Natural Gas Liquefaction

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Overview

- Natural gas use & energy content
- Natural gas transportation
- Joule-Thomson (J-T) expansion
- Expander cycle
- Cascade cycles

Incentives of natural gas use

- Environmental reasons (global warming) renewed interest in NG
- Greener fuel compared to coal & oil (Mitigate pollution (esp. urban))
- Lower cost H/C compared to oil (eg Russia)
- Relatively safe fuel (can power dual fuel vehicles)
- NG abundance is a major driver (hydraulic fracking)
- Can displace national oil use in oil producing countries
- Most versatile H/C: petrochemical feedstock, ammonia, domestic & industrial uses, heating

What is a trillion cubic feet (tcf) of NG?

- How much energy does 1 trillion cubic feet (tcf) of NG contain?

  Trillion cubit feet (tcf) of NG are used as a measure of the volume of gaseous fossil fuel reserves found in the ground (inland or offshore), or the annual natural gas (energy) consumption.

  1 TCF is sufficient to:

  – Heat some 15 million homes for 1 year, or

  – Generate 100 billion kilowatt-hours (kWh) of electricity, or

  – Power 12 million natural gas fired vehicles for one year, or

- Peak Cypriot natural gas demand: 600 MW (03/12/19)
- Available capacity: 1,178 MW (03/12/19), PVs: 104 MW

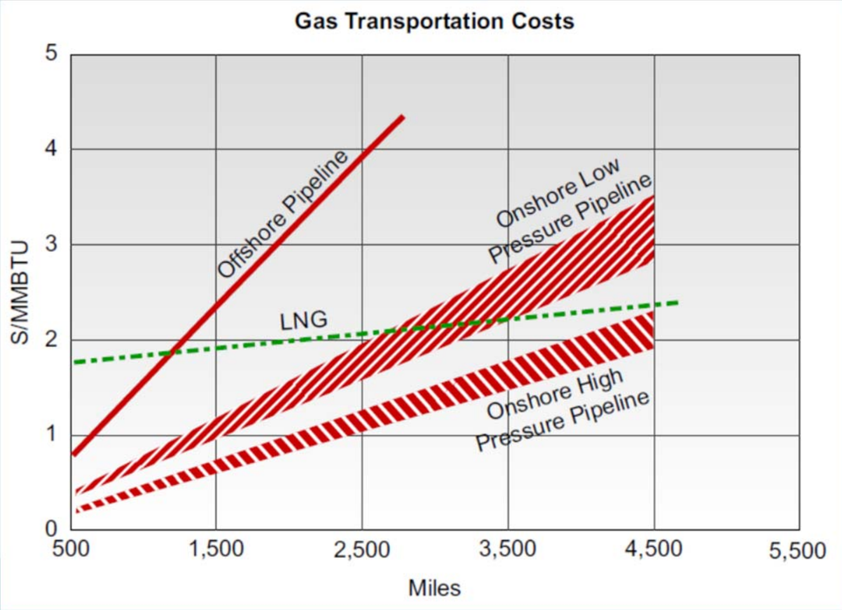
Natural gas transportation

Energy density and LNG

- For the same volume (@ ambient conds) gasoline contains ≈ 1,000× energy of gaseous NG
- Coal (anthracite; 31MJ/kg) contains 700x the NG energy
- LNG energy density: 2.4× CNG, 60% of diesel, 70% of gasoline
- What are the 2 energy density challenges for NG?
  - Use high pressure pipeline networks or storage tanks (CNG vehicles)
  - Difficult to accumulate large quantities of energy [gas] in storage facilities
- Sourcing the gas to customers involves:
  - 1. Extraction & Processing: Field extraction, gathering, transmission & processing
  - 2. LNG production: NG treating, NGL & condensate removal, liquefaction, storage & loading
  - 3. Shipping LNG (transportation)
  - 4. Delivery & distribution: LNG receiving terminal, storage, regasification & distribution

Characteristics of LNG

- LNG is *clear*, *odourless*, *colourless*, *non-toxic*, *non-corrosive*
- ρ_{LNG}= 430–470kg/m³. Does LNG float in water?
- LNG is economic for distances >~1,100km by sea or ~3,500km by land
- Offshore stranded gas is economic for LNG if d>1,100km from market

