EMBRACING DIVERSITY IN LNG LIQUEFACTION TECHNOLOGY - INNOVATION IN A CHANGING WORLD

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ABSTRACT

This paper outlines transitions within the LNG liquefaction business as it has moved from the remotest corners of the world to settle in more developed industrial environments including the US Gulf Coast. The innovative combination of elements from existing technologies together with creative engineering designs introduces an optimized facility process and execution profile as a means to better enable the successful realization of projects in these new market conditions. Departure from the tried and true is viewed with a healthy and appropriate dose of technical and commercial skepticism. Yet through application of proven technologies, including one with over 100 years industrial experience, it is possible to introduce enhancements to the LNG production process and generate surprisingly beneficial results. The increasing importance of thermal efficiency in LNG liquefaction facilities is addressed, including the appropriate selection of refrigeration compressor drivers as a means to lower GHG emissions, enhance production and facilitate startup. Using a current US Gulf Coast project as a case study, the effects of recovering waste heat to drive the pre-cooling process will be discussed and quantified. A discussion on the available alternatives for pre-cooling refrigerant is presented. The application of the Optimized Single Mixed Refrigerant (OSMR®) liquefaction process in a mid-scale LNG project is explored, in which existing technologies are combined in an innovative manner to improve key project attributes, enabling a creative, reliable and efficient design to be effectively delivered.

INTRODUCTION

The foundations of the global LNG industry were established on the firm bedrock of safety and reliability, consistent with the demands of a closed market with carefully balanced supply and demand. For the producers, the capital investments necessary in the LNG value chain have always been substantial, often with extended payout periods necessitating a high degree of certainty in the revenue streams to ensure the financial viability of the projects. For the consumers, access to a reliable supply of LNG has been vital to electricity generation, industrial consumption and domestic use underpinning national economies. The solution was a closed market with point-to-point deliveries from specific producers to specific consumers using dedicated shipping all locked together under long term highly restrictive contracts intended to protect the interests of all parties. Efficiencies, both energy and capital, were important but somewhat secondary considerations within the whole equation of project viability.

Today the LNG market is changing. While long term "take-or-pay" contracts still dominate the industry, an emerging spot cargo, short-term contract and arbitrage market has begun to free up opportunities for the nimble. Nominally 70% of the world's LNG still trades (at least initially) under the historic long term contract model but with this percentage slowly and steadily dropping as more producing nations and facilities enter the market[1]. An increasing abundance of available LNG production and shipping capacity coupled with the emergence of quicker-to-market floating storage and regasification units (FSRU's) in place of conventional land-based receiving terminals have contributed to the emerging market looseness. Throughout this market evolution and increasing flexibility in the value chain, the LNG base load production facilities have remained substantially unchanged. This extended design inertia in the face of changing industry dynamics has created the opportunity to take a fresh look at production facilities to generate innovation and diversity in the production market.

EVOLUTION IN THE MARKET

Since the inception of the commercial LNG industry in the 1960's, LNG projects have maintained certain defining characteristics:

- Historically, LNG projects have been limited to the domain of large integrated national and international oil companies. Only major organizations of this nature have had access to the technical, financial, logistical and managerial resources to successfully deliver projects of this cost and complexity;
- Facility owners have traditionally been involved in development of the entire gas supply value chain, from gas field discovery and assessment through production well installation, feed gas pipelines, LNG facilities, ship supply, shipping and marketing of the product. Often, the LNG facilities represent a means to monetize a stranded resource or a necessary component to accommodate associated gas production;
- LNG proponents have been (or partnered with) highly mature organizations with extensive global engineering standards, processes, procedures and existing operational petrochemical facilities;
- The LNG facilities themselves have been located in some of the world's harshest and most remote environments, challenging to reach let alone operate successfully within;
- Extensive logistics programs have been vital to operations and the success of the projects.

[1] 69% in 2014, International Gas Union World LNG Report – 2015 Edition

Absence of local or regional facilities are a hallmark of LNG sites – nothing is there, and so excellence in logistics planning and execution is essential to mere existence;

- Massive infrastructure development programs are necessary, sometimes requiring years to complete in themselves. The project sites can be hundreds of kilometers from existing regional infrastructure, no roads, no docks or marine facilities, no food, water or shelter, no electricity, no communications, no emergency response or security capacity. They can be subject to extreme weather conditions (desert heat, arctic cold, tropical monsoons) and high threats of disease such as malaria, dengue fever and dysentery. The costs of these infrastructure developments can run into the billions of dollars while providing zero direct return on their investment from an LNG production aspect;
- Regulatory programs at many of the traditional sites are loosely defined if existing at all with no previous industrial development of a similar nature. Overlaps, conflicts and gaps between local, regional and national requirements can exist; and
- LNG facilities in these locations can potentially represent life-changing and culture-changing transitions in the local communities. Great care and planning must be taken to ensure the new facilities and the associated construction and operational workforces can harmonize with the region, providing positive catalyst for necessary and positive changes without altering the very nature of the communities being served.

