GLYCOL INJECTION FOR REFRIGERATION AND JT PLANTS

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Mark Bothamley
Mark Bothamley Consulting, LLC
Sheridan, WY 82801
markb@markbothamleyconsulting.com

ABSTRACT

This paper provides an in-depth, but practical, analysis of the glycol injection process for mechanical refrigeration and Joule-Thomson gas plants. The principles covered are also applicable to hydrocarbon dewpoint control turboexpander plants. The coverage of this subject area has typically been at a high level and fairly general in nature.

The industry has historically used a general guideline of 80 → 70, 10 wt % dilution for setting total glycol injection rates for these plants. This paper will show that in many cases this guideline is inadequate and will result in the risk of hydrate formation at various locations in the plant. Other areas covered in the paper include:

1) What are the appropriate glycol injection points and why?
2) How should the glycol be injected?
3) How much glycol should be injected at each point?

These are topics that for many plants are not well defined. Some plants get by without major problems, some do not. Various problems encountered at different plants over the years will be discussed.

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INTRODUCTION

The purpose of this paper is to take a detailed look at the glycol injection process as typically utilized for hydrate inhibition in mechanical refrigeration and Joule-Thomson natural gas liquids recovery plants. There is surprisingly little published literature dealing with this subject.

The glycol injection process has been utilized in refrigeration and JT plants around the world for many years, and yet some of the design details and operational aspects of this process remain somewhat ill-defined. This paper will discuss the typical practices employed in the industry, and provide recommendations for modifying these practices, where warranted, with the focus on how much glycol should be injected, and where.

DISCUSSION

Glycol – usually ethylene glycol – is injected in the cooldown section of mechanical refrigeration, Joule-Thomson (JT) and turboexpander hydrocarbon dewpoint control and moderate NGL recovery plants, to prevent hydrate formation. This process is typically employed instead of traditional gas dehydration technologies like TEG and solid bed methods. The normal operating temperatures in these plants are generally too cold – and the associated water contents too low – for "typical" TEG dehydration units, and the glycol injection system saves the cost of a potentially large and thick-walled contactor. Mole sieve systems are expensive and somewhat of an "overkill" from a water removal standpoint given the warmer operating temperatures of these plants. **Figures 1** and **2** show process flow diagrams of typical refrigeration and JT plants respectively. Of course, other configurations are possible.

Figure 1 Typical Refrigeration Plant PFD

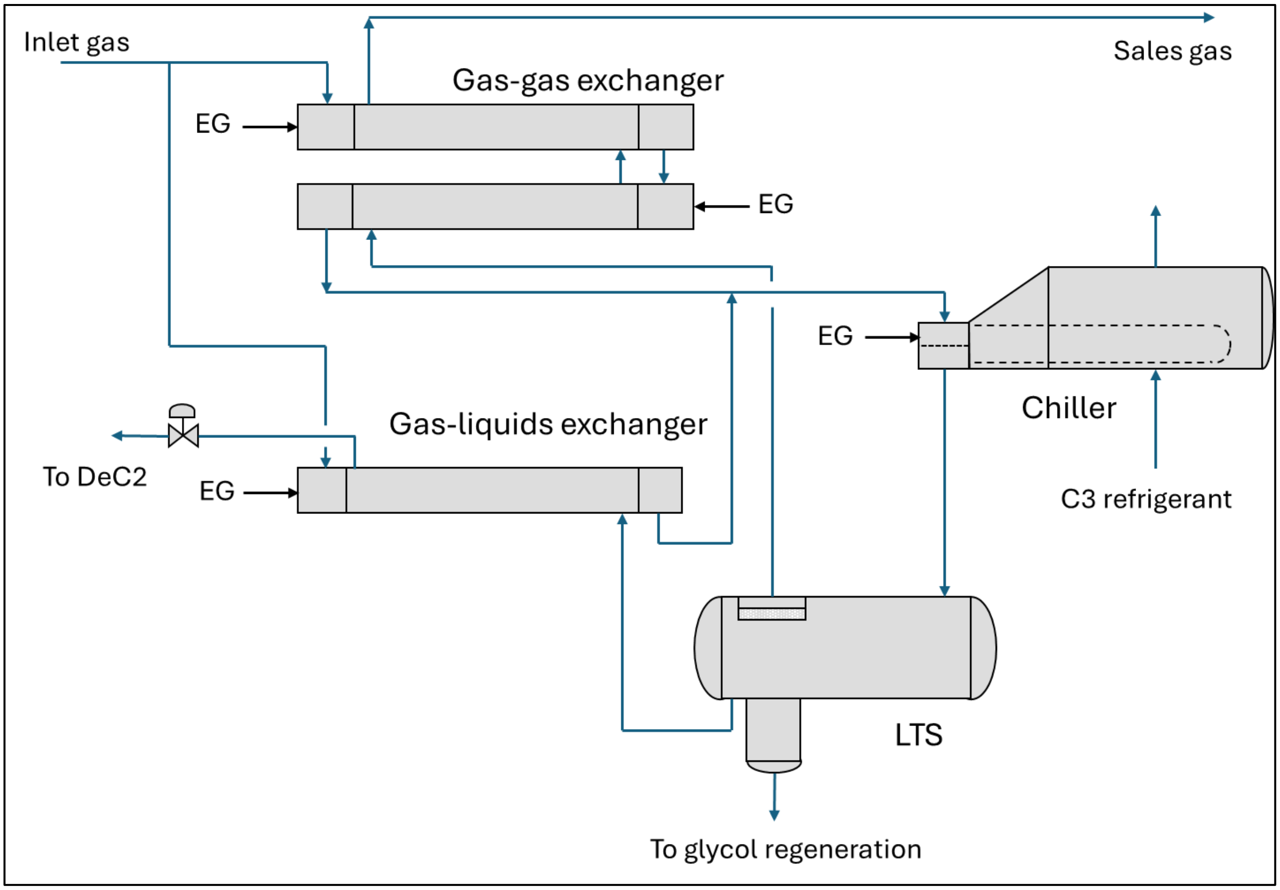
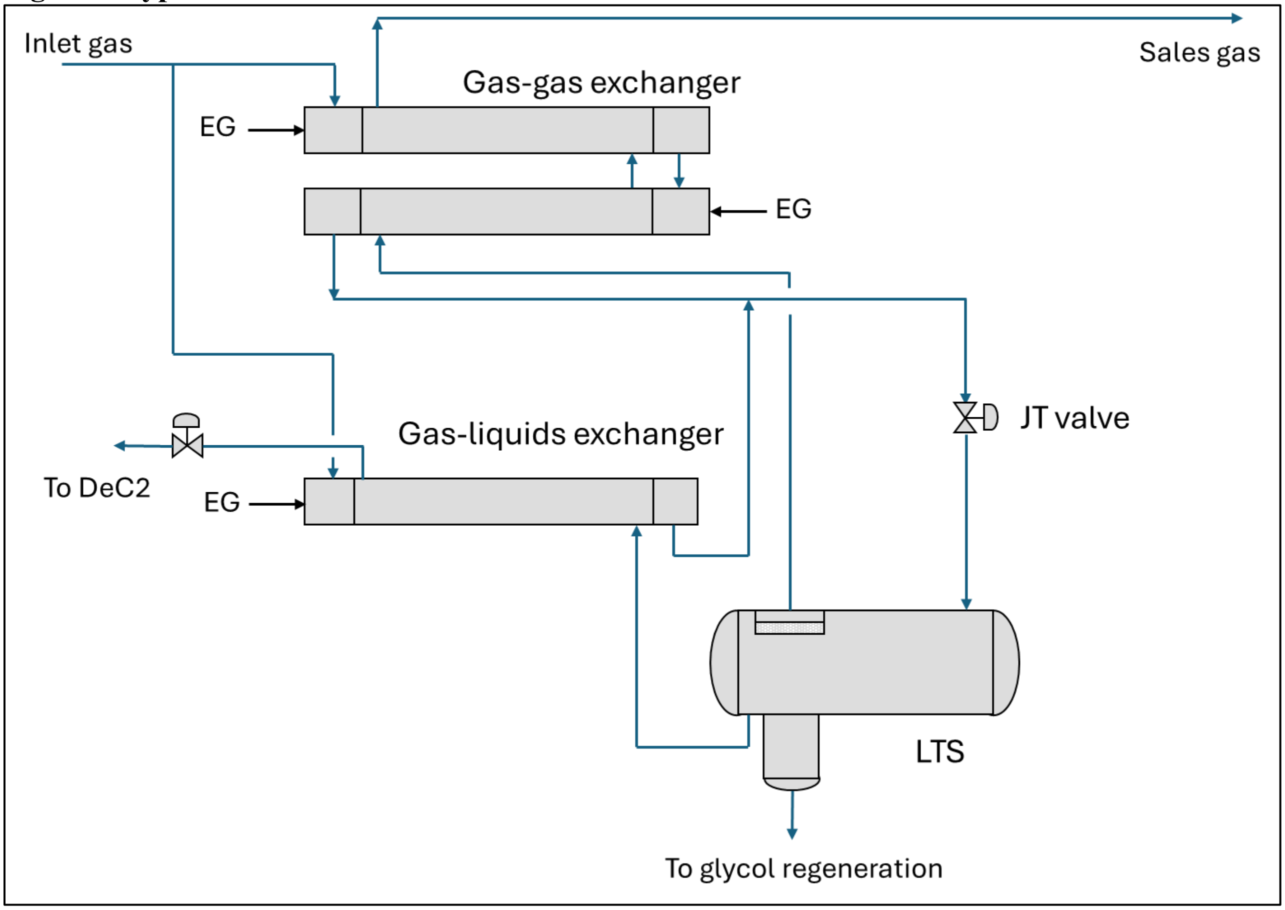

Inlet gas
Sales gas
Gas-gas exchanger
EG
EG
EG
Chiller
C3 refrigerant
Gas-liquids exchanger
To DeC2
EG
LTS
To glycol regeneration

Figure 2 Typical JT Plant PFD



The cooldown sections of refrig plants tend to operate in the 600 – 1,100 psig range while JT plants often operate at higher inlet pressures – up to 1,500 psig. Temperatures entering the cooldown sections of these plants range from 40 to 120 F depending on the inlet gas supply system and plant location (latitude). Low temperature separator (LTS) temperatures range from ~ 10 F to ~ -30 F, depending on the processing objective, ie. hydrocarbon dewpoint control (C6+ recovery) or moderate NGL recovery, eg. 50-60 % C3+, and plant type. Refrigeration plants are typically limited by a reasonable temperature approach to the boiling point of propane refrigerant, ~ -40 F, at near atmospheric pressure on the shell-side of the chiller. Hydrocarbon dewpoint control plants typically operate on the warmer end of the LTS temperature spectrum given above but depending on the nature of the hydrocarbon dewpoint spec and the LTS operating temperature, LTS temperature requirements can be surprising cold.

JT plants are not limited by the propane refrigerant temperature and could operate colder but typically don't. JT plants are relatively rare because of the imposed high pressure – and associated costs – on the upstream gathering system and wells. For fields with excess deliverability/high reservoir pressure, a JT plant can be a good low upfront cost option, allowing the delay of expensive compression and/or a refrigeration system.

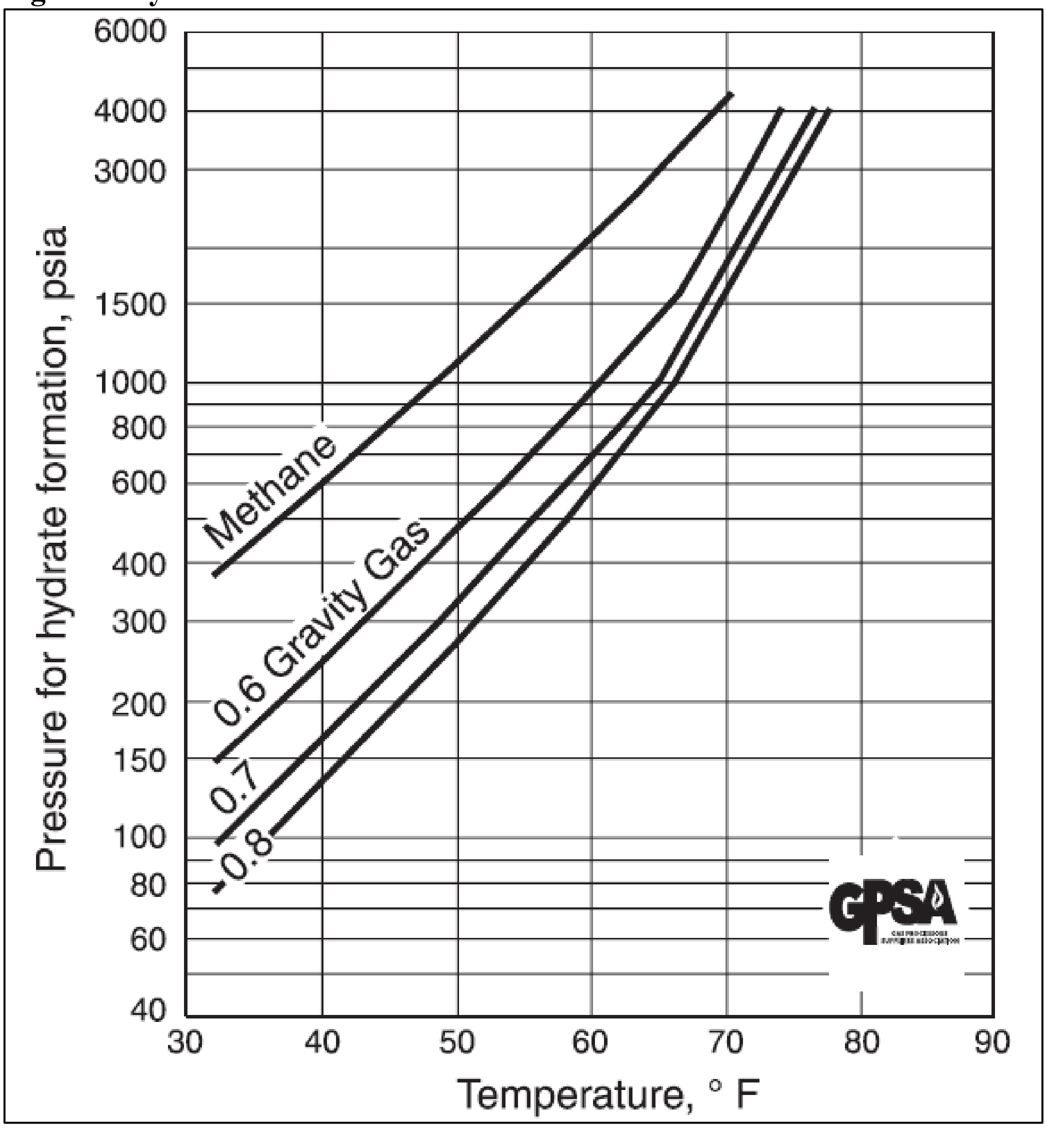
The remainder of this paper will focus primarily on refrigeration plants, although most of the discussion is equally applicable to JT plants.

