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# SUCCESSFUL APPLICATION OF NITROGEN TURBOEXPANDERS-COMPRESSORS TO FLOATING AND LAND-BASED LIQUIFIED NATURAL GAS (LNG) FACILITIES

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## ABSTRACT

LNG production in the form of large land-based Mega-trains and floating production, storage and offloading facilities (FPSO's) have been of particular interest in recent years and will likely continue to be of interest as natural gas usage worldwide evolves. The task of designing and building these facilities and the successful integration of equipment into them can be challenging at the least. Considerations in the scope of the equipment, design features and goals as well as the applications specific needs and end user desires must be considered to end up with a successful design.

This paper will explore the differences and similarities in the successful development and application of nitrogen turboexpander-compressors (companders) for both land based and floating LNG (FLNG) applications. The intent is to share general learnings from specific projects and present a roadmap to assist in the successful development and execution of such a product effort. In addition, specific takeaways on the application of machinery to both land-based and shipboard applications will also be presented.

All aspects of the process of applying this equipment will be reviewed, from inception through detailed design and manufacturing of the equipment, shop testing, packaging and concluding with installation, commissioning, startup and on-stream operational experiences.

Focus will first be given to the up-front planning and discussions that are required to properly map out the product requirements and

the path forward for the efforts to come. The need for early involvement of the end customer and persons integrating the equipment into the facility will be reviewed.

An approach for evaluating the level of risk and the process of developing mitigating actions to be taken during the design, manufacturing and testing efforts will be discussed.

The importance of timely information sharing, development of scope and design decisions, and interactions between the EPC, end customer, and equipment supplier throughout the concept, design, fabrication, and testing process will be discussed. Learnings on balancing control of the design, maintaining project schedules, and controlling costs while maintaining good working relationships with the EPC and customer will be reviewed and recommendations presented.

Finally, the “retrospective observations” through the conclusion of startup and handover for commercial operation will be reviewed. These observations include learnings and successful experiences for not only the work processes but also those specific to the machinery and technical design aspects of equipment for these gas processing facilities.

## INTRODUCTION

Application of specialized machinery to complex, large scale projects such as land based LNG mega-trains or shipboard floating LNG (FLNG) applications can be quite challenging and provide many opportunities for issues and missteps along the way. This paper presents a recommended approach for dealing with such issues to help ensure a successful project.

As presented, the information is not (and really cannot be) a sequential guide to approaching a project like this, but rather is a set of guidelines, observations and recommendations on how to handle the various aspects of a significant project of this type with some specific examples from our experiences.

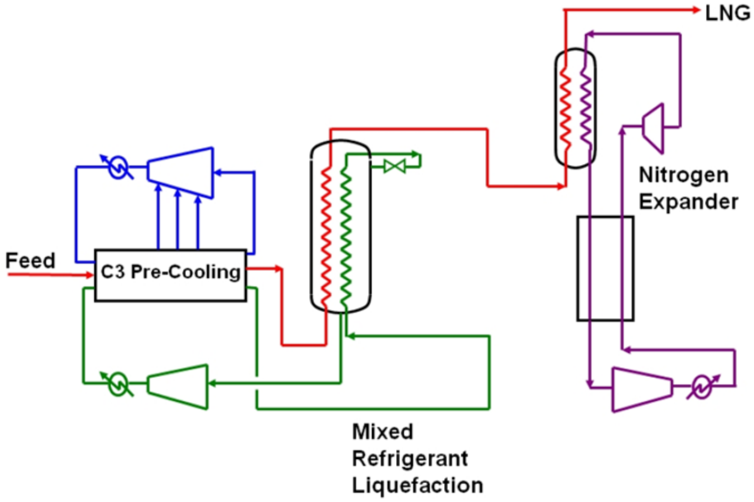
The nitrogen recycle expander plant is a well-known technology, used extensively in the air separation industry for producing liquid nitrogen (N2) and oxygen (O2). The process uses the reverse Brayton cycle to create refrigeration by compressing nitrogen, removing the heat of compression, expanding the nitrogen through a turbo-expander to create a cold stream, and warming the stream against the heat load. This cycle has been used in hundreds of Air Separation Units (ASU) and dozens of LNG peakshaver plants.

Both the land-based and shipboard applications utilize a nitrogen recycle expander process loop with multiple companders with differing refrigeration duties to provide refrigeration used to help liquefy and subcool the LNG process flow. In these specific applications, the nitrogen is a refrigerant and loss of nitrogen to atmosphere is minimized as makeup supply is limited.

**The Projects**

*Land Based*

AP-X® LNG Process trains located in Ras Laffan City, Qatar, six 7.8 mtpa LNG trains with 4 companders per train

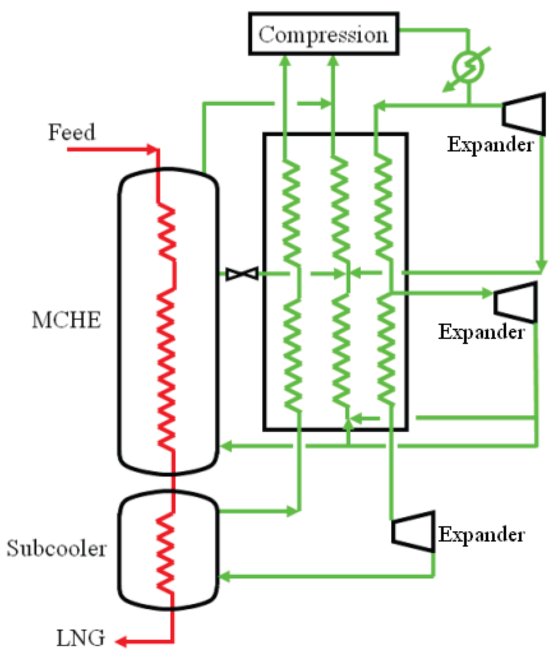



**AP-X® LNG Process**

The AP-X® LNG Process utilizes propane refrigerant for precooling, mixed component refrigerant for liquefaction (C3MR), and nitrogen refrigeration loop for subcooling. The nitrogen loop provides refrigeration that the propane/mixed refrigerant (C3MR) portion of the liquefaction area would otherwise be required to provide and enables single train production up to and exceeding 10 mtpa.

