

# **REVIEW OF COMMON DESIGN FLAWS IN ETHYLENE GLYCOL REFRIGERATION PLANTS AND THEIR OPERATIONAL IMPACT**

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## **ABSTRACT**

The purpose of this paper is to identify the common fundamental design flaws in ethylene glycol (EG) refrigeration plants, the operational challenges associated with them and what can be done to remediate them. The paper is an extension and revision of the “Optimizing Glycol Injection Refrigeration Plants” paper presented at LRGCC in 1991. The use of EG for hydrate inhibition in refrigeration plants to recover NGLs is a common practice. In Canada, the construction of EG refrigeration plants has risen dramatically as a result of the recent economic demand for liquid hydrocarbons. However, as a result of some common misconceptions, many of the EG refrigeration plants built in the past 26 years have fundamental design flaws causing unnecessary initial and continual operation expenditures. This paper, with the help of a comprehensive case study evaluation, aims to highlight these flaws, their subsequent operational challenges and common recommendations to remediate them.

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## **INTRODUCTION**

In reference to the published data from the Canada and USA emissions regulatory agencies, there are approximately 5,000 plants in Canada and 36,000 in the United States that are either dehydration or refrigeration units. Approximately 5 to 10% of these are refrigeration units using Ethylene Glycol (EG). Given the vast number of plants using the process and its long history, there is still a lot of misunderstanding around the design and operation of these plants.

The goal of this paper is to address the most common design flaws that we have experienced in EG refrigeration units, as well as to address the misunderstandings of the fundamental principals of this process, which leads to incorrect advice from the designers on how to operate these units.

In order to illustrate the issues facing these units, there will be one case study in this paper from a plant that Dehydration Experts has evaluated and an in-depth analysis of the key findings from this study will be presented.

## **THE ETHYLENE GLYCOL REFRIGERATION PROCESS OVERVIEW**

The main objective of the EG refrigeration process is to recover Natural Gas Liquids (NGLs). As an extra benefit, this process also results in a much lower natural gas water dewpoint than a *standard* Tri-Ethylene Glycol (TEG) dehydration process.

The wet inlet gas is first fed through an inlet separator to remove any free contaminants, both liquids and solids. This gas is then cooled in one or more gas/gas exchangers where water and NGLs are condensed out of the gas. In these exchangers, EG is injected into the process, upstream of the exchanger tubesheet, using spray nozzles to atomise the glycol as an aerosol so it can thoroughly mix with the inlet gas in the tubes of the exchanger. The gas/gas exchanger cools the inlet gas by cross-exchanging it with the cooled dry gas and/or NGL product (Liquid-to-Gas) exiting from the Low-Temperature Separator (LTS). As the gas temperature depresses over the exchangers, liquid hydrocarbon and water will condense out of the gas. If this condensation occurs below the hydrate formation temperature of the gas, then the process could freeze up with hydrates or ice. The injected glycol reduces the freezing potential of the water by forming an “antifreeze” blend that will not freeze at the process conditions. This gas may be further cooled in another gas/gas or gas/liquids exchanger, where more water and NGLs are condensed out and more EG is injected upstream of the tubesheet. The gas is cooled further in the chiller (which is usually a propane cooling loop) and additional EG is injected at the inlet to the chiller. This mixed three phase stream, gas-water/glycol-NGL mixture, is then sent to a low temperature separator (LTS) where the glycol/water mixture separates from the NGL by gravity separation. The dry gas exiting the overhead of the LTS is used as cooling gas in the gas/gas exchangers. The rich EG

(water/glycol mixture) is taken from the boot of the LTS and sent to the regenerator section of the unit to be re-concentrated and re-injected into the gas/gas exchangers and chiller. The NGL is skimmed off the top of the LTS and sent for further treatment to be sold as individual fractions or stabilized and sold as bulk NGL product.

The benefits of this process are that, while liquid condensate is being recovered, the cold sales gas (refer to Figure 1) will achieve both hydrocarbon and water dewpoints equal to the cold temperature in the LTS, which is often much lower than the required sales gas dewpoint specification.

