SELECTING DESIGN CRITERIA FOR NATURAL GAS LIQUEFACTION FACILITIES

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ABSTRACT

The design of a natural gas liquefaction facility must consider performance over a range of operating conditions. Among these are ambient temperature and vessel motion (for floating LNG platforms). Economic plant design necessarily involves tradeoffs, and selecting the design basis without proper judgment may negatively impact the LNG project economics. The design basis is generally selected to cover a reasonable range of operating conditions, with the understanding that plant performance will be lower when operated outside this range. The selection of an appropriate design value for each parameter is important to ensure that the facility is able to operate successfully over its lifetime, while also avoiding excessive overdesign.

Two case studies were performed to investigate the selection of design values for (a) ambient temperature and (b) floating vessel motion for an LNG facility. We show how the selection of these design criteria affects overall plant performance, and discuss how these important plant design variables should be carefully considered in the early stages of project execution to ensure that the overall liquefaction facility design meets the project goals.

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INTRODUCTION

The design of a natural gas liquefaction facility must consider the plant performance over a range of operating conditions. These operating conditions can be described by a set of *design parameters* and *operating modes*. A partial list includes

- Ambient temperature (affects both air coolers and GT driver power)
- Other cooling medium temperature (if not air-cooled)
- Feed gas composition
- Floating LNG vessel motion
- Holding/loading modes
- LPG storage/reinjection modes

A simplified outline of the facility design procedure is

1. Choose a plant configuration (select unit operations)
2. Determine a preliminary equipment list
3. Define the basis of design (BOD), including operating modes and design parameters, and operating goals to be met
4. Perform calculations (including computer simulations) to develop a heat and material balance (HMB) conforming to the BOD
5. Design equipment items to meet the HMB and BOD

An HMB can be generated for each Operating Mode (e.g. holding mode, then loading mode), and the design of any equipment common to both modes then selected to meet the most demanding service. Design for very large operating ranges or apparently contradictory requirements may need some thoughtful work, but is usually possible, sometimes by incurring additional cost. For example, a valve operation which needs to control flow at a high rate in one mode and a low rate in another mode may require a large valve and small valve in parallel to provide sufficient control range.

The plant must be designed for a range of operating conditions. The BOD could include several values for each design parameter, and the HMB be generated for each of several sets of parameters, with the equipment then designed for the most demanding service. However, this can lead to excessive overdesign of equipment if the values of the design parameters in the BOD are not carefully chosen.

For example, the ambient temperature has a large effect on the operation of a typical LNG facility. The power available from gas turbine drivers (GTD) varies widely, decreasing as the ambient air temperature increases. Air-cooling of process streams leads to wide performance differences as the air temperature changes from day to night and summer to winter, with the lowest performance typically at the hottest temperatures. To ensure that the required annual performance is achieved, should the plant be designed for the hottest month of the year? The hottest day of the year? The hottest hour? For a fixed production, designing for the successively higher temperatures results in each design requiring higher installed power and being more expensive than the previous. Also, some equipment items can only be designed with given operating range, e.g., 70-105% of design performance. If the design point is at an extreme hot temperature, the equipment may not perform as well at colder temperatures, which can actually result in lower annual performance.

Likewise, the motion experienced by a floating LNG (FLNG) vessel is determined by the various sea states over the course of the year and vessel design. Vessel motion impacts the flow patterns in two-phase streams, which can reduce process performance in rough seas. For good annual performance, should the plant be designed for the motion typical for 75% of the year, or more severe conditions, such as a 99% non-exceedance level (that which is not exceeded for 99% of the year)? While the mechanical design of equipment must take into account the worst conditions for survival, excessively severe motion conditions for process design will be more expensive than that for less severe conditions and may offer only marginal improvement of annual performance.

The appropriate values for the final plant design, without resorting to excessive overdesign, may not be obvious. Economic plant design necessarily involves tradeoffs, and selecting the design basis without proper judgment may negatively impact the LNG project economics. A design basis is generally selected to cover a reasonable range of operating conditions, with the understanding that plant performance will be lower when operated outside this range. Balancing this production or efficiency loss against the increased cost of a design to cover a wider basis is the goal of design optimization.