*Shipboard*

AP-N™ LNG Process trains located offshore Malaysia, a 1.2 mtpa LNG train in operation onboard FLNG Satu and a 1.5 mtpa LNG train onboard FLNG Dua currently in construction. Each LNG train is comprised of two machinery strings, 3 companders per string, thus 6 companders per FLNG vessel




**AP-N™ LNG Process (2-Pressure, 3-Temperature)**

Several variations of the N2 recycle process have been developed for an LNG plant. These trade off the number of expanders, pressure and temperature levels with process power efficiency. The figure above shows an AP-N™ LNG Process with two pressure levels and three expander temperatures.

Companders being installed on pedestal foundations (left) and shown after mechanical completion (right) for one of the six AP-X® LNG process trains in Ras Laffan City, Qatar - 7.8 mtpa


FLNG Satu:   World's first offshore FLNG facility utilizing AP-N™ LNG Process – 1.2 mtpa
Location: Kanowit gas field, South China Sea, Sarawak, Malaysia. Started-up: 2016

**Project Inception**

*Planning Phase*

Engage the customer early in the planning and design phases and try to ensure the correct personnel are involved on both sides. These should be people who are knowledgeable about the equipment and application and have the capability and authority to make judgement calls. If such people are not available, work with assigned staff and make efforts to include others in needed reviews and discussions to make appropriate, informed decisions.

For continuity, ensure that focused resources are available and involved from project inception. If this is not feasible, document all decisions appropriately, including the decision-making parties involved to avoid churn later in the project. Meeting minutes and notes from early-stage teleconferences and discussions can be used to frame the scope decisions and concessions made without the immediate need for formal specifications or contractual document revisions. However, as the project proceeds to the more advanced stages, this sort of "loose" control of requirements and scope will likely increase the effort, not reduce it.

Look to maximize the value-added scope for the machinery being supplied. For the compander applications, this included not only the companders and auxiliary (oil and seal gas) systems, but also critical valving (trip and recycle valves) as well as anti-surge controls and additional instrumentation scope. Consider including scope with the machinery/package OEM that:

a) protects the machinery
b) ensures operational success
c) is heavily integrated with machinery requirements

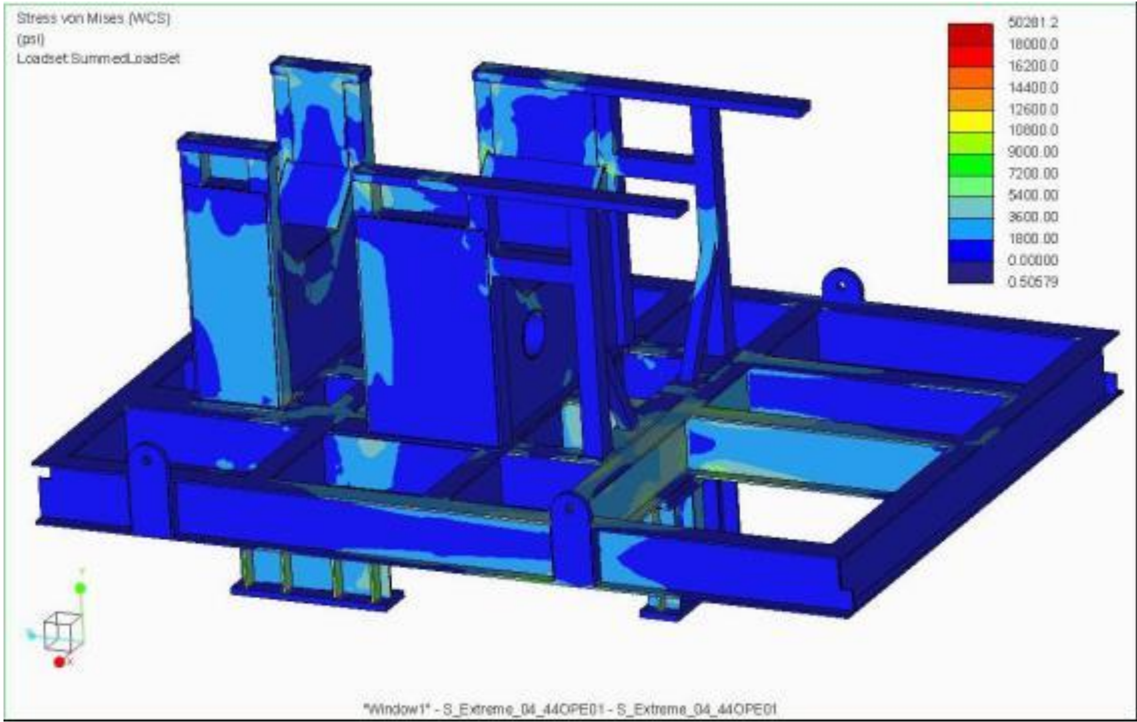
Other scope, while potentially adding some profit to the OEM or simplifying scoping strategies, can also add distractions and compete for resource time of the OEM, especially if that scope is not well defined. Typically, the scope of supply of non-value-added components and systems should be avoided.

If there is limited availability of the parties involved, look to focus first on the important technical/contractual concerns and discussions. Try not to get mired down in the smaller details that can be resolved later. Assumptions may be necessary and should be documented. If required, a change-in-work scope revision can be made to the contract to record these changes.

