A Focus on Balance – A Novel Approach Taking the Phillips Optimized Cascade LNG Process Into the Future

Wesley R. Qualls
ConocoPhillips, LNG Technology Licensing

Philip Hunter
Bechtel Corporation, Petroleum & Chemicals – LNG Group

3000 Post Oak Boulevard – Mail Stop 59
Houston, TX 77056

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Abstract
Capital cost, operations and maintenance costs, availability, production efficiency, and thermal efficiency are all common measurements used to compare technologies or even options within the same technology area. Within the LNG industry, availability and production efficiency are common measurement tools used to quantify such concepts as reliability, process stability, on-stream time, or percent of design production. However, availability and production efficiency are often overlooked or ignored early in the project in favor of reduced capital cost or improved thermal efficiency. On the other hand, with the growing importance of reducing emissions and energy consumption, thermal efficiency typically receives quite a bit of attention. Of course, the successful LNG project balances all project metrics, within project constraints, to offer the highest return on investment.

This paper will discuss the successful approach taken to date for the Phillips Optimized Cascade LNG Process. The concepts of the past and the successful adaptation to the present will be presented. A novel approach focusing on important project variables will then be presented to extend this same balanced and successful approach into the future.

1.0 Introduction

For any project, balancing variables such as capital expenditures, operations expenditures, thermal efficiency, production efficiency/availability, and schedule is or at least should be a necessary exercise. While this balancing act is routine, it is certainly not trivial. Some variables such as thermal efficiency, derived by dividing the higher heating value of the products by the higher heating value of the feed, are fairly straightforward. Others such as availability and production efficiency are more difficult. These particular variables are often derived through a detailed Reliability, Availability, and Maintainability (RAM) analysis considering the entire life cycle of the project. Due to various reasons, such as project funding requirements or fairness in design competitions, most project sponsors prefer the RAM analysis performed by an outside company with specialization in this area. Of the two terms production efficiency, which is predicted production divided by required production, is the most useful since it is a more appropriate measure of actual LNG produced on a life cycle basis. By contrast availability is more useful when considering total downtime and mean times to repair critical equipment. When even less definable variables such as process flexibility or stability are introduced, the exercise becomes even more complex. Balancing all the variables for several different configurations is a detailed and time-consuming process.

Process Engineers often churn through countless scenarios in order to determine an optimal project solution. Management, Marketing, Operations, Environmental, Quality Assurance, and other disciplines further define the project parameters by offering suggestions and perhaps necessary restrictions throughout the project that further increase the difficulty of balancing the variables. While this balancing act is sometimes frustrating, it is also necessary. It is a requirement to clearly define the boundaries unique to each discipline, preferably early in the project. Of course, the ultimate goal is an economical solution that fits within the defined boundaries. All too often net present value (NPV) is discarded in favor of low capital expenditures.

It is the task of the technology licensor to monitor and anticipate industry needs in order to develop competitive solutions that properly balance all considerations. Given the high importance of project schedule for an LNG project, one can see the importance of flexible and economical solutions that address typical industry requirements. Flexible solutions of this nature prevent completely “reinventing the wheel” on every project. It is also a given that technology improvements and advancements are imperative in order to remain competitive.

A novel solution utilizing the Phillips Optimized Cascade LNG Process has been developed for LNG production ranging from approximately 3.5 to 6.5 MTPA. However, as the solution to be presented capitalizes on a successful historical approach, a brief history is required in order to provide the proper perspective.

2.0 Early Phillips Optimized Cascade LNG Process

The first version of the Phillips Optimized Cascade LNG Process was successfully utilized for the Kenai LNG facility in Alaska. Figure 1 is a simplified graphical depiction of the process. The facility has been highly successful over the past 33 years of operation. In this configuration, feed is routed first through propane refrigerant followed by ethylene and finally methane. Each refrigerant is in a closed loop cycle with two or more refrigeration stages containing relatively pure single component refrigerants. The feed is simply chilled in successive refrigerant stages until LNG is produced. Of course, the JT effect from dropping feed pressure is also utilized in combination with the refrigeration cycles. Air or cooling water is utilized to condense propane, propane is utilized to condense ethylene, and ethylene is utilized to condense methane. Cooling water is utilized at Kenai. Boil off gas and ship vapors are simply compressed and used to supplement fuel gas requirements.