In this paper, we present the results of two case studies to show how the selection of ambient temperature and FLNG vessel motion affects overall plant performance, and discuss how these important plant design variables should be carefully considered in the early stages of project execution to ensure that the overall liquefaction facility design meets the project goals.

CASE STUDY 1: AMBIENT TEMPERATURE

METHOD

The study was carried out by computer simulation. The basis of the study is an Air Products AP-C3MR™ LNG Process using gas turbines for refrigeration drivers with air-cooling of the refrigeration streams. Liquefaction was assumed to take place in a single coil wound Main Cryogenic Heat Exchanger (MCHE). For simplicity, the feed gas is assumed to have been processed in an upstream NGL plant. This avoids the complexity of simulating the NGL plant or integrated scrub column. The plant fuel balance is closed by adjusting the MCHE outlet temperature to provide sufficient end flash gas to supply the GTD at an assumed thermal efficiency of 33%. [1]

Two locations were selected to represent typical LNG plant locales. The first represents a hot desert climate such as that in the Middle East and the second represents the US Gulf Coast. Climate data were obtained from ASHRAE 2013 [2] and several values are summarized in Table 1. The total available GTD power was estimated as a linear function of ambient temperature, between 1°C and 40°C.

Table 1. Temperature Summary

Location All values in °C	**Hot Desert**	**US Gulf Coast**
Extreme annual high (1)	47.0	36.4
99% summer high (2)	42.8	33.8
Highest monthly average	36.3	28.3
Average annual	28.1	20.4
Lowest monthly average	17.8	11.4
99% winter low (2)	12.8	1.0
Extreme annual low (1)	9.3	-4.1

Notes: (1) Maximum/minimum temperature observed in an average year
(2) Exceeded 1% of the hours in a year, 88 hours

Two types of cases were developed, Design cases and Rating cases, each at a selected value of ambient temperature over the range from 1 to 40°C.

DESIGN CASE. For each Design case, the LNG process was simulated at a given value of ambient temperature. The head and suction flow for all refrigeration compressors were designed to maximize LNG production, using polytropic efficiencies of 83%, while fully utilizing the available GTD power. Air coolers were assumed to have fixed temperature approaches, and the MCHE was designed to maximize the LNG production.

For each Design case, the HMB was used to develop typical compressor performance curves for head and efficiency vs. volumetric flow. These curves were used in the Rating cases.

RATING CASES. Using the compressor curves for a chosen Design case, the LNG process was simulated at warmer and colder ambient temperatures to rate the plant performance. The design of all other equipment, including air coolers was not held constant. This prevents those items from limiting production. However, it may also result in equipment being oversized at some ambient temperatures.

RESULTS

EFFECTS OF AMBIENT TEMPERATURE. The data in Table 1 above present several possible choices for the design point temperature for the two locations. Each of the Design Cases provides a sizing basis for the refrigerant compressors. Figure 1 shows the suction volume flow for the LP MR compressor and the first stage of the propane compressor as a function of design ambient temperature. The suction volume flow is a useful proxy for the overall compressor size and cost. The LP MR compressor increases in volume flow by about 50% from 40°C to 1°C due to increased LNG production.

The propane compressor also increases in size as temperature is reduced, but the effect is smaller at colder temperatures. The minimum allowable propane suction pressure is just above atmospheric pressure, to prevent operation in vacuum. The propane cooling duty is therefore limited by the boiling point of the low pressure propane, about -40°C, and so the duty is reduced at cold ambient temperatures. As a result, the propane compressor consumes a lower fraction of the refrigeration power and becomes smaller relative to the MR compressor.