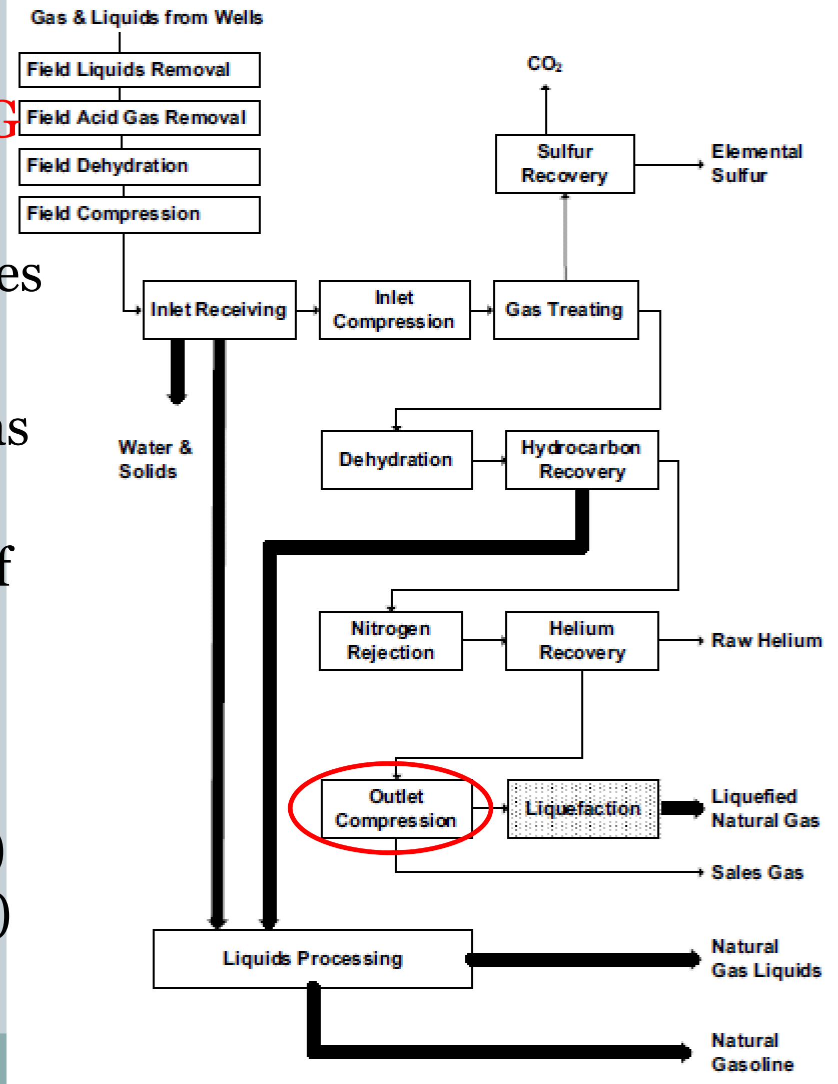


Gas flow characteristics

- Gas gathering pipelines (<30”, 76cm) & ‘trunklines’ (>30”)
- Gas streams to consumers carry single phase compressible NG mixture
- Onshore pipelines typically operate at: 700-1,100psi (~4,000 psi)
- Offshore pipelines typically operate at: 1,400-2,100psi
- Gas coolers installed at the discharge side of gas compressors. Why?
  - Regulate inlet gas temp. so as to avoid hydrate undue downstream pressure losses
  - Protect pipeline inner & external coatings against high temps