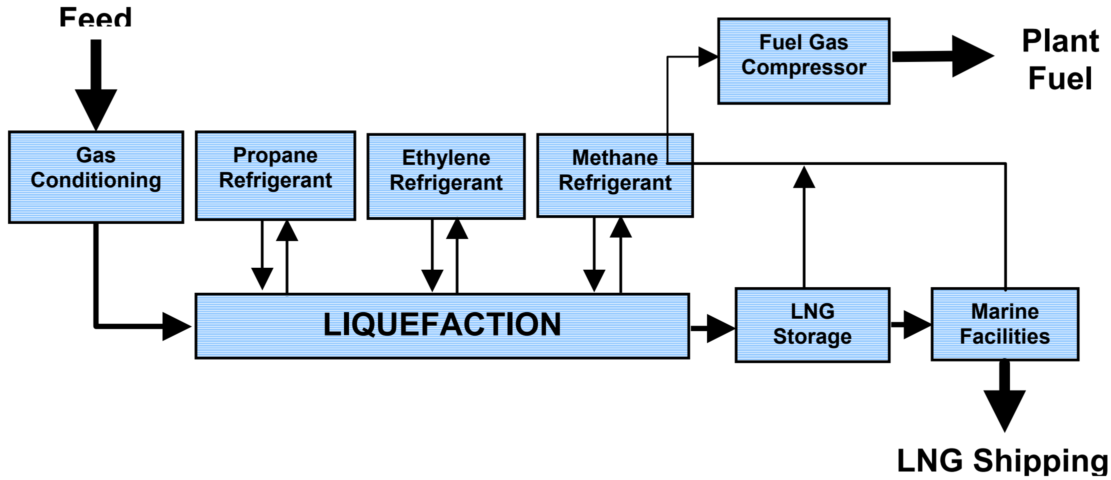
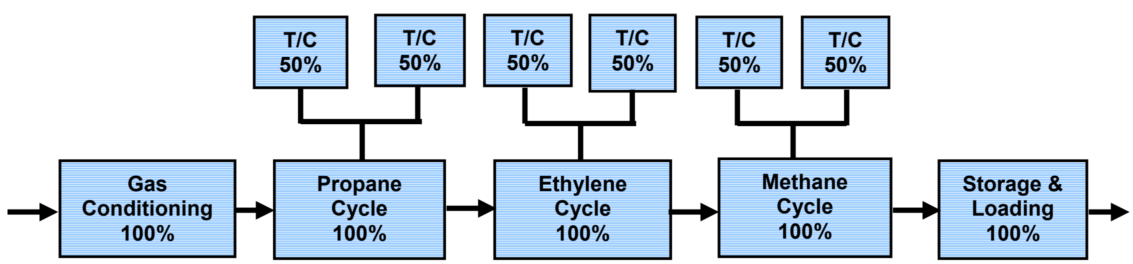


Figure 1: Simplified Schematic of Early Phillips Optimized Cascade LNG Process – Kenai Facility