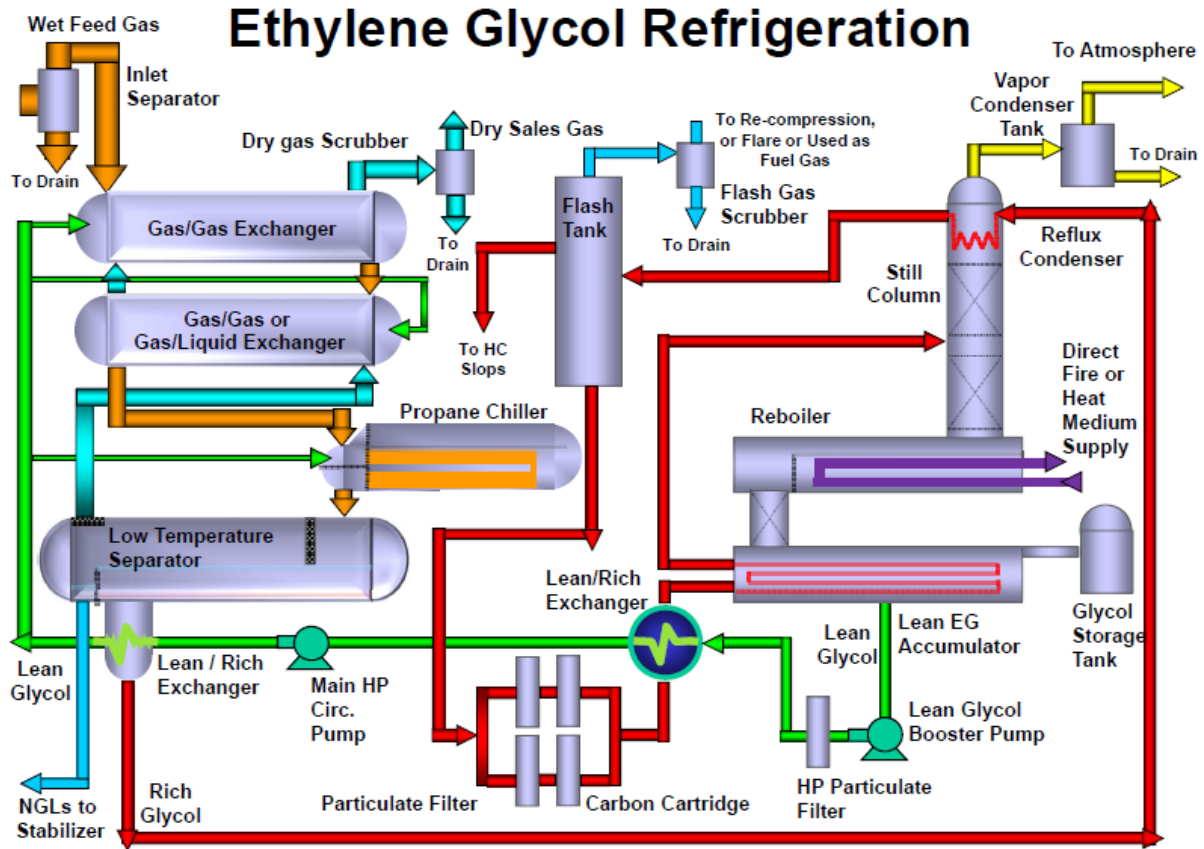


Figure 1 Process Flow Diagram of an EG Refrigeration Plant

Once the rich EG mixture exits the LTS, it enters the reflux coil in the still column (tube side), for pre-heating. From there, the stream goes to the flash tank where the pressure is dropped down to approximately 10% of the process pressure. This allows for the degassing of the entrained hydrocarbons from the stream and allows operations to skim entrained liquid hydrocarbons (if sufficient residence time is allowed). The rich EG stream then enters a series of filters (ideally, particulate, activated carbon then particulate) to remove solids and liquid contaminants. From there, the stream enters the tube side of a lean-rich exchanger (typically, located at the bottom of the EG accumulator and/or pipe-in-pipe setup) before entering the still column where it is distributed evenly over the packing. As the water is stripped from the rich stream, the re-concentrated lean EG enters the reboiler where it eventually cascades over a weir or stand-pipe; flowing into the accumulator. Depending on the reboiler temperature setting, the EG purity should be between 70 to 80 wt% EG (for optimal fluid physical properties). This hot lean glycol goes

through an exchanger in the bottom of the glycol accumulator tank and the coil exchanger loop in the boot of the LTS. This additional heat to the process assists with the NGL/glycol mixture separation. The EG exiting this coil in the boot is then pumped and reinjected into the process, and the glycol cyclic loop starts again.

## DESIGN AND OPERATIONAL PROBLEMS

The design and operational problems that are most often encountered are:

- Proper glycol injection rates
- Nozzle sizing, placement and location
- Recommended system temperatures
- System freeze-ups
- Glycol losses
- Emulsions / Foaming
- pH control
- System Filtration
- Initial start-up flush

To determine the required **glycol injection rate** in the gas/gas exchangers and chiller, we first must know the amount of water condensed from the gas stream based on gas temperature at the inlet and outlet of each exchanger. With this information, the amount of water that will drop out can be calculated and used to determine the amount of glycol required to create an EG/water mixture that will not freeze up in the tubes of the exchanger. In general, targeting a mixture with between 60 to 80 wt.% EG (with the balance being water) will ensure that the mixture does not freeze at the conditions present in a refrigeration system.

**Nozzle sizing** is an important design parameter to ensure adequate coverage of the tubesheet and proper distribution of the lean EG/water mixture into all tubes of the exchanger. This is one of the most overlooked areas in the design stage of exchangers and chillers in refrigeration units. The goal is to create a spray pattern that provides complete coverage of the tubesheet and produces small aerosol droplets, since the total available surface area coverage is better with smaller droplets. The smaller aerosols increase surface area coverage not only through an increase in the number of droplets, but also by allowing the aerosols to suspend in the gas longer so they can get evenly distributed into all areas of the exchanger tubes. Larger aerosols tend to collide with other large aerosols which tend to drop to the bottom of the exchanger thus coating only the lower tubes, which can leave the upper and outer tubes without the EG required for freeze protection.

For a given injection rate, the two main factors that affect aerosol size are: the pressure drop over the nozzle and the viscosity of the lean EG/water mixture. A higher pressure drop across the nozzles results in a smaller aerosol size, so it is recommended that the operator target a minimum nozzle pressure drop of 80 psi. The key factor that affect the viscosity of the EG/water mixture is temperature. Increasing the temperature of the EG which will reduce viscosity and decrease the aerosol size, as well as ensure the lean EG content does not exceed 80wt.%, otherwise the mixture will be too viscous and will result in larger and less effective droplets from the nozzle. In general, targeting a **lean EG temperature** that is 3 to 5°C (5 to 9°F) above the feed gas temperature is recommended. Typically, the temperature should be greater than 26°C (79°F) and less than 40°C (105°F).