The glycol injection process

Glycol injection is *not* actually a dehydration process. The glycol does absorb some water vapor from the gas but not very much, because the glycol concentrations utilized are relatively low. The primary purpose of the glycol is to prevent hydrates as the gas cools down and water condenses at conditions inside the hydrate forming region. The inlet gas is dehydrated but this is primarily due to the gas temperature reduction associated with the refrig/JT process. These temperatures are more than adequate to dehydrate the gas to a typical sales gas water content specification.

Figure 3 shows approximate hydrate formation conditions for different specific gravity/molecular weight gases.

Figure 3 Hydrate Formation Chart as a Function of Gas SG



What Kind of Glycol ?

There are three types of glycol that could be considered:

1. Ethylene glycol (EG or MEG)
2. Diethylene glycol (DEG)
3. Triethylene glycol (TEG)

EG is probably used in 95+ % of the refrigeration and JT plants worldwide. Its lower molecular weight results in lower injection rates than for EG and TEG, its solution viscosity is lower and vapor pressure losses are typically negligible. Note that DEG has occasionally been used for hydrate inhibition of wet gas pipelines but there are some different considerations for this application.

Methanol – while it has some advantageous properties – is not used in these plants mainly because its higher vapor pressure would result in significant continuous losses to the vapor phase.

Lean glycol – typically ~ 80 wt % glycol/20 wt % water – is injected into each of the different exchanger tube passes in the cooldown section of the plant. Water condenses out of the gas as the gas is cooled and glycol needs to be present at those locations where hydrate formation is possible. For most plants this means at locations less than ~ 65 F. The rich glycol, diluted by the condensed water, is recovered from the LTS, sent to regeneration to boil off the recovered water and is then ready to be used again for injection. Separation of the rich glycol from the condensed hydrocarbon liquid and subsequent regeneration of the glycol are not discussed in this paper.

<u>Glycol injection points</u>

Figures 1 and 2, shown previously, indicate the correct locations for glycol injection in refrigeration and JT plants respectively. Not all plants inject glycol at the recommended points. A closer look at the details involved with *how* the glycol is actually injected is necessary.

A reasonably large percentage of plants inject glycol *into the piping* ahead of the exchanger to be protected – sometimes with an injection quill or nozzle, sometimes just through a simple thread-o-let. There are a couple of possible explanations as to why this is done: 1) the designer thinks that the glycol is absorbing water vapor from the gas, ie. dehydrating the gas, and therefore the key requirement is good mixing of the injected glycol with the wet gas, and 2) it doesn't really matter how the gas is injected into the wet gas stream – the glycol will go where the gas goes and therefore be in the location when and where it is needed. Even if the right *amount* of glycol is injected, this is not going to work because the gas and glycol phases will separate in the piping and/or exchanger channels due to momentum and gravitational separation forces. The glycol needs to be sprayed onto *<u>each</u>* exchanger tubesheet in order to have the best chance of getting glycol into *each* tube. The wet inlet gas will flow into each tube and will condense out water as the gas is cooled down.

At locations with temperatures less than the hydrate formation temperature – typically in the 60-68 F temperature range for most plants, depending on gas compositions and operating pressures – hydrates will form if glycol is not present at an adequate concentration (the hydrate temperature is usually crossed at some point in the warm gas-gas exchanger). This will typically lead to the affected tubes "hydrating off". Gas flow through these tubes will cease, effectively removing heat transfer surface area and resulting in increased pressure drop across the exchanger. Loss of exchanger area will typically result in warmer LTS temperatures and/or increased chiller duty.

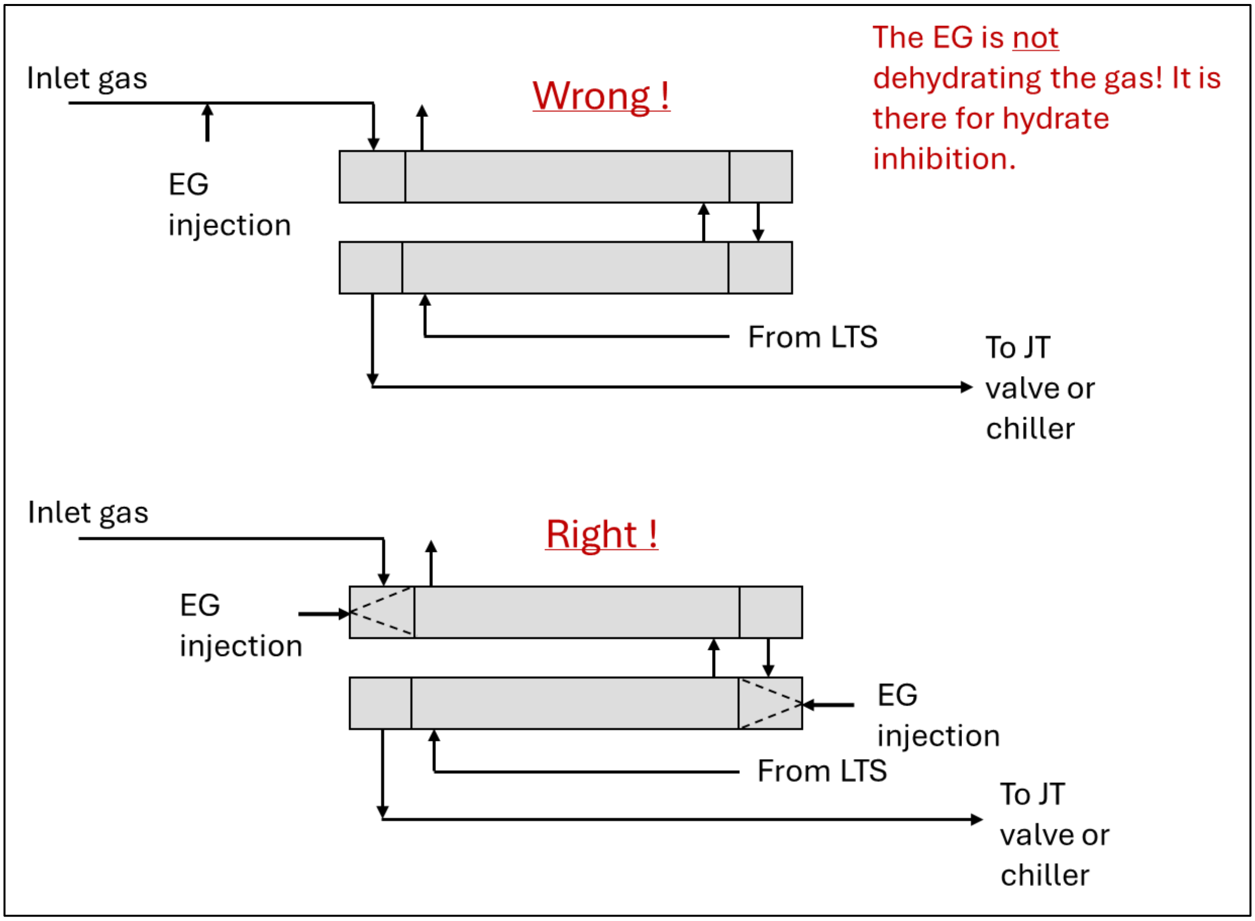
Higher tubeside pressure drops may or may not be a problem, depending on the application. The higher velocities through the remaining open tubes have been known to cause rich glycol-hydrocarbon liquid emulsions in some plants and subsequent liquid-liquid separation problems. An often overlooked subject is that the presence of glycol in the tubes negatively impacts the exchanger's overall heat transfer coefficient.

A large gas-gas exchanger can easily contain 2,000+ tubes per shell. It is very difficult to get glycol into all of the tubes even when using "proper" spray nozzle design, location and operating conditions. The gas typically enters the channel/bonnet head from the top at relatively high ρV2 levels, knocking the glycol spray down. This severely limits the ability to get glycol into the upper tubes in the tube bundle[1]. It should also be noted that irrespective of glycol spray considerations, the inlet gas flow distribution across all of the tubes is generally not uniform.

Figure 4 is a simplified close-up schematic of a typical 2-shell counter-current flow gas-gas exchanger, showing the correct and incorrect location of the glycol injection points. These principles apply to the gas-liquids exchanger and chiller as well.

Figure 4 Incorrect and Correct Spray Nozzle Locations for a Typical Gas-Gas Exchanger

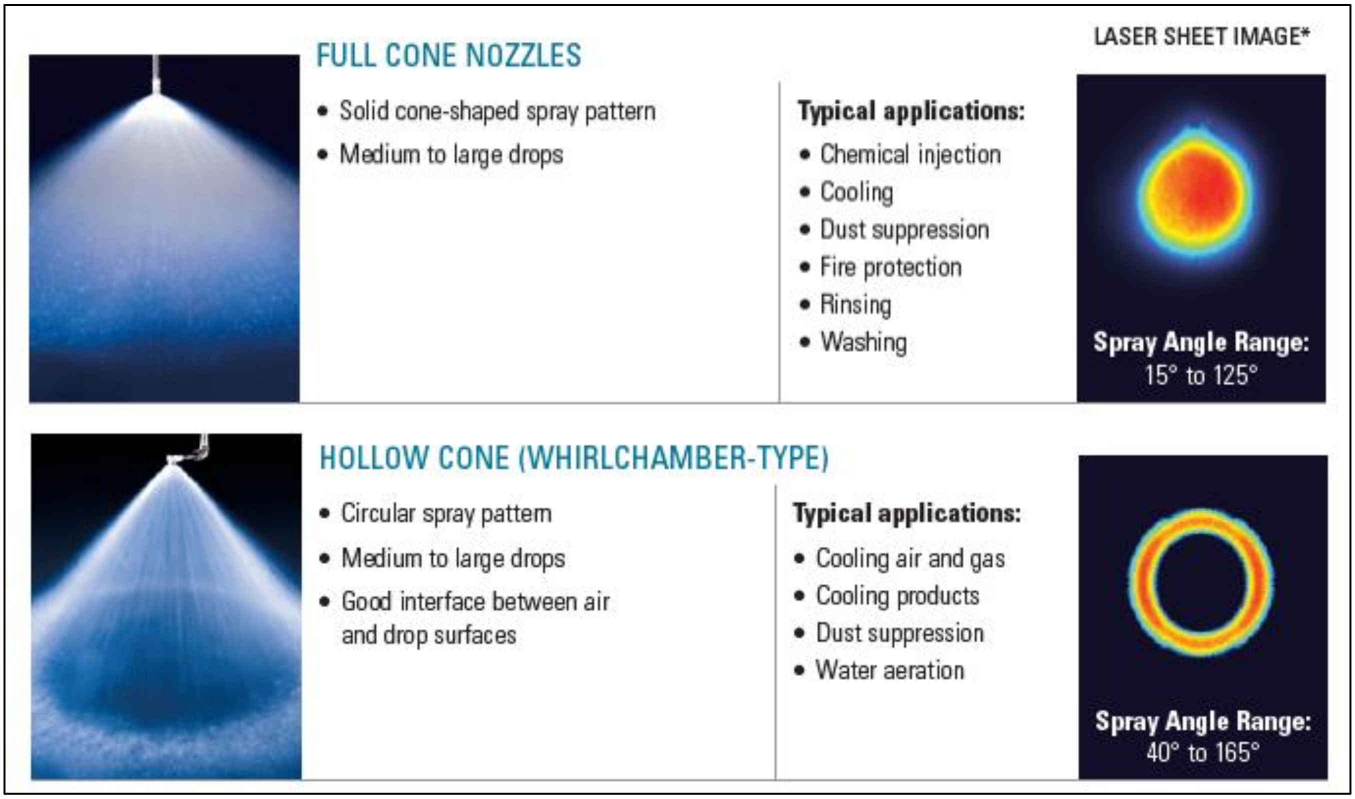
[1] ρV^2 (density x velocity^2) is a measure of a fluid streams' momentum or kinetic energy.