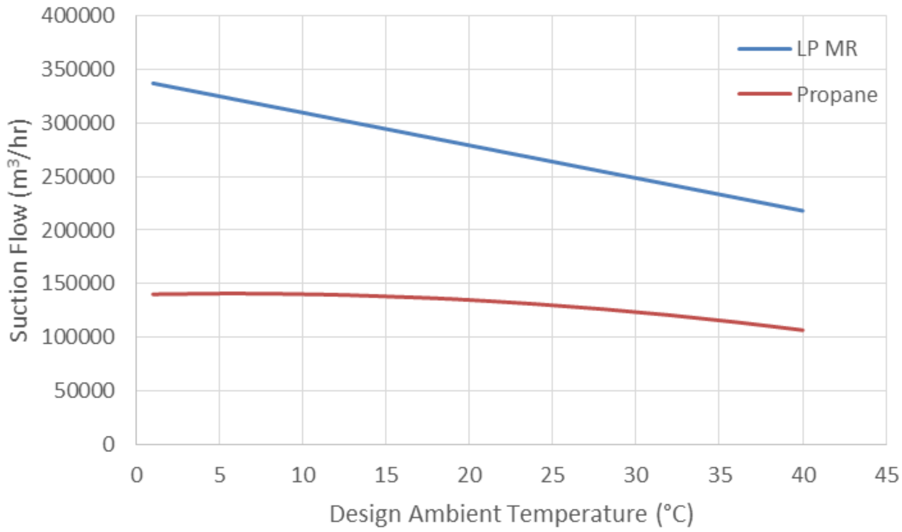

Figure 1. Design Case Compressor Suction Flow.

Figure 2 shows the LNG production as a function of ambient temperature. The Maximum Production curve is the set of all Design cases and gives the maximum LNG production at a given temperature, utilizing all the available GTD power. At each temperature point, all equipment is designed to maximize production at that temperature. The production increases about 80% as the temperature decreases from 40°C to 1°C, while the available power has increased only 34%. The additional improvement is the result of higher liquefaction process efficiency at the colder temperatures, due to the effect on feed gas and compressor intercooler temperatures, and reduced propane discharge pressure.

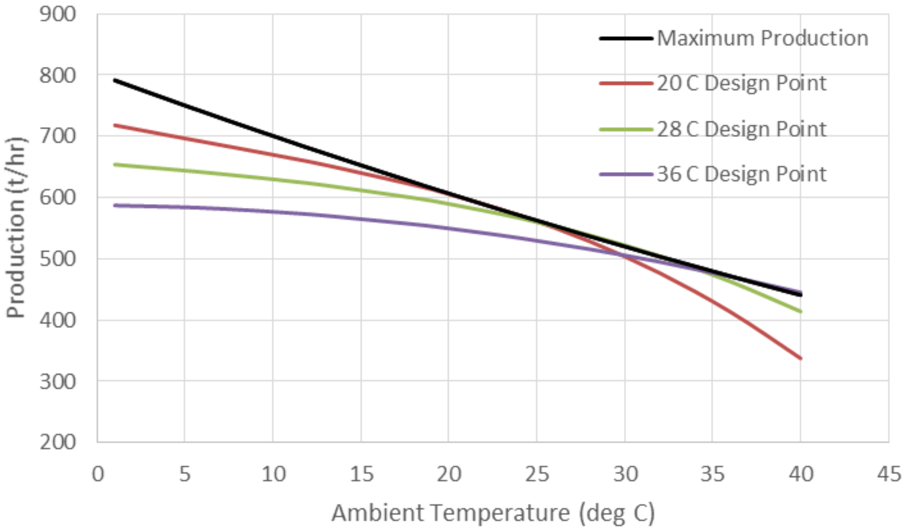

Figure 2. LNG Production over a Range of Ambient Temperatures.

The three other curves are constructed from the Rating cases for single plant designs based on design ambient temperature of 20°C, 28°C, and 36°C, respectively. The Rating cases were developed as described above. As expected, the production decreases as the ambient temperature gets warmer and increases as the ambient temperature gets colder. However, when not at the design ambient temperature, the production is always lower than the Maximum Production curve because the compressors are running at off-design conditions. This reduction is the off-design performance penalty.