To avoid **system freeze-ups**, it is important to ensure that the lean and rich EG/water mixture is between 60 to 80 wt.%, and to ensure complete coverage of the tubesheet when injecting the EG mixture into the process as an aerosol spray. Often, refrigeration units are operated like a dehydration unit where regenerating the EG to a higher purity (above 80 wt.%) will help improve the water removal from the process. This is not the case in refrigeration units. The purpose of the EG is not to dehydrate the gas (by absorption), but instead to act as a chemical hydrate inhibitor in the tubes of the exchanger and form a non-freezing mixture with the condensed liquids. The water (and hydrocarbons) are condensed out of the gas stream as the temperature decreases in the gas/gas exchangers and chiller, and not by absorption in the glycol as in dehydration units. It is extremely important to ensure that the tubesheet is covered completely by EG to prevent freezing since, without EG being distributed to all of the tubes in the exchanger, there will be no chemical inhibitor present to prevent a freeze up from occurring as the water (and hydrocarbons) condenses from cooling. This is one of the reasons why the upper and outer tubes of the exchangers have a higher tendency to freeze up more than the rest of the tubes, since these tubes often receive less EG from problems with the injection nozzles.

There will always be some **glycol losses** during normal operation from the regenerator, since there will be an equilibrium amount of glycol that will leave with the water in the regenerator overhead. An acceptable glycol loss rate is between 0.11 to 0.33 USG of EG per MMSCF (0.015 to 0.045L of EG per e<sup>3</sup>m<sup>3</sup>) of gas processed. However, higher than normal glycol losses are typically governed by other problems in the refrigeration plant, and the main source of high glycol losses will generally be from the regeneration still column. If NGL is carried over to the regeneration section as a result of poor separation in the LTS, it can make its way into the regenerator where it will flash off and carry more glycol out of the system than normal. For example, one (1) unit of liquid propane at normal LTS condition can expand as much as 270 units in volume at atmospheric temperature and pressure. With this immense rate of expansion, the velocity of the gas rising up through the regeneration still column will also increase; thus further increasing the rate of glycol being carried over. Other sources of glycol losses can be from: (a) glycol being carried over with the NGL product as a result of poor separation in the LTS, (b) excessive filter changes (since back flushing is required), (c) mechanical issues with the reflux coil at the top of the still and/or (d) a leak in the gas/gas exchanger.

**Emulsions and foaming** can cause separation issues in the LTS which can result in lower NGL production rates as well as foaming in the regenerator still column. In general, it has been found that the higher the wt% glycol concentration of the lean solution, the greater the tendency for emulsions to form. There is a definite advantage to maintaining the lean EG content below 80 wt%. Tight emulsions have been formed when impurities enter the plant and are not removed by inlet separation. These can be pipeline treating chemicals, heavy hydrocarbons and/or solids. Demulsifiers have proven to be an effective solution to this problem in the LTS. Foaming with these systems is more often attributed to mechanical frothing or physical mixing of the glycol in the exchanger tubes, rather than any significant foaming tendency in the glycol itself. When high gas velocities occur in the exchanger tubes (from plugging) and there is significant glycol flowing through the exchanger tubes (especially the lower ones), the solution will froth from the “whipping” of the glycol in the tubes. These solutions cannot be made to foam in a foam test. Proper injection characteristics (injection rates, spray coverage, concentration) will alleviate this problem.

The **solution pH** should be maintained at a slightly alkaline value of 7.5 to 9.5 for optimum process and corrosion control. Some producers successfully use Sodium Mercaptobenzothiazole (NaCap) as a solution inhibitor/buffer. However, NaCap is soluble in the condensate phase and quite often the NaCap leaves with the condensate phase requiring frequent addition. Also, the solubility of NaCap significantly reduces once the pH of the solution drops below 7, resulting in the precipitation of NaCap as a solid, which is often found on the surface of the particulate filters. A good inhibitor is alkanolamines, which have great reserve alkalinity and a high pH between the range of 10.5 to 12. The typical recommended dosage is 0.15 volume percent on inventory. The amine will not leave with the condensate and there is complete compatibility of the amine under the process operating conditions. Adding amine into the glycol will help to a degree, as long as the pH of the process glycol does not go above 10.5, because then the solution will have a greater tendency to stabilize emulsions. It is also important to realize that amine/water mixes have excellent hydrate inhibiting properties, almost as good as glycol, but it also has a greater tendency to draw hydrocarbon into the glycol regeneration loop.

The majority of refrigeration plants employ rich side **filtration** to protect the regeneration section from severe solids and hydrocarbon contamination. It is recommended to employ a filter on the lean stream to prevent solids from damaging/plugging the spray nozzles. Injection nozzles are equipped with strainers to catch some sediment prior to it damaging the nozzles. The advantages of strainers are that they can hold a higher amount of solids, and this makes back-flowing/purging the injection nozzles much easier while reducing concerns that parts of the internal nozzle assembly are partially plugged (essentially they act as a nozzle filter). If carbon filtration is utilized on the rich stream, the life cycle of the carbon bed is generally poor, because of the excessive quantities of hydrocarbons that have to be removed. Activated carbon can adsorb up to 15% of its weight under good conditions (proper flow rates and residence time of minimum 15 minutes). For example, a 50 lb activated carbon canister can theoretically hold only 7.5 lb of contaminants, translating to approximately 3.5 Liters (L) of liquid contaminants.

