG Facilities,  
Thermal Contraction Analysis,  
Piping Flexibility Design,  
Risk Assessment Framework

### **Abstract:**

The mega onshore liquefied natural gas plants are larger than previous liquefied natural gas plants, and they involve different stresses. Therefore, a article is needed in order to provide risk analysis for satisfactory and safe operation. These high level of loadings and interactions between the imposed thermal contraction due to the cryogenic conditions lead to very high stress concentrations. The nonlinear material behavior in cryogenic conditions is very important for the distribution of these stresses through large piping systems. The design of cryogenic piping systems, which must deal with differential contraction, accepts piping flexibility. For the protection of equipment, critical nozzle loads, i.e. loads at pipe nozzles arising from equipment, must be defined. A support philosophy must therefore accommodate both the restraint and thermal effects. 3-dimensional stress analysis can be used to resolve the various loadings and complex geometries which require consideration in a mega scale plant. Risk assessment methodologies, design factor selection and reliability centered maintenance programs contribute to lowering the risk of anchor point failure leading to catastrophic stress failure, nozzle overload, and supporting structural failure. The interface management between modularized construction and stick-built construction methodologies, and the understanding of how construction sequences impact operational load profiles in mega LNG facilities contribute to the safety margins and operational reliability.

## **1. Introduction and Literature Review**

Modern (mega) liquefied natural gas plants comprise the world's largest industrial installations used for the conversion of natural gas to LNG, and consist of hugely complex cryogenic plants located thousands of kilometers (miles) away from the LNG final destination, operating at many degrees below the gas boiling point, at pressures which are communicated to the converted gas over a distance of hundreds of kilometers (miles). Thermal stresses generated during cooldown operations can be more severe than those produced during normal industrial utilization, posing an engineering challenge. Conventional practice for cryogenic pressure design of small and medium LNG plants (stress analysis using conventional thermal analysis techniques, with some flexibility analysis for standard pressure vessels) is not sufficient for mega-scale plants. The combination of high thermal movement with highly constrained systems in large cryogenic installations demands new design

techniques. Studies have been conducted on the thermal loading of corrugated pipe systems at cryogenic temperatures; and it was found that thermal loading at the geometrical discontinuity creates a stress concentrator at the discontinuity [1]. Foundation movements and modular construction with complex loading scenarios are not currently within the state of practice in the industry. The engineering and technical literature on mega-scale cryogenic pipeline design notes that conventional assumptions about constant temperature and constant supports in piping stress analysis do not apply. Mega-scale cryogenic pipeline design extends further to include thermal contractions and thermal-mechanical behavior from supports and hangers in its design considerations. None of the cryogenic pipe design principles exist for smaller applications, and no design procedures exist for mega-scale applications. These would specifically involve construction sequence, modular interface and the integration of piping stress analysis with the structural system. The objective of this research was

to develop a general methodology for the stress engineering of mega LNG plants integrating thermodynamic and engineering construction focus and proposing design methods based on theoretical models and empirical knowledge. Since there are important gaps in the knowledge of current practices, the paper advances the state of the art with systematic methods for layout optimization, natural thermal accommodation, and risk assessment protocols. Protocols are used for large-scale cryogenic operations. The regulatory requirements for LNG facility design provide minimum design safety levels which may not be appropriate for mega scale development. The ASME B31.3 Process Piping Code gives a design basis for pressure piping systems [2]. The thermal stress used in the code, calculated based on temperatures found in normal use, would need to be considerably altered for a cryogenic process. Calculated thermal stresses could exceed operating stress levels. Although API codes provided specification guidance for the components, they provided no guidance for thermal process system stress mitigation. These factors, together with current regulatory requirements, must be incorporated in the design of mega LNG plants with an increased number of process units and increased complexity. Table 1 Comparison of existing regulatory frameworks with mega LNG facility requirements Source: ASME B31.3 Process Piping Code analysis and Los Alamos National Laboratory engineering standards