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With the emerging migration of LNG projects to the US Gulf Coast (USGC) and other economically and structurally developed regions, the project and proponent profile has changed radically and rapidly. Key differential characteristics of the current projects include:

- Brownfield or brownfield-type environments; many of the new US export facilities are converted import terminals with existing storage and marine facilities;
- Small, lightly funded, lightly staffed emerging Owner organizations; total company headcounts in the 100's rather than tens of thousands;
- Limited infrastructure development requirements; sites may have access to nearby regional power grids, water, roads, ports, telecoms, security and hospitals;
- Ready access to well-established regional supporting industries, often located amidst the world's largest petrochemical complexes;
- Ready access to supporting expertise – suppliers, contractors, subcontractors, engineers, craft skills, vendor service centers and representatives;
- Broad choice of readily available specialty chemicals and refrigerants;
- Third party gas supply from a national grid accessing multiple providers;
- Well-established regional and national regulatory processes with extended schedules
- Increased sensitivity to greenhouse gas emissions – whether one agrees or disagrees with the impact of greenhouse gasses on the global environment, there is certainly an enhanced interest in the topic;
- Existing background air emissions from existing regional industries that must be incorporated into plant emission modeling and limits; and
- Greater attention paid to plant energy efficiency – energy efficiency has always been a consideration, but at remote sites the gas is essentially "free" as it has no regional value unless converted into a transportable product such as LNG. On the USGC, LNG facilities have to pay for every Btu of gas they receive out of a pipeline so efficiency and its impact on project finances becomes more important and visible.

Fundamentally, this is not LNG "Business as Usual". Yet despite these substantial structural changes, the vast majority of current LNG plant development in North America is proceeding on the same technical and execution basis as the historical remote site facilities.

Table 1. Development of LNG Plants

	Typical 1980 Baseload Facility - Remote	Typical 2015 Baseload Facility - Remote	Typical 2015 Baseload Facility – USGC
Capacity	2.3 - 2.5 mpta[2]	4.5 – 5.0 mtpa	Same
Acid Gas Removal	MEA or Sulfinol	aMDEA	Same
Cooling Medium	Seawater	Air	Same
Heating Medium	Steam	Hot Oil	Same
Compressor Drive	Steam Turbine	Gas Turbine	Gas Turbine or Motor
Pre-Cooling Refrigerant	Propane	Propane	Same
Liquefaction Refrigerant	Mixed Refrigerant (MR)	MR or C2-C1 Cascade	Same

From the above table, the most significant changes over a 35 year period from 1980 to present include:

- Increase in capacity by nominally 100%;
- Migration from water cooled to air cooled;
- Migration from indirect fired steam turbine drive to direct fired gas turbine drive; and
- Emergence of the cascade liquefaction process as a base load technology

The same table also shows that the migration of LNG facilities from the remote environs to the substantially more industrially developed USGC has resulted in virtually no changes at all. The US/USGC facilities currently being constructed or newly in operation at Sabine Pass, Corpus Christi, Cameron, Freeport, Cove Point and Lake Charles Trunkline are virtually indistinguishable from their remote site cousins. This, despite the substantial structural differences highlighted above.

BARRIERS TO INNOVATION

Mankind inherently resists change; a report in the November 2010 Journal of Experimental Social Psychology[3] concluded that the longer something is believed to have existed, the more highly it is regarded. The nature of the LNG industry, with high development costs, long development schedules, delivery contracts of up to 20 years, criticality of supply reliability to importers and limited alternate sources, does not lend itself to risk taking. Several key groups must be satisfied with the project design concepts and arrangements to enable a project to move forward to market.

- **Investors** – For small companies requiring access to external funding sources, investors must be confident in the technology to enable the initial development funds to be secured to allow the project to be advanced through the design, estimating and regulatory

[2] "mtpa" = million metric tons per year, also Mt/a
[3] http://www.sciencedirect.com/science/article/pii/S0022103110001599

processes. For an LNG project, this level of investment can be significant (in excess of USD 100 million from inception to start of EPC when bank funding can be secured), and the entire development cycle from initial activities through to LNG production can take 6-7 years. High cost and long duration require a high degree of confidence by investors that the project and its technology will eventually generate a return on their investments;

- **LNG Purchasers** – When an LNG buyer signs up with a producer to provide LNG (through a tolling arrangement or conventional sales purchase agreement), they take themselves out of the market for that volume of LNG near the start of the project EPC phase, nominally 3-4 years prior to the actual delivery. The buyer makes onward commitments for the sale or use of that LNG and consequently must have confidence it will be available as contracted, as alternate sources may not be available at all or with acceptable economics. As with investors, the purchasers of LNG cast a wary eye on anything at all considered novel or new, as this represents risk to their business models and onward commitments;
- **Lenders** – Lending institutions are vital to developing projects, providing access to the significant capital requirements of LNG projects amounting to billions of dollars. Obviously, these organizations are not charities – they expect timely repayment and take a dim view of any perceived risks to this. The lenders must be confident that the facility will reliably and safely deliver LNG over its design life;
- **Insurers** – LNG facilities must obtain insurance coverage during the construction, start-up and operational phases, including construction all-risk, delayed start-up, business interruption and operations coverage. The insurance organizations closely review the risk profile of a facility to understand how it compares to the industry historical experience. Step-out technologies can make it challenging for insurers to perform their risk assessments to develop this profile, potentially impacting the availability and/or premiums for insurances;
- **Regulatory Agencies** – Stepping outside of a well-traveled technical or project execution pathway can result in the need for additional time for regulatory agencies to complete their activities and satisfy their obligations under governing laws. Conversely, innovations that inherently improve safety or reduce plant emissions can be viewed very favorably by regulators once they have gained familiarity with the arrangements; and
- **EPC Organizations** – LNG plant developments rely heavily upon the skills and knowledge of highly qualified EPC Contractors to deliver these complex facilities to market. Lending institutions require project developers to obtain guarantees from the EPC Contractors for plant capacity, fuel consumption and schedule, often including make-good obligations on production rates and contract terms with substantial performance damages for failure to achieve. Within this commercial environment, the EPC Contractors must be comfortable with the expected performance of the technology to avoid taking on excessive risk.