In regards to system flushes, an **initial start-up flush** generally involves a weak pre-flush followed by a main flush with a slightly alkaline solution; the temperature of the solutions should be maintained at approximately 60°C (140°F). Generally, the pre-flush removes a majority of the settlements and deposits, while the main flush is to remove surfactant products (i.e. rust prevention oil, etc.). Typically, the duration of the flush spans from 4-to-8 hours, depending on the size of the system and the amount of contaminants remaining in the final flush solution. There are ample flush procedures and literature regarding the sequential steps for a proper flush (i.e. LRGCC).

## **CASE SCENARIO – PROCESS OVERVIEW**

This Canadian gas facility processes a total of 260 million standard cubic feet per day (MMSCF) of natural gas in two identical trains, which primarily draw from their own gas wells and a small fraction of gas sources from other producers. The plant has two identical amine systems, processing a sour gas containing 6 mol% H<sub>2</sub>S, in front of the two identical EG refrigeration systems, fed in series by each of the upstream amine trains. Since both trains are a mirror image of each other and have experienced identical problems, Train 1 will be used as the focal point for this case scenario.

The Ethylene Glycol refrigeration (NGL Recovery) trains consist of the following:

- 2 – Gas-to-Gas Exchangers in series
- 1 – Propane Chiller
- 1 – Low-Temperature Separator (LTS)
- 1 – L/R Exchanger tube in LTS boot
- 1 – Flash Tank (with skimming line)
- 1 – Particulate Filter Vessel (bag filter)
- 1 – Charcoal Adsorber (8 canisters)
- 1 – Plate and Frame Exchanger
- 1 – Direct Fired Reboiler
- 1 – Still Column
- 2 – Primary Glycol Discharge Pumps
- 3 – Injection Nozzles

The newly built ethylene glycol refrigeration facility (Train 1) was commissioned in late 2014. The facility operated for less than 1 week, with the total run time being less than one day, before it had to be shut down because of multiple operational issues. During the initial start-up, plant operators noticed multiple occurrences of NGL carryover, which had caused the refrigeration unit to shut down. The process data summary from the prior week had indicated that the process was running fairly well until the temperature of the LTS dropped below -25°C. Once the temperature dropped below -25°C, high volumes of NGL would be carried over to the regeneration section of the refrigeration unit, which at times caused some of the lines and vessels to vibrate uncontrollably and cause the rich glycol to foam.

The unit was designed to produce up to 67 cubic meters per day (m<sup>3</sup>/day) of NGLs, but the actual production was less than 5 m<sup>3</sup>/day during the first week of start-up.

## **DESIGN AND P&ID REVIEW**

There were several critical design parameters that either did not match the current conditions in the plant or were not addressed properly prior to construction.

The first poor design parameter was the designated inlet gas temperature to the first exchanger. The temperature from the design company's simulation was set at 50°C, which was significantly higher than the historical temperature trend out of the amine contactor. The amine unit outlet gas temperature was typically measured between a minimum of 22°C, and a maximum of 35°C.

The second questionable parameter was the glycol injection rate proposed for this system at 18.2 gal/min, distributed evenly to all three nozzles at 6.07 gal/min each. By comparing Dehydration Experts' calculated injection rates with the designers suggested injection rates, the system was found to be over-circulating by approximately 4 to 7 times. When broken down to individual nozzles, the first injection nozzle was over-circulating by approximately 2 to 4 times the required rate, 5 to 11 times for the second nozzle and 12 to 23 times for the chiller nozzle.

The third parameter, which is typically overlooked by most designers and fabricators, is the insulation for the glycol injection lines. This is an important installation component, especially for facilities exposed to arctic winter conditions, as in Canada. The viscosity of the glycol can vastly change throughout the year as a result of the ambient temperature. Naturally, the colder the glycol, the higher the glycol solution's viscosity and therefore the lower the glycol injection capacity. In terms of glycol spray coverage, under colder injection conditions, the injected glycol aerosols are larger, and thus the aerosol distribution amongst the exchanger tubes is reduced (less surface area coverage). Often in cold weather, glycol pumps can over-pressure as a result of the increased glycol viscosity. For this plant, the temperature of the glycol injected into the exchangers prior to the installation of proper insulation was between 5 and 15°C, and after the installation, the glycol temperature was between 26 and 35°C.

The fourth questionable parameter related to the glycol injection coverage and the internal diameter of the gas/gas exchanger vessel. Based on recommended industry design and practice, the typical gas velocity going into the exchanger tubes should be between 12-20 ft/s, while co-currently having the glycol injected along with the gas stream. The recommended differential pressure of the injection glycol should be maintained between 80-120 psi. Based on research data from two injection nozzle manufacturers, with the consideration of tubular gas velocity, the maximum distribution range of the glycol trajectory on a single nozzle is between 12-15 inches each side, or 24 to 30 inches (full diameter) before the spray pattern heavily distorts. For this particular EG refrigeration unit, the internal diameter of the gas/gas exchangers was 42 inches, which, theoretically, means that a single nozzle will not be able to provide sufficient coverage to ensure that glycol is distributed to all of the exchanger tubes. The plant did attempt to address the inadequate glycol coverage by increasing discharge pressure close to the pump's Pressure Safety Valve (PSV) limit of between 180-200 psi, resulting in flowing twice the glycol volume necessary for hydrate inhibition. The attempt did slightly reduce the frequency of hydrate/freezing in the exchangers, but did not eliminate the problem.