## 2. Fundamental Stress Drivers and Material Behavior in Cryogenic LNG Systems

Cryogenic behavior is thermodynamically-controlled and LNG facility piping is subject to stress, so that the temperature dependence of the properties of the materials is strong. Near the boiling point of the natural gas, the heat motion of the molecules is limited by the low temperature, which causes the coefficients of expansion to vary considerably. These changes lead to stress states not usually encountered in industrial applications, and require modified methods for accurate modeling. Quantitative evaluations of the thermal contraction show that large piping can experience meaningful dimensional changes. The amount of contraction depends on the cryogenic temperature and the metallic material of construction. Carbon steels and stainless steels behave differently when undergoing cool down cycles in a plant, and further work on cryogenic mechanical properties shows these to be very different [3]. In mega LNG plants, the thermal expansion of long runs of piping (which

can undergo large dimensional changes in a thermal cycle) is an important design consideration. Multi-axial stress states are caused by pressure-temperature interaction which occurs in cryogenic piping where, during normal operation of the piping system, both pressure loading and thermal contraction effect simultaneously generate stresses and internal forces at so-called pipe branch connection points, where the pipe geometry changes and there are associated high stress concentrations. Another critical area is where nozzles are connected to equipment and where pressure and thermal loads occur. Different methods of stress calculation are used for different metals in cryogenic applications because of the different properties each metal has at cryogenic temperature. For example, carbon steel loses ductility at cryogenic temperatures. A number of stainless steel alloys have been developed with properties suitable for cryogenic use, since stainless steel behaves differently to carbon steel at cryogenic temperatures. The NIST Cryogenic Material Properties Database has wide-ranging data for the alloys commonly used in LNG service [4]. When operating, the thermal expansion, strength and fatigue resistance of the material should be considered at the operating temperature. Fatigue considerations are also applicable to mega LNG plants, where the number of fatigue load cycles can be huge, with each start-up and shut down of the plant. Eventually in these cases, the fatigue damage would amass over time, and the component would ultimately fail. Low-cycle fatigue is the dominant mechanism when plastic deformation is caused by thermal cycling within an LNG plant at high stress. High-cycle fatigue is the dominant mechanism at low stress levels and a high number of cycles. When modeling the fatigue behavior of materials, it is important to understand the influence of the stress range and the mean stress. Secondary effects can also have an effect, which are on a much smaller scale than the thermal ones, such as differential settlement of large foundation systems which can couple with the thermal stresses to create geometric incompatibilities at system scale, as affected by stresses at the very large distances typical of mega scale LNG plants. Other issues arise when interfacing modular prefabricated systems to site built systems, e.g., the wind load on a large diameter pipe rack results in dynamic loads in addition to the static thermal loads imposed on it in a seismically active area. High temperature piping systems are mainly affected by thermal expansion and related thermal stress when the operating temperature is increased. Cryogenic piping systems are also subject to thermal stress, but when the system is at cryogenic operating temperature the

cryogenic materials need to be evaluated for thermal contraction. The effect is normally larger for cryogenic systems. As a rule, while high temperature systems tend to be very tolerant of any provision for expansion using flexible connectors or expansion joints, expansion and shrinks, as well as any possible embrittlement, need special considerations for cryogenic systems. Different applications need different selection criteria according to their failure modes and performance requirements. Figure 1. Stress distribution patterns showing high-stress concentrations at equipment nozzles, anchor points, and branch connections in cryogenic LNG piping systems