DRIVERS FOR INNOVATION

"We cannot solve our problems with the same thinking we used when we created them" – Albert Einstein

The question, "Why Innovate?" seems almost silly. Drive an automobile from the 1970's or 1980's, replete with an AM radio and maybe an optional 8-track player, hand crank windows, bias ply tires, solid rear axle suspension and hard starting carburetors, and the benefits of innovation become quickly obvious. Similar with late-80's era brick-like analog flip phones. Companies innovate to respond to the demands of an evolving market, lest they quietly die away to join the likes of American Motor Cars and Blackberrys. In the case of LNG, the market has indeed changed although in more subtle ways, fundamentally:

- **Efficiency Matters**: Purchasing feed gas from third parties makes plant energy efficiency an economic necessity. For a 10 mtpa LNG facility, a nominal change in the retainage (quantity of feed gas consumed as fuel) from 8% to 6% of feed gas represents an annual savings to the facility of USD 35 million at USD 3.00/million Btu gas purchase price to produce the same quantity of LNG;
- **Emissions Matter**: According to the US Energy Information Administration[4], burning 1 million Btu of natural gas generates 117.0 pounds (53.1 kg) of CO_2. Reducing the retainage from 8% to 6% of feed gas in a 10 mtpa LNG facility reduces the CO_2 emissions by 1.38 billion lbs/year (626,000 metric tons per year CO_2 emissions reduction);
- **Reliability Matters**: Engineering to achieve high levels of simplicity and providing facilities with inherent redundancy increases reliability;
- **Flexibility Matters**: With the nature of the US gas supply market (not accessing a designated gas field), there is a need for production flexibility. These emerging projects are benefitted by having LNG trains with designs that enable significant turndown and feed flexibility capability; and
- **Safety Matters**: Simplification also promotes inherent safety – the safest piece of equipment in a process facility is the one that was eliminated. Reducing quantities of flammable and explosive hydrocarbons through improved configurations and use of alternate refrigerants promotes inherent safety.

Overall, the status quo is comfortable but is inherently incapable of advancement. Innovation is a necessity.

KEY ELEMENTS IMPACTING LNG PLANT EFFICIENCIES

LNG plant efficiencies can be addressed in two fundamental ways – process selection and plant configuration. Process selection garners the most attention, representing the core of the LNG technology licenses and technologies commonly applied (ConocoPhillips Optimized Cascade®, Air Products' AP-C3MR™, Split-MR™ and AP-X®, single mixed refrigerant (SMR) processes, dual mixed refrigerant (DMR) processes) including the choice of refrigerants. Numerous papers have been published on the topic, and not all have performed comparisons of process efficiencies on the same basis nor have they demonstrated a consensus agreement on the results (typical examples [5] [6] [7]). Comparing inconsistent elements of plant configuration can contribute to differences, and others may not have had access to the latest optimizations applied to the designs. An additional complication is that in some cases (i.e. C3MR vs. DMR) the differences in process efficiencies are quite small such that variations in the assumptions used in the modeling (ambient temperature, refrigerant compositions) can impact the results.

[4] https://www.eia.gov/tools/faqs/faq.cfm?id=73&t=11

[5] Bronfenbrenner, James C. et al, Selecting a Suitable Process, LNGINDUSTRY.com, Summer 2009

[6] Vink, K.J and Nagelvoort, R. Klein, Comparison of Baseload Liquefaction Processes, LNG 12, Perth, Australia, 1998

[7] Ransbarger, Weldon, A Fresh Look at LNG Process Efficiency, LNGINDUSTRY, Spring 2007

Plant configuration can have as large or larger an impact on the effective efficiency of a given LNG installation. Plant configuration in this context refers to driver selection (steam turbine, industrial frame gas turbine, aeroderivative gas turbine, motor), waste heat integration (process heating duty oil/water coils, combined cycle steam systems), application of liquid expanders, application of LNG product flash gas as a heat sink, number of refrigerant stages selected, cooling medium (air vs. water) and to some extent where the system boundaries are drawn (i.e. including or excluding infrastructure utility loads). Setting aside the hyperbole, some generalizations can be made:

- The difference in efficiency between facilities with the greatest and the least efficiency is not numerically large, representing only a few percent of the feed gas supply to an LNG plant regardless. The best achievable LNG plant efficiencies run in the range of 92-94%, while the lowest run in the range of 88-90%;
- While these differences are small numerically, considering the large gas flow rates into an LNG facility they are significant on an absolute basis;
- Mixed refrigerants are generally more efficient for liquefaction than pure component refrigerants, as the natural gas cooling curve can be more closely approximated. Depending on the composition of the natural gas and the number of refrigeration stages selected this difference can be minor or it can be more significant;
- Pre-cooled liquefaction arrangements are generally more efficient than arrangements using a single refrigerant. It is challenging to maintain close approach to the natural gas cooling curve over the entire range of ambient down to -160°C (-260°F) with a single refrigerant selection;
- Nitrogen expansion processes are some of the least efficient;
- Gas turbine plants deliver their greatest efficiency when the gas turbines are run at full capacity;
- Aeroderivative gas turbine drivers are more efficient than industrial gas turbine drives (again in most cases, as some of the newer generation industrial machines deliver efficiencies as high as or higher than those of competing aero machines);
- Newer generation gas turbines are more efficient than earlier generation machines;
- Addition of waste heat recovery can greatly increase the overall gas turbine cycle efficiency. A common industrial frame gas turbine efficiency is on the order of 32-34%. Adding "light duty" process heating recovery can push this up to 36-38%. Aeroderivative & high efficiency industrial machines provide efficiencies in the range of 40-45%, while incorporation of combined cycle can push delivered efficiencies up to the range of 50% and higher;
- Motor drives introduce additional inefficiencies. Instead of direct coupling a gas turbine to a compressor, the gas turbine drives a generator, which then drives a motor, which drives the compressor. Some of the additional inherent added inefficiencies induced by the generator and motor can be recovered if the power plant efficiency is high enough; and
- Steam turbine driven LNG plants, while highly reliable, are among the least efficient.

REFRIGERANT SELECTION

A dizzying array of refrigerants have been named, ranging from chlorofluorocarbons (CFC), which themselves are now avoided due to their high ozone depletion potential (ODP), to conventional hydrocarbon refrigerants (propane, ethylene) and "natural" refrigerants such as carbon dioxide, ammonia, nitrogen and even air. ANSI/ASHRAE 34 (American Society of Heating, Refrigeration and Air-Conditioning Engineers) names refrigerants (i.e. R12, R134a, R717) according to a protocol established initially by DuPont, describing a shorthand way of identifying refrigerants, and also assigns safety classifications based on toxicity and flammability data. A typical list of ASHRAE named refrigerants runs to over 300 compounds and can be broadly classified into the following categories:

Table 2. Refrigerant Classifications

Type	Name	Components
CFC / CFO	Chlorofluorocarbon / Chlorofluoroolefin	Cl, F, C
HCFC / HCFO	Hydrochlorofluorocarbon / Hydrochlorofluoroolefin	H, Cl, F, C
HFC / HFO	Hydrofluorocarbon / Hydrofluoroolefin	H, F, C
HCC / HCO	Hydrochlorocarbon / Hydrochloroolefin	H, Cl, C
HC / HO	Hydrocarbon / Hydroolefin	H, C
PFC / PFO	Perfluorocarbon / Perfluoroolefin	F, C
PCC / PCO	Perchlorocarbon / Perchloroolefin	Cl, C
H	Halon / Haloalkane	Br, Cl, F, H, C
n/a	Natural Refrigerants	Various (i.e. NH_3, CO_2)

Refrigerant selection criteria varies widely with application (i.e. automotive vs. large industrial have very different objectives). Of increasing importance are environmental issues, including ODP (ozone depletion potential), GWP (global warming potential) and efficiency (indirectly impacting the GWP). LNG projects, by their nature, are effectively restricted to those refrigerants that are suitable for the significant cooling duties and low temperatures necessary to liquefy natural gas in large or very large quantities. This, coupled with the availability considerations highlighted above as well as cost of the refrigerants themselves has resulted exclusively in the selection of HC (hydrocarbon) refrigerants for cooling and liquefaction duties.

ODP Value Ranges – Ozone Depletion Potential ratings were initially established in the early 1980's due to emerging concerns with the loss of the Earth's high atmospheric ozone layer and the potential impact on human health. The ODP of the once-common CFC refrigerant R-11 (trichlorofluoromethane, CCl3F) was set at 1.0 and others rated relative to this base. CFC ODP's are all in the range of 1.0 and are no longer widely used.

GWP Value Ranges – The concern over potential impact of the release of chemicals on the Earth's climate has focused increasing attention on the Global Warming Potential of various compounds. In LNG plants the refrigerants are used in closed loop systems, limiting releases to fugitive emissions and maintenance releases. The GWP of CO_2 is set at 1.0.

Table 3. Typical ODP and GWO Ranges for Refrigerants

Type	Example R-number	Typical ODP Range	Typical GWP Range[8]
CFC	R11, R12	1.0	5,000 – 15,000
H	R12B1, R13B1	5 – 15	2 - 7000
HCFC	R22, R123	0.005 – 0.2	77 - 3150
HFC	R23, R134a	0	675 - 14800
HC	R170, R600	0	5 - 1000
Natural	R717, R728	0	0 - 6

The category of "natural refrigerants" are starting to garner more attention due to their zero ODP, low (or zero) GWP and inherently high efficiencies. Natural refrigerants are chemicals that occur in nature's biochemical processes. These products were widely used prior to the 1950's, before fluorocarbon refrigerants became commonplace, with some being used in industrial refrigeration applications (i.e. ammonia refrigerant for ice production) in the 1800's. Common natural refrigerants include carbon dioxide, ammonia, nitrogen, and even water. Hydrocarbon refrigerants are often also classified as naturally occurring.