Spray nozzle selection is a specialized but important subject. There does not seem to be a consensus as to the "best" spray nozzle type, eg. full cone, hollow cone, fine spray, etc for this application[(1)] (**Figure 5**). It should be noted that "full cone", "hollow cone", etc are general categories – there are several variations of each of these. The main performance criteria should be to get reasonably good glycol spray distribution into all the tubes. A full cone nozzle type would seem to be the obvious choice, but there are a number of factors involved that need to be considered.

The amount of deflection (knockdown) of the spray is highly dependent on the momentum ratio $q = (\rho V^2)_{spray}/(\rho V^2)_{inlet\ gas}$. Higher momentum ratios result in reduced spray deflection. The spray droplet sizes also play a role. Full cone nozzles generally produce larger droplet sizes than hollow cone nozzles, and the higher momentum of the larger droplets should make them less prone to deflection though also more susceptible to gravity separation. On the other hand, very small droplet sizes/fog might be expected to "follow the gas flow" and have a better chance of getting into all the tubes. It is not clear that this is actually what happens in practice.

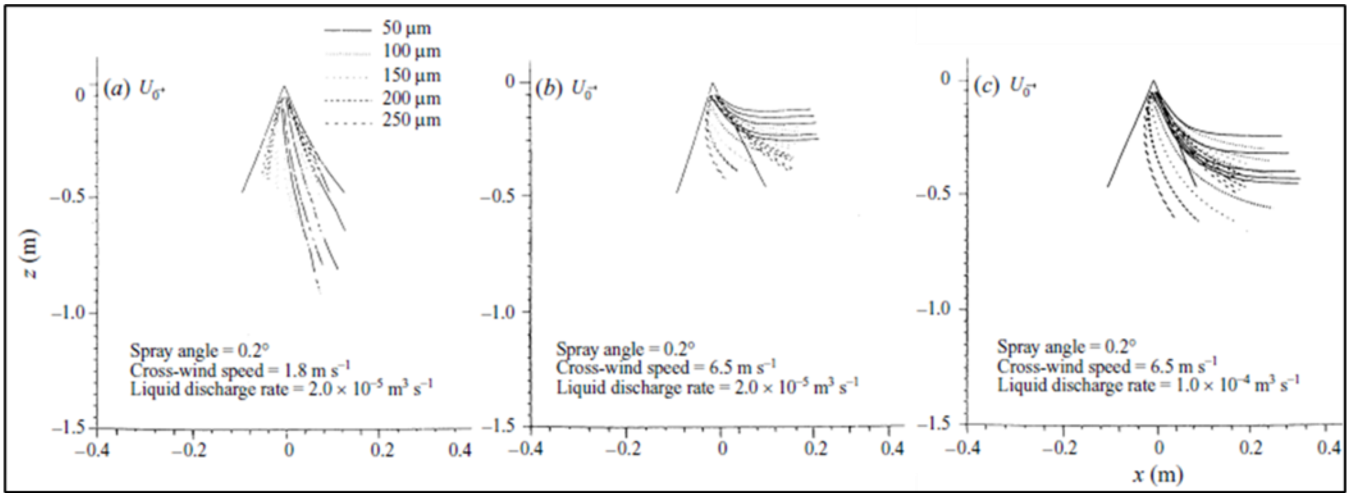
Figure 5 Typical Spray Nozzle Types



Spraying Systems Co.

Though not strictly representative of the glycol injection application, **Figure 6** provides useful insight into some of the factors involved[(2)]. This figure reflects a downward oriented spray nozzle discharging water into a horizontal cross-wind. The "cross-wind" in this gas would be approximately analogous to the gas entering the heat exchanger channel/bonnet head. As a point of reference, typical exchanger gas inlet velocities would be in the range of 15-25 ft/sec (4.6-7.6 m/s) though the ρV^2 value for the inlet gas would be ~ 50 times higher than atmospheric pressure "wind" due to the much higher gas density at the elevated operating pressure. **Sub-figures (a)** and **(b)** show the effect of cross-wind speed on the spray droplet trajectories for a range of droplet sizes. Clearly the higher cross-wind velocity **(b)** deflects the spray droplets much more, and small droplets are deflected more than large droplets. **Sub-figure (c)** shows that higher nozzle flowrate/exit velocity reduces droplet deflection for a given cross-wind speed.

Figure 6 Effect of Cross-wind on Spray Pattern



Other factors including installation geometry details in particular, are also important. A simple step to help mitigate the knockdown effect would be to locate the spray nozzle(s) higher. Large exchangers may require more than one spray nozzle per tubesheet. Another approach would be to use an axial flow "cone-type" head on the inlet end of the exchanger which theoretically should minimize the spray knockdown effect. This seems like a good idea but is rarely seen in practice.

The lean glycol solution should be delivered to the injection nozzles at a relatively warm temperature, eg. 80-100 F in order to keep viscosity down and allow proper spray nozzle operation. Normal operating nozzle ΔP is ~ 100 psi. It is the *actual* spray characteristics in service that are important, which may be significantly different than the generic/idealized characteristics presented in the spray nozzle manufacturer's literature. There are a number of additional details involved with spray nozzle selection, sizing, installation and operation. This is an area that requires more research, testing and modeling.

A final point regarding injection points in a JT plant. Is it necessary to inject glycol directly ahead of the JT valve? This is not a "spray coverage of the tubesheet" issue as there is no tubesheet. There are a couple of options here:

i) Inject glycol onto the cold gas-gas tubesheet at concentrations sufficient to prevent hydrates in this exchanger and also inject glycol ahead of the JT valve based on conditions (colder + additional condensed water) downstream of the valve.
ii) Inject enough glycol onto the cold gas-gas exchanger to protect against the conditions downstream of the JT valve.
iii)

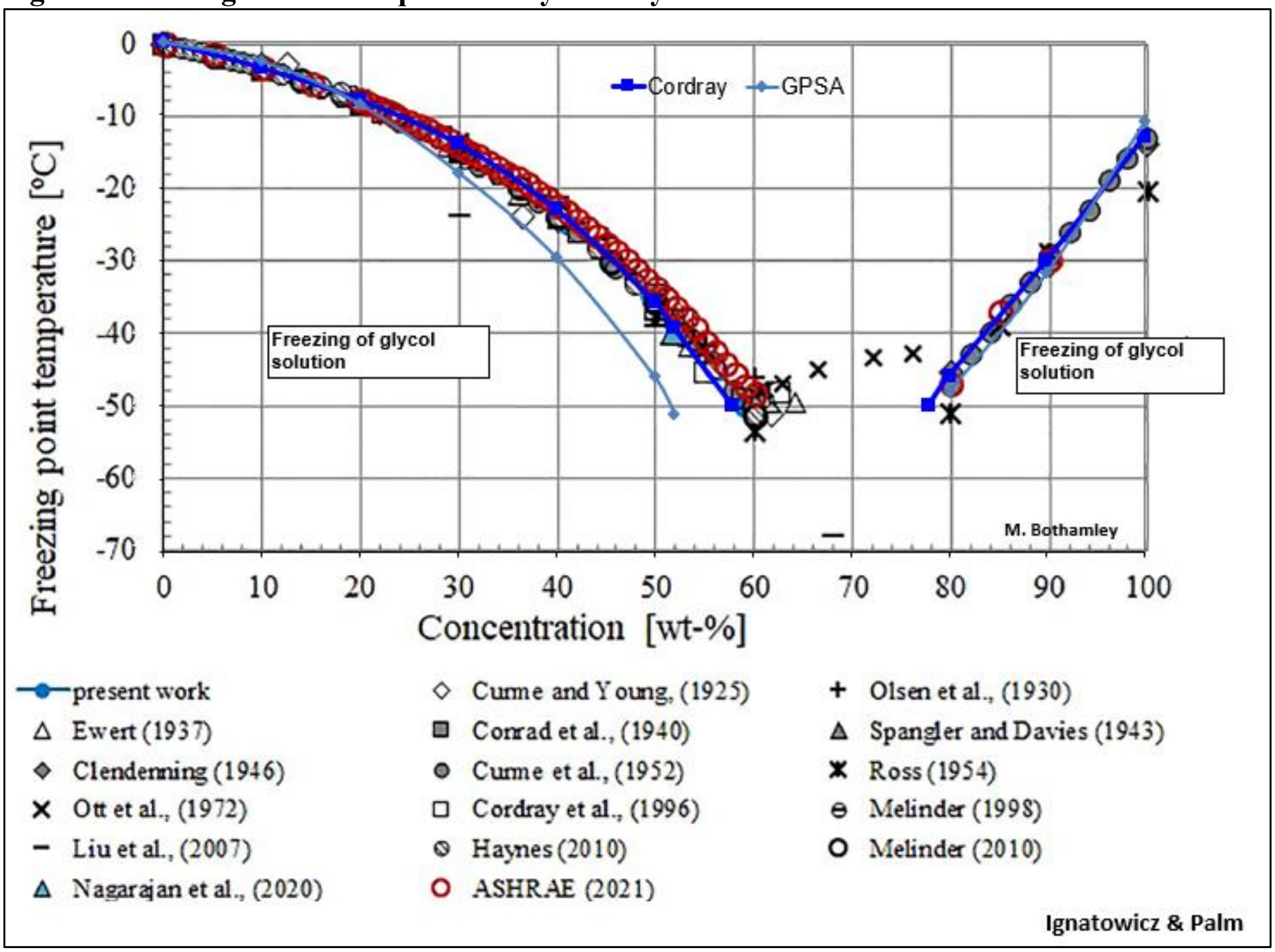
Option (ii) is probably most common.

<u>Glycol injection rates</u>
<u>The 80→70, 10 wt % dilution guideline</u>

Historically, glycol injection rates have typically been set based on a weight % dilution criteria, eg. inject lean glycol with a concentration of ~ 80 wt % at a rate that provides a returning rich glycol concentration of ~ 70 wt %, resulting in a 10 wt % dilution due to condensation of water out of the feed gas from the reduction in temperature. This methodology has more or less worked for quite a long time, although design guidelines and operational parameters are somewhat loose, ie. several key details of the process are often not well defined. It should be noted that some literature sources have recommended returning rich glycol concentrations as low as 55-65 wt %.

The lean glycol concentration limitation of ~ 80 wt% is based on the need to avoid the semi-solid/slushy region associated with higher glycol concentrations and low temperatures as shown on the right-hand side of **Figure 7**(3). This chart shows the data from a number of sources including Cordray et al(4) and the GPSA Data Book(5). The Cordray data is representative and will be used in this paper.

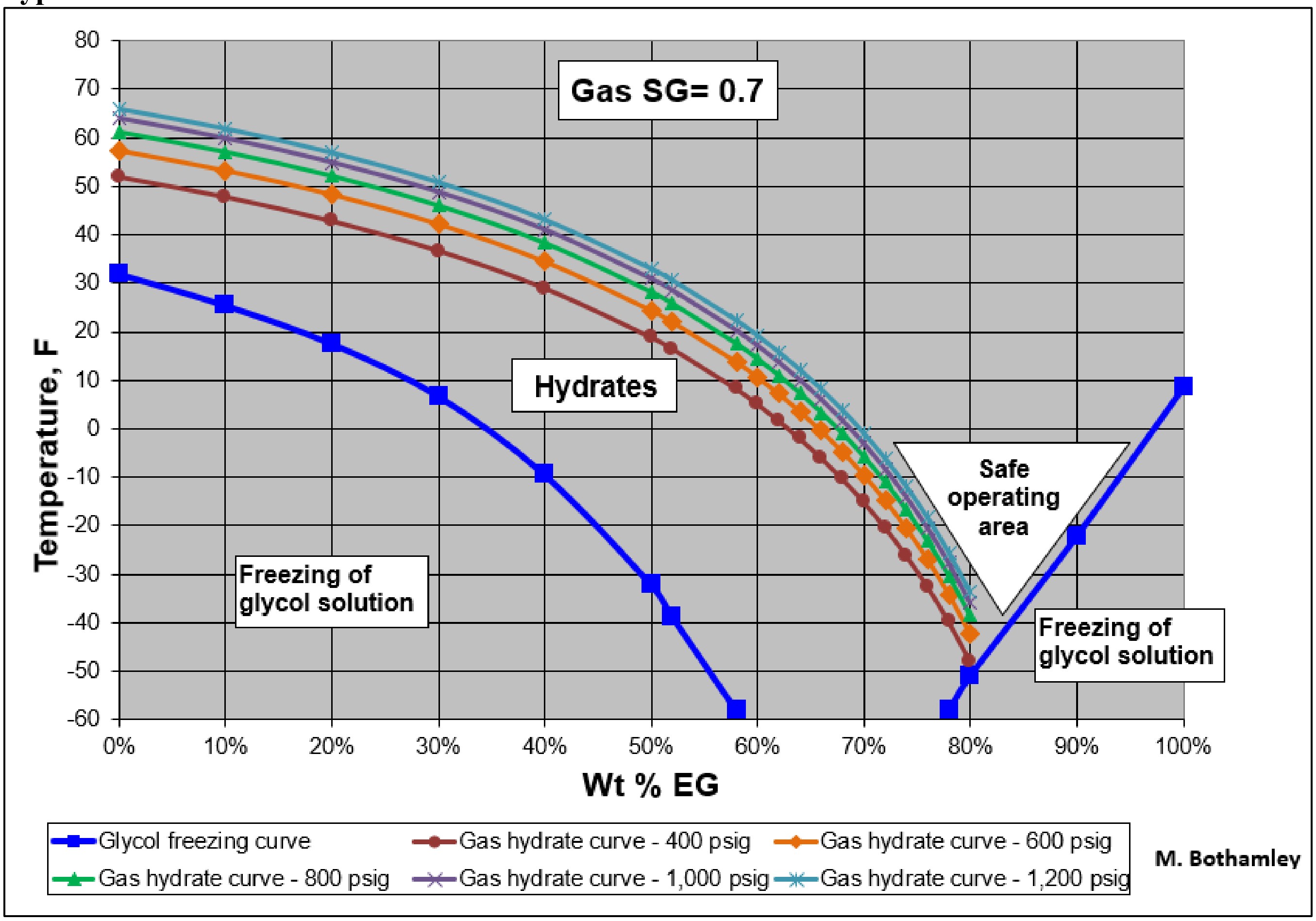
Figure 7 Freezing Points of Aqueous Ethylene Glycol Solutions



As can be seen from **Figure 7**, the 80 wt % upper concentration limit is somewhat conservative (low), ie. at normal minimum chiller outlet temperatures of -30 to -35, the freezing point of aqueous EG solutions is in the 85-86 wt % range. This might seem like a minor point but as will be shown later in this paper, the difference between 80 and 85 wt % lean glycol concentration can have a large impact on the required injection rates.