The performance reduction at off-design conditions is primarily due to capacity limitations of the refrigeration compressors. The propane compressor discharge pressure is set by the condenser temperature. The propane compressor operating point moves toward stonewall at cold temperatures (low head) and toward surge at warm temperature (high head). Typical compressor curves are shown in Figure 3. Compressor operation away from the design point results in non-optimal refrigerant flow and pressure, and also adversely impacts the compressor efficiency. At sufficiently hot temperatures, the operation near surge forces the compressor into recycle. Operation at very cold temperatures can also result in recycle operation, to prevent the compressor suction from being drawn into vacuum.

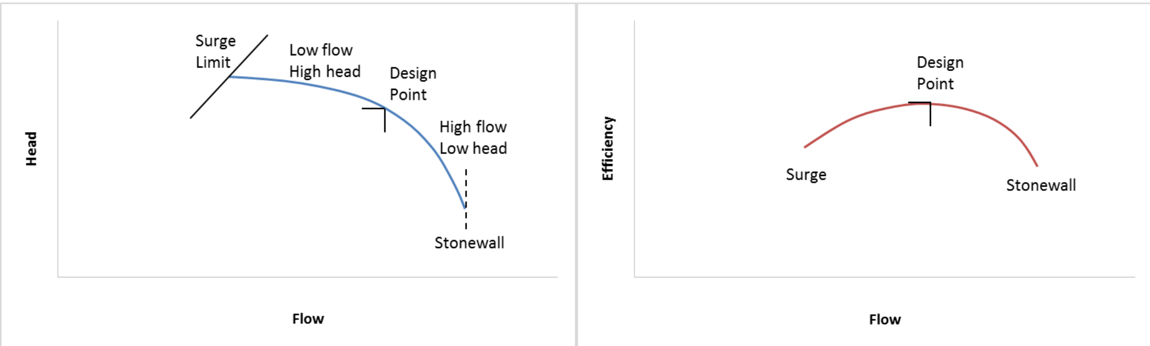

Figure 3. Effect of Flow on Compressor Operation.

For the LP MR compressor, the design suction volume flow is sensitive to the ambient temperature due to the wide range of LNG production. The 36°C Design case suction volume flow is about 80% of 20°C Design case volume flow, about the same ratio as the LNG production. In off-design warm temperature operation, the flow determined by the compressor curve is too large, and the LP MR compressor suction pressure is reduced, which reduces the HP MR discharge pressure and results in lower process efficiency. At cold operating temperatures, more suction flow would be preferred to allow more LNG production, however the MR compressor operation is restricted by the compressor curve stonewall limit. There is also some reduction of compressor efficiency due to operation closer to stonewall.

ANNUAL PERFORMANCE. Since the actual LNG facility will need to operate over a range of temperatures throughout the year, the choice of design temperature affects the annual expected production from the facility. Using the climate data described above, one can construct a model of the facility operation over the course of a year. It is possible to use a sophisticated analysis to attempt to obtain a highly reliable estimate, for example, using a statistical model for operating conditions and a Monte Carlo simulation to determine plant performance within some probability window. For illustrative purposes, we will use a much simpler approach.

The curves of Figure 2 provide the LNG production at any operating temperature, for each of the three design point temperatures. For each month of the year at a given location, the monthly average temperature was obtained from the ASHRAE Handbook. The monthly production was then assumed to correspond to the production, as provided by Figure 2, at the average temperature for that month. Figure 4 shows results for the Hot Desert climate. The monthly average temperature is plotted on the right axis and the resultant production curves on the left axis. For the Hot Desert climate, the monthly average temperature ranges from 18°C in the winter to 36°C in the summer. The three Design Point curves each show the production for compressors which are sized using the respective design point temperature. The Maximum Production curve of Figure 2 is included in the analysis for comparison. This represents a hypothetical plant in which the compressors are not fixed in size, but instead are always operating at the optimum point for any air temperature. This is the maximum possible production for the basis of design chosen for the study.