The fifth questionable parameter related to pressure and temperature indicators ( $T_i$  &  $P_i$ ) after each pass of the gas/gas exchanger(s). These two process parameters are extremely important, as the differential temperature across each exchanger determines the theoretical injection rate(s) required, and differential pressure indicates if the injection glycol flow rate was adequate. The differential pressure across each exchanger should be fairly constant (assuming gas flow rates are relatively constant), an increase of the differential pressure typically indicates hydrate formation, signaling an inadequate volume of hydrate inhibition chemical. These indicators will allow Operations to conduct measures to remediate/troubleshoot hydrate problems associated with mechanical (plugged, worn, & fouled nozzles) and/or the process (flow rates, injection differential, & glycol concentration). Unfortunately, neither of these indicators were installed on the gas/gas exchangers,



leaving limited room for optimization and/or troubleshooting, let alone monitoring day-to-day performance of the system.

## ONSITE INVESTIGATION

Prior to the site visit, Operations had already changed the spiral nozzles that came with the original package to a hollow cone atomizing nozzles that are generally selected for EG refrigeration units. It was found that the primary application for these spiral nozzles was for fruit and vegetable washing and that they were not meant for the EG refrigeration process application. Both injection nozzles and glycol rates were addressed prior to the site visit based on our previously provided recommendations (Dehydration Experts).

During the first week of start-up, the sales gas was not able to meet sales water dewpoint. The exchanger tubes were pressure tested for leaks and the pressure held, and there was no indication of inlet and sales gas communication. It was later determined that the shell side of the exchangers had residual pressure testing fluid left in some of the baffled chambers, indicating that it was not drained out adequately prior to installation. The cold dry gas picked-up the additional water as it passed through the shell chamber of the exchangers, which then caused the water dewpoint of the sales gas to be out of specification. The LTS was approximately  $-25^{\circ}\text{C}$  and the sales gas was between  $-4$  to  $-6^{\circ}\text{C}$  in relative dewpoint. In a properly functioning unit, the LTS temperature should equal both the water and hydrocarbon dewpoint temperatures of the sales gas.

While onsite, it was found that the glycol had extremely high levels of suspended solids, and hydrocarbon contaminants were discovered in the lean and rich glycol. It was determined that the extremely high level of suspended solids was accumulated from a combination of sources, including construction/fabrication material (e.g. rust, dirt, mill scale, etc.), carbon pellets from a burst carbon canister, waxes/asphaltenes from the gas stream and fouled hydrocarbon products. As for the liquid hydrocarbon seen in the samples, it was determined that NGL was being carried over into the regeneration system. The entrained gasses in the rich glycol were not being adequately liberated in the flash tank, causing large gas pockets to accumulate in the filter vessel. It was believed that 90 volume percent of the filter vessel was filled with entrained gasses, therefore solids and contaminants in the glycol were not being efficiently removed. Through field analysis of the glycol/NGL samples, it was determined that excessive injection rates, improper rich glycol ratio and interface emulsions had all contributed to the NGL carryover.

Photos taken of the glycol samples appear to consist of dirt, rust and organic plant matter. One NGL/glycol picture stood out specifically, which had a strand of grass along with various solids suspended between the interface. It was later found that an initial system flush did not take place, because fabrication inspectors told Operations that the vessels appeared to be “quite clean” and a flush may not be necessary. The construction team was in agreement, because a system flush would have delayed the start-up as a result of the need for transportation, storage and disposal of the flush fluids.

During the on-site inspection, it was noted that the low-temperature separator boot was located about  $2/3^{\text{rd}}$  of the way to the NGL weir, which works out to be approximately  $8\frac{1}{2}$  feet from the weir. The distance of the LTS inlet to the weir is approximately 26-feet in length. As a good design practice, the separator boot should be placed as close to the weir as possible, maximizing the fluid separation time. Based on the Gravity Settling Method for liquid/liquid separation, this design

resulted in the settling time being essentially reduced by  $1/3^{\text{rd}}$ , meaning that if the LTS was initially designed to have 30 minutes of liquid settling time, the actual settling time was estimated to only be around 20 minutes, which is not adequate for liquid/liquid separation. The liquid residence time must be at least 30 minutes.

It is also important to distinguish the technical definition between settling and residence time for a liquid/liquid separator vessel, or in this case, the LTS vessel.

Settling time: the amount of time required for liquid droplets to settle out from the continuous phase (another liquid phase).

Residence time: Residence time is defined as the amount of time a fluid remains within the settling compartment of the separator.

There are a number of parameters that contribute to the settling and residence time.

- 1) Glycol circulation rate – Volume of glycol solution feeding into the LTS
- 2) Glycol concentration – Viscosity of glycol solution
- 3) LTS temperature – Viscosity of the glycol solution
- 4) Level of the liquid interface – The layer between NGL and glycol solution

The higher the ethylene glycol purity then the more viscous the solution becomes, which will in turn delay NGL liberation from the glycol solution. The recommended practice is to have the rich glycol between 55-65 wt%. The higher the water content in the rich stream, the better the NGL/glycol separation. The reason is that the glycol solution viscosity decreases with high water concentration, which allows the NGL droplets to rise faster out of the glycol phase. And with more water, which is a polar molecule, the natural tendency is to repel hydrocarbon in the glycol solution phase. However, maintaining a minimum 55 wt% glycol concentration is required for better freeze-point protection.

In regards to temperature, the colder the LTS temperature the more viscous the glycol solution becomes, translating to a longer settling time requirement. In addition, from the lower sub-zero temperatures, more liquid hydrocarbon products will condense out which also adds to a higher settling time requirement. Relating back to the plant, operations personnel noticed an immediate difference in terms of hydrocarbon carryover if the LTS was at  $-25^{\circ}\text{C}$  versus  $-30^{\circ}\text{C}$ . From simulation, the theoretical NGL production at  $-25^{\circ}\text{C}$ ,  $-30^{\circ}\text{C}$ , and  $-35^{\circ}\text{C}$  are approximately 14, 33 and  $67 \text{ m}^3/\text{day}$ , respectively.