Figure 8 shows the predicted hydrate formation conditions for a typical 0.7 SG (MW= 20.3) sweet natural gas at five different pressures superimposed on the Cordray et al solution freezing curves from **Figure 7**. The hydrate formation curves were calculated using the Neilsen-Bucklin(6) correlation, which will be discussed in more detail later in this paper. A "safe operating region" is indicated on the chart between the semi-solid region on the right-hand side and the hydrate curves on the left. ** Note that this chart is for an SG= 0.7 gas. For heavier gases the hydrate curves would shift upwards, reducing the "safe operating region", with the opposite behavior for lighter gases**. The returning rich glycol concentration guideline of 70 wt% has historically been considered to be sufficient to prevent hydrate formation in most applications, but as shown in **Figure 8**, this criterion requires closer inspection.

Figure 8 Freezing Points of Aqueous EG Solutions with Hydrate Formation Conditions for a Typical Sweet Gas at Various Pressures



Several observations can be derived from **Figure 8**:

1. The "safe operating region" gets narrower as pressure increases and in particular as temperature decreases. As a point of reference, typical minimum LTS operating temperatures for a refrigeration plant using propane as the refrigerant, are in the -30 F range, possibly slightly colder. It can be seen that the operating window for the glycol "pinches out" as temperatures approach ~ -35 F.

2. While the traditionally utilized 80 → 70 guideline concentrations are adequate for warmer and/or lower pressure operations, they are *too low* for colder, higher pressure operations and typically result in operation "to the left" of the hydrate formation curve, at least for the chiller and LTS.

3. The “overall” dilution guideline does not provide any indication as to the appropriate glycol injection rates for each of the exchangers in the cool-down train.

The 80 → 70, 10 wt % dilution guideline is generally considered to be conservative, ie. it results in higher glycol injection rates than are strictly necessary, the logic being, i) it is hard enough to get the glycol into all of the tubes, injecting more should help, and ii) the cost of the glycol injection/regeneration system is relatively small and not worth skimping on and risking hydrating off the plant gas flow.

In fact, as discussed, these concentrations are probably *too low* for the colder, higher pressure plants. An 85 → 80, 5 wt % dilution guideline would be more appropriate and even this target is not particularly conservative. It should also be pointed out that the hydrate formation issue is not limited to heat exchangers. Hydrate formation in the mist extractor of an LTS, and the resulting localized high gas velocities, can lead to significant carryover (hydrocarbon liquid and glycol) from the LTS and damage to the mist extractor. A potential drawback of higher lean/rich glycol concentrations is the somewhat higher solution viscosity, particularly at chiller-LTS operating temperatures, but this effect should be fairly minor. The slightly higher regeneration temperature required to achieve 85 wt % lean glycol is also not a significant issue.

In lieu of “rules-of-thumb” guidelines, the starting point for the determination of the required glycol injection rate is the estimation of the aqueous phase concentration of glycol actually needed to prevent hydrate formation at the prevailing operating conditions at various locations through the cool-down section of the plant. This calculation can be performed by a process simulator but for the purposes of this paper we will look at hand calculation options.

There are two calculation methods normally considered:

1. The Hammerschmitt equation.
2. The Neilson-Bucklin (NB) method.

The NB equation is more accurate, especially at high glycol concentrations, and typically matches the rigorous hydrate prediction methods used in commercial process simulators quite well.

NB correlation:

While the NB correlation was originally developed for methanol inhibition, it has been found to work well for glycol also.

The first step is to calculate the inhibitor (glycol) concentration required at the location of interest which requires determination of the hydrate temperature depression required:

$$X_{R,mole} = 1 - e^{d/A} \qquad \textbf{Eqn 1}$$

$$d = A \ln\left(1 - X_{R,mole}\right) \qquad \textbf{Eqn 2}$$

Where:

$X_{R,mole}$ = the required glycol concentration in the aqueous solution to prevent hydrate formation, mole fraction
d= the hydrate temperature depression required, F (hydrate temp without inhibitor – actual temp)
A= constant = -129.6

The NB correlation is a bit cumbersome in that $X_{R,mole}$ is a *mole* fraction, whereas aqueous glycol solution concentrations are typically expressed in terms of *weight* fraction.

The conversion equation is:

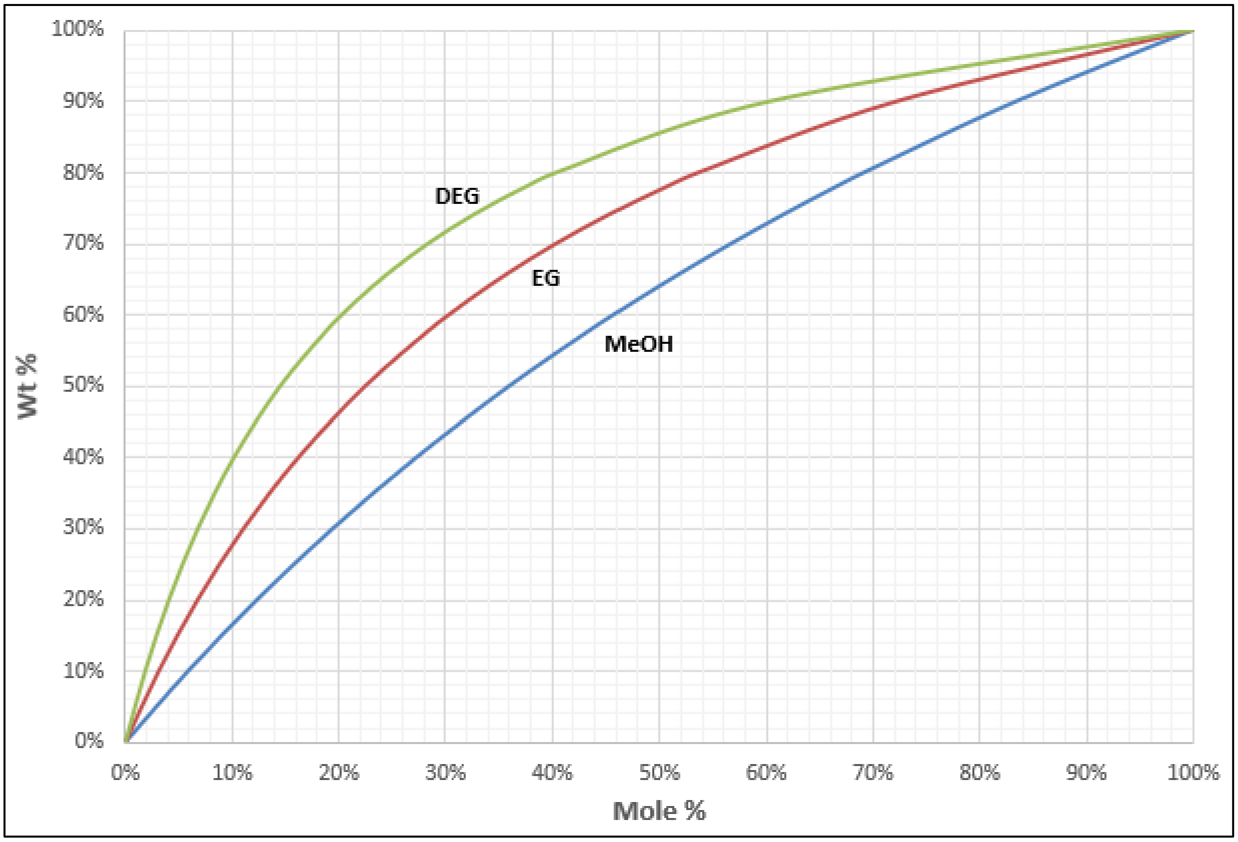
$$X_R = \frac{X_{R,mole}/MW_i}{\left(\frac{X_{R,mole}}{MW_i} + \frac{1 - X_{R,mole}}{MW_{water}}\right)} \qquad \textbf{Eqn 3}$$

Where:

X_R= mass fraction inhibitor in aqueous phase
$X_{R,mole}$= mole fraction inhibitor in aqueous phase
MW_i= molecular weight of inhibitor (62 for EG)
MW_{water}= molecular weight of water (18)

Figure 9 shows this equation in chart form for the three most commonly used inhibitors.

Figure 9 Mole % to Weight % Conversion



The next key piece of information is the amount of water condensed out of the inlet gas as a function of temperature. This can be estimated using a water content chart like that shown in **Figure 10**.

