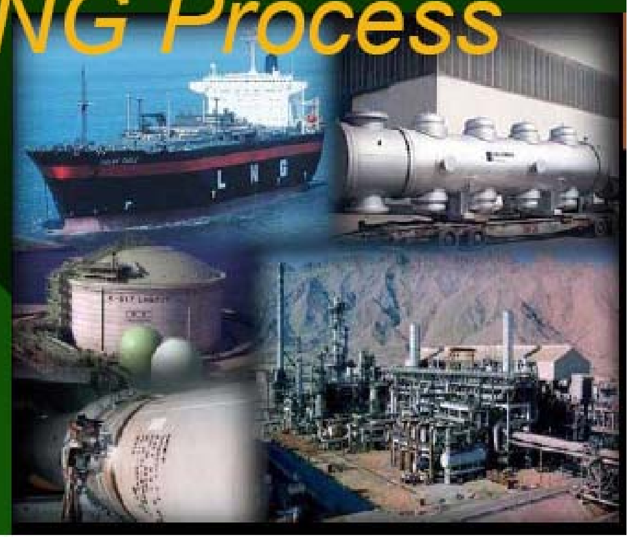
Kryopak PCMR® and EXP® LNG Process



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Why and What is LNG……

LNG is an acronym for Liquefied Natural Gas. The purpose of liquefying natural gas at very low temperatures is to enable transportation from the producing region to a distant market. The liquefied natural gas occupies a volume that is approximately 1/600th of the volume occupied by the gas at atmospheric pressure. The process of liquefaction is energy intensive, and it is only economically feasible to do when the distance to the market is too large for conventional pipeline transport.

All of the processes to produce LNG are based on a common concept – cool the natural gas down to a temperature where it is a liquid at ambient pressure, approximately –161°C (–258°F). The method of cooling the natural gas is where the processes differ. All of the LNG processes begin in the same way. Wet natural gas passes through the pre-treatment section of the plant, where it is treated to remove carbon dioxide, hydrogen sulphide, mercury, mercaptans and dehydrated to remove water. The treated, dry gas is then precooled to an intermediate temperature, approximately –35°C (–31°F). This will cause the heavier hydrocarbon components, which can freeze at very low temperatures, to condense and separate from the gas. The lean gas, mainly methane and ethane, is then sent to the liquefaction section of the plant, where it is cooled to approximately –161°C (–258°F) before sending it to storage. The liquefied heavier hydrocarbon components can be shipped as condensate products, or can be fractionated into pure marketable products, including propane and butane.

What LNG Processes are Available……

Where the LNG processes differ is with the different processes used for the cooling (refrigeration). There are three major commercial mixed refrigerant processes, developed for base load LNG plants and currently dominate the market, APCI's C3MR (Propane Mixed-Refrigerant Process), ConocoPhillips' OCR (Optimized Cascade Refrigeration Process) and Prico (Single Mixed-Refrigerant Process), generally called MR (Mixed Refrigerant Process).

There are several other processes, such as Shell's DMR (Dual Mixed Refrigerant Process), Liquifin Axens Process, SFMR (Single Flow Mixed Refrigerant Process), MFC (Mixed Fluid Cascade Process) and ABB's Dual TEX Cycle, are for limited applications or under development.

Observing the Q/T diagram of a typical gas liquefaction process, three zones could be noted in the process of the gas being liquefied. (See Fig.-1). A pre-cooling zone, followed by a liquefaction zone, and completed by a sub-cooling zone. All of these zones are characterized by having different curve slopes, or specific heats, along the process. All of the LNG processes are designed trying to closely approach the cooling curve of the gas being liquefied, by using specially mixed multi-component refrigerants that will match the cooling curve at the different zones/stages of the liquefaction process to achieve high refrigeration efficiency and reduce energy consumption.

