LNG Terminal Operator's Design Feedbacks and Technical Challenges

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ABSTRACT

Pyeong-taek Terminal II (560,000m³ and 720 t/h) is now under construction in order to comply with the abruptly increasing gas demand in Korea. For the optimum design of the new terminal, the impacts of the main equipment's reliability and availability on both the stream line availability and construction and operating costs have been carefully evaluated. Other important design parameters, such as the variation of the imported LNG heating values and the high seasonal gas sendout demand, have also been optimized in the new terminal design.

This paper presents the practical design improvements that have been directly applied to Pyeong-taek Terminal II in order to reduce costs and to enhance the terminal's availability. These involve economical vapor handling and re-condensing, zero emission of LNG vaporization, and an optimum sparing level of the main equipment based on an actual 18-year operating record of reliability and availability of the main equipment.
INTRODUCTION

In order to meet the abruptly increased natural gas demand, Pyeongtaek terminal has continuously been expanded. The terminal added consecutively LNG storage tanks, re-gasification facilities, and an unloading berth. Presently, 10 units of storage tanks are under operation with a total capacity of one million cubic meters and 2,020 t/h re-gasification facilities.

During 18 years of operation of the terminal, the existing conventional designs have been improved upon enhancing the terminal reliability, achieving high controllability, and keeping a high level of safety. The terminal operator’s design improvements, as well as experiences in operation and maintenance, are valuable for the LNG industry. However, the operation feedbacks have been limited so far even though their role of receiving LNG is important in an LNG chain.

This paper presents the terminal operator’s practical design improvements against the conventional design problems occurred unexpectedly during terminal operation and maintenance. These design improvements, applied to the design of Pyeongtaek Terminal II for reducing costs, involve economic vapor handling and recondensing, zero emission vaporization, and an optimum sparing level of the main equipment with their 18 years of operation records. This paper also discusses the impact of reliability and availability of main vapor handling equipment on revenue losses and total expenditures based on life cycle costs.

PRACTICAL DESIGN IMPROVEMENTS

Boil-off Gas Handling

The mixing of pressurized Boil-Off Gas (BOG) with the sub-cooled LNG in the re-condenser will increase the temperature of the LNG, resulting in a decrease in liquid density. The temperature and density of mixed LNG depends on the temperature and flow coming to the re-condenser of both the LNG and BOG. Consequently, the change in liquid density affects pump performance. One or two boosting pumps are running according to the send-out demand. The first role of a boosting pump is to compensate the low suction pressure of secondary pumps due to the operating pressure of re-liquefaction system. In order to save operating costs of boosting pumps, the variable frequency drive pumps were installed so that operating costs of the boosting pumps can also be saved. The process flow diagram for vapor recondensing is shown in Fig. 1.

The total BOG rate depends on the terminal operating mode, season, temperature, day/night, etc. It varies from 20 to 30 t/h in normal holding mode operation and increases by about 10 t/h during LNG unloading mode. The terminal has high BOG rate because of a high BOG rate of storage tanks (0.1% per day and 10 storage tanks) and vapor returned from cold energy utilization facility. Normally, one BOG compressor will be added during the LNG unloading operation (in some cases, it requires adding two units). The required number of BOG compressors depends on the LNG sources and ship’s saturation pressure.

Two different types of BOG compressors have been used: Horizontal ring-type reciprocating (4 sets) and vertical compressors with contactless labyrinth pistons (2 sets). The design capacity of
each compressor is 12,000 Nm$^3$/h of BOG with a maximum discharge gauge pressure of 10.6 barg and a discharge temperature range from 14 to 47°C. The vapor of the compressed BOG and returned re-gasified gas from cold energy utilization plant is used as fuel gas for the tank vacuum breaker, internal consumption (gas firing absorbed type heating/chilling unit), and neighboring KIA Motors.