The success of this earlier cascade process is largely centered in process flexibility and reliability [1]. For the Kenai facility design, an emphasis was placed on reliability. This is understandable for a stand-alone facility for a remote location in the 1960's. The driver and compressor configuration as related to inherent process reliability has proven a key factor in this success. Figure 2 represents a simplified graphical representation of this configuration as related to the remainder of the process. This arrangement is typically referred to as "two-trains-in-one". The idea is quite simple in that equipment with lower reliability such as turbines and compressors are duplicated, while more reliable equipment is not. In retrospect, the original design intent was achieved, as equipment employed in the main process area has proven quite reliable. For instance, brazed aluminum exchangers were used extensively in the liquefaction section. After more than 33 years of operation, Kenai has not experienced a single brazed aluminum exchanger leak nor missed a shipment of LNG. It is easy to understand that with duplicated turbine/compressor sets, the entire process will not shut down if one turbine/compressor set shuts down. A total shutdown occurs only if both turbine/compressor sets for a common service are down at the same time. The production efficiency advantages are obvious. The historical production efficiency for the Kenai facility is greater than 95%.



Overall Plant Production Efficiency	>95%
➢ Kenai – 33 Years Operation	
Operational Flexibility	0 – 105%
➢ Full Rate	80 - 105%
➢ One T/C Down	60 – 80%
➢ Half Rates	30 – 60%
➢ Idle	0 – 30%

Figure 2: Simplified Driver Configuration Schematic - *Kenai & Atlantic LNG Facilities*

2.1 Current Phillips Optimized Cascade LNG Process

Modern process simulation and other design tools were used to update original design. However, the key concepts that proved successful at Kenai, such as high reliability, were held paramount throughout the design. The key modifications from the earlier design to the current solution are cited below:

- Balanced refrigeration loads - Provides better utilization of available horsepower. Methods to continually adjust and maintain balanced refrigeration loads upon ambient temperature or feedstock changes were incorporated into the design.
- Open methane refrigeration loop – Improved thermal efficiency, while helping to balance refrigeration loads. As fuel gas is taken from one of the methane stages, stand-alone fuel gas compression requirements are eliminated.
- Optimized cold box configuration.
- Integration of LPG and condensate recovery. The initial Kenai feedstock was predominantly methane and ethane.
- Improved plant layout to reduce piping, improve hydraulics, and provide for ease of modularization and construction.

The resulting process provides higher thermal efficiency with even greater process flexibility, while reducing capital cost [2]. The technology has provided cost competitive solutions that have been successfully licensed for multiple trains at Atlantic LNG in Trinidad [3,4]. The process has also been selected for the ongoing Darwin, Australia and Egyptian LNG projects. Several other LNG projects utilizing versions of the process are at various stages of development. Figures 3 and 4 provide simplified graphical depictions of the current Phillips Optimized Cascade LNG Process. In order to better illustrate the core process, LPG and condensate recovery are omitted from Figure 4. Also, the type and physical location of this equipment will vary as feed composition and product requirements vary. As an example, for some LNG designs, LPG recovery may not be practical based on feed compositions and/or market conditions.