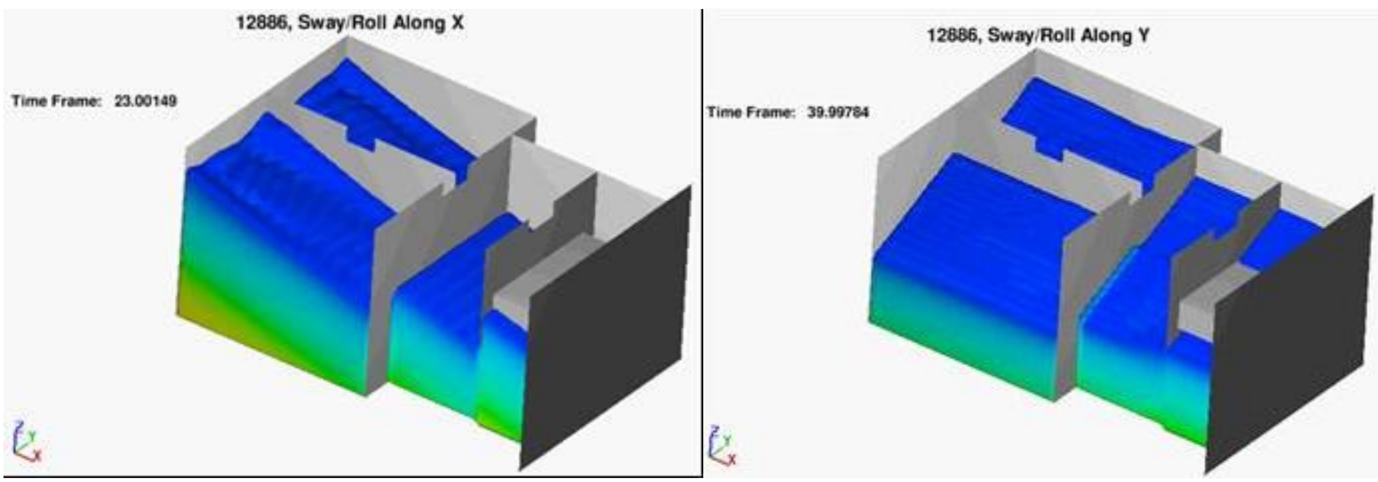
The supplier and purchaser should consider and employ third-party audits/consulting as appropriate for step outs and introduction of new or novel technologies or approaches. The timing of these efforts needs to be coordinated to maximize the benefits. If these audits are conducted too late, any recommended actions coming out of them may not be feasible or able to be implemented based on project schedules.

For the land based AP-X® companders aerodynamic stage design audits were performed and mechanical audits were performed both on impeller designs and the rotor/bearing system itself. The outcome of the resulting audits resulted in no significant findings and no significant design changes. In general, third-party audits bolster the confidence in the design and design work processes for not only the EPC and customer but also the supplier, especially if step outs or new technology is employed.

For the shipboard applications, audits were performed on the companders themselves, skid structure and reservoir for ship motions concerns. The provided topside wave motion and acceleration data effects on rotordynamics were quantified and found they could be ignored for the robust, stiff shaft rotor design of the companders. A general audit was also performed by a third-party with extensive shipboard equipment design and packaging experience on the basic design and packaging approaches proposed for the companders in this application. No issues or concerns were presented for the work that was done to date and in fact several observations were made of overdesign or excess conservatism. Due to the timing of the feedback relative to contractual definitions, actions could not be taken to de-scope the offering. The companders themselves remained largely unchanged between the land based and shipboard versions with the exceptions of some enhancements in the area of both ambient atmosphere and galvanic corrosion prevention for the machine externals and appurtenances and some enhanced maintenance procedures and methodologies for dealing with shipboard motions and accelerations.




Skid structural analysis was performed to ensure satisfactory performance of the structure under all envisioned and contractual operating conditions.




Reservoir sloshing analyses were performed on the compander lube oil reservoirs for the various contractual loading and motion that could be applied to the equipment.

*Customer Communication*

Expect that on a major project, proper communication will be a significant effort regardless of when it occurs. It is best, however, to have the major technical and scope related discussions up front, then manage those decisions with ongoing feedback throughout project execution.

As decisions are made, ensure there is proper buy-in on scope, deviations, etc. from all parties involved. If that is not feasible, then, at a minimum, create firm contractual documentation to solidify scope and ensure that all decisions made are clearly conveyed. This will avoid confusion that may create issues later in the project.

The initial project stage is the time to agree upon and establish the communication protocols that will be used going forward. Look to define simple, straightforward requirements for documentation and communication. Remember that a project like this can involve thousands of pages of customer and industry specifications and standards and require hundreds of individual document deliverables.

These deliverables could comprise of tens of thousands of pages of information and require thousands of e-mails and other correspondence between the supplier, EPC and customer for each package or system.

At this point and throughout the project, documents defining and communicating important information are necessary, but documents and correspondence creating churn and change need to be managed and minimized.

*Integration*
Don't underestimate the impact that controls and instrumentation can have on machinery performance and reliability, bearing in mind that approaches on controls and instrumentation can be quite specific to the customer, EPC and OEM.

Realize that the opportunity for change and positive integration steps is highest early in the project where it will have the greatest impact. Control system details are often overlooked until later in the project, when they can cause issues if they deviate significantly from assumed configurations and initial control approaches.

Regarding required controls and instrumentation, one needs to consider basic startup, shutdown, and other transient and nonstandard operability methods along with those for typical steady state operation. Understanding and communication between the machinery OEM, the EPC, the end customer and those associated with process design (if not one of those three) needs to be well managed to ensure that the equipment design can support all the process and customer requirements and that the process and operational philosophies recognize any limitations and characteristics of the machinery provided.

*Risk Evaluation*
Ensure that adequate mitigation actions and appropriate fallback scenarios are identified early. Mitigation actions could take the form of customer, EPC and/or OEM sponsored activities and actions. Mitigating actions and fallback scenarios should not simply be considered something that is the full responsibility of just the OEM; depending upon the impact, these actions and scenarios may need to be discussed and agreed upon with the EPC and customer.

The supplier/OEM should not be quick to abandon designs and practices that have worked well previously to comply with customer requests or specification requirements. It is best to inform and attempt to work with the customer to choose the direction that is likely to yield the greatest success. All parties can often learn from each other in their various viewpoints and experiences and utilize them to get to the best solution. Mitigating actions can also be executed to demonstrate that OEM standard practices are suitable for the application.