The operating pressure range of the storage tank is from 50 - 170 mbarg. BOG compressors are started by tank pressure manually or automatically, which can be selected by operator’s choice. Combined operation concept - continuous and intermittent operation - has been used for the BOG compressor operation. When the LNG tank operation pressure reaches 150 mbarg, a unit of compressor stopped. If tank operating pressure continuously decreases, an additional compressor will be stopped. Conversely, a BOG compressor will be added when the tank operating pressure reaches 170 mbarg. Capacity controllers (50, 75, and 100%) are also used to control the compressor’s operation capacity.

The suction temperatures of the BOG compressors are slightly different in each operation mode as follows:

- **Holding mode:** -100 to -110°C
- **Unloading mode:** -110 to -120°C

During the terminal intermittent operation the suction temperature varies minus 60 - 70°C after 10 hrs of stopping compressors (no operation of BOG compressors). It requires about 5 to 10 minutes until the compressor reaches normal operation. The horizontal compressors require suction vapor desuperheating by using LNG spraying at the BOG knockout drum inlet, while the vertical compressors can quick start without desuperheating.

The basic principle of the BOG recondensing system is to cool, recondense and send-out the excess vapor of natural gas by mixing it with a sub-cooled LNG taken from the LP LNG header line. In order to improve the heat and mass transfer of gas and liquid phases, the condensation takes place in a packed tower where gas and liquid enter the top of the re-condenser and flow co-currently through the bed of metal rings, where both phases come in close contact. The re-condenser operating level is carefully monitored and maintained at half height [1].

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**Thermally Integrated Vaporization**

LNG is stored in storage tanks at cryogenic temperature of approximately minus 160°C at near atmospheric pressure. The LNG is regasified and warmed to temperatures near 0°C and desired send-out pressure. LNG is most commonly vaporized in Open Rack Vaporizers (ORV’s) against the seawater or in Submerged Combustion Vaporizers (SCV’s) where the cold energy contained in the stored LNG is wasted during the regasification process. An LNG terminal has a large storage of cryogenic energy, which has to be released in order to re-gasify LNG. On the other hand, a power plant must reject heat to condense steam and to cool equipment.

The terminal integrated thermally with an adjacent Pyeong-taek Thermal Power Plant, of which has equipped four 350MW steam power generation and 480MW Combined Cycle Gas Turbine (CCGT). The power plant has owned and operated seawater lift structure for the power plant cooling purpose. The seawater that used for steam condensing in the power plant increases in temperature. This warmed seawater is used for LNG vaporization as shown in Fig. 2.

The thermal integration of the two plants, supplying warmer seawater from the power plant to the terminal, results in significant benefits:

- Sharing of the seawater lift facility, which reduces high capital costs;
- Reduction in thermal pollution, which results in environmentally friendly energy plants;
- Reduction in regasification costs by using the warmed seawater;
Since the terminal uses the warmed seawater discharged from the power plant, the terminal eliminates intrinsically the operation of SCV's, which can only be used for back-up or peak shaving. As a result, this integration leads to no emission of green gas for LNG vaporization.

In order to reduce the natural gas (NG) production costs, the terminal has been designed to maximize the use of seawater discharged from the power plant. The lifted seawater goes to the power plant and excess seawater bypasses and is mixed with the warmed seawater discharged from both thermal power plant and the CCGT. Figure 3 illustrates the seawater configuration. A portion of seawater is used for the ORV group #1 through pump station #1. The seawater discharged from the ORV group #1 will be determined to reuse it for ORV group #2 by controlling the re-usage valves. It depends on the available amount of seawater, seawater temperature, and gas sendout demand. This re-usage concept of seawater could save an additional seawater lift structure, resulting in low costs LNG vaporization by maximizing heat usage from seawater.