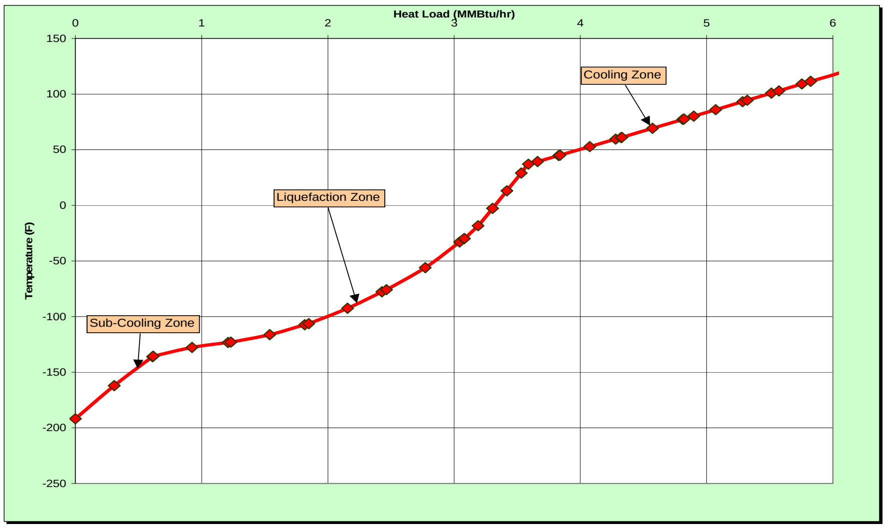

Fig.-1: Q/T Diagram of Typical Gas Liquefaction

Kryopak PCMR® and EXP® LNG Process……

Kryopak has developed two LNG processes, *Kryopak PCMR® (PreCooling Mixed Refrigerant)* and *Kryopak EXP® (Expander Refrigeration),* which have been commercially applied.

Kryopak PCMR® process utilizes a mixed refrigerant (MR), composed of nitrogen, methane, ethane, propane, butane, and pentane. The component ratio is carefully chosen to closely match its boiling curve with the cooling curve of the natural gas feed. The closer the curves match, the more efficient the process is. The cold box design could achieve 1°C minimum temperature approach and 2-5°C weighted LMTD.

As shown in Fig.-2, the mixed refrigerant is compressed and partially condensed by precooling (ammonia or propane) and flashed into vapor and liquid prior to entering the highly efficient plate-fin heat exchangers, collectively known as the “cold box”. The cold box contains a number of plate-fin heat exchanger cores, which allow multiple streams to be heated/cooled to extremely close temperature differences. The vapor of the flashed mixed refrigerant (MR) is then fully condensed in the cold box before it is flashed across an expansion valve, which causes a dramatic reduction in temperature. This very cold vapor is used to cool the MR streams (condense the flashed MR vapor, and sub-cool the flashed MR liquid), as well as the natural gas feed stream. The warmed low-pressure MR vapor is then mixed with the sub-cooled MR liquid after JT expanded to provide the medium temperature cooling, and finally warmed up to a closed temperature to inlet of the feed gas before sending to the MR compressor for recompression. The natural gas feed stream enters the cold box and is initially cooled to about -35°C (–31°F). The gas is then sent to a separator to remove the heavier components, which are sent to the fractionation plant.