Natural gas transportation

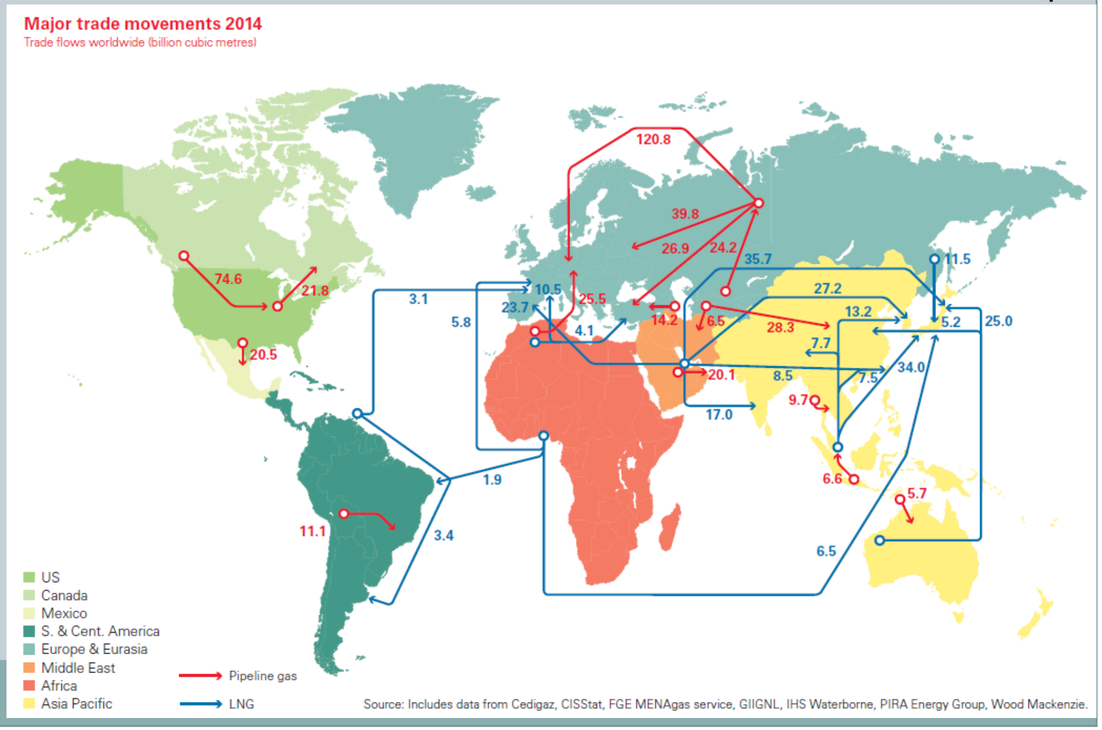
- Processed (or refined) NG source to markets by pipeline(s), as LNG or CNG
- Pipelines natural choice (inexpensive)
- Submarine pipelines: 10x inland p/lines
- LNG is technology proven & safe
- For LNG receiving & export terminal as well as LNG ships are expensive
- LNG carriers account for about 30% of LNG export costs
- Liquefaction & transport energy expenditure: 25% of gas!
- Marine compressed natural gas (CNG) is another transport mode (future one)



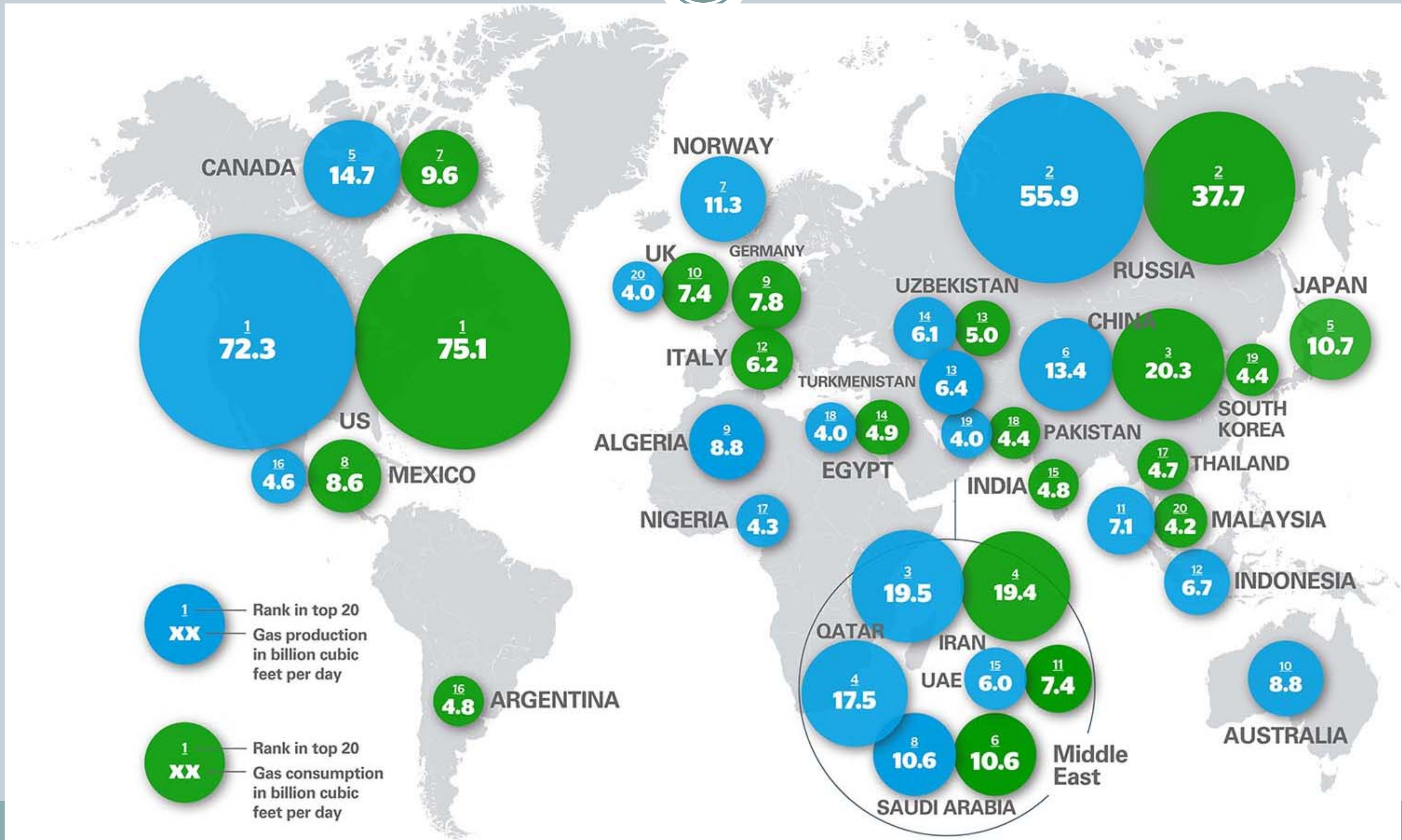
World natural gas trade movements (2012)