**LNG TERMINAL OPERATION RELIABILITY**

**Definition of Reliability, Availability, and Risk**

There is often confusion between the terms Reliability, Availability, and Risk. So far it has been seen that there is a need for a scientific definition of reliability and for a method of reliability evaluation which can be applied to a wide range of technological projects. Reliability related to the overall LNG terminal can be defined as the probability that the terminal as designed will perform its function (unloading LNG/storage/regasification) over a specified period of time under normal operating conditions. Similarly, the availability of an LNG terminal is the fraction of time that it can perform its function under normal operating conditions. On the other hand, a dictionary definition of risk is “the possibility of loss or injury to people and property”. In this study, the following conventional definitions of the reliability and unit availability are used [2-4].

\[
RT = \frac{TOT}{TOT + UT_f} \tag{1}
\]

\[
AT = \frac{MTTF}{MTTF + MTTR} \tag{2}
\]

where,

\( RT \) : Equipment Reliability

\( TOT \) : Total operating time of equipment
Equipment Reliability and Availability

The sendout availability of an LNG terminal is largely determined by the major equipment items included LNG pumps, vaporizers, and compressors. The equipment provided within the terminal can be categorized as follows in terms of contributions to overall reliability and availability: static equipment and key regasification equipment.

Static equipment include a flare stack, vent stack, and instrument air receivers (vessels). These items are, in general, very reliable with very low failure rates (typically one failure per 100,000 operating hours), provided the design and fabrication are performed according to recognized codes and standards.5

Key regasification equipment consists of pumps, vaporizers, and compressors. These equipment items are provided with spare capacity so that full sendout can be maintained while one item is out of service. Since the ORV’s have no moving parts, they are essentially very reliable. However, they are also susceptible to surface fouling due to exposure to seawater. This fouling potential is controlled by hypo-chlorination, but periodically the units must be taken out of service for cleaning and painting. In order to make up for this short fall the submerged combustion vaporizers (SCV’s) will be kept in rolling standby mode so that it can rapidly respond to the increase in sendout. Since several compressors are provided to handle excess displacement vapour during the ship unloading operation and a few are required to handle normal BOG, a spare machine normally exists.

In order to permit full sendout flow in spite of failures in main rotating equipment, the plant design assumes rotating equipment failure, which is generally lower reliability than non-rotating equipment. It is a general rule in LNG terminal design to have a couple of spare pumps. Therefore, the availability of the pumping system is considerably high. Since the effect of an unavailability of a pumping system, vaporizing system, and Vapour handling system directly affects the terminal stream production, this paper focuses on the effect of reliability and availability of those key systems. This paper also discusses the economic impact of different types of ORV and BOG compressors on both the probable revenue losses and life cycle operating and maintenance costs.

Data Collection

The company developed the equipment history card system and has applied it from the startup operation of the terminal. This includes the equipment tag number, purchase date, installation date, operation history, and maintenance history. The actual operation records were analyzed to get the operation hour of main equipment of regasification. Each of the operation hours was then summed to the same equipment type. Since equipment capacity installed at the initial stage are different from those of expansion, operation records were separately collected for the different equipment sizes even with the same type. On the same token, the maintenance history records of each equipment have been investigated and collected based on the type of failure, including preventive (regular planned) maintenance.

Analysis of Reliability Data

The reliability data base for the main regasification process units was established based on 18 years of operation at Pyeongtaek Terminal. Table 1 presents the summarized reliability database.

LNG Storage In-tank Pumps

At the initial design of the terminal, two LNG in-tank pumps per an LNG tank were installed. Three LNG tanks were dedicated for the initial operation in 1986. One year later, the fourth LNG tank was added. By the consecutive expansion, ten LNG tanks (above-ground membrane type tank), of which capacity is 100,000 m³ each, are under operation. A total of 22 LNG in-tank pumps have been operated. An MTTF of 3,221 hours was obtained. This value is lower than the MTTF values reported by GIIGNL.
(6100 hrs) and by GRI (3900 hrs) [5]. The GRI study is based on US plants that are mainly peak shaving plants, where pumps would largely be used intermittently.