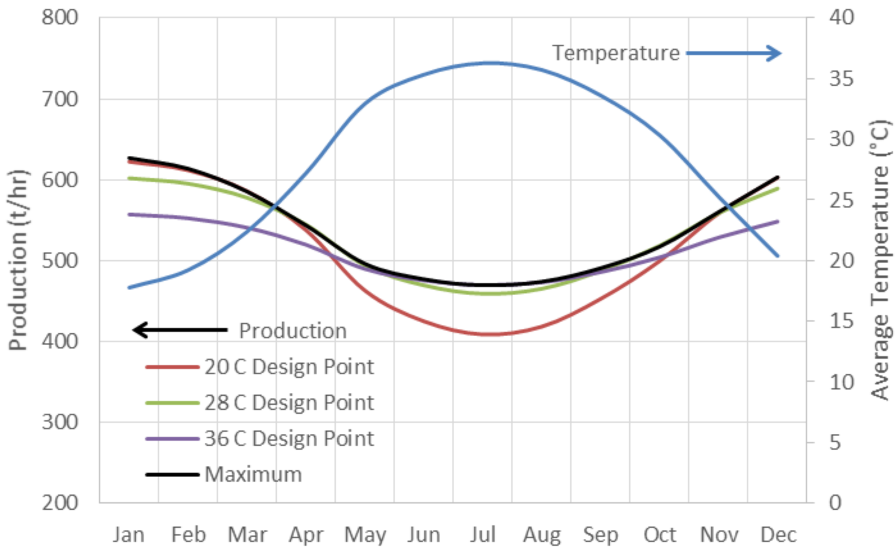

Figure 4. LNG Facility Performance for Hot Desert Climate.

One sees that no one curve can match the Maximum Production curve at all times during the year, but there are areas of overlap when the ambient temperature is close to the particular design point. The 36°C curve closely follows the Maximum Production curve during the summer months, while the 20°C curve nearly matches during the winter months. At other times of the year, the two curves show a clear production deficit relative to the Maximum Production curve. To maximize the annual production, the design point curve should follow the Maximum Production curve as closely as possible, and for this case the 28°C curve appears to give the best overall performance. Table 2 gives the average annual production for the Maximum Production curve and the three choices of design point. For simplicity, the annual production is calculated assuming 100% availability. The 28°C curve provides 98.5% of the maximum possible production, well above the other two curves.

Table 2. Annual Production for Hot Desert Climate

Design Point	Maximum Production*	20°C	28°C	36°C
Annual Production (MTPA)	4.71	4.52	4.64	4.49
Percent of Max. Production	100	95.7	98.5	95.2

*Hypothetical production in which the refrigerant compressors are optimized for each ambient temperature point.

The same analysis can be carried out for the US Gulf Coast climate. As this is a milder climate, one may expect that the optimum design temperature would be lower, and it is. Figure 5 and Table 3 provide the details.

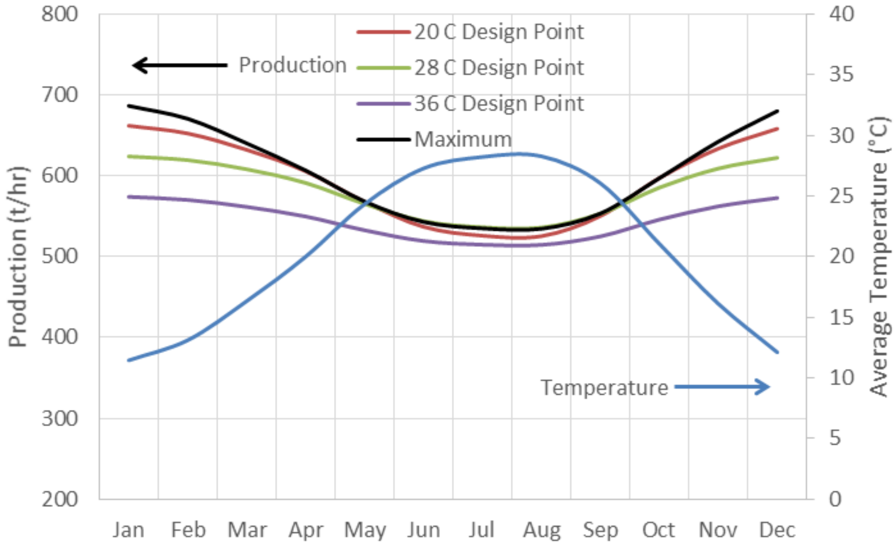

Figure 5. LNG Facility Performance for US Gulf Coast.