- Trade movement of NG (2012):
  - Total NG exports: 1,033 bcm
  - By pipelines: 705 bcm (imports, 68%)
  - LNG: 327 bcm (exports, 32%)
- Largest LNG import countries:
  - Japan: ≈119 bcm
  - South Korea: 50 bcm
  - Spain: 21.4 bcm
  - China: 20.5 bcm
  - India: 20 bcm
- Major LNG export nations:
  - Qatar: 105.4 bcm
  - Malaysia: 31.8 bcm
  - Australia: 28.1 bcm
  - Nigeria: 27.2 bcm
  - Indonesia: 25 bcm

Year 2014

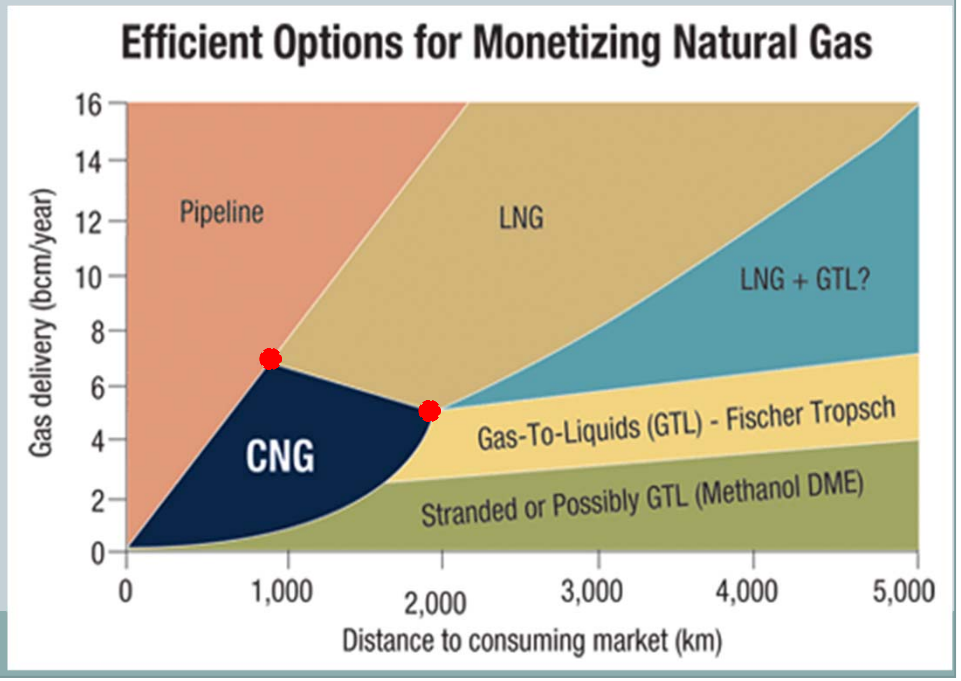


Major natural gas producers & consumers (2017)



Marine compressed natural gas (CNG)

- Marine CNG competitive for small volumes (1-2 bcm/y) over short distances (<2,000 km)
- Volume ratios: CNG (200:1); LNG (600:1)
- CNG requires no liquefaction plant or regas terminal. Pressurized gas
- CNG carriers constitute major cost investment



LNG economics

- Note: transportation >> wellhead costs > liquefaction > regas
- An LNG ship may cost $220m (end 2012; 160,000m^3)
- Need to build the LNG vessels
- The longer the distance from loading to discharge higher the costs
- Cyprus wellhead costs much higher…

Cost Breakdown in $/MM Btu for LNG Plants

Project	Wellhead Gas	Liquefaction	Transportation	Regasification	Minimum CIF Cost[a]
Qatar	0.50–0.75	0.40–0.60	1.10–1.20	0.40–0.60	2.45
North West Shelf (Australia)	0.65–0.95	0.40–0.60	0.75–0.95	0.35–0.55	2.15
Bontang, Indonesia	0.60–0.80	0.45–0.65	0.55–0.75	0.30–0.60	1.90

[a] CIF = Carriage + insurance + freight (i.e., cost delivered to customer).