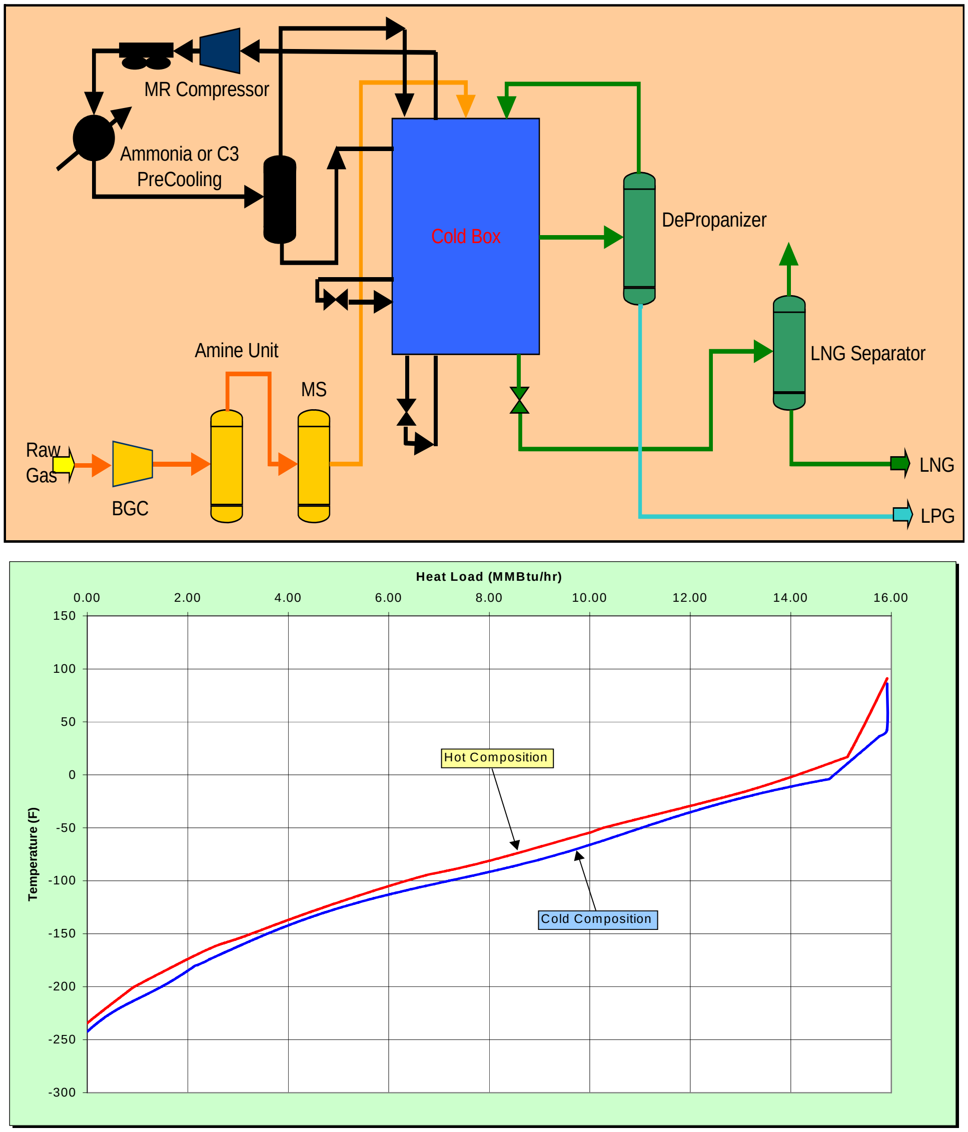

Fig.-2: Simplified *Kryopak PCMR®* Process Diagram and Q/T Composition Curves

Using this design philosophy, the *Kryopak PCMR®* process is able to achieve a lower level specific refrigeration energy consumption of 0.19 hp/lb LNG (13.0 kW/ton-day LNG) compared to the reported design energy consumption of 0.18-0.25 hp/lb LNG (12.2 – 16.8 kW/ton-day LNG) for the existing MR LNG processes. One of our typical designs with 200,000 Nm^3/day (160 tons /day LNG) has a total refrigeration energy consumption of only 2,100 kW.

Kryopak EXP® process employs refrigeration generated by a single semi-closed isentropic expansion of gases. The composition of the refrigerant gas is the same as the vapor generated from final product flash. (See Fig.-3). By this means no mechanical refrigeration is used in the system as seen in the MR processes, simplifying the process accordingly.