Figure 10 Water Content Chart for Sweet Natural Gas

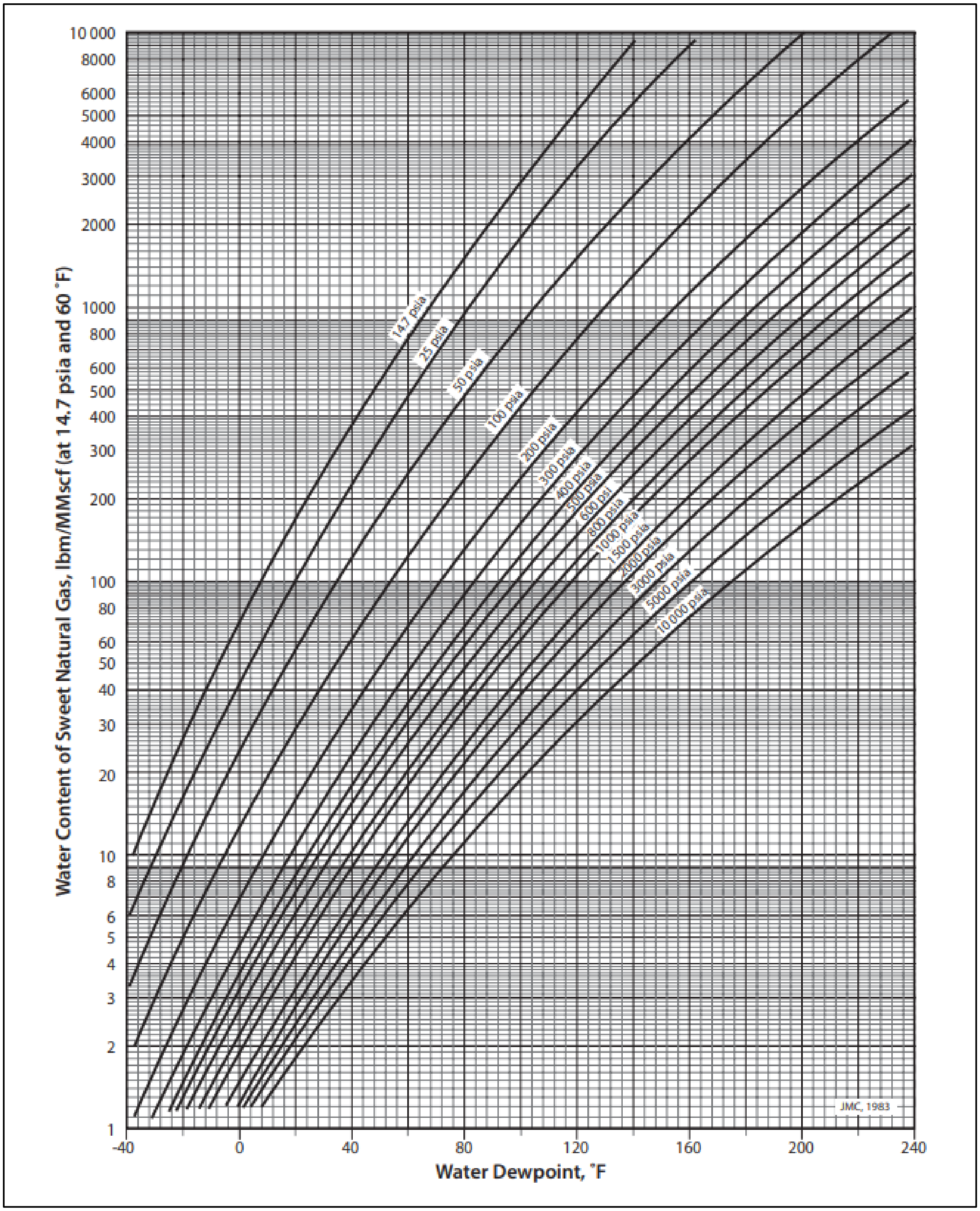
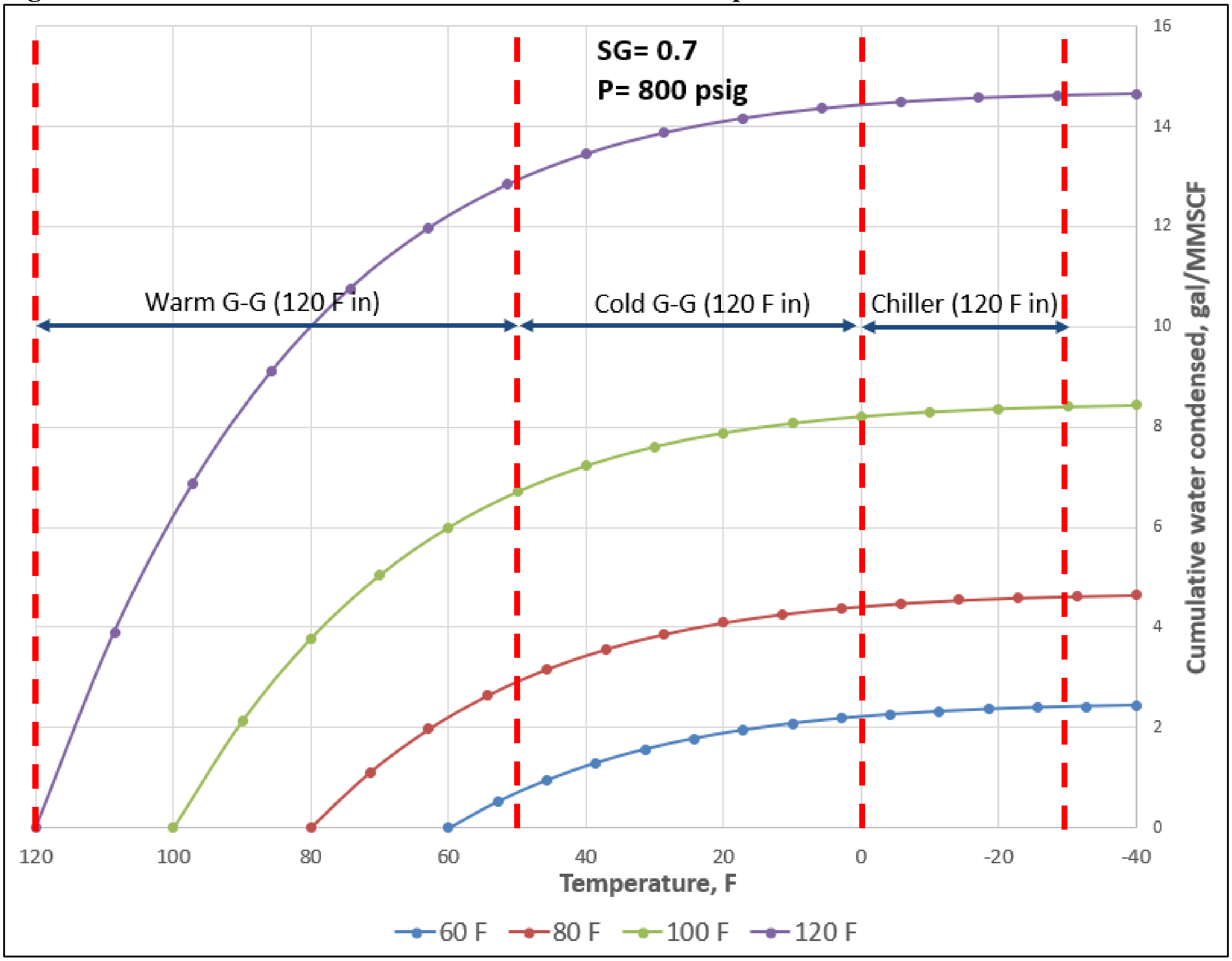


Figure 11 gives an indication of the amount of water condensed out of a 0.7 SG sweet gas as a function of temperature for a nominal operating pressure of 800 psig for a range of inlet gas temperatures, assuming the gas is water saturated. The approximate operating temperature ranges for the gas-gas exchanger and chiller, assuming a 120 F inlet gas temperature, are shown on the chart. The exchanger operating temperature ranges would get narrower and shift to the left for lower inlet gas temperatures.

Figure 11 Cumulative Amount of Condensed Water vs Temperature



A couple of points re: **Figure 11**:

1. The inlet gas temperature – assuming saturated conditions – has a large impact on the inlet gas water content and subsequently the amount of water condensed during cooldown, which will require higher glycol injection rates to achieve the required aqueous phase concentration (X_R). Plants utilizing inlet compression or an amine contactor for sweetening will have much higher cooldown section inlet temperatures than those plants with gas coming in directly from a high-pressure gathering system at a flowing temperature of 40-60 F, or less, from a buried pipeline, depending on location and time of year.
2. The bulk of the water condenses out in the gas-gas exchanger, especially the warm exchanger. Very little water condenses out in the colder chiller. However, the low temperature of the chiller results in the highest required X_R values.

With the required glycol concentration, X_R, and the amount of water condensed known, the lean glycol injection rate can be calculated:

$$m_I = \frac{X_R m_{water}}{X_L - X_R}$$ **Eqn 4**

Where:

m_I = Lean inhibitor injection rate, lb/day
m_{water} = Condensed water, lb/day
X_R = Required rich inhibitor concentration to prevent hydrates, mass fraction
X_L = Lean inhibitor concentration, mass fraction

This equation is valid for a tube pass that doesn't have any rich glycol from upstream entering the channel with the inlet gas. Referring back to **Figures 1** and **2**, this situation would apply to the warm gas-gas and gas-liquid exchangers. For the cold gas-gas exchanger and chiller, the inlet gas *will* contain rich glycol, from the upstream exchangers. This situation requires a modification of **Eqn 4** as follows:

$$m_I = \frac{X_R\left(m_{i,pure,up} + m_{w,tot}\right) - m_{i,pure,up}}{X_L - X_R}$$ **Eqn 5**

Where:

$m_{i,pure,up}$ = Pure (100 %) glycol entering from upstream, lb/day
$m_{w,tot}$ = Total pure (100 %) water at the outlet of the exchanger = water from upstream + water condensed in this tube pass, lb/day

To convert to gallons per minute, the following equation can be used:

$$q_I = \frac{m_I}{1440(8.33)(SG_L)}$$ **Eqn 6**

Where:

q_I = lean glycol injection rate, gpm
SG_L = lean glycol specific gravity (~ 1.09 for 80-85 wt % EG)

Note that for both **Eqns 4** and **5**, as X_R approaches X_L as it does for the lowest temperature parts of the plant, ie. the chiller outlet, the required lean glycol injection rate increases rapidly. This is one of the main reasons for increasing the lean glycol concentration, X_L, to ~ 85 wt %. This behavior is illustrated in **Figure 12** for lean glycol concentrations of 80 and 85 wt %.

For example, if a rich glycol concentration, X_R, of 75 wt % is required, the injection rate for X_L= 80 wt % is ~ 115 gal/MMSCF while for X_L= 85 wt % the injection rate is only 55 gal/MMSCF.

Figure 12 Effect of Allowable Glycol Dilution on the Required Injection Rate

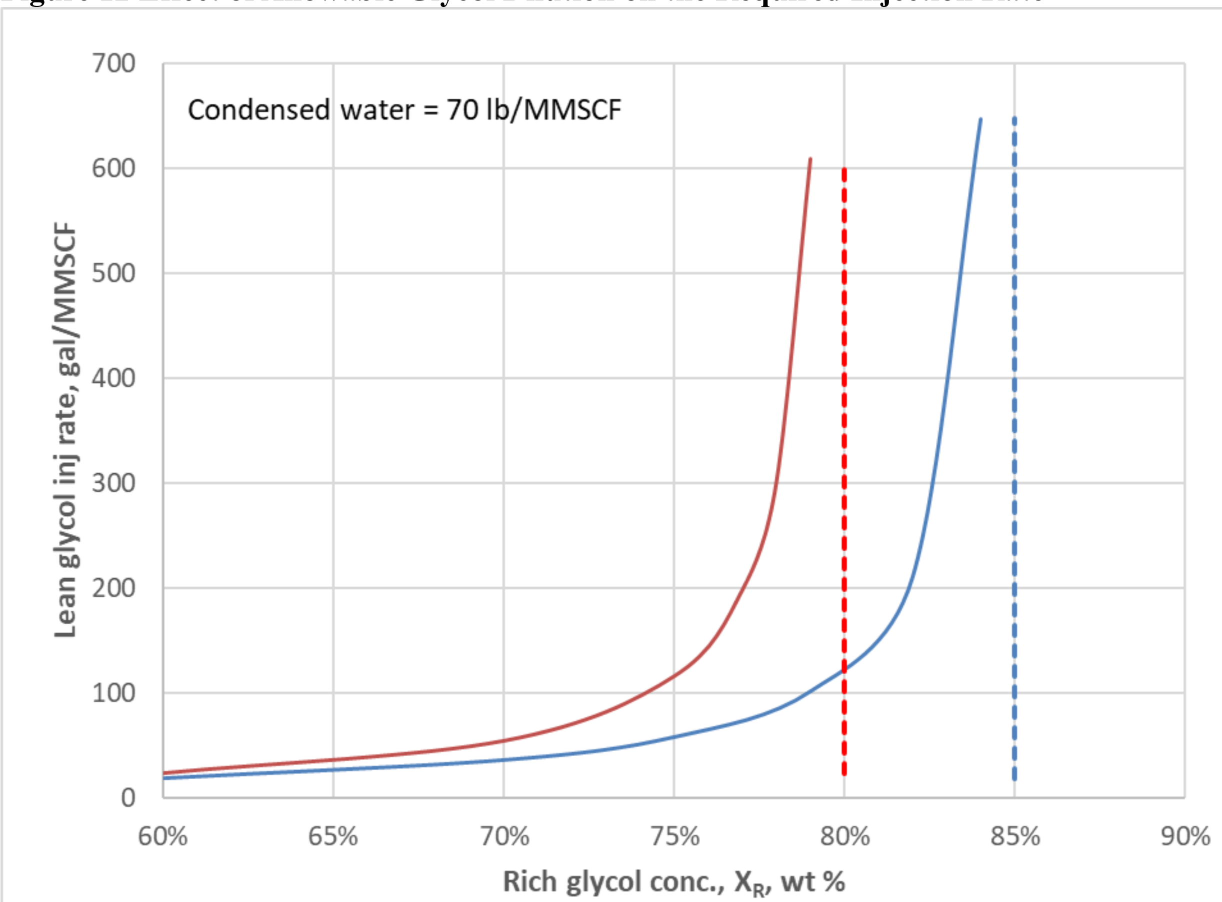
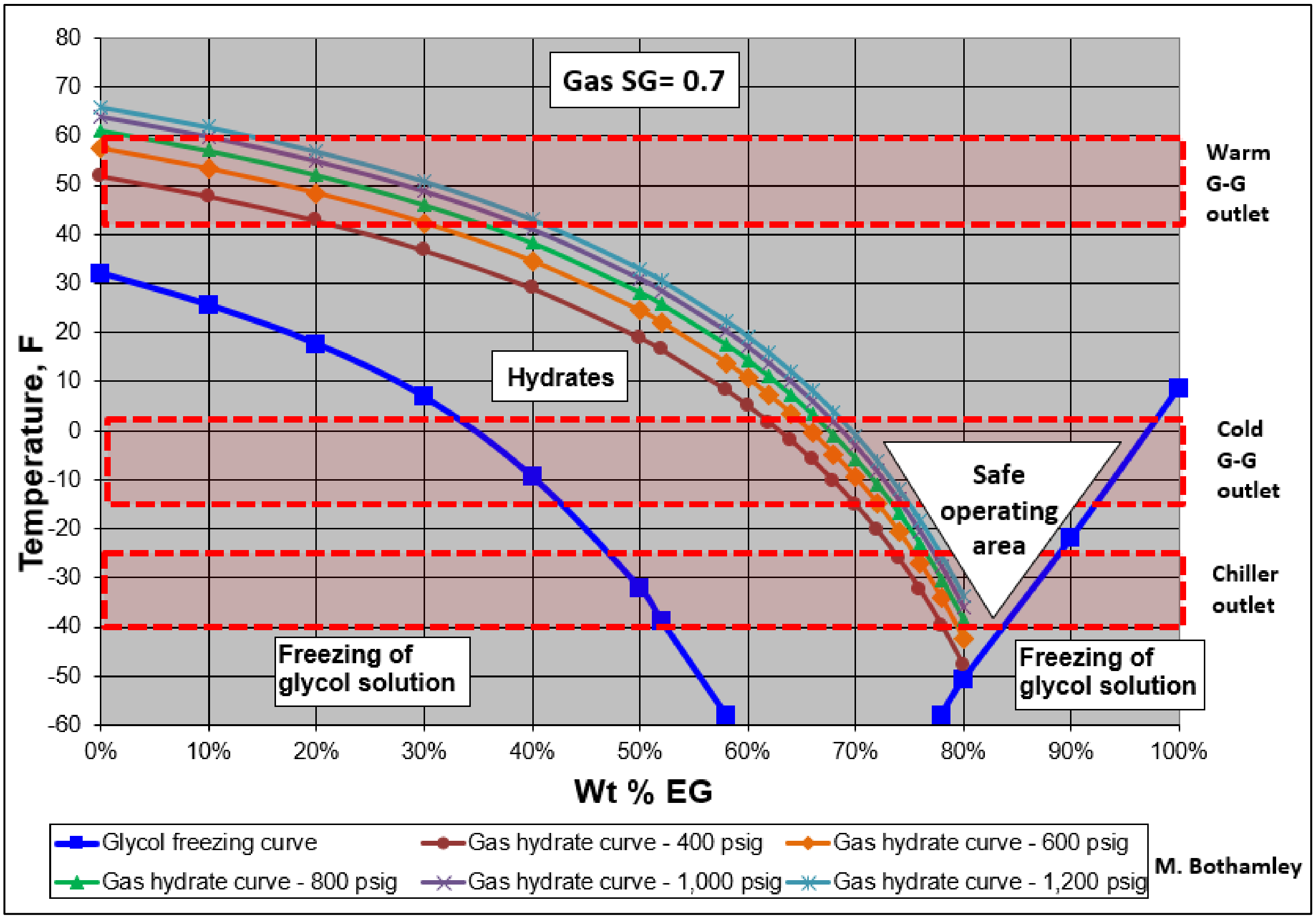