The level of the liquid interface sets the allowable accumulation of glycol and/or NGL in a set volume such as the LTS. For example, if the glycol level is set higher from the typically 40% NGL and 60% glycol in the liquid level, the residence and settling time for the glycol solution will be higher. Often the interface level is adjusted in favor of the glycol solution to mitigate NGL carryover to the regeneration loop. This adjustment was proven to be quite effective for this particular plant, assisting in terms of the reduction of hydrocarbon carryover. However, beyond 70% glycol level, glycol was detected in the NGL product. While this level can be easily adjusted by temporarily limiting the glycol dump valve, the NGL product must be monitored continuously to avoid glycol carryover as well.

For the filtration vessels, the particulate and charcoal canisters were adequately sized in this plant. Based on the circulation rates, the charcoal vessel had approximately 20 mins of residence time, which was adequate with respect to the minimum requirement of 15 mins. Typical problems associated with these filter vessels are gas pockets being built-up within the vessels, thus limiting the active filtration and carbon adsorption area. These gas pockets are formed by entrained hydrocarbons (gas & liquid) in the rich glycol solution, which are liberated at lower pressure and/or higher temperature conditions. Without a continuous gas bleeding line and/or a full time operator degassing the vessel, the filters become ineffective. When changing out the particulate filters and carbon bed, there were distinct lines where the gas/liquid interface was located. This suggested inadequate removal of the liberated/flushed gas in the filtration vessels.

Dehydration Experts considers having a skim line in a glycol accumulator important, so that operations personnel can easily remove surface contaminants which build-up within the vessel. Often these surface contaminants form a layer of sludge when mixed with suspended solids like carbon fines. Typically, these sludge compounds will make their way back to the injection nozzles, where they plug up the injection orifice and stop the glycol from injecting into the exchangers.

### **LESSONS LEARNED**

There are a number of preliminary design, construction and operational mistakes made prior to and during start-up. These incidents had caused the plant to incur significant expenditures and loss of production time. Even after the eventually successful start-up, the plant continues to have problems with the oversized equipment. The following economic analysis will help to better understand the impact of these design flaws on this operating company.

For this economic analysis, the proposed start date was 24<sup>th</sup> November 2015 and the actual date that full rates were finally achieved was 21<sup>st</sup> January 2016. During this 58-day period the gas and NGL production were only 37% and 30% of design, respectively. Fortunately, majority of the gas were able to be processed in other sections of the plant, therefore minimizing production losses.

**Table 1** Economic Evaluation of Plant Revenue Losses

<b>Performance Parameter</b>	<b>Design</b>	<b>Actual</b>	<b>Difference</b>
<b>Revenue</b>			
Gas production	22,330,000	8,262,100	-14,067,900
Liquids Production	1,624,000	485,760	-1,138,240
Gas processed in TEG dehydration units	0	12,000,000	12,000,000
<b>Total Revenue</b>	<b>23,954,000</b>	<b>20,747,860</b>	<b>-3,206,140</b>
<b>Expenditure</b>			
EG	14,085	134,642	-120,557
Methanol	0	30,657	-30,657
<b>Total Expenditure</b>	<b>14,085</b>	<b>165,299</b>	<b>-151,214</b>
<b>Total Revenue after expenditure</b>	<b>23,939,915</b>	<b>20,582,561</b>	<b>-3,357,354</b>

Note that the theoretical glycol replacement consists of filter changes, glycol addition, nozzle blow-backs / purges, process skimming (flash & accumulator) and typical glycol losses.

Total Revenue lost (from proposed to actual start-up – 58 days) was **\$3,357,354 or 3.36 Million dollars, or \$57,885 per day.** Incorrect design assumptions and misunderstanding of the process had a major impact on plant's revenues.

It is also important to note that other expenditures, including additional field equipment, staff, transportation and construction costs were not accounted for and would have been a significant cost as well.

### **Actions for the future (designer, operator...etc.)**

Based on the case study, all the equipment was oversized because of the overly conservative chosen inlet gas temperature. By over-estimating the inlet gas temperature (50°C), the theoretical water content was determined to be 230% of the actual water content from the inlet feed gas.

It is important to create simulations based on proper inlet conditions. Obtaining a wide range of simulations with various theoretical plant conditions is also good practice. Key parameters to adjust when making these simulations are:

- Temperature
- Pressure
- Flow Rates
- Gas composition
- Always obtain hydrate inhibition injection rates for both gas and liquid phase

Always conduct a system flush prior to a start-up. There are a number of flush procedures available from technical sources such as LRGCC and chemical providers.

Obtain technical data from vendor sources. Contact and get to know multiple filtration and chemical vendor representatives. They are imperative to successful operation.

When addressing glycol injection rates, consider addressing the following:

- Pump, does it have adequate
  - Pressure
  - Flow rate
  - Safety valve rating
- Flow rate indicators with proper flow ranges
  - Consider installing flow indicators in a warm area to prevent freeze ups and contaminant settling and fouling of the indicators and sensors
- Glycol concentrations (lean & rich)
  - Lean - 80/20 to 70/30
  - Rich – 60/40 to 55/45

- Differential water (content between lean and rich EG (target 5 to 10 wt%)
  - 5 wt.% for exchangers >32" Internal diameter
  - 10 wt.% for exchangers <32" Internal diameter

It is important to note that the ideal water pickup ratio is approximately 20 wt.%, but because of a number of non-ideal conditions, a hefty safety factor is put into place. In particular, the non-ideal conditions are associated with co-current feed gas intersecting the injected glycol and uneven glycol aerosol distribution.