In providing the companders for both the land based and shipboard applications several aspects of proven designs were retained despite being somewhat contrary to customer requirements and/or industry standards. Both oil lubricated and magnetic bearing technologies were evaluated for both the land based and shipboard applications. With the potential for reduced weight, footprint and component count magnetic bearings showed some desirable characteristics for both applications. In both instances, however, it was determined that the transient thrust loadings that would be encountered as part of the compander startup and shutdown requirements in these specific process applications could not adequately be controlled to allow the use of magnetic bearings. Even with the use of active thrust control schemes, actions to carefully control process pressures and venting of nitrogen inventory were not deemed adequate to mitigate the overthrust risks. These standard compander designs have always utilized a fully passive thrust balancing system and oil lubricated thrust bearings capable of handling all anticipated thrust loadings, as opposed to the active thrust control mentioned in both the API-617 standard and customer specifications. With a long, successful history of our design being robust and reliable from a thrust management standpoint, the passive thrust control design and oil-lubricated bearings were included as part of the contractual offering.

Thrust loadings of the magnitudes predicted in both the land based and shipboard applications during startup and shutdown actions were realized and validated in the field. In addition, some unplanned loadings (generally during non-rotational conditions) exceeded all of the design values. These validations supported the decision to utilize the oil bearing designs in both cases.

Another feature was a robust nozzle mechanism design and actuation that deviated from some customer specifications. With adjustable nozzle mechanisms being a challenging design aspect of cryogenic turboexpanders, this was another area where we did not want to deviate from its successful experience.

The impeller to shaft torque transmission drive was yet another instance of a deviation from the customer expectations, despite a proven history of successful operation. To assuage customer concerns and demonstrate performance, a scaled mock-up of the drive was constructed and successfully tested at extreme temperature and torque operating conditions.

*Contractual Definition*
Probably the clearest way to have a well-defined scope of supply ensuring that all parties' needs and expectations are met is to ensure there is a thorough ITP and a contractual definition of required documents (drawings, datasheets, etc.). It is also important to have a negotiated, agreed upon order of precedence for these types of documents (versus customer-issued documents) in the early stages of the project. Agreeing upon the order of precedence can help ensure that, as other individuals come on board, there is minimal deviation from scope documents that have been reviewed and agreed upon early in the project. Based on experience, it is commonplace to have new customer and/or EPC team members alter or even completely reverse decisions and directions given by others earlier in the project. Having strong document control and order of precedence system can help prevent rework such as drawing/document revisions or changes requested during manufacture without proper change in work authorizations from the customer.

In the ITP and scope documents, focus on providing value added activities and inspections. Where other customer required activities must be included, be sure to make the requirements clear, concise and as easy to manage as possible.

For the activities, approvals and inspections listed, try to consider and address possible "what if" scenarios up front. Also look to negotiate and document a reasonable extent/level of impact of customer actions/approvals/decisions.

The contractual documentation should include language to help ensure that decisions are technically based and do not have significant schedule impact due to extended debates/discussions or unnecessary bureaucracy. Our experience suggests that it is best to use standard OEM practices and procedures as much as possible, provided they largely meet the requirements for the application and customer expectations. This experience further suggests that standard practices and procedures should be augmented as needed due to either customer or application specific requirements that cannot be avoided or waived.

When the contractual documentation is firmed up and the scope is well defined, all parties involved in the project need to make the shift to executing the project with a tighter control of changes and churn.

*Detailed Design*

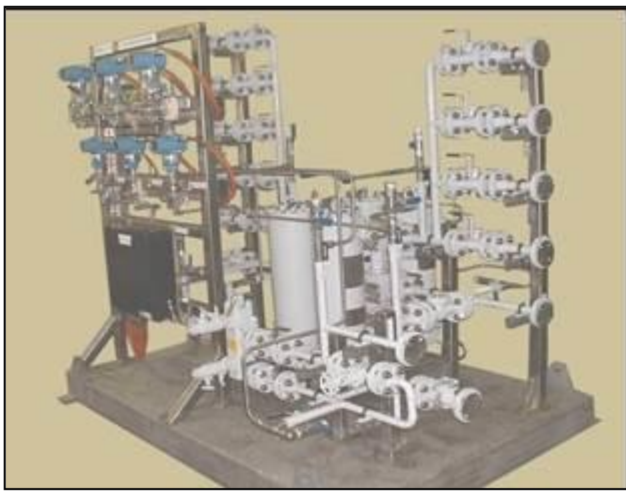
Application Specific Concerns/Tradeoffs

a. Space vs. Capital Cost and Minimizing Hardware.
    i. Land Based
        An approach of combined larger skids with fewer pieces of equipment was chosen which leads to easier and less maintenance activities, and simplified sparing approaches. Tradeoffs between combining services and auxiliaries and the ability to operate and maintain equipment separately must be weighed.
        For this application, a single oil system with significant redundancy and provisions for maximizing on stream reliability was chosen over individual systems with more components to fail and a requirement for a larger inventory of spares.

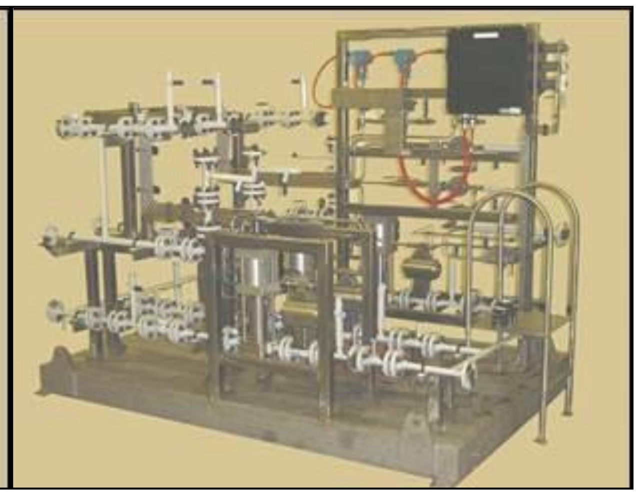
Oil reservoir/pump skid (combined for 4 compander support)