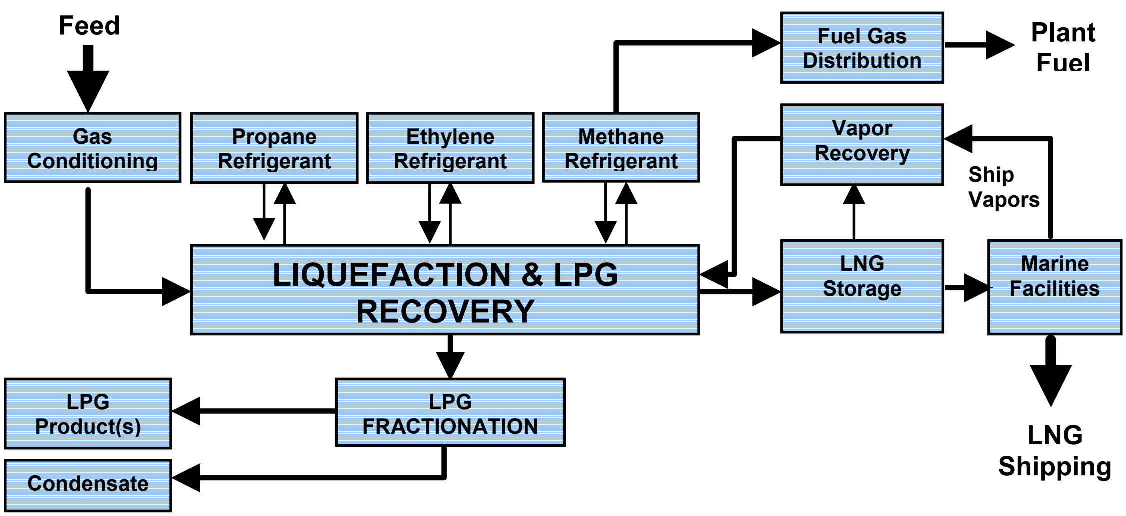


Figure 3: Simplified Block Schematic of Current Phillips Optimized Cascade LNG Process

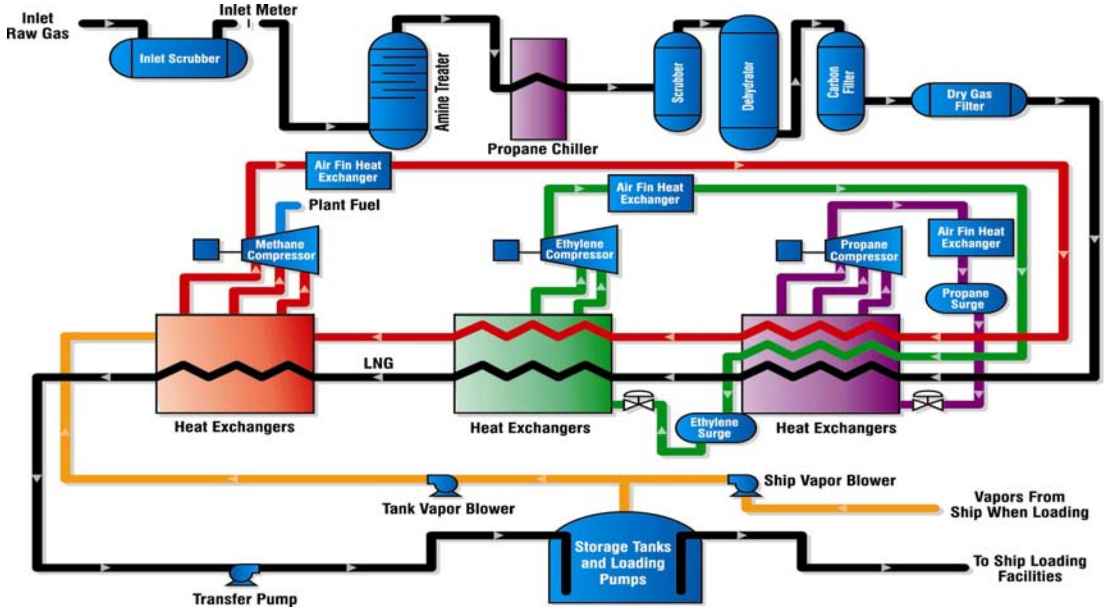


Figure 4: Simplified Process Schematic of Current Phillips Optimized Cascade LNG Process

2.2 Driver/Compressor Configurations

For many LNG projects, driver configuration remains one of the largest areas for study. This is to be expected, as the driver and compressor configuration represents a large percentage of capital cost for an LNG project. It is also the area that typically represents the bulk of fuel gas consumption and emissions. Although the "two-train-in-one" option as shown in Figure 2 is not a requirement for the Phillips Optimized Cascade LNG Process, it remains highly recommended for many LNG projects. This is especially true of stand-alone or grass root facilities or where a single train is envisaged, such as offshore floating options. This solution also tends to provide an excellent balance of project variables for many other project conditions. Designs utilizing this particular approach to balance project variables have provided successful solutions for multiple LNG projects in the 2.9 to 5.2 MTPA range. Since LNG production for any given compressor configuration is highly dependent on ambient temperature and feedstock conditions such as composition and pressure, it is difficult to provide a definitive range. Conversely, designs utilizing single turbine drivers have been provided for various projects as applicable, including one at 3.5 MTPA.