### 3. Design Methodology and Layout Optimization Strategies

The general principles of systematic piping layout design form the basis of thermal stress control for mega LNG plants in the Natural flexibility methods. Essentially, thermal stress control is to design the piping layout in such a way that the stress load on the equipment is not excessive. The optimizations are done during the conceptual design stage with the balance of process and thermal requirements, and routing variation with elevation changes. These configurations distribute thermal stresses over longer lengths of pipe; avoiding more localized stress concentrations and reducing discrete areas of restraint on the system. Pipe stress analysis recommendations advocate for addressing thermal stresses during layout design [5]. Equipment Protection Requirements are the design limits for nozzle loads or stresses beyond which damage to rotating equipment is anticipated. In cryogenic service centrifugal pumps, the allowable nozzle loads or stresses through the piping are extremely low. Although excessive nozzle loadings can adversely affect internals, equipment manufacturers provide load bulletins for their equipment with various service conditions, and that guidance must be followed. These considerations are more relevant in cryogenic services because there is a higher risk of brittleness leading to brittle fracture, and because of the effects of thermal expansion and pressure loading. This equipment will therefore be preserved, and the process will continue. One essential demand of the support philosophy is to prevent thermal movement from exceeding allowable limits and to alternately restrain at the same time to minimize stress concentrations. Excessive restraint leads to thermal stresses, as can be seen by the shunting of expansion forces onto rigid anchor points. Another is under-restraint, where movement and vibration are allowed. The optimal support philosophy is to

restrict thermal movements to the wanted directions only, and only to transfer those forces. The construction of the support structures associated with mega LNG terminals can provide unique design challenges. One example of this is that, when the terminal is operational, multi-directional displacement (3D thermal movement) will occur in the pipes that are routed through these support structures. All piping thermal movement and structural response interactions must also be understood on piping racks or modularized pipe, equipment and structure platforms. Large racks and/or independent pipe and equipment support structures will have thermal movements, deflections and loads imposed by the piping thermal movement-accommodation requirements. In modular construction, the behavior of prefabricated modules with regard to thermal expansion is considered in the integration design, which allows a high degree of freedom at module interfaces. Local loadings are generated by externally induced loads at equipment connections, where the cylindrical shell effects can affect the structural response [6]. With the increasing complexity of the geometry and the loading conditions for mega LNG applications, 3D stress analysis modeling is required. The construction sequence and thermal loading histories can be considered for the complete process unit (and complex equipment flexibility) in the 3D finite element model to ease design optimization for various configuration alternatives. Furthermore, the search for systematic solutions seeks to minimize the stresses with respect to the process constraints, whereby the response behavior here is determined dynamically. The solution is valid as the limits and the characteristics of the material are known. Flexibility analysis can be applied to L-shaped pipework systems, expansion loops and spring hanger systems. In L-shaped pipework, beam bending mechanisms are provided to absorb thermal forces by elastic deformation. Expansion loops are bends in a pipeline that provide sufficient space for expansion. Spring hanger systems can accommodate static vertical loads and thermal expansion. Which system of flexibility should be chosen depends on the available space and the range of thermal movements. A combination flexibility system is usually preferable. Stress level requirements also influence the measure of flexibility used for the system. The interface management is different for stick built and module construction. Also, the behavioral thermal transients of stick built piping are different than that of the shop assembled piping systems of the same service. Construction tolerances, welding code, and materials may be different depending on

construction method. The construction zones' interfaces have to be leak-tight but may be allowed to move relative to each other. With flexible interfaces, expansion joints or specially shaped spool pieces may be used to allow axial or lateral movements between the construction zones. The design of the interface is treated in the practice guide for large diameter steel pipelines [7]. The zoning of the structural and technical plant, the construction sequence and the installation and fitting of piping systems must be taken into account when the detailed design is made and when preparing the construction work planning, because this influences the initial stress state and operation. Where rigid connections are curbed, i.e. installed too early, locked-in or installation stresses occur. These raise the expected stress state. Hydrotest stress states can also influence the final stress state of the system. The benefit of construction sequencing is to align piping installation activities to construction and commissioning activities to achieve the assumptions of the piping design. The timing of connections and installation of restraints is critical to achieving design performance.