Oil cooler/filter/control skid for all four companders

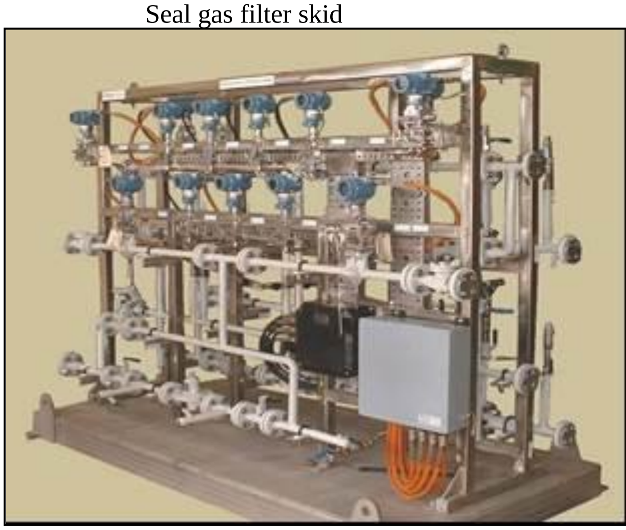
In the case of the seal gas systems, it was decided to have separate seal gas control panels at each machine, simplifying operation and allowing operational flexibility (different adjustments for each machine) and providing better condition monitoring of the seals. However, pre-conditioning functions of the seal gas system (filtration and booster/amplifier functionality) were however combined in single skid designs with redundancy along the lines of the lubricating oil system.
To ensure success in field installation, interconnecting piping between the seal gas control panels and the compander skids were provided as part of the package scope.



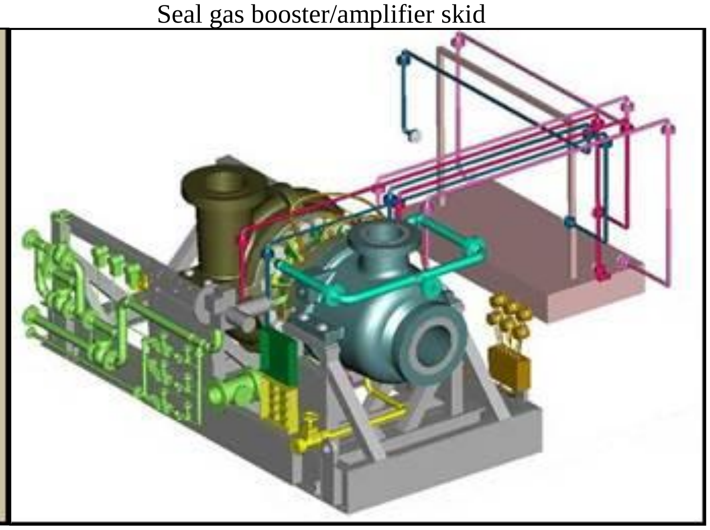
Seal gas filter skid



Seal gas booster/amplifier skid



Seal gas control panel (one for each compander)



Interconnecting piping from control panel to compander skid

ii. Shipboard

Although weight control and minimizing footprint are key considerations in offshore applications, the design of offshore equipment often utilizes a modular approach. This modular approach and limited space can often result in multiple elevation levels or significant location differences on modules for related equipment. This can prohibit combining equipment support systems to reduce weight and space.

As has been experienced in the FLNG application, the major equipment arrangement may dictate the number of systems and skidding decisions.

In this instance, with multiple expander-compressor systems per train, the approach was to have single skids with the required oil and seal gas auxiliary systems integrated into the skid. This approach is common for many types of rotating machinery in offshore environments, whether for platform or shipboard installations.

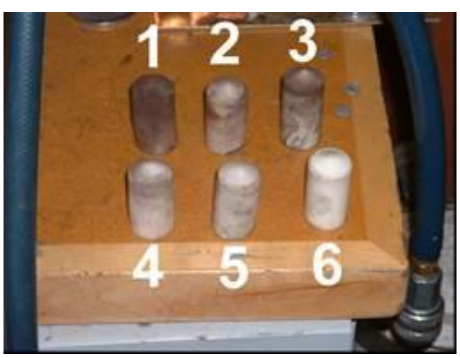
Single compander skid complete with lube oil and seal gas systems integral to the skid for an AP-N™ LNG Process train.

For shipboard applications, careful consideration must be given to all aspects of maintenance, including equipment isolation from process and utilities, lifting requirements and provisions, laydown areas, as well as wave motion safety considerations during all phases of maintenance.

Additional considerations related to maintenance activities are the required level of disassembly, and impact on surrounding structures and piping and electrical systems, as well as space limitations and access constraints that will be experienced during the actual maintenance activities. The required maintenance areas and facilities must be assessed early in the project to ensure adequate space and features are included as adjustments to modules and equipment layout will likely be less flexible in the latter stages of shipboard projects compared to land-based projects.

b. EPC/Customer Involvement

Don't underestimate or trivialize customer experiences or requirements written into customer specification that do not necessarily align with recognized industrial standards or practices, but be sure to understand the reasoning and basis for them when possible. Proposing alternatives or compromises may provide a mutually beneficial way of addressing them. Be sure to focus on the success of the equipment in operation.




For example, pigging of the small-bore seal gas lines was a customer requirement on the AP-X® compander seal gas systems. This cleaning method was accepted and utilized although not the normal practice for seal gas system cleaning. Although a bit cumbersome and costly to perform, technically the process worked well.

Left: Pigs used in the pigging of a specific seal gas line on one of the AP-X® seal gas control panels, showing the progression of cleanliness

Another customer recommendation/request was to utilize centrifugal pumps in lieu of positive displacement screw pumps for the combined lubricating oil system for the four companders per train on the AP-X® companders. With the ability to operate the plant with four, three or two companders online and the desire for redundancy for onstream reliability, a three centrifugal pump arrangement was chosen. This enables the system to be operated with one, two or all three pumps in operation for all required oil consumption levels for the companders. Oil flow requirements at the high end was 350% of that for the minimum flow case. The chosen pump arrangement and hardware performed well, allowing smooth transitioning during pump startup and shutdown.