Within a given LNG technology, driver/compressor configuration also represents one of the largest areas for client preference. For instance, some clients insist on two-piece impeller designs or perhaps limit choices specifically to those previously employed in LNG refrigeration service. Others may require full string testing in the exact configuration to be installed, which is often difficult for larger compressors. While seemingly harmless, stipulations such as those mentioned not only dictate the maximum compressor size but may also impact schedule. Less obvious design details such as whether the nozzles are top or bottom entry may also be impacted. As another common example, some clients prefer aeroderivative drives without reservation, while others accept only aeroderivative drives proven in mechanical drive service, while still others absolutely refuse to entertain the idea at all.

It would be impractical to list all driver/compressor design considerations, industry concerns and client preferences. However, it is clear that a licensor of LNG technology cannot rely on only one solution. Additionally, for licensed technologies, continued advancement is expected. At the same time, the LNG industry as compared to other technology areas remains quite conservative with regard to new innovations. Given the relatively large capital cost investment of an LNG facility, this conservatism is also to be expected. Consider that as the industry searches for the optimal economy of scale, the general trend is for larger and larger LNG trains. Larger train designs are requested, but the desire is to maintain within proven areas of experience. This sometimes results in a difficult balancing act.

It is with these concepts in mind that the following solution for larger capacity trains was developed. As before, the focus remained on proper balancing of typical project variables. A large train solution was sought that maintained or improved upon the historical high process reliability (production efficiency), improved thermal efficiency, and reduced capital costs. Other factors such as typical or common client preferences or stipulations were also considered throughout the development. It is obviously advantageous to develop responsible and flexible solutions that can be utilized in a wide variety of projects. It does little good to develop solutions that are technically viable but perhaps not technically acceptable to LNG clients.

3.0 An Alternate Approach

Given the relative cost of drivers and compressors to overall LNG equipment, the obvious method of reducing capital is to reduce the number of drivers and compressors. Eliminating the “two-trains-in-one” concept and installing larger turbines and compressors is one method of accomplishing this goal. One can easily see that for the same LNG production, larger turbines are required for the remaining drivers. In addition to reducing capital, larger turbines tend to have higher efficiencies. Exploring other methods of further improving thermal efficiency led back to the idea of waste heat recovery, which has been studied in various configurations on several occasions.

As represented in Figure 4, the Phillips Optimized Cascade LNG process employs three relatively pure refrigerants. The first resulting configuration is a single gas turbine driving propane, a single gas turbine driving ethylene and a single steam turbine driving methane. Steam for the methane driver is produced using a combination of waste heat recovery and supplemental exhaust stack firing. For cases where horsepower is fully utilized, the result is improved thermal efficiency. For the particular case studied in detail, dual GE Frame 5D turbines were replaced with single GE Frame 7EA turbines for the propane and ethylene circuits.

The initial expectation was to install larger compressors along with the larger turbines. As always, there were trade-offs. The detailed study that followed led to multiple compressor cases for both propane and ethylene. Previous compressor configurations for propane and ethylene contained multiple stages within single cases. A detailed analysis revealed several reasons to move to multiple cases. Multiple cases allowed the design to remain well within the proven range of experience, minimized schedule impacts, and addressed some common client concerns/preferences in manufacturing techniques and testing requirements. Additionally, in some cases, the slower speed of the GE Frame 7EA turbines made it difficult to maintain the previous achieved compressor polytropic efficiencies.