Figure 13 shows typical operating temperatures for the gas-gas exchanger and chiller added to **Figure 8** (for simplicity the gas-liquids exchanger, if used, is not included). These temperature ranges are dependent on several factors, in particular the inlet gas temperature, required LTS temperature and surface areas of the exchangers.

Figure 13 Figure 8 with Exchanger Operating Temperatures Added



The hydrate curves shown in **Figure 13** for the different operating pressures are obtained by assuming values for X_R (wt % EG in the aqueous phase), converting to $X_{R,mole}$ in the NB equation and then solving for the corresponding value of "d", the hydrate temperature depression achieved for a given value of X_R. The value for "d" is then subtracted from the uninhibited hydrate temperature (wt % EG = 0) on the vertical axis in **Figure 13** or from **Figure 3**.

The dilution guideline – at least how it is typically used – will allow the required *total* glycol injection rate to be calculated, if the total amount of condensed water is known. Use of the Neilson-Bucklin equation is not actually required. However, *not* doing the calculation is one of the reasons the 80 → 70 guideline is regularly used and is often inadequate.

The dilution guideline – by itself – does not provide guidance as to how the *total* lean glycol injection rate should be apportioned between the different injection points, eg. warm gas-gas, cold gas-gas, gas-liquid and the chiller. **Figure 13** shows that the required rich glycol concentrations (X_R values) exiting the warm gas-gas exchanger, cold gas-gas exchanger and chiller are in the ranges of 10-30 wt %, 63-73 wt % and 75-80 wt % respectively. However, there are some additional considerations required before these "X_R" values can be converted into injection rates via **Eqn 4**. The individual tube passes cannot be looked at in isolation. For example, while the theoretical X_R value for the warm gas-gas exchanger outlet may only be in the 10-30 wt % range per **Figure 13**, this rich glycol continues downstream and will "see" the cold gas-gas exchanger temperatures and eventually the even colder chiller outlet/LTS temperature as well, which require increasingly higher values of X_R to avoid hydrate formation. Ultimately all of the gas, condensed water, condensed NGL and glycol will "see" the coldest (LTS) conditions and enough lean glycol must be injected to achieve the corresponding "worst case" value of X_R that is required. There are several different ways to apportion the total lean glycol rate required between the different injection points and this will be discussed later in this paper.

There is another consideration:

How do the liquids – in particular the rich glycol – exiting the tubeside of a given upstream exchanger, distribute into the tubes of the subsequent (downstream) tube pass ? Ie.:

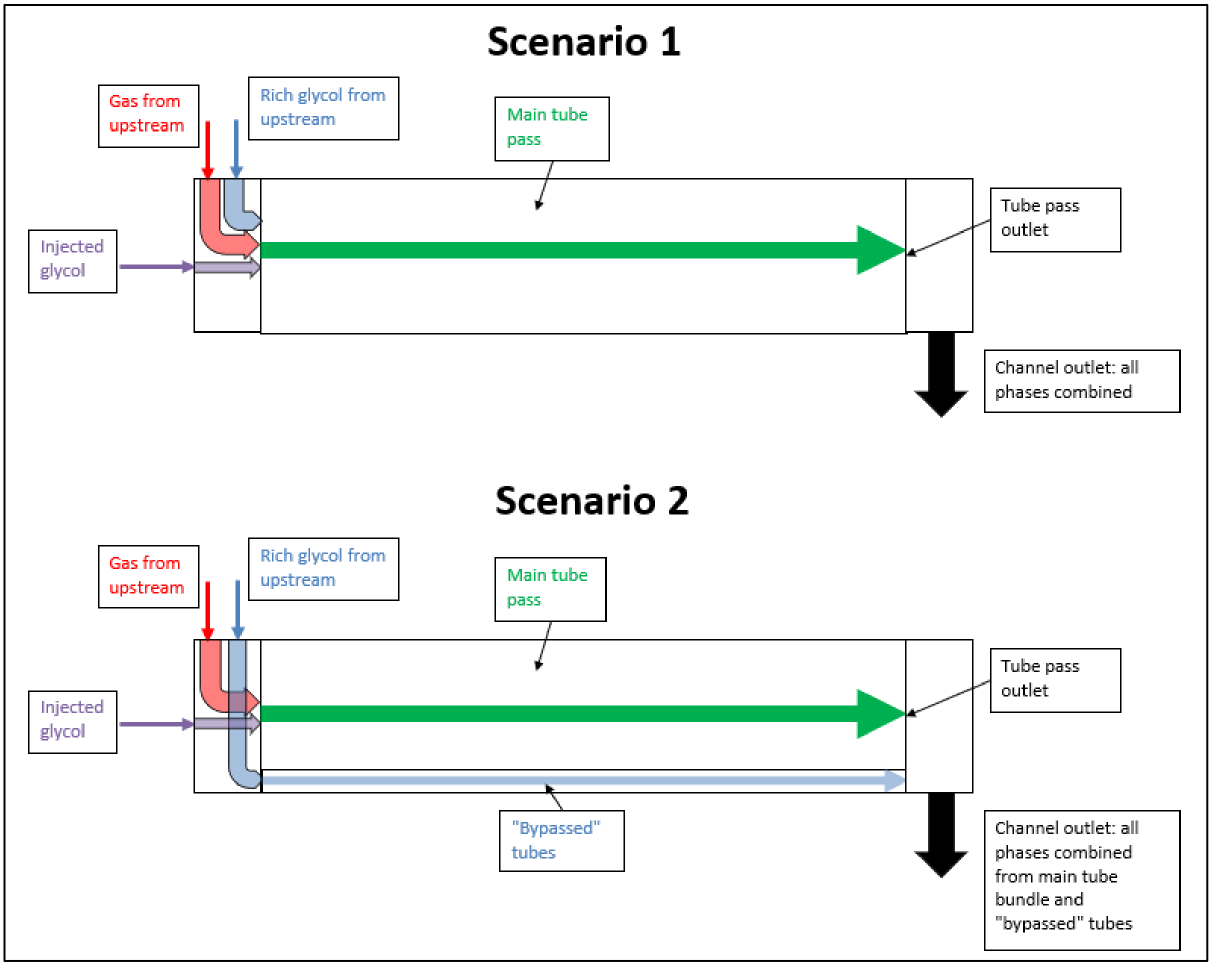
- Exiting the warm gas-gas tube exchanger → entering the cold gas-gas exchanger
- Exiting the cold gas-gas exchanger → entering the chiller

Two limiting scenarios can be defined:

Scenario 1: The liquids distribute uniformly across the tubesheet into all the tubes.
Scenario 2: The liquids – because of momentum and gravity – drive more or less directly down to the bottom of the inlet channel/bonnet, then flow through the bottom 1-2 rows of tubes, essentially bypassing the tube bundle.

These two scenarios are illustrated in **Figure 14**.

Figure 14 Distribution of Liquids Entering from Upstream



The actual distribution of the liquids is probably somewhere in between these limiting cases, though likely much closer to Scenario 2. This assertion is based on an estimation of the rich glycol droplet sizes entering the channel combined with a simple "elbow bend" separation calculation. This behavior is one of the main reasons that glycol must be sprayed onto *each* tubesheet.

While Scenario 2 is probably most representative of what is *actually* happening, assuming the more idealized conditions of Scenario 1 leads to more straight-forward – but still correct – calculations of the required lean glycol injection rates for each exchanger. This is because – in either scenario – hydrate protection must be ensured at the *channel outlet conditions* where all the phases – whether exiting the main tube pass or the "bypassed" tubes – are combined and are exposed to the pass outlet temperature. For this reason, the actual injection rate calculations presented later in the paper will assume the Scenario 1 model applies.

<u>Specific exchanger considerations</u>

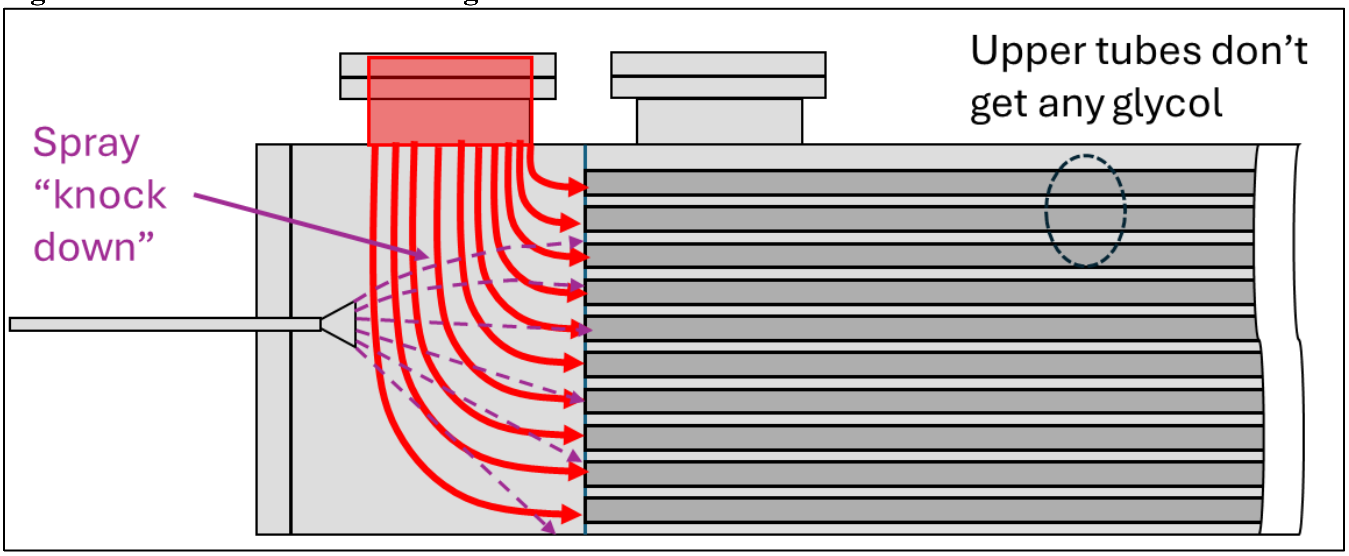
<u>Warm gas-gas exchanger</u>

The warm gas-gas exchanger is typically a counter-current TEMA NEN design. This is a fixed tubesheet exchanger equipped with removable channel covers. BEM designs are also common.

The inlet gas entering the channel (tubeside) of the warm gas-gas exchanger should be essentially liquids free. The glycol spray will likely experience significant "knockdown" resulting in minimal glycol entering the top tubes, leaving them subject to hydrate formation. Increasing amounts of glycol can be expected to exist in the tubes lower in the tube bundle.

Eqn 4 can be used for calculating the required lean glycol injection rate.