**Manufacturing**

a. During the manufacturing process, be sure to do what you say and say what you do. Ensure the ITP accurately reflects the inspections and tests to be performed, includes levels of witness and defines clear acceptance criteria. Focus on requirements that are out of the norm for machinery manufacturing processes and ensure they are performed properly to get the desired benefit.
b. OEM's should look to provide useful input and experience-based guidance as to which customer or project specific requirements provide honest benefit based on the applications and usage of the actual machinery designs.
c. Ensure there is proper coordination and communication for in process inspections. Delays during the manufacturing, assembly, and/or testing may impact equipment delivery due to strict manufacturing schedules and limited contingency time for delays.

**Testing**

a. The role of the customer and extent of involvement in testing should be determined early. While the EPC or customer are often just an observer, there are some instances where the EPC or end customer may have experience and input that can be useful in truly ensuring the equipment is suitable for service.
b. In setting up and determining the testing requirements, thought should be given to how much of the testing efforts will be focused on segmented testing versus more complete string testing. When evaluating the approach to testing, all parties must objectively evaluate the greater concerns for equipment validation and the most important aspects of the equipment to be proven/validated during testing. An evaluation should be made of the specific application and proposed equipment and scope of supply. The evaluation is to consider the areas of biggest risk. Is the bigger concern the integration and compatibility of the systems working together or is it a focus on the equipment design, step-outs and application of new technology? If there are issues with any of the considerations, which of those will be the hardest to address in the field?

   For the land based AP-X® application, the step out in compander size and power led to inclusion of a full load, full pressure (FLFP) test and cryogenic test of the compander design.

   The FLFP test included the demonstrated use of a contract inlet trip valve and dry gas seal control panel. The companders were operated at full process pressures and powers and included compressor performance testing to PTC-10 and surge curve validation efforts.

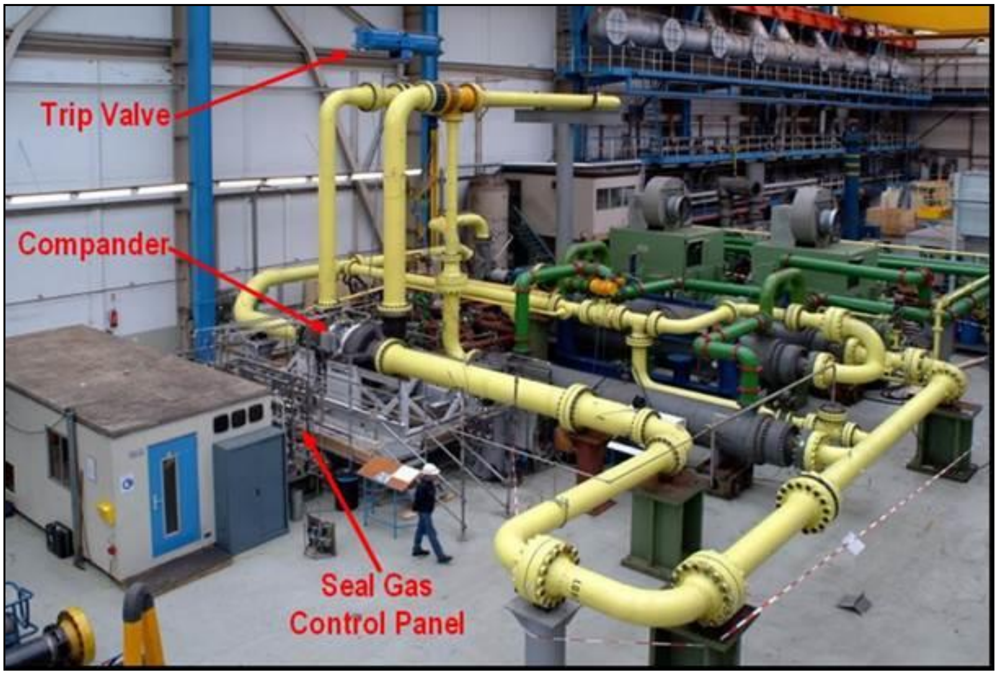


Photo of the full load, full pressure testing, showing the compander, seal gas control panel and trip valve

During the cryogenic testing, the expanders were operated at temperatures 50° C colder than design inlet temperature. The expander nozzle mechanism movement and shaft vibration were proven to be insensitive to the cryogenic process conditions.


Photo of the insulated compander during cryogenic testing.

Photo of the Air Products Express Services (APEX) pumper truck that pumps and heats liquid nitrogen to the desired conditions for testing.

c. Alternate testing efforts to the traditional final FAT tests can include pre-testing inspections of component as well as scaled, or representative testing. It should be determined whether these approaches make sense. Component and representative tests can provide feedback earlier in the schedule, allowing more time, if needed, to adjust designs or implement fallback actions.
One example of such a test is the torque transmission testing performed for the AP-X® compander. This test was to verify the traditional design for torque transmission for impellers to the customer. The same rig was subsequently used to verify that a different torque transmission method was appropriate for a specific application before inclusion in the design. The rig, as designed, permitted testing of the full-scale drive mechanism with the same rotor materials and component design at both warm and cryogenic conditions. For the AP-X® application, the drive mechanism performed without issue when tested at warm and cryogenic conditions at up to 400% of the design torque.


Torque test being conducted at cryogenic conditions

**Packaging and Preservation Efforts**

Ensuring that equipment shipped to the field stays in good condition through transport, laydown, installation, commissioning and handover for operation is not a trivial task. There is a body of literature that documents the considerations for safe storage of equipment for typical land-based applications. Factors such as the duration of storage, storages conditions, and the type of equipment to be packaged, all influence the methods used for packaging and preservation.