The resulting configuration, shown in Figure 5, is a technically viable and acceptable solution with lower capital costs and higher thermal efficiencies. The main trade-offs are a reduction in process flexibility and production efficiency. The loss in production efficiency is due to eliminating driver/compressor redundancy as compared to the “two-train-in-one” configuration. Multiple compressor cases, longer startup cycles for the larger gas turbines, and steam system commissioning/warm up times were also negative impacts in the production efficiency analysis. Features were added to the design to minimize these negative impacts as much as possible. The completed detailed analysis showed a drop in production efficiency from over 95% to around 93%, which is more typical of the LNG industry. The loss in flexibility is mainly due to single large fixed speed gas turbines as compared to multiple dual shaft variable speed gas turbines. However, when all is considered and balanced, the resulting configuration provides a technically and cost competitive solution.

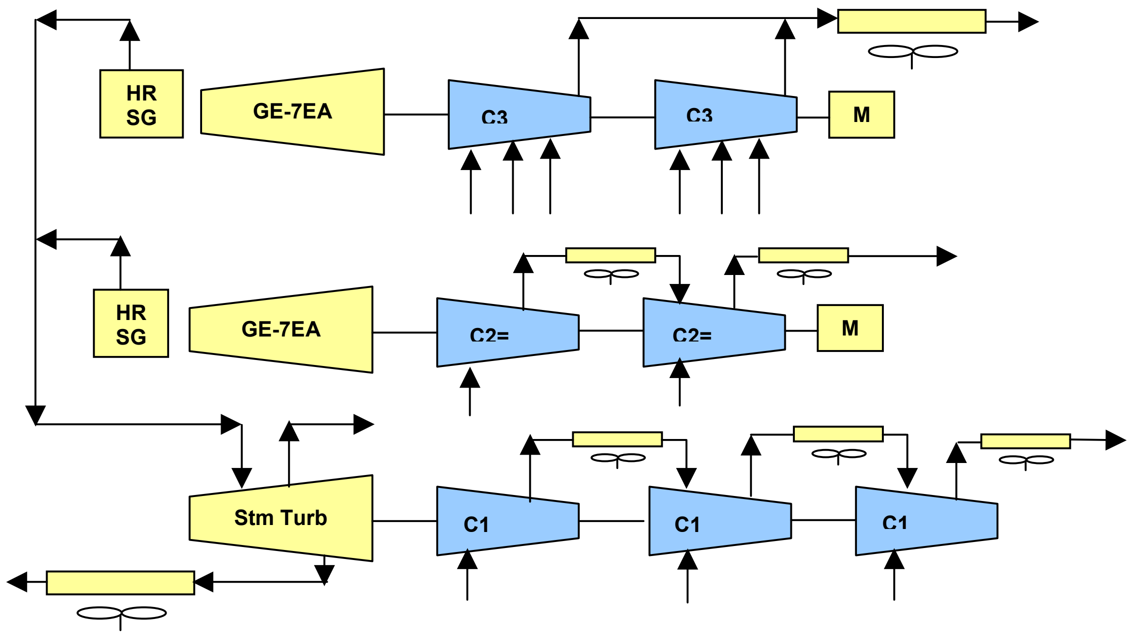


Figure 5: Single Turbines Drives With Waste Heat Recovery

3.2 Furthering the Approach – Rebalancing the Variables

While the approach outlined in Figure 5 provides a technically viable, technically acceptable and cost competitive LNG solution, another option has since been developed that further improves upon the concept. To assist in the discussion that follows, please refer to Figure 6.

It was noted that the multiple compressor cases selected for the larger gas turbine drives were numerically and physically similar to previous "two-train-in-one" configurations. In terms of total compressor cases, size, and flow characteristics, there is little difference. This led to an inventive solution of combining propane and ethylene compressor cases on one shaft with 50% compression requirements. Comparing to the previous configuration, shown in Figure 5, the total number of cases on the respective gas turbine shafts remains unchanged. A dynamic review of startup and operational requirements provided quite similar results to that of the previous option in Figure 5. The net effect was a significant improvement in production efficiency due to redundancy, with very little impact to other considerations, such as equipment cost and thermal efficiency. Additionally, operational flexibility such as efficient turn down capability improved greatly. Thus a good balance was accomplished for the propane and ethylene systems.