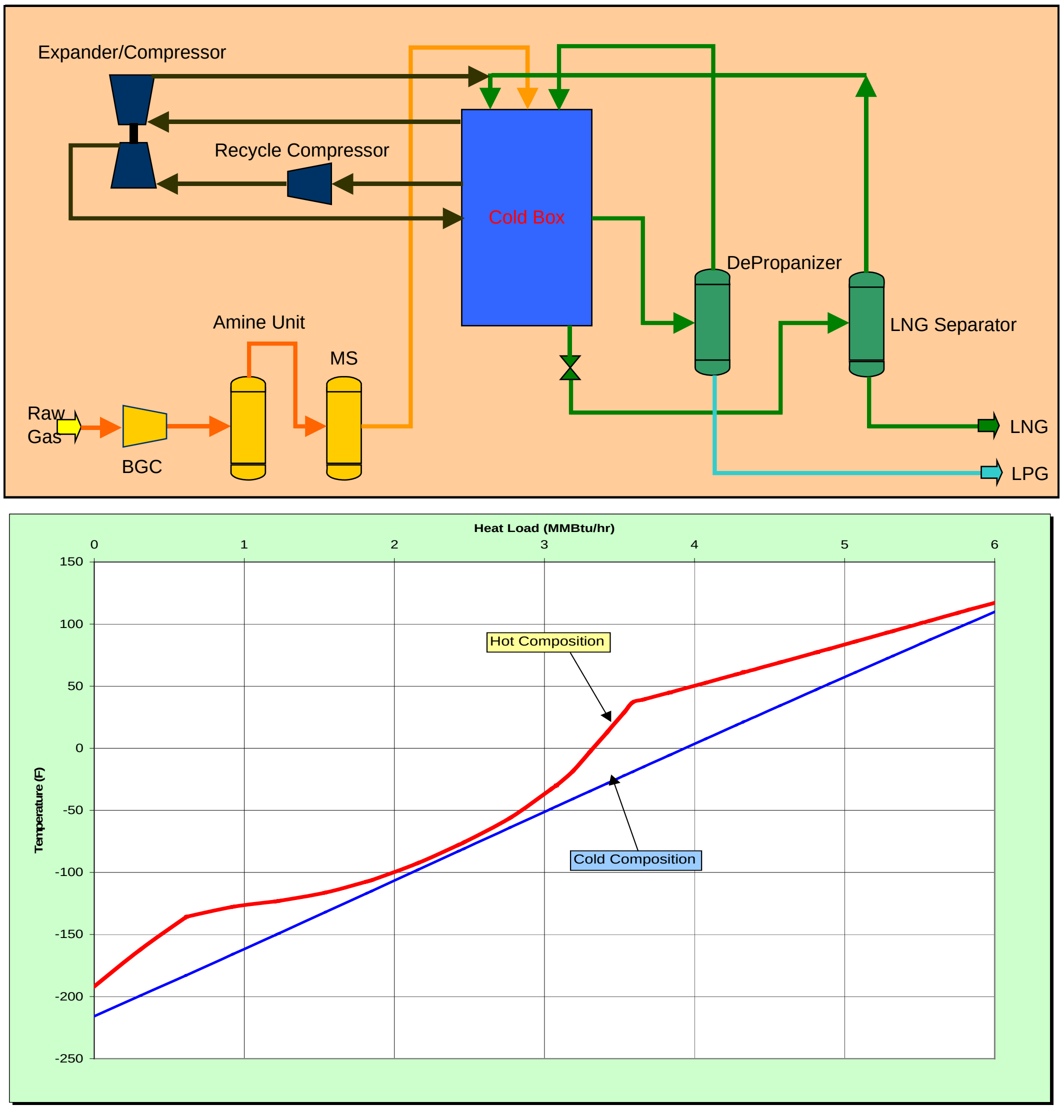

Fig.-3: Simplified *Kryopak EXP®* Process Diagram and Q/T Composition Curves

By recycling the gas in the *Kryopak EXP®*, the slope of the Q/T curves are accordingly changed per the cooling input at the different zones by the recycling refrigerant gas, obtaining profiles close to the gas refrigerant been used, thus minimizing deviations due to gas composition fluctuation. The amount of flow used in the recycles, the feed gas, and refrigerant pressure levels alter the shape of the Q/T curves, which are part of the design parameters used in achieving an optimum design. The control system will recognize these fluctuations and automatically change as required for optimum system performance.