#### **4. Risk Assessment Framework and Failure Mode Analysis**

It is important to identify the potential mechanisms of stress-related failure and consequences for mega-scale LNG plants, where the combined effects of cryogenic liquefaction temperatures, elevated operating pressures and large LNG inventories give very different behavior to industrial plants. For example, an LNG plant may be at risk from brittle fracture of piping due to thermal stress concentrations, over-stressing of equipment nozzles, and structural failures of multi-unit facilities. The large size can also lead to the situation that a large amount of hazardous material may be released in the case of an accident, with the increase in the crack speed at cryogenic temperatures exacerbating the loss of toughness. Quantitative reliability analyzes of stress-based failure allow uncertainty in loading and material properties to be taken into account by treating variables in a probabilistic sense. Monte Carlo sampling of these distributions can then be used to quantify the probability of failure. The strength of materials, the coefficients of thermal expansion of materials, and the loads imposed are factored into the risk analysis. Norms for risk assessment of hazardous industrial installations indicate how to assess probabilities of process plant failures [8]. Reliability analyzes include time dependent degradation mechanisms such as fatigue damage accumulation. The failure probabilities can

be weighted to account for the importance of the system and the consequences of a failure. Model uncertainty in the analysis procedures and operating conditions can also be accommodated by the framework. Unidentified failure modes can include those caused by stress which might not be adequately covered by facility design and operations, including anchor point failure due to thermal stress exceeding the structural integrity of the anchor points, concrete pullout or weld failure at the points of restraining. The most common failure mode is overloaded at the equipment nozzle due to piping load but can also occur if the supports are unable to handle the complete thermal movements and displacements on the system. Both of these failure modes can be detected using monitoring and inspection methods. The catalog allows for risk mitigation by prioritizing by both likelihood and consequence. In the case of stress related failures of mega LNG installations the effects of such leak events can be minor but also range to very serious events. Depending on the specific conditions, the leak events can lead to very large quantities of LNG which can lead to large vapor clouds near the facility. Additionally, such vapor clouds could result in fire or explosions in much of the facility, and the fire or thermal radiation hazard of such LNG releases may present a risk to personnel in the vicinity of the facility. Production losses can be one of the biggest economic impacts, particularly as mega LNG projects are very capital intensive. Environmental risk assessments of LNG plants find that large spills can have serious consequences [9]. Reliability-centered maintenance and a structural strain monitoring system could provide an advance warning of impending failure. Strain gauges installed at expected stress points could detect increasing strain, the failure of a support or an increase in loading. Vibration monitoring systems should also be able to monitor dynamic loads such as those causing fatigue. Temperature readings at important points can be used to validate thermal analyzes and detect abnormal situations. Integrated monitoring techniques offer multiple ways to assess piping condition, enabling predictive maintenance and the prevention of a deterioration of piping and the associated issues. A common observation in these case studies of stress incidents in LNG facilities is that the incidents are caused by the same particular combination of factors. The major historical incidents of LNG storage tanks also indicate that design controls did not consider thermal stresses. A common contributing factor is poor communication between the piping designers and the structural designers. Gas pipeline incident data indicates that one of the most frequent causes

of a gas pipeline incident in cryogenic service is thermal stress[10]. Carrying out a full stress analysis and construction sequencing and carefully monitoring the operation of a facility may prevent a similar incident occurring elsewhere. The trade-off between ensuring safety and avoiding excessive cost, including the provision of margins against uncertainty, must be carefully managed. The choice of limiting design factors for the allowable stresses can vary widely from project to project depending on the consequences of failure and the reliability of the analysis. Most methods incorporate features that

restrict the effect of a single-point failure. These also rely on frequent monitoring, inspections and maintenance. But when prevention fails, emergency response actions can further reduce the impact of such scenarios. Mitigation options depend on the risk profile and regulatory structure of the facility, and cost-benefit analysis helps prioritize mitigation expenditure. Figure 2 represents risk assessment matrix showing the relationship between failure probability and consequence severity for various stress-related failure modes in mega LNG facilities.