Of the three design points studied, the 20°C curve appear to give the best overall performance. The 28°C curve provides slightly better performance in summer, at the expense of production in winter. As we shall discuss below, this design point may be preferable in some circumstances, due to the fact that its curve is less peaked summer-to-winter, than the 20°C curve. The 36°C design point gives less production year round than either of the two alternatives. Designing to this value, the Extreme Annual High, would appear to offer little benefit.

Table 3. Annual Production for US Gulf Coast Climate

Design Point	Maximum Production	20°C	28°C	36°C
Annual Production (MTPA)	5.30	5.22	5.11	4.78
Percent of Max. Production	100	98.5	96.4	90.1

*Hypothetical production in which the refrigerant compressors are optimized for each ambient temperature point.

Here, the best design temperature is 20°C, for which the annual production is 98.5% of the maximum possible. We note that in both locations, the highest average annual production corresponds to a design point at the average annual temperature. This is probably not so much coincidence, but rather the effect of the shape of the various curves. The monthly temperature trend is reasonable symmetric around the average annual value, and the production curves of Figure 2 are also almost symmetric around the design point temperature.

PROJECT OPTIMIZATION. The previous discussion implicitly assumes that the goal of the project is to produce the most LNG for a selection of refrigeration compressor drivers. However, if a fixed annual LNG production is required and it is less than 4.64 MTPA (28°C design point in Table 2) for the Hot Desert location, then a higher ambient temperature design point may have a lower CAPEX. Likewise, if less than 5.22 MTPA annual production is required for the US Gulf Coast location (20°C design point in Table 3), then a higher ambient temperature design point may be more economical. This is demonstrated in Table 4.

The table shows the average, maximum, and minimum production rates for the two locations and three design points. One can see that for the Hot Desert location and a 28°C design point, the average production rate is 530 tonne/hr, corresponding to the 4.64 MTPA value in Table 2. However, the maximum production rate is 602 tonne/hr, which occurs during the colder part of the year. For the set of Rating cases performed for each Design Point, only the compressors were fixed. The design of the other equipment was assumed to be based on the most demanding conditions throughout the year, which is typically at the maximum production rate. To achieve the 4.64 MTPA annual production, the front end units, including acid gas removal, dehydration, and NGL removal, and the storage tanks would all need to be designed to support the maximum production rate, which is about a 14% overdesign compared to the average rate.

Table 4. Production Flow Rates

	Design Point	20°C	28°C	36°C
Hot Desert	Average production rate (t/hr)	515	530	512
	Maximum production rate (t/hr)	622	602	557
	Minimum production rate (t/hr)	409	459	470
US Gulf Coast	Average production rate (t/hr)	596	583	545
	Maximum production rate (t/hr)	662	624	574
	Minimum production rate (t/hr)	525	536	515

If the full 4.64 MTPA annual production is not required, the plant could be designed with the 36°C Design Point compressors. This would achieve 4.49 MTPA annual production, about 3% lower, but the maximum winter production rate is 557 tonne/hr, and therefore the required capacity of the front end and storage systems would be about 7.5% lower. This may be a more economical design if the additional production is not required.

If the 28°C Design Point is used, and the plant simply scaled down to make 4.49 MTPA annually, the summer production is lower than for the 36°C Design Point (see Figure 4), and the winter production rate is about 580 tonne/hr to make up the difference. This is larger than the 557 tonne/hr winter rate for the 36°C Design Point, and therefore implies that the scaled-down 28°C design would still require 4% larger front end and storage systems. One sees that the flatter production profile of the hotter temperature design can be an advantage, as long as the overall lower annual production is acceptable.

At 20°C, the average production is lower, and the maximum flow rate is higher, than at 28°C. This would require a facility with larger front end and storage systems, to support the high winter production rate, but one that provides lower annual production. Designing to a temperature lower than the annual average would therefore appear to lead to no benefit, unless there is a reason to maximize LNG production in the winter.