GAS TURBINE SELECTION

As highlighted above, gas turbine driven LNG plants represent an inherently efficient approach to delivering refrigeration power, as intermediate (efficiency reducing) components are eliminated with the gas turbines coupled directly to the refrigeration compressors. It is important to recognize that there is no ideal solution, one size or type is not best for all applications, and a number of different size and types of gas turbines have been successfully utilized for LNG plant compressor drivers. Key considerations in selecting a gas turbine driver for an LNG plant application include the following:

- Matching Gas Turbine power to compressor load – gas turbines are only available in specific discreet sizes and operate most efficiently when running at 100 percent power. Efficiencies drop off below 100% load and, depending on the turbine characteristics, radically below 70% load. Consequently, the plant designers must aim to align plant size and compressor duties with available turbine sizes to obtain the greatest efficiencies. Helper motor/turbine arrangements can help to ensure maximum gas turbine power utilization in some arrangements;
- Commonality – plant designers seek to provide uniformity to the selection of gas turbines across the facility, applying the same machine in multiple services. The advantage of this is to minimize costly spare parts requirements and facilitate familiarity with the machines for operations and maintenance. The potential disadvantage is potentially sub-optimizing the process design, fitting the process to the turbines rather than vice versa. Some gas turbine plants have elected to increase process and operations complexity to enable commonality of drivers to be achieved;
- Type of Gas Turbine – generally, aeroderivative gas turbines are more efficient than industrial frame machines, consuming less fuel per unit of delivered power. Aeroderivative machines typically require higher fuel pressures, are more sensitive to fuel composition variations, are more sensitive to ambient temperature variations (which can be addressed

[8] Net, 100 year

with inlet air chilling) and generate greater quantities of NO_x pollutants but less CO_2 per unit of delivered power than industrial frame machines. Aeroderivative gas turbines are commonly more tightly packaged than industrial frame units, with arrangements yielding easier/faster core swaps;

- Cost – the higher efficiencies and tighter packaging of the aeroderivative machines typically comes with a higher initial CAPEX than industrial frame machines, although commercial competition can narrow this significantly;
- Maintenance Requirements – this varies significantly between machines and must be assessed carefully. Considering long term LNG facility operations, commonly the two most substantial OPEX costs are personnel salaries and gas turbine maintenance;
- Shaft Design – single shaft gas turbines must spin up the direct coupled refrigeration compressor together with the gas turbine itself. To enable this, a combination of large helper motor/turbine plus initial depressurization of the refrigerant loop is necessary to meet the gas turbine ramp up profile. Multi-shaft gas turbines decouple the compressor load, enabling the gas turbine to ramp up largely independently of the compressor; and
- Experience – as outlined above, novelty is avoided in LNG plant applications.

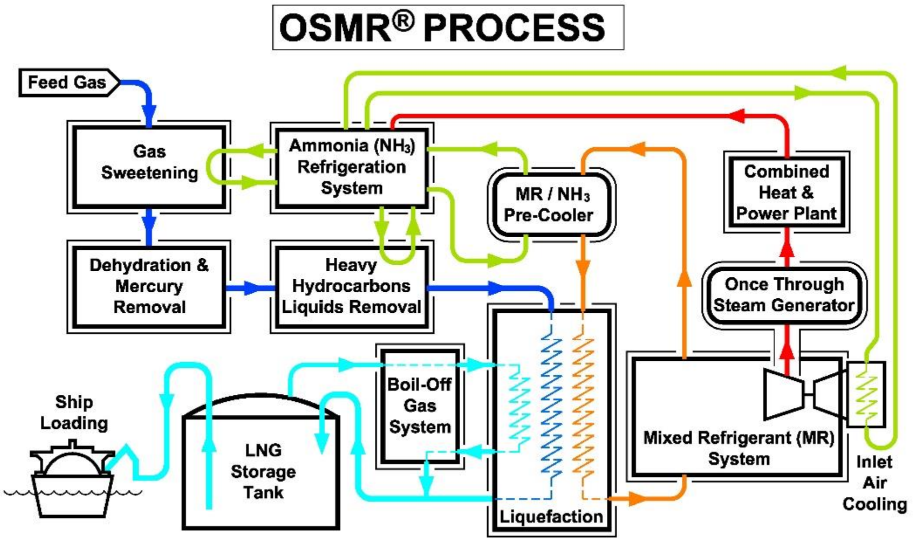
OSMR® FOR THE MAGNOLIA LNG PROJECT – INNOVATION FOR A CHANGING WORLD

An Australian based company is seeking to establish a concept of mid-scale, low cost, efficient, reliable and repeatable natural gas liquefaction projects for the world's energy market. The market entry project has been identified as a 4 x 2 mtpa liquefaction facility (8 mtpa total) on the US Gulf Coast in Lake Charles, Louisiana. As an emerging LNG proponent (as opposed to the major established national and international energy companies historically building and operating LNG facilities), they recognized it would be challenging to compete for project opportunities without bringing specific advantages to the table. Four key principles were established to deliver the necessary advantages – industry leading capital cost; optimized plant energy efficiency; shortened development and construction schedules; and an overall smaller environmental impact footprint including reduced carbon emissions relative to other LNG technologies. Without clear advantages such as these, investors and LNG buyers would simply stay with the established LNG producers.