Source: Troner (2001).

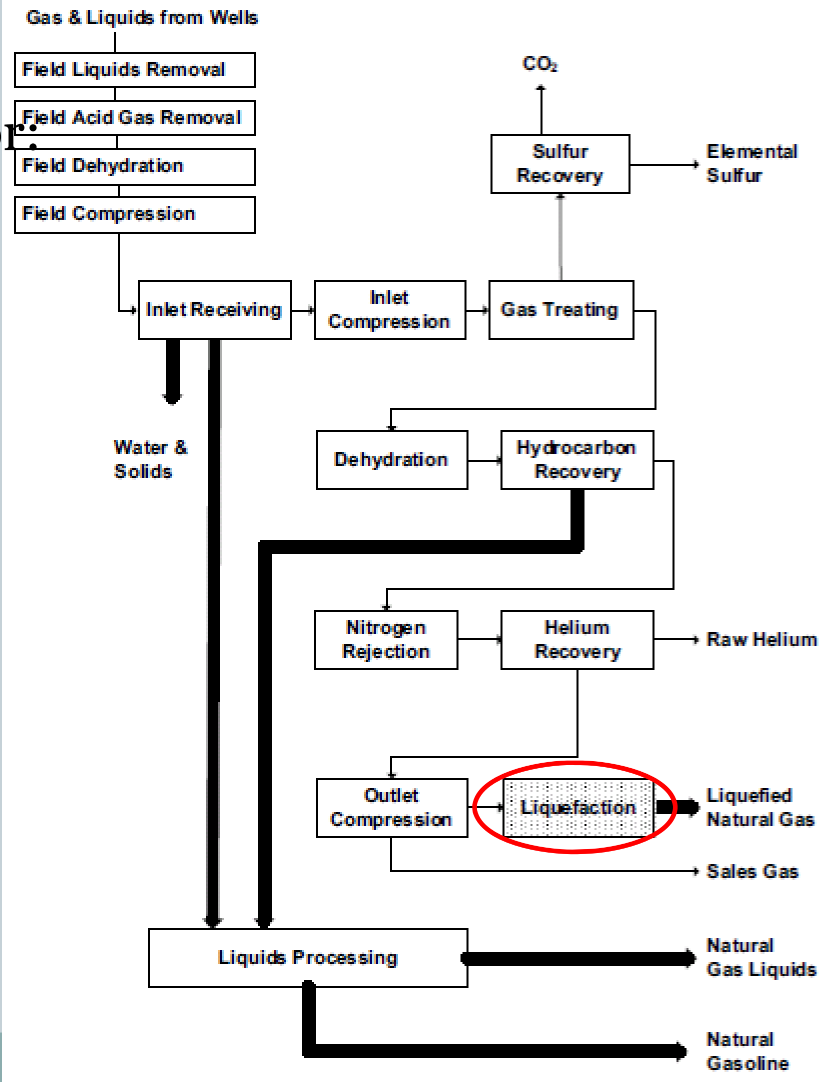
Cost of LNG plants

- Btw 1959 & 1970s design improvements in LNG plants & LNG carriers led to reduced LNG plant costs
- In 1980s, the cost of construction of an LNG facility cost $350/tpa
- In 2000s, it cost $200/tpa (of LNG)
- In 2012, because of an increase in the price of steel costs soared to $1,000/tpa
- The construction cost of greenfield LNG projects started to escalate >2004 from $400/tpa to $1,000/tpa as of 2008
- The main reasons are:
  - Low availability of EPC contractors as result of extraordinary demand for ongoing petro projects
  - High cost raw material as result of surge in demand
  - Lack of skilled labor in LNG industry
  - Devaluation of US dollar