- Injection nozzle selection

One of the most important pieces of equipment for the EG refrigeration unit are the injection nozzles (which typically cost less than \$100 each). These injection nozzles are often the bottleneck for any process changes and optimization.

Ethylene glycol systems are inherently dirty, especially during start-up. Often liquid and solid contaminants make their way through the glycol regeneration process and get stuck in the injection nozzles. The nozzles can then get plugged, worn, corroded and sometimes damaged to the point where the injection rates and spray pattern are negatively affected. These problems will amplify the potential for hydrate/freezing to occur in the Gas/Gas exchanger(s) and chiller.

The details of the injection nozzle are often left out from the original design and, even if included, the detailed specifications are not readily available. To replace the nozzles, it is required to depressurize and shut down the exchanger(s) and physically uninstall them to get the model and make of the nozzles. A general survey on the nozzles installed in this and other EG refrigeration plants suggests that a large fraction of the nozzles are selected and installed based on availability, or what the nozzle vendors have in stock.

There are a number of parameters to consider prior to the selection, which will determine the type of nozzle to select.

### **Criteria for selection**

- Quill length – distance of injection line inserted into the exchanger
- Port size – Size of the line (3/4", 1/2", 1/4" and 3/8" are the most common)
- Distance of injection nozzle to tubesheet
- Fluid viscosity (Based on glycol concentration and temperature)
- Glycol discharge pressure (Differential pressure)
- Exchanger ID size (Surface area of exchanger tubesheet)
- Injection ports
  - >32" – two injection nozzle ports or multi-nozzle attachment
- Plant Turnaround Frequency

It is important to note that a majority of the injection nozzles are made from stainless steel (SS316) and based on technical data, these nozzles should maintain their structural integrity for approximately 1½ years before the injection orifice begins to deteriorate. The deterioration is

mostly caused by abrasion from dissolved and suspended solids. Most plant turnarounds are prolonged to a span of 3-5 years for economic reasons, therefore, a more abrasion resistant material may need to be selected to avoid injection problems over the operational life of the nozzles. The most common abrasion resistant material used for injection nozzles are carbide based, and can have abrasion resistance 20 times that of stainless steel. Unfortunately, because of the special type of material used for its construction and demand, these carbide type nozzles are limited in terms of availability and usually have a very narrow flow rate span, often less than 10 L/min. In addition, delivery times can take up to 8 weeks.

### **Injection nozzle selection**

There are 3 primary types of nozzles used in EG refrigeration facilities. Advantage(s) and disadvantage(s) are listed for each nozzle type.

#### 1. Full Cone nozzle

Uniform, round and full spray pattern with medium-to-large sized droplets. More for aerosols with a high forward propelling momentum (velocity) or direct spray.

*Advantages:* Can operate at a wide range of flow rates.

*Disadvantages:* Difficult to optimize flow because of heavy center distribution, large aerosols tend to co-mingle and form heavy droplets which settle at the bottom of exchanger, lowest theoretical surface area coverage from aerosol size, can be plugged easily with suspended solids in solution.

#### 2. Hollow Cone nozzle

Hollow round spray pattern with small-to-medium sized drops. More for surface area coverage and should be used if the solution being sprayed is fairly clean.

*Advantages:* Wide angle of aerosol coverage, evenly distributed with co-current gas flow, extremely fine aerosols with 5-times the theoretical surface area coverage compared to full cone spray, wider angular coverage compared to full cone (at identical C, P & Q).

*Disadvantages:* Limited range of flow rate for specific connector size, can be plugged easily with suspended solids in solution.

#### 3. Impingement type nozzle

Mist spray pattern with small sized drops. Often described as fog generating nozzles. Works by aerosolizing the deflected flow, intersecting the flow head-on with an impinger rod. More for surface area coverage and to be used for solutions with the potential of ingressed solids.

*Advantages:* Mist generation is exterior of the nozzle fitting, will not plug easily as assembly does not contain a whirlwind mist generation chamber, extremely small aerosols with 5-7 times the theoretical surface area coverage compared to full cone spray.

*Disadvantages:* Impinger tip can physically misalign due to solids/liquid contaminants interacting with impinger rod; impingement tips are more susceptible to abrasion (i.e. erosion corrosion)

### **Injection rate calculations**

There are a number of equations that estimate the necessary injection rates for EG refrigeration systems.

#### 1. Hammerschmidt equation

The Hammerschmidt equation has been the go-to equation to determine the volume of hydrate inhibition chemical required for gas transmission, often used for methanol (MeOH) and ethylene glycol. The calculation has two conjoined segments, the first segment determines the necessary rich water content for the glycol solution, the second segment, integrates the rich water content in a mass balance equation to determine the necessary injection flow rate.

$$W = \frac{100(M)(\Delta T)}{M(\Delta T) + K}$$

T = the hydrate temperature depression from the equilibrium temperature at a given pressure

M = Molecular weight of the inhibitor (Ethylene glycol = 62.07 g/mol)

W = weight fraction of the inhibitor in the rich-water phase

K = constant, a function of inhibitor used and the phase into which it partitions

The K values below were used in the past and are currently used by a number of producers:

Extremely high rate of glycol distribution error, K = 1855

High rate of glycol distribution error, K = 2335

Medium rate of glycol distribution error, K = 3200

Low rate of glycol distribution error, K = 4000

It is well known that the K value for EG in the Hammerschmidt Equation (HSE) has changed over the years, the K value varies from 1855 to 4000. A number of sources state that the HSE is fairly accurate in predicting the amount of EG solution required in a pipeline hydrate inhibition aspect. But once the concentration of EG is above 50%, which is usually the case for EG refrigeration systems, the accuracy becomes unreliable.