The Optimized Single Mixed Refrigerant process (OSMR®) was created with the above four principles as a goal, with an emphasis on reliability and safety, to result in a facility that is relatively simple to design, construct, operate and maintain. This technology development was considered broadly, representing an execution strategy as well as a process technology itself. At the core, OSMR® represents an innovative combination of elements of existing technologies with inventive engineering process design and configuration in a mid-scale (nominally 1.5 – 3.0 mtpa) train capacity to address the shifting priorities in the LNG market. The creativity of this arrangement lies in the unique synchronization of all elements of the facility to achieve the maximum process and cost efficiencies in a reliable plant. LNG production is physics, not chemistry; it "cannot not work" – gravity cannot fail and neither can refrigeration nor heat transfer. Elementally, the configuration represents a pre-cooled mixed refrigeration liquefaction system, which in itself represents a major foundation element of the LNG industry.

A simplified process schematic is shown in Figure 2, below. Pipeline feed gas from the US gas grid is pretreated to remove sulfur, carbon dioxide and any trace mercury, dehydrated, and processed to remove heavy hydrocarbons that could potentially freeze in the liquefaction process. The feed gas is pre-cooled with a single component refrigerant, then liquefied with a mixed component refrigerant selected to closely mimic the cooling curve of the natural gas to achieve best efficiency. The pre-coolant refrigerant also serves as a means to pre-cool the mixed refrigerant to further enhance the efficiency. The high pressure product LNG is then flashed into storage for export.

Figure 1. Overall Simplified OSMR® Process Schematic



Elements of OSMR® Technology that enable the project to meet the corporate objectives are as follows:

Selection of Pre-Cooling Refrigerant

Larger base load LNG facilities have historically utilized pre-cooling refrigerant as a means to optimize the process. Propane has been the universal selection as it represents an efficient refrigerant well suited for large industrial applications and, importantly, could be extracted from the feed gas of remote location facilities. US Gulf Coast pipeline feed gas facilities (as well as coal seam gas plants in Queensland, Australia) have little or no propane in the feed gas, necessitating the import of pre-cooling refrigerant. Anhydrous ammonia (R717) was selected over the traditional propane for a number of reasons (below). Ammonia is commonly used as a primary refrigerant across many applications and industries requiring high cooling duties including cold storage, food and drink processing, ice production and skating rinks as well as in ammonia production facilities themselves. NASA also selected ammonia refrigeration to provide cooling duties for the International Space Station. Supportive characteristics of ammonia refrigerant include:

- Readily available and relatively inexpensive refrigerant;
- Equipment costs are low; like propane, ammonia refrigeration systems require only carbon steel and not expensive alloys;

- With lower swept volumes ammonia refrigeration plants provide a smaller equipment and piping, reducing capital costs;
- Ammonia is a highly efficient refrigerant; a side-by-side comparison of Ammonia and Propane refrigeration circuits delivering the same cooling load is shown below:

Table 4. Comparison of Ammonia and Propane Refrigerants

	Ammonia	Propane
Mass Heat Capacity	1	0.80
Mass Flow	1	3.94
Discharge Volume Flow	1	1.15
Suction Volume Flow	1	1.25
Compressor Power	1	1.02
Condenser Duty	1	1.00
Condenser Area (UA)	1	2.00

- Ammonia is classified as a natural refrigerant; it is environmentally friendly and naturally occurring with a life cycle in the atmosphere of less than one week. It has a Global Warming Potential of Zero and an Ozone Depletion Potential of Zero;
- The relatively high efficiency of ammonia refrigeration also reduces indirect environmental emissions as less energy is necessary to deliver the required cooling duty. The use of natural refrigerants is endorsed by prominent environmental stewardship groups[9];
- Industry experience with ammonia refrigeration systems is extensive, and there are well established regulatory frameworks in place. For LNG projects in the United States, the Federal Energy Regulatory Commission (FERC) hold primary responsibility, support by cooperating agencies including the Environmental Protection Agency (EPA) and the Office of Safety and Health Administration (OSHA). There are over 7,000 ammonia processes in the US covered under the EPA Risk Management Program, including more than 2,000 ammonia refrigeration facilities. Similarly in Australia, the Hazardous Industries and Chemicals Branch (HICB) regulates the use of ammonia in LNG plant designs;
- Ammonia is an inherently safe refrigerant choice, as evident by its wide use for industrial cooling duties. The toxicity of anhydrous ammonia in relatively low concentrations must be managed (by comparison, propane is a simple asphyxiant) but it provides a number of advantages including:
  - Ammonia is not readily flammable – in most situations ammonia can be considered effectively non-flammable;
  - Ammonia is not readily explosive;
  - Ammonia is lighter than air, so as it warms it tends to rise and naturally dissipate;
  - Detection of releases in relatively low concentrations is rapid and reliable; and
  - Mitigation of ammonia releases is reliable and effective through the use of simple water sprays due to ammonia high affinity to, and solubility in, water.