In the *Kryopak EXP®* process, work and refrigeration are extracted from the expansion process. The refrigeration is used to aid the liquefaction process and the work extracted is utilized to partially recompress the refrigerant gas. Thermodynamically speaking, this expansion cycle is as efficient as the most advanced mixed refrigerant cycles. Today, compressor/expander efficiencies are reaching more than 85%. This represents an emerging opportunity to insist in the utilization of this technology in the LNG business.

Using this design philosophy, the *Kryopak EXP®* process is able to achieve a mid level specific refrigeration energy consumption of 0.20 - 0.23 hp/lb LNG (13.5 – 15.5 kW/ton-day LNG) compared to the reported design energy consumption of 0.18-0.25 hp/lb LNG (12.2 – 16.8 kW/ton-day LNG) for the existing MR LNG processes. One of our typical designs with 150,000 Nm^3/day (125 tons /day LNG) has a total refrigeration energy consumption of only 2,550 kW.

The *Kryopak EXP®* process has the advantage of using a simple cooling system with a relatively small number of pieces of equipment operating at cryogenic temperatures and a fast approach to equilibrium upon warm start-up. The simplicity of the design and the self-equilibrating nature of the process provide straightforward operation. The process is not very sensitive to reasonable changes in feed gas composition and does not need premixed refrigerant.

Gas and LNG Facts……

Typical Components of Industry Gas Streams

Names	Components											
	CO2	H2S	N2	C1	C2	C3	iC4	nC4	iC5	nC5	C6	C7+
Inert Gas	x		x									
Acid Gas	x	x										
LNG			x	x	x	x	x	x				
Natural Gas	x	x	x	x	x	x	x	x	x	x	x	x
LPG					x	x	x	x				
Natural Gasoline						x	x	x	x	x	x	x
NGL					x	x	x	x	x	x	x	x
Condensate (Stabilized)							x	x	x	x	x	x

Definitions of Words and Terms Used in the Gas Processing Industry

Cricondenbar	The highest pressure at which liquid and vapor phases can exist at equilibrium in a multicomponent system.
Cricondentherm	The highest temperature at which liquid and vapor phases can exist at equilibrium in a multicomponent system.
GPM	Preferably Gal/Mcf (gallons per thousand cubic feet): This term refers to the content in natural gas of components which are recoverable or recovered as liquid products.
Mcf	An abbreviation for one thousand cubic feet of gas.
MMscf	An abbreviation for one million cubic feet of gas.
RVP (Reid Vapor Pressure)	The vapor pressure of a material measured by the Reid Method and apparatus as detailed in ASTM Test Procedure D-323.
Wobbe Number	A number proportional to the heat input to a burner at constant pressure. In British practice, it is the gross heating value of a gas divided by the square root of its gravity. Widely used in Europe, together with a measured or calculated flame speed, to determine interchangeability of fuel gases.
Heating Value (Heat of Combustion)	The amount of heat obtained by the complete combustion of a unit quantity of material. The gross, or higher, heating value is the amount of heat obtained when the water produced in the combustion is condensed. The net, or lower, heating value is the amount of heat obtained when the water produced in the combustion is not condensed.