Figure 15 Warm Gas-Gas Exchanger Inlet

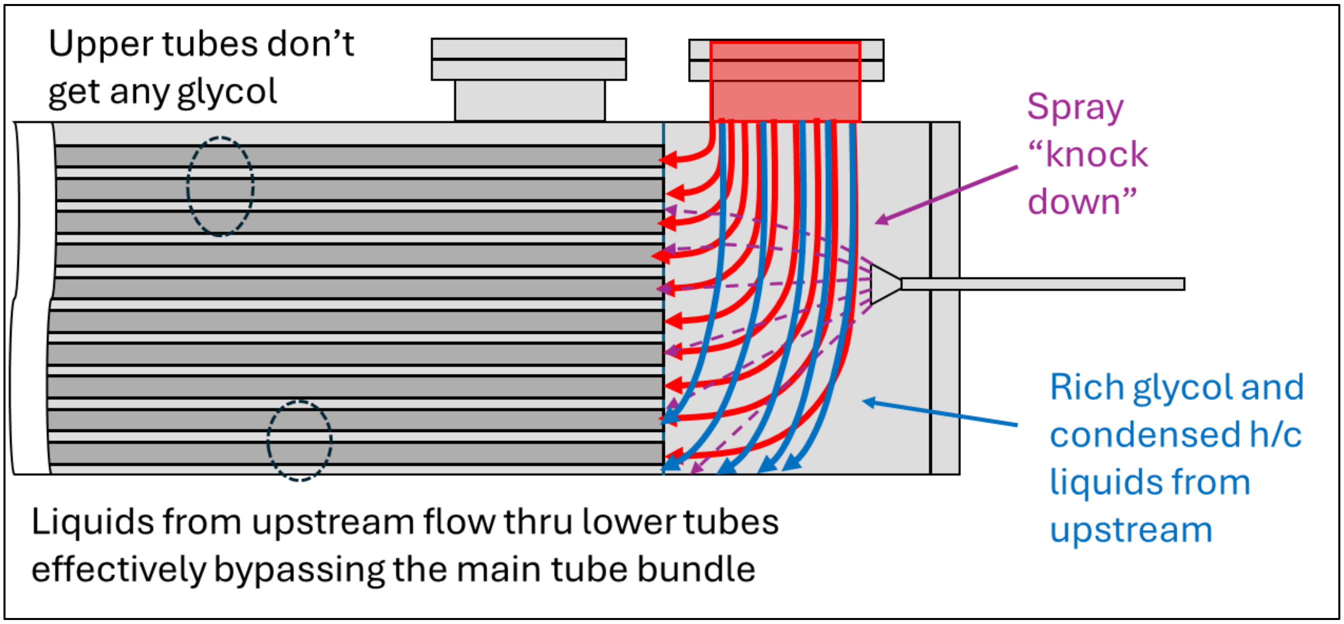


Cold gas-gas exchanger

The cold gas-gas exchanger is typically of identical design to the warm gas-gas exchanger. It is very common for the warm gas-gas exchanger to be located directly above – "piggy-back" style – the cold gas-gas exchanger.

The cold gas-gas exchanger is somewhat more complicated in that in addition to sprayed-in glycol, there is rich glycol from the warm gas-gas exchanger entering with the inlet gas.
Eqn 5 can be used for calculating the required lean glycol injection rate.

Figure 16 Cold Gas-Gas Exchanger Inlet



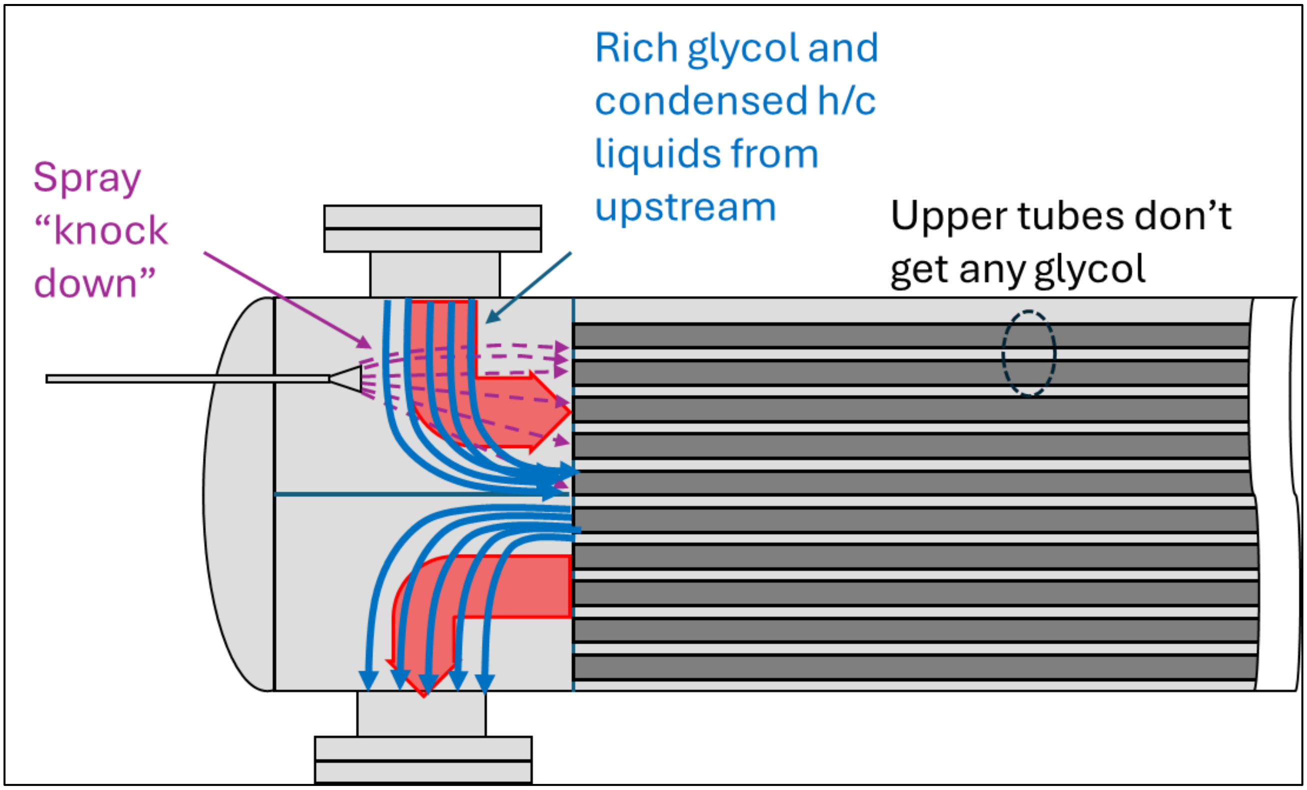
Chiller

The chiller is usually a BKU design although other configurations are sometimes used. Most of these chillers use a two tube pass configuration, the minimum for a U-tube design.

The U-tube bundle is normally installed with the bends vertically oriented. If the *upper* tubes in the first pass do not get any glycol it will be the *lower* tubes in the second pass that don't have any glycol. Similarly, if most of the entering liquids from upstream end up flowing through the *lower* tubes in the first pass, they will flow through the *upper* tubes in the return pass. The U-tube bend radius decreases from the outside of the bundle to the inside. Any maldistribution of fluids at the entrance to the first pass will persist through the second pass. It should also be noted that a floating head design, eg an AKT, would not be a good choice for a chiller as getting good glycol distribution via spraying into the second pass would not be possible.

The calculations for the chiller are essentially the same as for the cold gas-gas exchanger.
Eqn 5 can be used for calculating the required lean glycol injection rate.

Figure 17 Chiller Channel



Example calculation results

Inlet gas flowrate:	100 MMSCFD
Gas SG:	0.7
Inlet gas temperature:	100 °F
Inlet gas pressure:	800 psig
Glycol type:	EG
Lean glycol concentration, wt %	85
Hydrate inhibition calculation method	Neilson-Bucklin or simple dilution
Lean glycol injection rate multiplier/safety factor	1.0

Several cases will be evaluated that consider:

- the distribution of liquids from upstream (Scenarios 1 and 2 in Figure 14).
- different methods for determining X_R.
- Different options for allocating lean glycol injection to the various injection points.

Case 1

- No rich glycol from upstream enters the subsequent tube passes.
- Glycol injection rates calculated for each tube pass based on the pass outlet T and P and water condensed in the pass using NB.

** This is not a valid case as the rich glycol from the upstream passes is of insufficient concentration to provide hydrate inhibition at the colder conditions of the downstream exchangers. These injection rates provide a point of reference against which the more realistic cases can be compared. **

Case 2

- Any rich glycol from upstream injection points enters the subsequent tube passes.
- Glycol injection rates calculated for each tube pass based on the pass outlet T and P and the cumulative glycol and water present at the pass outlet using NB.

Case 3

- Any rich glycol from upstream injection points enters the subsequent tube passes.
- Glycol injection rates calculated for each tube pass accounting for the cumulative amount of glycol and water present at the pass outlet using an X_R value for each pass determined for the worst case (chiller outlet) condition as calculated by NB.

Case 4

- Any rich glycol from upstream injection points enters the subsequent tube passes.
- The total glycol injection rate is based on the same X_R value as Case 3 but is equally split (33.3 % each) between the three exchangers.

** Note that in the calculation results below, the dewpoint depression/dehydration effect of the glycol has been ignored. The impact of this assumption should be minor.**

Table 1

Case 1				
	Warm G-G	**Cold G-G**	**Chiller**	**Total**
T_{in}, F	100	50	0	
T_{out}, F	50	0	-30	
Fraction of liquid water and glycol from upstream entering exchanger tubes.	0%	0%	0%	
Water condensed, lb/MMSCF	55.8	12.6	1.7	70.0
Required hydrate temperature depression, d, at channel outlet, F	11.08	60.95	90.82	
Required rich glycol conc at channel outlet, X_R, wt %	23.5%	67.4%	77.8%	
Lean glycol injection rate safety factor multiplier	1.00	1.00	1.00	1.00
Lean glycol inj rate, gpm	0.16	0.37	0.14	0.67
Lean glycol inj rate, gal/MMSCF	2.3	5.3	2.0	9.6
Fraction of total glycol injected, %	24.4%	55.2%	20.4%	100.0%
Actual rich glycol conc at channel outlet, X_R, wt %	23.5%	42.9%	70.0%	
Hydrate temperature margin at channel outlet, F	0.0	-35.4	-24.0	

Case 1 observations

As mentioned previously, this is not a feasible case – except for the warm gas-gas where there are no liquids entering from upstream – but shows the results of looking at each tube pass strictly in isolation, ignoring the effects of any rich glycol entering the exchanger with the inlet gas. The calculated glycol injection rates are very low, and vary by exchanger due to the relative contributions of the required X_R values and the condensed water volumes. As shown by the "Hydrate temperature margin at channel outlet" values, the cold gas-gas and chiller outlets are severely under-inhibited.
Note that some of the published literature that deals with this subject suggests that most of the lean glycol should be injected into the warm gas-gas exchanger because that is where most of the water condenses out. Depending on the calculation methodology, it doesn't work out that way, mainly because of the low required X_R value which in turn is mainly a result of the relatively warm temperature at the warm gas-gas tubeside outlet.

Table 2

Case 2				
	Warm G-G	**Cold G-G**	**Chiller**	**Total**
T_{in}, F	100	50	0	
T_{out}, F	50	0	-30	
Fraction of liquid water and glycol from upstream entering exchanger tubes.	100%	100%	100%	
Water condensed, lb/MMSCF	55.8	12.6	1.7	70.0
Required hydrate temperature depression, d, at channel outlet, F	11.08	60.95	90.82	
Required rich glycol conc at channel outlet, X_R, wt %	23.5%	67.4%	77.8%	
Lean glycol injection rate safety factor multiplier	1.00	1.00	1.00	1.00
Lean glycol inj rate, gpm	0.16	1.84	3.76	5.76
Lean glycol inj rate, gal/MMSCF	2.3	26.5	54.1	82.9
Fraction of total glycol injected, %	2.8%	31.9%	65.2%	100.0%
Actual rich glycol conc at channel outlet, X_R, wt %	23.5%	67.4%	77.8%	
Hydrate temperature margin at channel outlet, F	0.0	0.0	0.0	

Case 2 observations

This is a more realistic scenario with entering upstream rich glycol accounted for in the downstream exchangers. The calculated lean glycol injection rates ensure that each exchanger is adequately inhibited but there is a wide variation in required injection rates. Note that these injection rates are calculated for each exchanger using the NB method. This might not be particularly practical for an actual plant operation, or ideal from design point of view – pipe sizing, spray nozzle selection/sizing, etc. The

"Hydrate temperature margin at channel outlet" values show there is no "excess margin" for any of the exchangers.

Table 3

Case 3				
	Warm G-G	**Cold G-G**	**Chiller**	**Total**
T_{in}, F	100	50	0	
T_{out}, F	50	0	-30	
Fraction of liquid water and glycol from upstream entering exchanger tubes.	100%	100%	100%	
Water condensed, lb/MMSCF	55.8	12.6	1.7	70.0
Required hydrate temperature depression, d, at channel outlet, F	11.08	60.95	90.82	
Required rich glycol conc at channel outlet, X_R, wt %	23.5%	67.4%	77.8%	
Lean glycol injection rate safety factor multiplier	1.00	1.00	1.00	1.00
Lean glycol inj rate, gpm	4.59	1.04	0.14	5.76
Lean glycol inj rate, gal/MMSCF	66.0	14.9	2.0	82.9
Fraction of total glycol injected, %	79.6%	18.0%	2.4%	100.0%
Actual rich glycol conc at channel outlet, X_R, wt %	77.8%	77.8%	77.8%	
Hydrate temperature margin at channel outlet, F	79.7	29.9	0.0	

Case 3 observations

This case is a "weight % dilution" case applied to each exchanger with the rich glycol concentration set by an NB calculation at the chiller outlet (worst case) operating conditions, in this case X_R= 77.8 wt %. This results in an 85 → 77.8, 7.2 wt % dilution. The glycol injection rates for each exchanger are adjusted to achieve X_R= 77.8 wt % at *each exchanger outlet*. While the total injection rate for this case, 5.76 gpm, is the same as for case 2, the individual exchanger injection rates are much different, almost reversed. In this case the individual injection rates are primarily driven by the corresponding exchanger condensed water volumes. Case 3 has similar practical implementation issues as identified for Case 2.