Off shore applications command some of the most significant efforts in protection of equipment against damage and degradation prior to being put into final operation. Preservation, connection covers, purging, and other means may need to be employed due to significant construction durations for shipboard applications. Because some equipment may need to be installed a year or more in advance of sail away, the equipment must be suitably protected to prevent deterioration and ensure top performance. Protective coatings and corrosion resistant material selections must be selected for the application to ensure the equipment is protected from degradation. Austenitic 316 stainless steel is a common construction material that when combined with coatings of paint or rust preventive mastic forms an excellent corrosion resistant system. High strength alloy steel bolting can be coated with PTFE corrosion resistant layers that provide protection from the elements and sea salt. For machined surfaces that cannot be painted or clad, suitable marine grade rust preventive coatings should be applied to protect the surfaces from corrosion. Marine grade petrolatum tape can also be installed to protect against moderate mechanical damage from dropped tools or fasteners.

Purged shipping/storage containers should be considered for high dollar items that can be shipped and stored on that manner. For offshore applications, more significant packaging efforts, such as packaging to MIL-STD-2073 methods 30 or higher should be considered. Below are pictures showing a compander skid with method 50 (formerly MIL-P-116J Method II) preservation being employed.

Shipboard compander skid at initial stages of packaging

Compander skid fully wrapped and ready for crating

Protective coatings of various types are useful in equipment preservation/protection. The types of coatings employed can include the following:

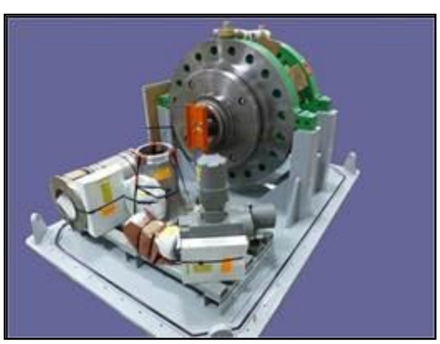
a. Temporary coating protection. These can include spray or brush on coatings that have varying levels of protection and efforts of removal.
b. Special coatings on fasteners. The use of fastener coatings can affect friction factors so care must be taken to adjust torque values on torqued fasteners.
c. Paint systems. These systems should be designed for marine environments and applied properly. Proper attention to recommended DFT's and dry times are critical to paint system durability. Touch up painting/coating on site may provide an economical means to ensuring prolonged equipment protection. The OEM and EPC should coordinate such efforts.
d. Corrosion-resistant materials. Extensive use of these materials is common in offshore environments and ease the need for preservation methods on all equipment.
e. Cladding and weld overlays. Use of these on surfaces may be appropriate for certain applications.
f. Petrolatum tape and mastics. These can be applied to provide both corrosion resistance and some moderate level of protection from mechanical damage.

If materials of construction are altered for a first offshore application, it is important to pay attention to introducing additional possibilities of galvanic corrosion due to dissimilar material contact.

Purging and desiccant application are common approaches to prevent moisture accumulation in equipment internals and are also useful to protect offshore equipment. Appropriate periodic inspection protocols for purges and desiccant applications are required to ensure they are providing adequate protection. The desiccant may require frequent replacement/refreshing in a high humidity environment such as an offshore location.

One of the best ways to ensure that critical machinery does not get damaged during construction and pre-mechanical completion activities is to simply keep the most critical hardware out of harms way. A mock-up may be considered where high dollar value machinery cartridges can be shipped and stored separate from the equipment package/skid. Compander plug-in units, or mechanical center sections (MCS), are a type of rotating machinery that can benefit from the use of a mock-up during shipment and skid installation. This approach permits the critical machinery to be stored in a clean, preserved state for as long as possible before the required installation date, which minimizes the risk of degradation.

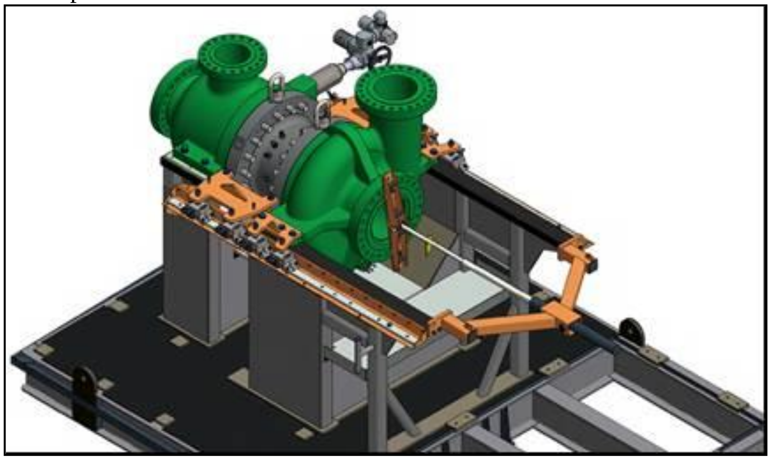
This picture captures several preservation methods employed on offshore applications. Coated fasteners and marine paint systems are displayed. Also shown are temporarily applied coatings on machined surfaces. Finally, the large orange flanged center section is a compander MCS mock-up, which also replicates instrument connection points and is designed to allow low pressure blowdowns of piping prior to installation of the MCS. The mockup allows all fit up of piping and instrumentation to be conducted in the factory and field without the need to install the actual equipment.



These pictures show the completed MCS mounted into the base of a purged shipping container (far left) and the fully assembled container, complete with inspection window (to permit visual inspection of the machinery condition), orange document container and onboard N2 blanket system. With the use of a mockup, the contract MCS's can stay protected until they are needed for final installation prior to commissioning. The containers also provide convenient long-term storage of the spare MCS and simplify transport for refurbishment.

**Installation and Erection**

Special tooling may be required for installation and maintenance. Various components may be staged for integration into the plant construction schedule. An understanding of the construction schedule and plan aids in ensuring that any special tooling required for installation can be designed to accommodate the timing of use, space constraints, critical application requirements, and other non-standard aspects, especially for shipboard applications. Special tooling can be required to prevent unintentional movement due to wave motion and address space constraint concerns.