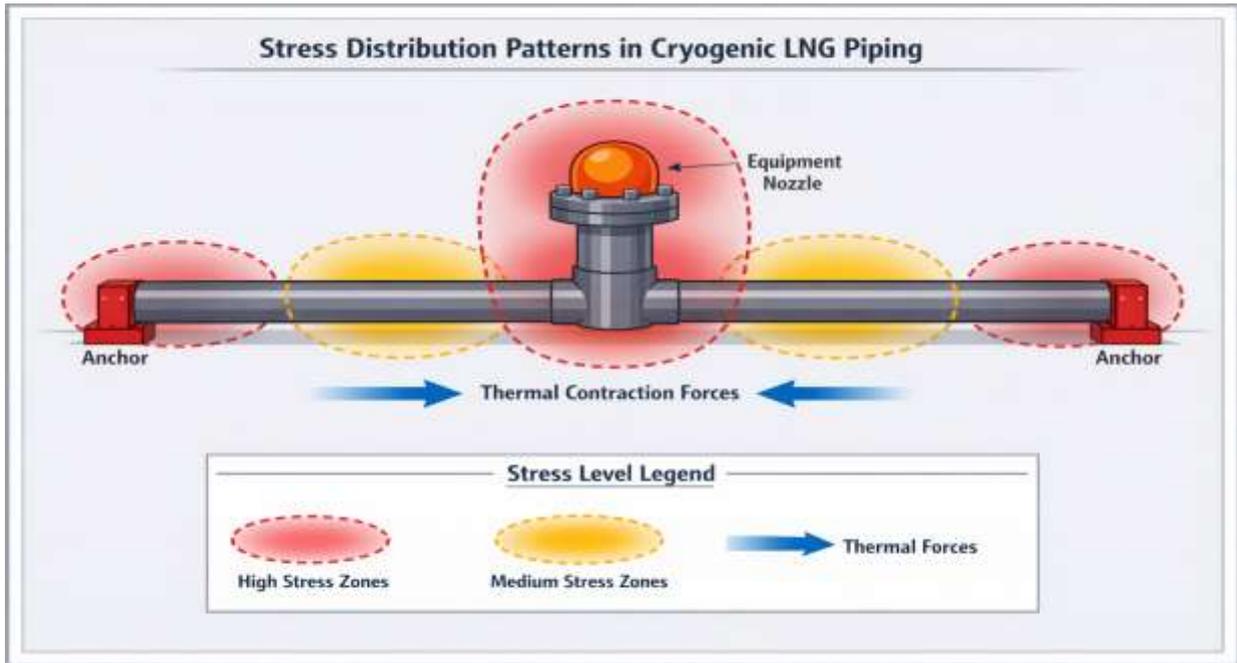


Figure 1: Stress Distribution in Cryogenic Piping Systems. [3, 4]