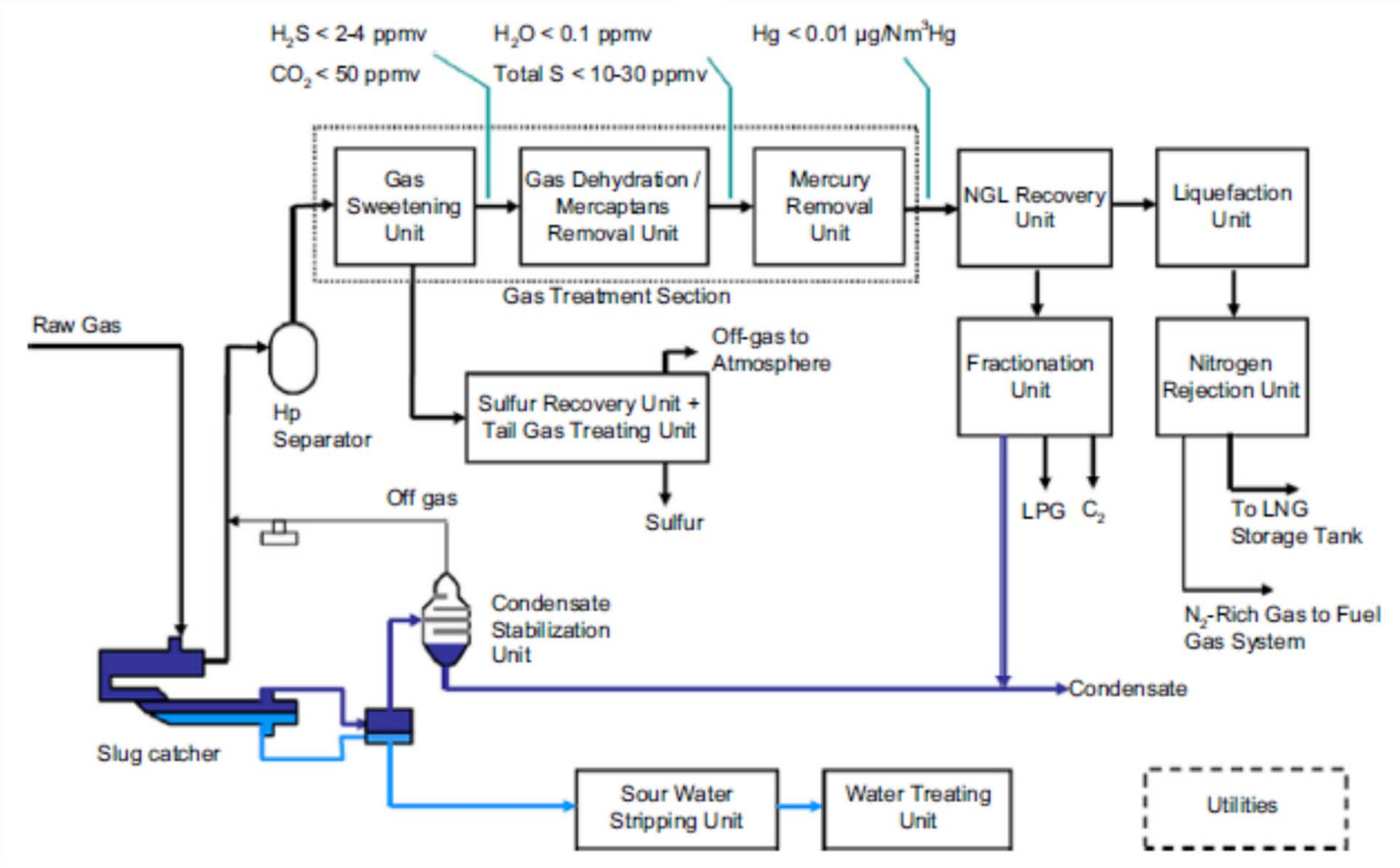
Natural gas liquefaction

Natural gas liquefaction

- Volume reduction of NG: 600-630:1
- Energy dense liquid NG is attractive for:
  - Storage, &
  - Transportation
- Proved technology
- LNG storage at:
  - Liquefaction facilities
  - Peak shaving installations
- For an LNG plant to become viable 3 tcf suffice
- Newer LNG plant designs put this to as low as 1 tcf