**Table 1 - Reliability database for key Regasification Equipment**

<table>
<thead>
<tr>
<th>Process Unit</th>
<th>MTTF</th>
<th>MTTR</th>
<th>N</th>
<th>TOT</th>
<th>UT</th>
<th>RT (%)</th>
<th>AT (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-tank Pump</td>
<td>3,221</td>
<td>37</td>
<td>22</td>
<td>698,957</td>
<td>1,085</td>
<td>99.85</td>
<td>98.86</td>
</tr>
<tr>
<td>Sendout Pump</td>
<td>4,277</td>
<td>44</td>
<td>20</td>
<td>770,040</td>
<td>1,620</td>
<td>99.79</td>
<td>98.98</td>
</tr>
<tr>
<td>BOG Comp (Vert)</td>
<td>5,970</td>
<td>100</td>
<td>2</td>
<td>95,516</td>
<td>272</td>
<td>99.72</td>
<td>98.35</td>
</tr>
<tr>
<td>BOG Comp (Horz)</td>
<td>4,596</td>
<td>147</td>
<td>3</td>
<td>220,608</td>
<td>1200</td>
<td>99.46</td>
<td>96.90</td>
</tr>
<tr>
<td>ORV (U type)</td>
<td>3,288</td>
<td>116</td>
<td>2</td>
<td>105,248</td>
<td>960</td>
<td>99.10</td>
<td>96.59</td>
</tr>
<tr>
<td>ORV (I type)</td>
<td>7,012</td>
<td>61</td>
<td>7</td>
<td>273,507</td>
<td>390</td>
<td>99.86</td>
<td>99.13</td>
</tr>
</tbody>
</table>

Notes:
1. One compressor recently operated in 2002 is not included.
2. These are operational data recorded from 1987 to 2002.

**LNG Booster Pumps**

A total of six units of high booster pumps, of which capacity is 80 t/h, have been operated since the terminal started its operation. Different capacity (110 t/h) of LNG booster pumps have been installed at the expansion stage. A total of 20 units of LNG pumps are presently under operation.

**BOG Compressors**

Three horizontal ring-type double stage BOG compressors have been operated since 1987 with a recorded 4,596 hrs of MTTF, while two vertical compressors with contactless labyrinth pistons have been operated since 1995 and showed 5,970 hrs of MTTF (about 30% higher than the horizontal). The higher MTTF of the vertical compressor leads to the fact that the field person has a general tendency to use more this type of compressor, which is more reliable.

**Open Rack Type Vaporizers (ORV’s)**

Two different types of HP ORV’s have been operated: the top reserve type design (“U” type) and the trough type design (“I” type). 3,288 hours and 7,012 hours of MTTF have been obtained for the “U” type and the “I” type, respectively. The difference can be interpreted as manufacturing reliability, which is also an important parameter in unit equipment reliability, as well as terminal availability. Because of frequent problems of the “U” type, such as corrosion and erosion of heat exchange tubes, and thereafter gas leaks, the company is under replacing the “U” type vaporizers by “I” type vaporizers.

**Reliability Estimation of LNG Terminal**

The unit equipment reliability may be different from that of the sendout system because the sendout system consists of several types of equipment system. These involve key main equipment as discussed in this study. However, the sendout system is simplified consisting of storage LP in-tank pumps, HP boosting pumps, vapor handling compressors, and vaporizers (ORV’s). Seawater pumps and SCV’s are excluded in this estimation. Terminal sendout operation availability can be a useful guideline in determining the level of back-up facility.

In a serious configuration as shown in Fig. 4, a failure of any component/subsystem results in a serious reduction in the sendout capacity. It is found that the terminal regasification is arranged reliability-wise in a series configuration. In the case where the failure of a component affects the failure rates of other components (i.e. the life distribution characteristics of the other components change when one fails), then the conditional probabilities must be considered.
In a serious configuration, the component with the smallest reliability has the biggest effect on the system’s reliability. There is a saying that “a chain is only as good as its weakest link.” In a chain, all the rings are in a series and if any of the rings breaks, the whole system fails. In addition, the weakest link in the chain is the one that will break first. The weakest link dictates the strength of the chain in the same way that the weakest component/subsystem dictates the reliability of a series system. As a result, the reliability or availability of a system is always less than the reliability/availability of the least reliable component.