For methane compression requirements, one concept considered was to remain with a single steam turbine driving three-100% methane compressor cases. Another option was to provide two smaller (50%) steam turbines in order to regain redundancy. Reducing the number of cases per shaft was briefly considered and once again quickly rejected. For methane compression, separate cases for each refrigeration stage have proven the efficient and practical choice. To maintain efficiency, inter-stage cooling is required for high compression ratios. A comparative study of the two options revealed that the additional capital cost of dual turbine/compressor trains was not prohibitive. In addition to improving reliability and process flexibility, there were several other advantages to utilize smaller 50% steam turbines. When the balance of all variables was properly considered, it proved advantageous to provide full redundancy in the methane system. The trade off is increased reliability and flexibility for higher capital cost. The net overall result is a flexible and reliable "two-trains-in-one" design effectively incorporating waste heat recovery. Refer to Figure 6.

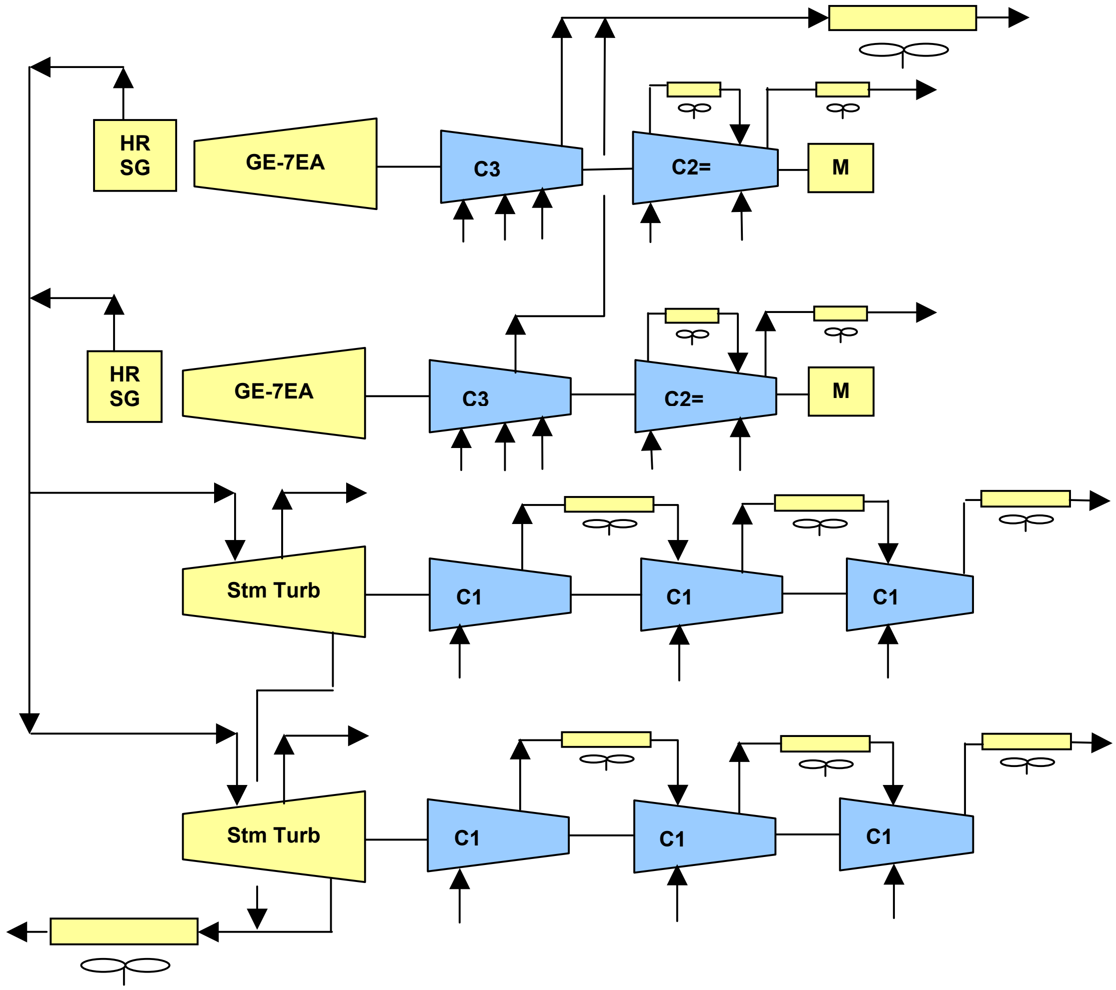


Figure 6: Two Gas Turbines w/ Waste Heat Recovery – "Two-Train-In-One" Design

4.0 Results and Conclusions

A study was performed with the configuration shown in Figure 6 using typical feed compositions, pressures, and ambient temperatures. For the case considered, the results were quite positive for a nominal production of 5.5 MTPA. Supplemental power may also be provided via the starter/helper motors. However, for the purpose of the study, supplemental motor power was held at only that necessary to overcome starting torque requirements. Depending on the facility electrical distribution and steam balance requirements, startup/helper steam turbines may be used in place of electrical motors. An analysis of production efficiency resulted in a value around 95%. Thermal efficiency results were above 93%. A conservative approach was taken in determining both of these values [5]. It was decided to use a typical overall LNG facility as the basis including feed pretreating through storage and loading as well as utilities. For instance, fuel requirements for acid gas incineration, supplemental exhaust stack firing, power generation, and even flare purge were included. Supplemental firing of the exhaust stacks is one method of producing the proper steam conditions for the methane circuit steam turbine drivers. Steam could be supplied or supplemented from other sources if available. In fact, slight improvements in production efficiency due to faster warm up and commissioning times were possible with an alternate supplemental steam supply. For comparison purposes, no vapor or liquid expanders were utilized anywhere in the facility, which is also a conservative approach as there is no power augmentation.