Table 4

Case 4				
	Warm G-G	**Cold G-G**	**Chiller**	**Total**
T_{in}, F	100	50	0	
T_{out}, F	50	0	-30	
Fraction of liquid water and glycol from upstream entering exchanger tubes.	100%	100%	100%	
Water condensed, lb/MMSCF	55.8	12.6	1.7	70.0

Required hydrate temperature depression, d, at channel outlet, F	11.08	60.95	90.82	
Required rich glycol conc at channel outlet, X_R, wt %	23.5%	67.4%	77.8%	
Lean glycol injection rate safety factor multiplier	1.00	1.00	1.00	1.00
Lean glycol inj rate, gpm	1.92	1.92	1.92	5.76
Lean glycol inj rate, gal/MMSCF	27.6	27.6	27.6	82.9
Fraction of total glycol injected, %	33.3%	33.3%	33.3%	100.0%
Actual rich glycol conc at channel outlet, X_R, wt %	69.6%	74.8%	77.8%	
Hydrate temperature margin at channel outlet, F	54.9	19.6	0.0	

Case 4 observations

The total glycol injection rate is calculated as per Case 3, ie. 85 → 77.8, 7.2 wt % dilution but this time the individual exchanger injection rates are simply each set at 33.3 % of the total. While 33.3 % splits are not "optimized" by any means, they actually work out quite well, are simple, and help with respect to piping & spray nozzle sizing. As shown by the "Hydrate temperature margin at channel outlet" values, the warm gas-gas and cold gas-gas exchangers are somewhat over-inhibited but this is not a problem, it just reduces the required injection rate for the chiller. It turns out that hydrate inhibition for all 3 exchangers can be achieved over a fairly wide range of "splits". For example, splits of 5-40-55 for the warm gas-gas, cold gas-gas and chiller, respectively, still provide hydrate inhibition for all 3 passes, with more equalized hydrate temperature margins, though the warm gas-gas glycol injection rate is quite low.

Would the 33.3 % splits (assuming 3 injection points) be appropriate for all design/operational scenarios ? The author has investigated several sensitivities to key parameters – mainly the temperature profile through the cool-down section of the plant, and the 33.3 % splits look quite reasonable. The key point is making sure the *total* lean glycol injection rate is adequate. This can be done fairly simply knowing the lean glycol concentration, X_L, the required rich glycol concentration, X_R, for the worst case (coldest) condition and the total amount of condensed water.

Of course there are other exchanger train configurations and operating conditions that could be utilized. The principles and calculation methodologies discussed in this paper should still be applicable. For the configurations shown in **Figures 1** and **2** which include a gas-liquids exchanger, it is anticipated – though the calculations have not been performed – that equal splits of 25 % each for the 4 exchangers would work fine.

Glycol injection rate safety factors

The injection rates shown in **Tables 1-4** above do not contain any "safety factor" allowance. There are a number of potential sources of variability/uncertainty in the injection rate calculations:

1. Variation in gas flowrates
2. Variations in temperatures – and pressure – through the cool-down facilities.
3. Variation in gas composition.
4. Maldistribution – including "knockdown" – of injected glycol.
5. Worn spray nozzles.
6. Maldistribution of gas flow through the exchanger tubes.
7. Variability in lean glycol concentration.
8. Uncertainty in hydrate inhibition calculations, eg. calculation of required "X_R" values.
9. Etc.

Additionally, as mentioned earlier, the glycol injection/regeneration system does not reflect a particularly large fraction of the plant investment or operating costs. It is better to be on the safe side and design for, and operate with, a significant safety margin re: glycol injection rates.

It is not unusual for actual design and operating injection rates to be 100-200 % higher (safety factor multiplier of 2-3) – or more – than the theoretically required injection rates.

Table 5 shows the results for the Case 4 scenario above (33.3 % splits) for a safety factor multiplier of 2. As a point of reference, liquid flow rates of ~ 4 gpm are easily handled by ¾" pipe.

Table 5

Case 4				
	Warm G-G	**Cold G-G**	**Chiller**	**Total**
Tin, F	100	50	0	
Tout, F	50	0	-30	
Fraction of liquid water and glycol from upstream entering exchanger tubes.	100%	100%	100%	
Water condensed, lb/MMSCF	55.8	12.6	1.7	70.0
Required hydrate temperature depression, d, at channel outlet, F	11.08	60.95	90.82	
Required rich glycol conc at channel outlet, X_R, wt %	23.5%	67.4%	77.8%	
Lean glycol injection rate safety factor multiplier	**2.00**	**2.00**	**2.00**	**2.00**
Lean glycol inj rate, gpm	3.84	3.84	3.84	11.52
Lean glycol inj rate, gal/MMSCF	55.3	55.3	55.3	165.8
Fraction of total glycol injected, %	33.3%	33.3%	33.3%	100.0%
Actual rich glycol conc at channel outlet, X_R, wt %	76.5%	79.6%	81.2%	
Hydrate temperature margin at channel outlet, F	75.1	37.1	14.6	

An alternative means of providing an injection rate safety factor would be to increase the required outlet rich glycol concentration from the chiller. For example, for the above cases the dilution guideline could be changed from 85 → 77.8, 7.2 wt % dilution, to 85 → 80, 5 wt % dilution. This would be equivalent to a safety factor multiplier of 1.48.

The lean glycol injection rates vary directly with the safety factor multiplier. **Figures 18** and **19** show the effect of the safety factor multiplier on the rich glycol concentration at the outlet of each exchanger and the corresponding hydrate temperature margins, respectively.

Figure 18 Effect of Injection Rate Safety Factor Multiplier on X_R for Each Exchanger

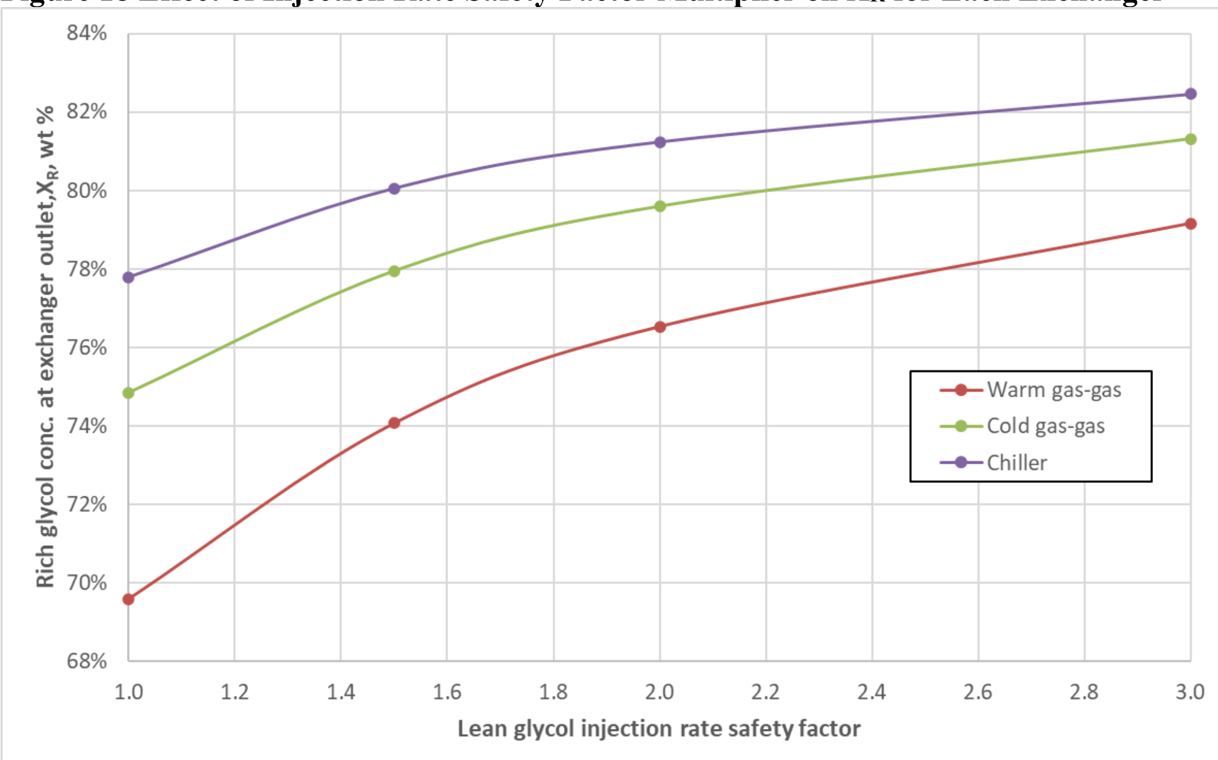
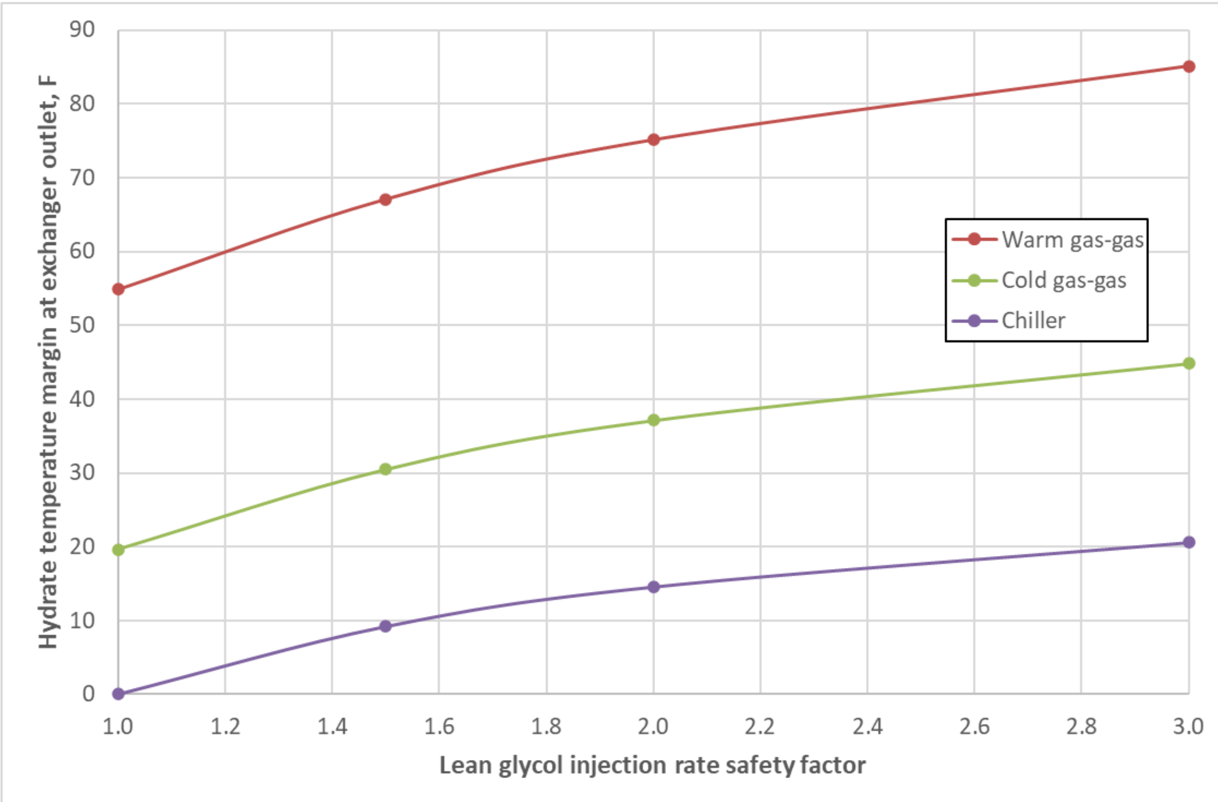


Figure 19 Effect of Injection Rate Safety Factor Multiplier on Hydrate Temperature Margin for Each Exchanger



CONCLUSION

This paper has provided a fairly detailed evaluation of the glycol injection process as typically utilized for hydrate inhibition in moderate NGL recovery mechanical refrigeration and Joule-Thomson gas plants. Recommended practices for glycol injection point locations have been provided as well as recommendations regarding calculation of injection rates. Spray nozzle selection and performance considerations are discussed, but more work is needed in this area. A key emphasis of this paper has been that the traditionally used 80 → 70, 10 wt % dilution guideline for calculating total lean glycol injection rates is inadequate in many cases and leads to plant hydrate problems. Additionally, a lean glycol concentration of 85 wt % is recommended vs the traditional 80 wt % value, especially for colder, higher pressure LTS operating conditions. An 85 → 80, 5 wt % dilution guideline with equal splits per exchanger would be conservative for nearly all possible operating conditions and be straightforward to implement.

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