This picture shows special tooling (in orange) that allows the MCS to be removed and installed safely in a shipboard environment. The tooling provides precise positional control of the MCS for installation and removal while also preventing unwanted movement of the MCS due to wave motion, which poses a risk of machinery damage and threat to personnel safety.

The shipboard compander skids were designed for module installation. Installation of machinery and equipment on modules may occur much earlier in the project than with traditional land based efforts. Many of the skids are installed a year or more before the rotating equipment.

Equipment packages are likely to be without supporting systems, lubricating oil, seal gas, purge gas, instrument air/N2 for longer than a comparable land based plant, due to the shipbuilding methodology and modular construction. Equipment package designs need to address corrosion concerns and ensure prevention of moisture/salt ingress and accumulation during this construction period when normal support systems are unavailable. Special, temporary systems such as rust preventive coatings, connection covers, and mastics may need to be installed during this period. Discussions with the EPC and customer about the level of special protection required is paramount to ensuring the equipment remains in pristine condition.

**Training**

*Scope*
Training should include both Operational and Maintenance focuses. It is important to understand the customer specific division of responsibilities to ensure the appropriate actions and concerns are emphasized for the appropriate audience. Management overview training can also be beneficial for the customer. This training can help management ensure that adequate resources are available for the unique equipment and system requirements and operational and maintenance activities.

*Delivery*
The training should be presented in a way that is both interactive and engaging. Thought provoking questions should be included throughout the training. Videos and animations are valuable to help visualize more complicated efforts, keep the interest of the participants and communicate more sophisticated concepts. Quizzes or comprehension questions should be considered but need to follow the norms of the end customer.

**Commissioning, Startup, Handover**

It is important to identify the shipboard systems that will need to be commissioned and functioning prior to sail away versus those that will be needed for actual plant operation. Items needing completion and commissioning prior to sail away could include:

1. Systems that support safety critical aspects (emergency alarms, fire and gas protection, life boats, etc.) and personnel (power generation, potable water systems, etc.). These systems should be fully tested and functional.
2. Utility systems used to ensure successful protection and preservation of the equipment during transport.
3. Systems that are more likely to need land based support during commissioning or require materials that are not readily available at sea.
4. Systems that need to be commissioned as part of a risk management mitigating action to ensure proper operation.

Considerations on a larger scale should also be given to systems where pre-commissioning or commissioning may be best achieved in the shipyard versus offshore. Systems that are more likely to need remedial or fallback actions if an issue is uncovered during system checkouts are prime candidates for commissioning prior to sail away as there are fewer options for workarounds and remedial actions and fewer support personnel once the equipment is offshore.

### Retrospective Observations

Throughout execution and as part of any project closeout effort, there should be efforts to not only react to findings and learnings for the current efforts but also to document learnings, best practices, potential improvements, and unresolved and resolved issues that were encountered for use/improvement on the next project.

Below are various observations from those experiences:

a. Work Process
   1. Document, document, document… Be sure that at the start of the project, the intended scope (hardware, efforts/services, testing and contractual documentation to be supplied) is clearly defined and agreed upon by all parties.
   2. Streamline documentation, drawings, datasheets, and other design information based on customer feedback.
   3. Clarify items that may not have been clear during project execution and caused unnecessary rework, confusion, or delays. An example may be an unclear or ambiguous acceptance criteria for an inspection on an ITP.
   4. Changes recommended in the field (during commissioning or operation) may be too late to implement due to customer resistance. For example, an aspect of the control logic is found to have a flaw that permits improper operation, but system complexity prevents the flaw from being resolved as desired. A suitable "fix" may need to be devised, implemented, and tested in an impromptu manner to support the commissioning and startup schedule.

b. Machinery and Technical Design Aspects
   1. Atypical requirements can cause issues/questions that are often easy to answer/correct but can be nuisance because of required documentation revisions.
   2. If it is thought that something might cause problems or questions in the field, it probably will…

c. Application and Operational Observations
   1. While the best planning, analysis, design, execution, testing, commissioning, and startup plans can identify and resolve many issues, unforeseen issues do occasionally arise. An adept supplier can react to these problems as they are encountered and work with the EPC and customer to develop appropriate solutions. An in-depth knowledge of the equipment, system, and operation is needed to resolve these issues in an efficient and effective manner. For example, an undesirable sequence of valve closures results in a higher pressure in a piping circuit than was estimated using a dynamic model. Because the higher pressure could cause operational issues with equipment that could lead to damage or failure, the supplier, EPC, and customer must work together to first identify the problem, determine a suitable solution, and implement and test it.

## CONCLUSIONS

The application of specialized machinery to complex, large scale projects can be quite challenging and provide many opportunities for issues and missteps along the way. While the actual equipment design may not vary much between land based and shipboard applications, the packaging and installation and maintenance philosophies can require adaptation for shipboard use. By following a structured approach that considers the possibility of potential problems and helps prevent them, one can realize a successful application of equipment and technology satisfying project objectives and meeting customer expectations.

## NOMENCLATURE

| | |
|---|---|
| C3MR | = Propane / Mixed Refrigerant |
| Compander | = Expander/Compressor stages on a common unit |
| DFT | = Dry Film Thickness |
| EPC | = Engineering and Procurement Contractor |
| FAT | = Factory Acceptance Test |
| FLFP | = Full Load, Full Pressure (Test) |
| FLNG | = Floating Liquified Natural Gas |
| FPSO | = Floating Production, Storage and Offloading |
| ITP | = Inspection and Test Plan |
| LNG | = Liquified Natural Gas |
| MCHE | = Main Cryogenic Heat Exchanger |
| MCS | = Mechanical Center Section |
| mtpa | = Million Metric Tonnes Per Annum |
| N2 | = Nitrogen |
| O2 | = Oxygen |
| OEM | = Original Equipment Manufacturer |

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