![Fig. 4 – Simplified LNG Regasification Process](image)

The effect of each subsystem’s availability on the overall regasification system availability is presented in Table 2. The first row of the table shows the availability of each unit. Subsystem availability is a matter of spare unit. The next row shows the required number of units followed by the total number of units, including spare units. Since the rotating pumps have low reliability, it is assumed that in-tank pumps and booster pumps both have two spare pumps. It is also assumed that three BOG compressors have 50% capacity. Each subsystem availability is shown in the table.

**Table 2 – Example Estimation of Regasification System Availability**

<table>
<thead>
<tr>
<th>Description</th>
<th>Intank Pump</th>
<th>Horiz BOG Comp.</th>
<th>Vertical BOG Comp.</th>
<th>Booster Pumps</th>
<th>“I” Type ORV</th>
<th>“U” Type ORV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit Availability (%)</td>
<td>98.86</td>
<td>96.90</td>
<td>98.35</td>
<td>99.8</td>
<td>99.13</td>
<td>96.59</td>
</tr>
<tr>
<td>Required number of units</td>
<td>5</td>
<td>2</td>
<td>2</td>
<td>5</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Spare Units</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Total number of Units</td>
<td>7</td>
<td>3</td>
<td>3</td>
<td>7</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Subsystem Availability</td>
<td>1.000</td>
<td>0.9818</td>
<td>0.9946</td>
<td>1.000</td>
<td>0.9985</td>
<td>0.9782</td>
</tr>
<tr>
<td>Total Sendout Availability with “I” Type ORV Horiz BOG Comp.</td>
<td>0.9802</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vertical BOG Comp.</td>
<td>0.9930</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Sendout Availability with “U” Type ORV Horiz BOG Comp.</td>
<td>0.9603</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vertical BOG Comp.</td>
<td>0.9728</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Equipment combination is based on 700-900 t/h (750 – 1,000 MMScf) sendout

**ECONOMICAL IMPACT OF RELIABILITY/AVAILABILITY**

**Unavailability**

LNG terminal unavailability can be defined as the number of days a year the terminal is not on stream due to the system/equipment failure (unscheduled down time) in view of statistical probabilities. The above include the time required for cooldown, warm up, etc. In other words, it is the period of time the terminal is not sending out the regasified LNG. The scheduled down time depends on the type, size and number of system/equipment requiring regular maintenance, as well as local regulations, like statutory inspection of system/equipment. Scheduled down time also depends on the maintenance program and the philosophy of the terminal operator.

Unscheduled downtime depends on the failure of any system/equipment in the terminal that would force a shutdown. These failures are considered random events with constant failure rate
distributions, i.e., any system/equipment is equally likely to fail at any one time as any other. In an LNG terminal, a high percentage of this downtime is associated with the type and number of rotating equipment – mainly pumps and compressors \([6,7]\). The total terminal unavailability is then the sum of unscheduled terminal shutdown because the scheduled shutdown of system/equipment is either done during the spare unit operation or during low gas demand seasons.

Figure 5 illustrates the relationship between Availability and unavailability of the BOG compressor system. BOG system availability increases with an increase in unit availability. Conversely, the unavailability of the BOG system decreases as unit availability increases. Mathematically, unavailability can be obtained from deducting the availability from one (1). The unavailability of a Horizontal compressor system is higher than that of a vertical compressor system.

The unavailability of the “U” type ORV is relatively higher than the “I” type. The unavailability with Horizontal compressor and Vertical compressor are 0.0397 and 0.0272, respectively. Since lower unavailability seriously affects the terminal on stream availability.

**Economic Impact of Availability**

The economic impact of the availability of the vapor system is further investigated. Table 3 summarizes the probable revenue losses of the two cases: vertical compressors and horizontal compressors. Probable revenue losses are estimated based on $4.00/MMBtu. Figure 6 presents the sensitivity study of revenue losses with the regasified gas price ranges $2.5 – $6.0/MMBtu. The difference between the four cases of the probable revenue losses with the different types of ORV’s and BOG compressors increases with an increase in the regasified LNG price. The revenue losses are based on probability.
Table 3 - Unavailability and Revenue Losses