For the US Gulf Coast climate, the maximum annual production of 5.22 MTPA is achieved at 20°C, but a design at 28°C could provide 5.11 MTPA, which is a 2% reduction. The required capacity of front end and storage systems, as determined by the maximum production rates of 662 and 624 tonne/hr respectively, would be 6% lower for the hotter design point, and may therefore offer some CAPEX savings. Moving from 28°C to 36°C, the annual production loss would be about 6%, and the maximum flow rate about 8% lower, which indicates less favorable marginal savings of CAPEX to production.

So what is the optimum design point? The answer (as so often) is that "it depends". In this case, it depends on the project requirements. Some general factors can be considered:

- Minimum instantaneous production – The facility will almost certainly need to produce above some minimum LNG flowrate, to meet customer demand. The minimum production occurs at the warmest ambient temperature. Designing for a higher ambient temperature (up to the highest temperature seen for a significant part of the year for the plant location) gives a higher minimum production.
- Average annual production – The plant will produce more LNG as the ambient temperature gets colder. Designing for a colder ambient condition (as cold as the annual average) increases annual production, but required larger equipment.

- Maximum instantaneous production – if the customers can take more production when the plant is operating at colder temperatures, then the maximum production may have value.

Each design temperature has specific characteristics

- Average design temperature (e.g., 28°C for the Hot Desert climate) – this gives the highest average production, but the plant must be designed for high flow rates during the cold part of the year.
- Hot design temperature (e.g. 36°C for the Hot Desert climate) – this gives the highest minimum production during hot parts of the year, but may have a lower maximum rate in cold times. The loss of some annual production may be offset by the possible reduction of equipment size to make this an economical alternative, if it is not necessary to obtain the highest possible annual production.
- Cold design temperature (e.g., 20°C for the Hot Desert climate) – this gives larger production rate swings between hot and cold parts of the year, and a lower annual production than at the average temperature. The high maximum rates which require larger equipment capacities, combined with the lower annual production, would appear to make this unattractive compared to either of the other two.

CASE STUDY 2: FLNG MOTION

METHOD

The basis of the study is an Air Products AP-DMR™ LNG Process with precooling and liquefaction in coil wound heat exchangers (CWHE). The HMB was chosen to represent an FLNG facility with capacity of about 3.5 MTPA.

For a particular FLNG vessel design, operational motions are determined by a statistical analysis of the possible sea states. The motion basis shown in Table 5 was selected to be representative of conditions ranging from moderate to severe sea states, and is specified in terms of a return period for a 3 hour sea state. The term return period is statistical prediction of how frequently a particular sea state is expected to occur. For example, a sea state with a 1 year return period is expected to occur annually. Return period can be converted to a measure of the fraction of time that the sea state will be exceeded by using the equation below:

$$Percent\ Exceedance = \frac{Length\ of\ Sea\ State\ (hr)}{8760 \cdot Return\ Period\ (yr)} \cdot 100\%$$

Table 5. FLNG Motion Occurrence

Return Period (yr)*	**0.5**	**1.0**	**10**
Percent Exceedance	0.068	0.034	0.0034

*Return period for a 3 hour sea state.

One can see that these sea states are relatively rare. FLNG equipment design will also include more severe motions that are typical of catastrophic storms, towing conditions, and vessel damage conditions, in which the facility is not expected or designed to operate. Those additional conditions are required for a complete mechanical design of the equipment, but are not directly relevant for the process (thermal) design discussed here.

The FLNG motion basis impacts the design of processing equipment that requires liquid distribution, such as heat exchangers with two-phase flow, absorbers, and distillation columns. In general, increased pitch/roll motion or vessel heel/trim results in higher lateral accelerations within the equipment, which can cause non-uniform flow. To obtain the required performance from this equipment, the motion and tilt effects must be mitigated by proper design. [3, 4]

Air Products has carried out an extensive design verification program to validate CWHEs for FLNG service. [5] This work included fundamentally-based experiments, pilot scale test units, and dynamic simulation. The fundamentally-based experiments investigated the flow of hydrocarbons across the tubes in a CWHE to quantify the flow behavior under various motion conditions. The experimental results were used to develop a proprietary model which predicts the shell-side liquid distribution as a function of heat exchanger geometry, vessel motion, and process conditions. The model was validated in a pilot scale wound coil exchanger bundle, and incorporated into Air Products' well established heat exchanger design methods. Air Products can use the computer models to predict the performance of a given design, when subjected to a specific level of motion. The design can then be adjusted to eliminate the effect of motion on the overall heat transfer performance. Note that if the vessel motion is larger than that considered in the process design, the process will still perform, but efficiency or production may be reduced.