Gas Properties and Pre-Treating for LNG

Components	MW	Boiling Temp		Freezing Temp		Gas Purity to LNG
		(^{o}C)	(^{o}F)	(^{o}C)	(^{o}F)	
Nitrogen	28.013	-195.80	-320.44	-209.90	-345.82	<1% (Note 1)
CO2	44.010	-78.50	-109.30	-56.60	-69.88	<50-100ppmv (Note 2)
H2S	34.080	-85.55	-121.99	-60.35	-76.63	<4ppmv
Methane	16.043	-161.49	-258.68	-182.48	-296.46	
Ethane	30.070	-88.63	-127.53	-183.27	-297.89	
Propane	44.097	-42.07	-43.73	-187.69	-305.84	
i-Butane	58.124	-11.73	10.89	-159.60	-255.28	
n-Butane	58.124	-0.50	31.10	-138.35	-217.03	<2%
Neo-Pentane	72.151	9.50	49.11	-16.55	2.21	<5ppmv
i-Pentane	72.151	27.85	82.13	-159.90	-255.82	
n-Pentane	72.151	36.07	96.93	-129.72	-201.50	<0.1%
n-Hexane	86.178	68.74	155.73	-95.35	-139.63	<0.5%
Mcyclopentan	84.162	71.81	161.26	-142.46	-224.42	
Benzene	78.115	80.10	176.18	5.53	41.96	1-10ppmv (Note 2)
Cyclohexane	84.162	80.74	177.33	6.55	43.80	1-10ppmv (Note 2)
Mcyclohexane	98.190	100.93	213.68	-126.59	-195.87	
Toluene	92.141	110.63	231.13	-94.91	-138.84	
E-Benzene	106.169	136.19	277.13	-94.98	-138.96	
p-Xylene	106.169	138.85	281.93	13.26	55.87	
m-Xylene	106.169	139.10	282.39	-47.87	-54.17	
o-Xylene	106.169	144.41	291.94	-25.18	-13.33	
n-C7	100.206	98.43	209.17	-90.61	-131.10	
n-C8	114.233	125.67	258.20	-56.80	-70.23	
n-C9	128.260	150.79	303.42	-53.52	-64.33	
H2O						<0.5ppmv
Mercury						<0.01microgram/Nm3
						<10Nanogram/Nm3

Note: 1. Limited by product specifications for particular projects

Note: 2. Depends on overall composition

LNG Process Energy Usage Comparison (Assumed 100% Compression Eff)

Process	Energy Consumption		Application
	kW/ton-day LNG	HP/lb-LNG	
APCI (C3MR)	12.2	0.18	Base Load
ConocoPhillips (OCR)	14.1	0.21	Base Load
Prico (SMR)	16.8	0.25	Base Load, Small Scale
Sell (DMR-SMR)	12.5	0.18	Base Load
ABB Dual Expander Cycle			
TEX + C3R	13.5	0.20	Small Scale
Dual TEX Cycle	16.5	0.24	Small Scale
Pre-Cooled Dual TEX Cycle	13.0	0.19	Small Scale
Kryopak EXP®	15.5	0.23	Small Scale
Kryopak PCMR®	13.0	0.19	Base Load, Small Scale

Note: C3MR - Propane Mixed Refrigeration
OCR - Optimized Cascade Refrigeration
SMR - Single Mixed Refrigeration
DMR - Dual Mixed Refrigerant
C3R - Propane Pre-Cooled
PCMR – Pre-Cooled Mixed Refrigerant
EXP - Turbo-Expander
TEX - Turbo-Expander

Useful Conversions

1 million tones LNG	=~	2.2 million cubic meter LNG
1 million tones per year (tpy) LNG	=~	140 million standard cubic per day (MMscfd) gas
100 MMscfd gas	~	730,000 tpy LNG
	~	2,100 tpd LNG
1 million cubic meter LNG	=	6.29 million bbl LNG
	=~	460,000 tonnes LNG
1 cubic meter LNG	~	600 cubic meter gas
	~	21200 cubic foot gas
	=~	
1 standard cubic foot (scf)	=	0.0268 normal cubic meter (Nm^3)
1 standard cubic meter (scm)	=	1.057 normal cubic metter (Nm^3)
1 kmole gas	=	22.41 Nm^3 @ 101.325kPa(A) and 0^oC
1 lb-mole gas	=	379.49 scf @ 14.696psia and 60^oF

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