[9] http://www.greenpeace.org/international/Global/international/planet-2/report/2009/5/natural-refigerants.pdf

Liquefaction Refrigerant and Cold Box Selection

OSMR® applies a patented[10] mixed refrigerant (MR) liquefaction process using conventional cold boxes. Refrigerants are selected to best approximate the expected natural gas feedstock cooling curve, and can be adjusted during operation to optimize for changes in feed gas and seasonal variations in ambient temperature. The MR is comprised of nitrogen, methane, ethane and butane, all of which are readily available on the US Gulf Coast. Chart Industries has been selected as the cold box / BAHX (brazed aluminum heat exchanger) supplier based on their extensive experience in this field eliminating any issues with performance for this critical equipment.

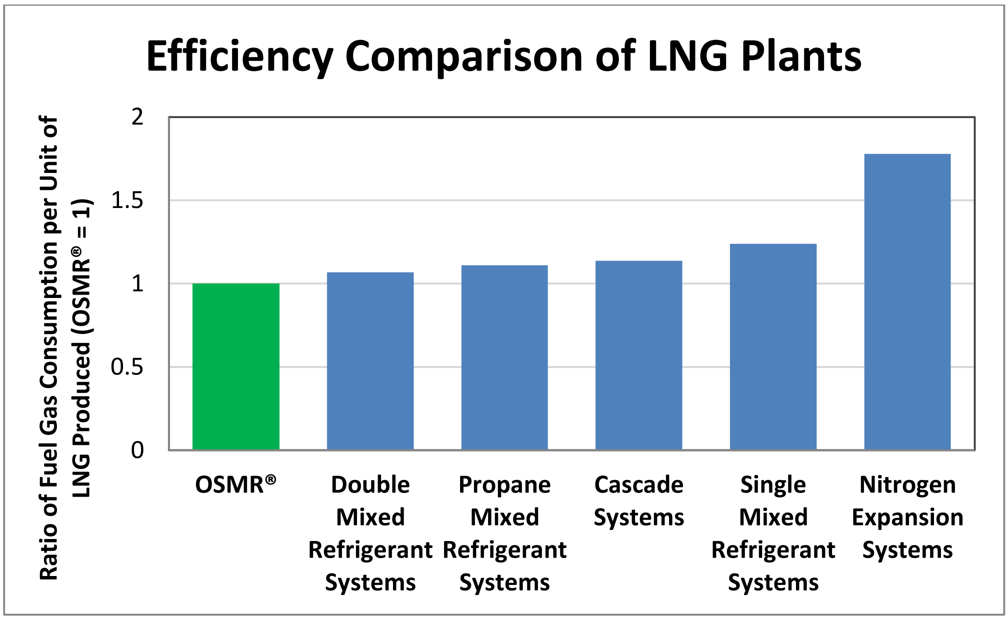


Figure 2 – LNG Plant Efficiency Comparatives (see page 6 also)

Boil-off Gas Handling

An innovative and patented[11] boil-off gas handling system is applied. The boil-off gas is lightly compressed, re-liquefied in the LNG train cold boxes, then passed through a liquid methane separator and returned to the LNG storage tank. This system enables recovery and re-liquefaction of low temperature boil-off gas while minimizing compression losses / compression heating that are commonly present in other design arrangements.

Refrigeration Compressor Driver Arrangement & Selection

One of the key elements in obtaining the high efficiencies of the OSMR® arrangement is the utilization of combined cycle refrigeration. Specifically, the MR refrigeration compressors are driven by high efficiency gas turbines; the waste heat in the gas turbine exhaust stream is used to raise steam, which then provides the majority of the motive power for the ammonia refrigeration compressors. Consequently, not only is the ammonia system inherently efficient itself, the ammonia compressors are driven by energy obtained almost entirely from waste heat (a small amount of additional steam is independently raised in auxiliary boilers to enable steam

[10] Australian Patents PCT/AU2008/001010 and United States patent US 9,003,828 B2; others granted or pending

[11] Australian Patent PCT/AU2008/001011; others granted or pending

balance control). Additionally, the MR and ammonia refrigeration strings are driven by different motive systems (gas fired and steam, respectively), with no need to force fit the duties or add complexity to the designs to balance identical driver loads. A "best fit" gas turbine is selected for the MR, then the ammonia steam turbine drive custom-designed to match (since steam turbines can be optimized to the required point). A Siemens SGT-750 gas turbine MR driver was selected. This is the newest generation of a design that originated in the 1960's with the SGT-600 and then SGT-700 machines, with over 300 machines in this family in service. The Siemens SGT-750 is technically an industrial gas turbine, but it blurs the line between the industrial and aero styles. The SGT-750 provides the same efficiency as similar aero units, as well as a tight package and the same high degree of maintenance accessibility, all while generating the low NO_x emissions and providing the robustness of an industrial unit.