<table>
<thead>
<tr>
<th>Description</th>
<th>“U” Type ORV</th>
<th></th>
<th>“I” Type ORV</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Horiz Comp</td>
<td>Vert Comp</td>
<td>Horiz Comp</td>
<td>Vert Comp</td>
</tr>
<tr>
<td>Total Sendout Availability</td>
<td>0.9603</td>
<td>0.9728</td>
<td>0.9802</td>
<td>0.9930</td>
</tr>
<tr>
<td>Unavailability of Sendout</td>
<td>0.0397</td>
<td>0.0272</td>
<td>0.0198</td>
<td>0.0070</td>
</tr>
<tr>
<td>Pressure Sendout Interruption (hrs)</td>
<td>348.2</td>
<td>238.3</td>
<td>173.5</td>
<td>61.3</td>
</tr>
<tr>
<td>Probable Revenue Losses ($million)</td>
<td>63.8</td>
<td>43.7</td>
<td>31.8</td>
<td>11.2</td>
</tr>
</tbody>
</table>

*Note: Revenue losses are estimated based on $4.0/MMBtu gas price*

Fig. 6 – Effects of System Unavailability on Revenue Losses

Since the comparison of equipment costs and spare part costs is beyond the scope of this study, the same equipment costs are applied to the economic analysis. Spare part costs depend on the machine type and the reliability of the machine. However, it is also assumed that spare part costs are equivalent to 2.5% (Actual spare part costs for the Laby are only about 25% of the costs for horizontal compressors, as there are no piston rings, no rider bands and no cylinder liners to replace) of equipment cost for one time maintenance (MTTF basis). The maintenance costs are a strong
Table 4 - Summary of Operation and Maintenance Costs  

<table>
<thead>
<tr>
<th>Description</th>
<th>Horizontal BOG Compressors</th>
<th>Vertical BOG Compressors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probable Flaring/Venting BOG</td>
<td>27</td>
<td>8</td>
</tr>
<tr>
<td>Yearly Allocated Utility and Consumables</td>
<td>3.7</td>
<td>2.9</td>
</tr>
<tr>
<td>Yearly Allocated Maintenance Part Costs</td>
<td>258</td>
<td>202</td>
</tr>
<tr>
<td>Yearly Allocated Labor Costs</td>
<td>129</td>
<td>88</td>
</tr>
<tr>
<td>TIC of BOG Compressors</td>
<td>31,725</td>
<td>31,725</td>
</tr>
<tr>
<td>Expense NPV</td>
<td>-62,615</td>
<td>-61,462</td>
</tr>
</tbody>
</table>

Note: TIC stands for Total Installed Costs.

The electric costs for the compressor operation are not included in the Expense NPV because those are assumed to be the same power consumption. Economic parameters used in economic evaluation are as follows:

- LNG terminal life time: 30 years
- BOG compressor unit: 3 sets
- Discount rate: 10%/y
- Tax rate: 35%
- Inflation rate: 2.5%/y
- TIC factor: 2.25

The expense NPV of the vertical Compressors is $1.2 million less than that of the horizontal compressors. This difference does not include difficulty of maintenance work for horizontal compressors against vertical compressors. The horizontal compressors require more careful efforts in maintenance, which generally takes more time (about 45% more hours). The actual maintenance records clearly show that the vertical compressors with contactless labyrinth pistons required less maintenance hours and 20-30% less spare parts costs.

CONCLUSIONS

1. The terminal has achieved zero emission in LNG regasification and has reduced its costs through thermal integration with an adjacent power plant.
2. The main equipment reliability and availability have been estimated based on 18 years of actual terminal operation records. The estimated terminal sendout availability is strongly affected by the number of spare units or equipment reliability. Low reliability equipment reduces the terminal sendout availability on stream production.
3. The company decided to replace the existing “U” type ORV’s by the “I” type ORV’s because the “U” type ORV shows low reliability and would result in low availability.
4. The vertical compressors with contactless labyrinth pistons show less probable revenue losses than horizontal compressors because of high availability.
5. The vertical compressors with contactless labyrinth pistons are highly reliable, resulting in less operation and maintenance costs based on life cycle costs, compared to those of horizontal compressors.
REFERENCES CITED