A follow up study was then completed substituting Frame 9E's for the Frame 7EA's and utilizing larger steam turbines. For this case, an LNG production of 6.5 MTPA was achieved, while maintaining similar thermal and production efficiencies. Again, the helper motor power was held at only that necessary to overcome starting torque requirements and no power augmentation from vapor or liquid expanders in the process was considered. Development work in the ConocoPhillips/Bechtel LNG Product Development Center (PDC) continues for even larger train size configurations that offer a similar balance of variables.

From a broader perspective, the concept is similar to co-generation where electrical power is produced along with waste heat recovery steam. The concept presented in Figure 6 is essentially co-generation with direct transmission of power to the compressor shafts. Where the design intent is to fully utilize available driver horsepower in order to produce a maximum amount of LNG, the advantages are obvious. Consider for example that the intermediate steps from power generation to electric motor drives is eliminated along with the associated distribution equipment. Of course, power generation requirements for other facility usage remains.

Configuring a direct-coupled co-generation concept in a "two-train-in-one" arrangement effectively minimizes the number of gas turbines required and provides a novel LNG solution. There are many advantages to consider. Fewer turbines offer less emissions point sources while the larger gas turbines are generally more efficient, which also helps reduce emissions. Process turndown, which is always a concern for large LNG trains utilizing single shaft turbines, becomes much easier with dual 50% equipment. Consider that half of the turbines and compressors can be taken offline while the others remain fully loaded. Smaller 50% compressors make it easier for manufacturers to remain within their proven experience ranges. This offers greater selection where competitive bidding of the equipment becomes more plausible. The configuration presented offers a flexible, reliable, efficient, and balanced LNG solution appropriate to a wide range of applications while addressing many industry concerns.

5.0 References

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