Gas Turbine Inlet Air Chilling

Gas Turbine power output falls off with increasing ambient temperature. The selection of a high efficiency industrial gas turbine (as opposed to an aeroderivative) reduces this relationship to a degree, and the seasonal temperature variations on the US Gulf Coast are not extreme. The Project location's general climate classification is humid subtropical with a strong maritime influence. The predominant wind direction is from the south (off the Gulf) for much of the year, which tends to subdue extreme summer heat. Average monthly high temperatures range from 16°C (60°F) in January to 33°C (91°F) in August. Inlet air chilling using ammonia refrigerant is provided for the gas turbines, which ensures a consistent power output over the calendar year as well as supporting replication of design in alternate locations and climates.

Dual Drive Arrangement

In order to provide the maximum level of availability and reliability, each of the refrigeration compressors in the OSMR® design is arranged in a 2 x 50% "two-in-one" arrangement. Modules 4 and 5 (see section below) each house a steam turbine driven ammonia pre-cooling compressor including the ammonia condenser and air cooled steam turbine surface condenser. Modules 2 and 3 each house a gas turbine driven mixed refrigerant compressor, MR air coolers and MR ammonia coolers, and a dedicated cold box. Reliability, availability, maintainability (RAM) studies identify an availability in excess of 95%. In addition to the inherent reliability imparted (an LNG train can continue to operate at 50%+ capacity even in the event of the loss of any single compressor), the arrangement provides excellent flexibility for turndown operations as required in response to customer requirements.

Fit-for-Purpose

The facility design team expended substantial effort to generate a simple, fit-for-purpose project consistent with the US Gulf Coast location with its access to extensive supporting regional infrastructure and organizations. Well proven Contractor and Vendor standards have been applied. The extent of in-plant infrastructure was optimized to take advantage of available regional services. The compact 5-module arrangement also helps meet corporate objectives; typical modular LNG plant designs necessitate a relatively large number of modules per LNG train, spreading systems and pipe racks across multiple modules and yielding a large quantity of field hook-ups. The OSMR® approach to modularization in the mid-scale facility is to utilize only five modules for each liquefaction train incorporating both pipe racks and process units:

- Module 1 Gas Treating / Utilities
- Module 2 MR Liquefaction
- Module 3 MR Liquefaction
- Module 4 NH_3 Pre-cooling
- Module 5 NH_3 Pre-cooling

Modules 2 & 3 and 4 & 5 are identical, consistent with the dual drive arrangement outlined in item 5, above. Because the five modules are arranged by process systems, coupled with integration of the main train pipe rack into the process modules themselves, module-module interconnections are minimized reducing the number of field hook-ups and the associated time and site labor necessary accomplish project completion. The combination of a compact site coupled with a high level of hydrocarbon processing project activities in the site region makes modularization a necessity. Modularization also supports the corporate objective of replicating the design in subsequent projects. A substantial effort was applied to the project to minimize the physical size and weight of the process modules, supporting an optimized project schedule together with very competitive project economics.

Site Selection Process

The site for the project underwent a screening study to identify the most suitable location, with the final selection make for a number of reasons:

- The land is owned by the Port of Lake Charles and zoned as industrial property with no nearby residential or commercial retail properties;
- The site is readily accessible from existing roads including an all-weather road running the length of the south side of the property;
- The site lies adjacent to an Industrial Canal (IC) and associated turning basin on the immediate north side. The IC has been used for LNG ship transportation since the early 1980's, servicing LNG imports to the Trunkline LNG receiving terminal (slated to be put into future export service as Lake Charles LNG). Maintenance of the IC including dredging is the responsibility of the US Army Corps of Engineers;
- No jetty is required; a berth pocket will be dredged out of the property adjacent to the Industrial Canal and the LNG ship dock constructed along the new bulkhead. In addition to the absence of a jetty, no breakwater or other marine facilities outside of the mooring, breasting and loading facilities themselves are required;
- An existing 42" Kinder Morgan Louisiana Pipeline runs along the south side of the

property; a simple interconnect into this existing adjacent pipeline provides the natural gas feed to the Magnolia LNG facility;

- The property itself is nominally 30 feet above mean sea level compared to a hurricane storm surge of 11 feet. The elevation was created in the 1970's as dredge spoils from the construction of the Industrial Canal;
- Electrical power is available from an existing substation located less than two miles from the site;
- The site is within the coverage area of existing telecommunications and internet service providers;
- Hospital emergency rooms are located within 15 minutes of the site;
- The Lake Charles region, part of the Beaumont – Port Arthur – Lake Charles "Golden Triangle" is home to numerous industrial and infrastructure support services organizations and contractors; and
- The total 115 acre size of the Magnolia LNG property, while challenging for initial construction due to the limited laydown area, is ideal for an operational mid-scale facility. Other regional LNG proponents had previously discarded the location as being too small for conventional plant designs while the compact OSMR® 5-module trains are well suited to this location.

SUMMARY

The LNG industry was founded on the basis of remote site liquefaction facilities shipping a critical product with limited availability to destination customers under long term contracts. This approach fit a specific set of needs but did not foster innovation or rapid development. With the recent transition of the liquefaction industry from the most remote corners of the planet to highly developed industrial zones, the opportunity to diversify the production of LNG have emerged – a "one size fits all" approach is no longer the only choice available to further the competiveness of the LNG industry.