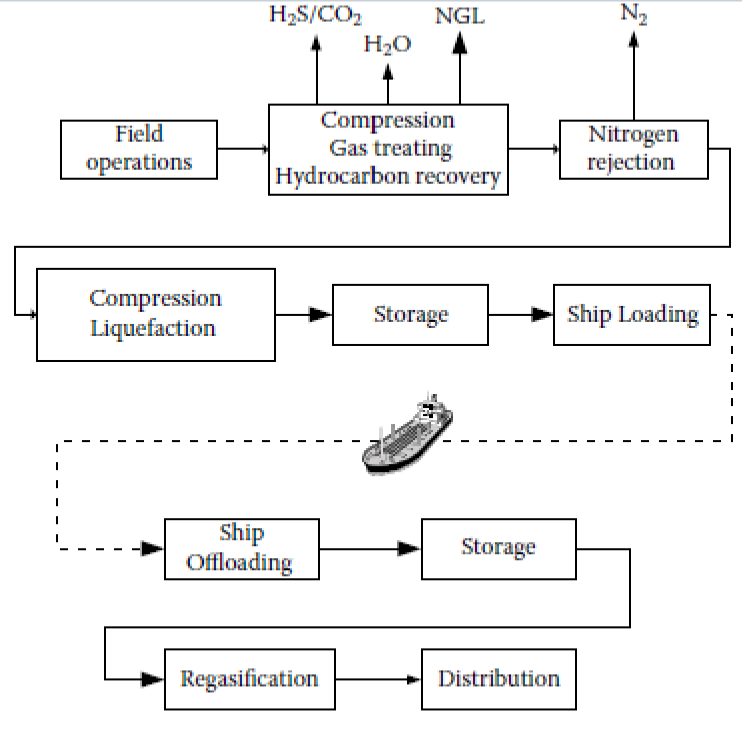


LNG production plant



The LNG value chain

- Upstream: NG production, transmission & liquefaction
- Midstream: LNG sales
- Downstream: LNG regasification, LNG storage & transportation
- ≈10% of the NG received by a liquefaction plant is used to liquefy gas



Baseload plant

Gas treating prior to liquefaction

- NG destined for liquefaction must be 'purer' than sales gas
- NG for LNG must contain less H_2O, N_2, CO_2. Why?
  - Solid depositions plug heat exchangers
- Combination of elemental mercury destroys heat exchangers

Compositional Specifications on Feed to LNG Plant and on Pipeline Gas

Impurity	Feed to LNG Plant[a]	Pipeline Gas[b]
Water	< 0.1 ppmv[c]	150 ppmv, (7.0 lb/MMscf, 110 kg/Sm^3)
Hydrogen sulfide	< 4 ppmv	0.25 – 0.30 gr/100 scf (5.7 – 22.9 mg/Sm^3)
Carbon dioxide	< 50 ppmv	3 to 4 mole%
Total sulfur (H_2S, COS, organic sulfur)	< 20 ppmv	5 – 20 gr/100 scf (115 – 459 mg/Sm^3)
Nitrogen	<1 mol%	3 mol%
Mercury	< 0.01 μg/Nm3	
Butanes	2 mol% max	
Pentanes+	0.1 mol% max	
Aromatics	< 2 ppmv[c]	

[a] Foglietta (2002).
[b] Engineering Data Book (2005a).
[c] McCartney (2005).

LNG composition [17 samples]

- Produced LNG (not feed gas)

Typical LNG Compositions

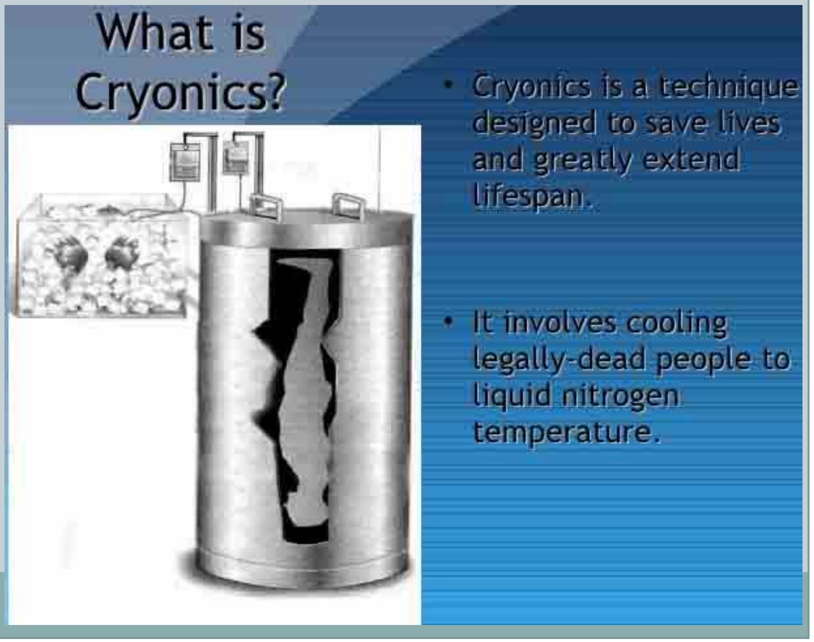
Component	Composition Range (mol%)
Nitrogen	0.00 – 1.00
Methane	84.55 – 96.38
Ethane	2.00 – 11.41
Propane	0.35 – 3.21
Isobutane	0.00 – 0.70
n-Butane	0.00 – 1.30
Isopentane	0.00 – 0.02
n-Pentane	0.00 – 0.04
HHV gas	1021 – 1157
Btu/scf (kJ/Sm^3)	(38,000 – 43,090)
Wobbe number	1353 – 1432
GPM, on C_2+ basis	0.71 – 4.08
(m^3/1,000m^3)	(0.094 – 0.543)

Source: McCartney (2003).