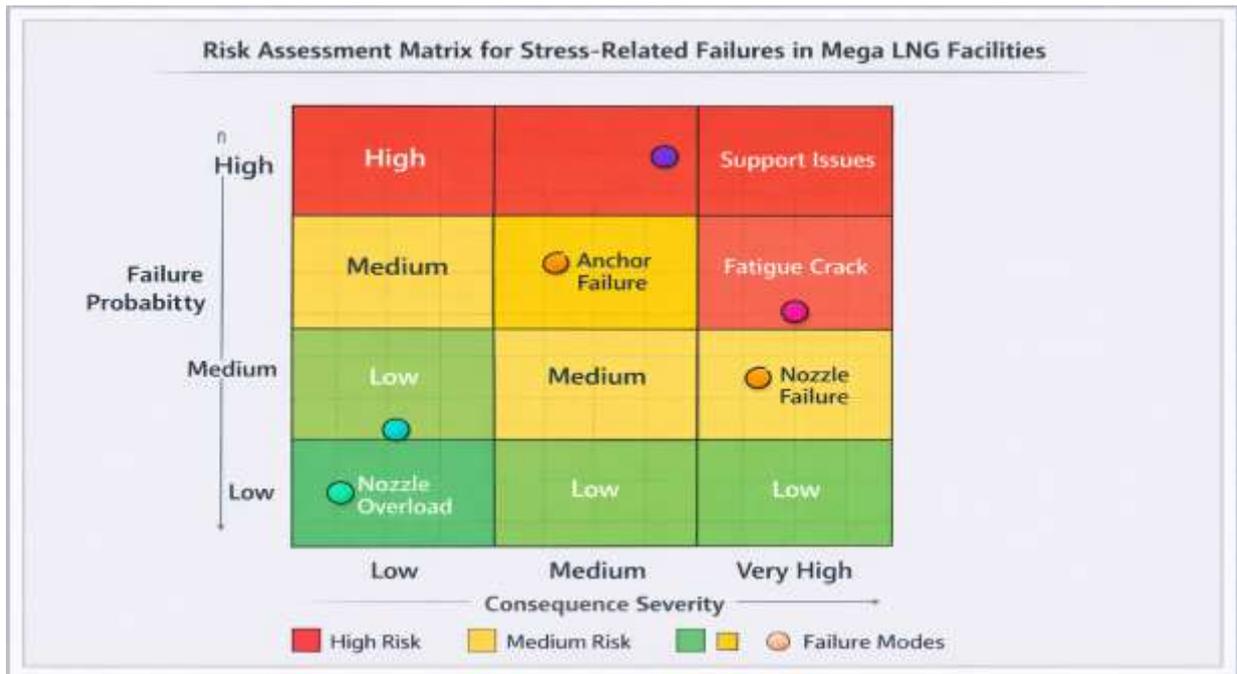


Figure 2: Risk Assessment Matrix for LNG Facility Design. [9, 10].

**Table 1: Regulatory Framework Limitations in Mega LNG Applications. [1, 2]**

Framework Component	Current Scope	Mega LNG Requirements
ASME B31.3 Thermal Analysis	Conventional temperature ranges	Cryogenic adaptation needed
API Standards Coverage	Individual components	System-level integration
Code Compliance Methods	Standard applications	Supplementary criteria required

**Table 2: Material Property Comparison at Cryogenic Temperatures. [3, 4]**

Material Type	Strength Characteristics	Thermal Behavior	Ductility Response
Carbon Steel	Adequate strength retention	Standard contraction	Reduced ductility
Stainless Steel	Enhanced strength properties	Different contraction rate	Better ductility retention
Cryogenic Alloys	Superior strength	Optimized thermal response	Excellent ductility

## 5. Conclusions

The article establishes a comprehensive framework for addressing stress engineering challenges in mega liquefied natural gas facilities through integration of fundamental thermodynamic principles with practical design considerations. Successful stress management in these complex installations requires early consideration of thermal effects during layout development, comprehensive material property evaluation at cryogenic temperatures, and systematic risk assessment protocols that account for the unique failure modes associated with large-scale cryogenic operations. Equipment protection strategies must balance process requirements with thermal accommodation needs while support system design optimizes restraint and freedom to achieve acceptable stress levels throughout facility operation. Advanced modeling techniques enable accurate prediction of stress distributions in complex geometric configurations while construction sequence planning ensures that design assumptions remain valid during project execution. The risk assessment framework identifies critical failure modes and establishes mitigation priorities based on consequence severity and failure probability calculations. Interface management between different construction methods requires specialized connection details that accommodate thermal response variations while maintaining structural integrity and leak-tight performance. Future developments in mega LNG facility design will benefit from continued advancement of stress engineering methodologies, integration of digital monitoring technologies, and enhanced understanding of material behavior under combined thermal and mechanical loading conditions. The framework presented provides practical guidance for engineering teams involved in mega LNG projects while contributing to improved industry standards for cryogenic facility design and operation.

## Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
- **Acknowledgement:** The authors declare that they have nobody or no-company to acknowledge.
- **Author contributions:** The authors declare that they have equal right on this paper.
- **Funding information:** The authors declare that there is no funding to be acknowledged.
- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.
- **Use of AI Tools:** The author(s) declare that no generative AI or AI-assisted technologies were used in the writing process of this manuscript.

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