#### Calculation Steps

- i. Calculate the hydrate formation conditions using the gas gravity chart (based on gas composition).
- ii. Calculate the temperature difference between the hydrate formation temperature and the lowest temperature observed in the process (i.e. the chiller)
- iii. Use the temperature difference calculated in step (ii) in the HSE to calculate the minimum concentration of the rich EG wt%.
- iv. Calculate the water content of the inlet gas using the gas composition and saturation temperature and pressure.

- v. Calculate the water content of the gas using the LTS temperature and pressure as the saturation conditions.
- vi. Calculate the total water condensed out using the water content of the gas phase from steps (iv) and (v).
- vii. Using the calculated water condensed from step (vi), the target rich EG concentration from step (iii) and the concentration of the lean EG being injected to calculate the required flow rate of EG

It is important to note that glycol concentrations are typically kept and operated between 60 to 80%; the varying K value is to compensate for the reliability limit of the HSE.

## 2. Mass balance method

The concept of the mass balance method (MBM) is to determine the injection rate(s) required to blend the condensed water from the gas stream with the injected lean glycol to achieve the desirable rich glycol concentration. With proper glycol distribution and adequate amount of glycol injected, hydrates should not form. This equation has proven to be the most reliable thus far, the results were mostly positive with minimal adjustment in safety factors.

The mass balance steps will be similar to the final steps of the HSE, the major difference is that the rich EG value is set, based on freeze point data, and physical properties.

### Calculation Steps

- i. Determine the water content of the gas based on the temperature and pressure.
- ii. Calculate the amount of water condensed based on temperature depression across each exchanger
- iii. Set the lean ( $L_{EG}$ ) and rich water content ( $R_{EG}$ ), typically 70/30 and 60/40, respectively. Take water pickup into consideration based on exchanger internal diameter
- iv. Apply the equation to each exchanger and chiller to generate the individual injection rates
- v. Calculate the mass of EG solution required to achieve the desired rich EG composition

Using the weight of water condensed from each exchanger & chiller

$M_{EG}$  = Mass of EG solution required (kg/day)

$R_{EG}$  = Rich glycol concentration (weight fraction)

$L_{EG}$  = Lean glycol concentration (weight fraction)

$W_c$  = Water condensed from gas stream (kg/day)

$$M_{EG} = \frac{R_{EG} * W_c}{L_{EG} - R_{EG}}$$

Similar to the HSE, this equation will also require safety factors to account for inadequate glycol distribution. The safety factor can range from 25% to 50% on top of the calculated injection rate(s).

## 3. Rule of thumbs (From EPCM & Fabrication Companies)



The stated rule of thumb has been around in the engineering industry for a number of years. A number of units in Canada have used this rule of thumb to determine the optimal injection rate for EG refrigeration units. This ratio is determined and compiled from a number of process simulations, predicting the EG injection rate required in order to mitigate hydrates in the gas phase.

- 1.3 to 2.0 lb H<sub>2</sub>O removed per gallon of EG injected

Field data suggest these ‘rule of thumb’ values can vastly over-predict the injection rate necessary to prevent hydrate in the liquid phase. In fact, this ratio often leads to oversized plant equipment (i.e. glycol pumps). This value was used in the case scenario in this paper.

There are a number of cases/facilities where this go-to rule-of-thumb was misinterpreted because of the way it is stated; “H<sub>2</sub>O removed” leads to the thought that EG is a liquid desiccant, similar to TEG. This incorrect assumption has led to more poorly designed plants than any other assumption.

#### 4. Process Simulation Program

A good portion of designers and operation personnel are still convinced that the purpose of the injected ethylene glycol is in fact for dehydration purposes and not the intended hydrate prevention/inhibition. When plants are constructed with misinformed fundamentals, often vessel and plant equipment are vastly oversized, at times to a point where optimization becomes difficult, and can not be implemented without capital expenditure.

Compiled field data suggests that injection rates determined by hydrate inhibition in the gas phase will often lead to lean-rich water pickup less than 3 wt.%, whereas, inhibition in the liquid phase will lead to lean-rich water pickup being greater than 12 wt.%. It is important to note that designers and fabricators should NEVER recommend the option to inject 100% of the EG into the first exchanger to prevent hydrates from forming in the subsequent exchanger(s) and chiller. In theory, this option should work, since there is enough EG in the process to form a glycol-water mixture that will not freeze, which is why the simulation software does not issue a warning or error for this method. However, in the process, what will actually happen is that the EG that is injected in the first exchanger will be unevenly distributed to the downstream exchangers (and chiller) since the effect of gravity alone will cause the glycol-water mixture to favour the lower tubes in the exchangers. The result of this is that there will be no EG (or not enough) in the upper tubes to form a glycol-water mixture that will not freeze when additional water is condensed out of the gas phase in the downstream exchangers and chiller.

## CONCLUSION

Based on the case study scenario presented in this paper, an obvious conclusion is that there were a number of engineering, fabrication and construction infractions that caused the start-up delay, which in-turn lead to substantial financial losses. The producers acknowledge the delays transpired from rushing the preliminary process, and were propagated by the inadequate knowledge of the fundamentals from all parties involved in the design. Fortunately, with a multitude of process corrections, the plant was able to process gas at rates close to the designed capacity.