The results below use the CWHE design as an example of the effect of properly designing FLNG equipment for the motion and tilt conditions. To investigate the effects of motion on equipment size, CWHEs were designed to satisfy the HMB requirements, at each of the conditions in Table 5. To investigate the effects of off-design motion on the CWHE performance, each design was rated for more severe motion conditions.

RESULTS

Designing equipment such as the CWHE for motion conditions representative of a 0.5 to 1 year return can typically be achieved with only a modest increase in size from the base case. In order to achieve full production for more severe motions, the required increase in equipment size may be substantial. However, as shown below, designing the equipment for severe motions has limited value due to the rarity of these conditions.

Aside from the possibility of increasing cost, the increase in exchanger size for the designs at higher motion is also significant because it will result in heavier equipment. This increase in equipment weight may result in additional impacts when the weight of the FLNG vessel is considered, due to the multiplying effect of increased weight for supports and other structures.

An FLNG facility designed for a given motion basis will have some performance loss when subjected to more severe motion. Each of the FLNG CWHE designs was rated to determine the performance at motion conditions more severe than the respective design point.

For the designs studied, the performance reduction at more severe motions is less than 4%. It is important to note that the off-design motion is relatively rare, and therefore the CWHE design using the mildest conditions (Design Point 1) is sufficient for good annual performance. Table 6 presents the annual performance of the facility for this CWHE, using conservative assumptions for the duration of off-design motion. While the Return Period was defined using a 3 hour sea state, the analysis below assumes that the FLNG production is impacted for 12 hours by the off-design motion, the production during that time is given by the motion condition at the more severe end of the interval, and there is zero production when motion condition 4 is exceeded.

Table 6. FLNG Annual Performance for Design Point 1 CWHE

Return Period (yr)	**< 0.5**	**0.5-1**	**1-10**	**>10**
Percent of Operation*	99.58	0.27	0.14	0.014
Instantaneous LNG Production (%)	100	99.3	97.7	96.4
Average Annual LNG Production (%)	100	99.998	99.995	99.994

*Assumed for 12 hours per occurrence.

One can see that the impact of the more severe motion is negligible. Designing the CWHEs for the severe motion results in larger, heavier equipment, and therefore higher costs, but no performance gain when the rarity of the severe motion is taken into account.

SUMMARY

By carefully choosing the design basis, the project goals for developing an LNG facility can be achieved without costly overdesign. Two case studies, examining the effect of the design ambient air temperature and the design operating vessel motion, show that designing to extreme conditions can have a significant impact on the sizing and cost of equipment while not significantly improving the LNG facility performance. We have also shown that it may be possible to reduce costs by selecting a design basis in which equipment is not overdesigned, while incurring a negligible or modest performance penalty. The balance of cost reduction versus performance reduction is at the heart of design optimization.

In general, for an air-cooled LNG facility, the colder the design air temperature, the larger the required process equipment and the higher the design point production. A similar situation holds for water-cooled plants, except the range of cooling water temperatures is typically smaller. The design air temperature that maximizes annual production is likely close to the average annual air temperature. A design temperature which is shifted slightly to a hotter value may result in a design which is less expensive, at the cost of some production. Design to more extreme hot conditions, or colder than average conditions, is likely to be economically disadvantageous.

For an FLNG facility, the size and cost of the process equipment is affected by the design motion conditions. An extreme design motion basis will significantly increase the size, weight, and therefore the cost of the equipment and FLNG vessel, while providing only a negligible benefit to annual production.

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