HHV: higher heating value
GPM: liquids recoverable

Natural gas liquefaction

- Gas liquefaction occurs when gases are cooled below their critical temp.
- Cryogenics is the science of attaining very low temperatures (>−150°C, −123 K) & the study of the behavior of materials at those temperatures.
- Cryogenics is not (≠) cryonics (cryopreservation @ −196°C, liquid N_2)
- Liquefaction cycles:
  - Joule-Thomson expansion
  - Expansion in an engine doing external work

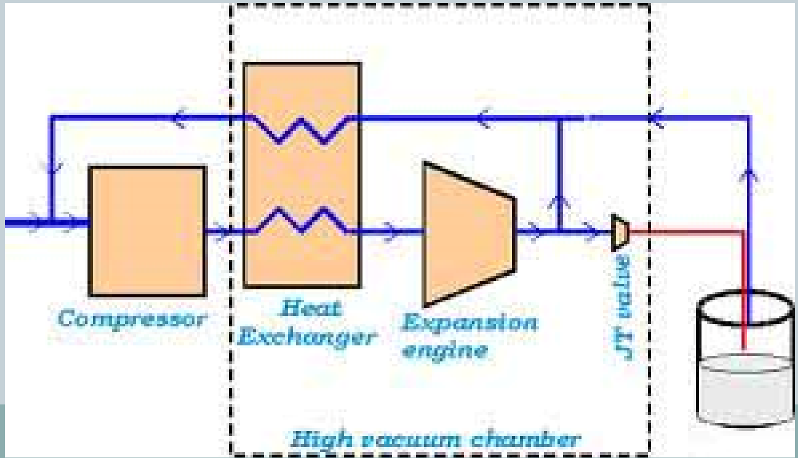


Keeping the Covid-19 vaccine cool

- Pfizer-BioNTech mRNA vaccine needs to maintained at −70°C
- Conventional refrigeration reaches −25°C
- Hospitals do not have the facilities to maintain the vaccine
- Logistics are an issue
- Neither do the companies have the means to deliver the medicine
- German 'thermoboxes' made of vacuum insulation panels (10× better)

1. Joule-Thomson LNG cycles

- Discovered in 1852 by James Joule & Lord Kelvin
- Idea: convert pressure into temp. drop
- Joule-Thomson effect is the temperature drop of a *gas* or *liquid* when allowed to expand through a valve
- Insulation minimises heat losses
- *Adiabatic* expansion through a valve, *no external work is done*
- Internal energy manifests as pressure drop



Joule-Thomson

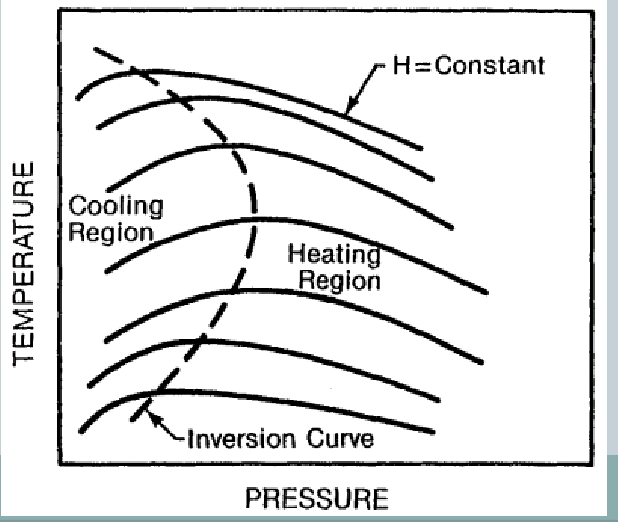
- Theory#3

Joule-Thomson effect

- Also known as *throttling* it is an inherently *irreversible* process
- Slope of an *isenthalphic* curve is the Joule-Thomson coefficient:

$$\mu = \left(\partial T / \partial P\right)_h .$$

- If μ>0 (ie, +ve), gas *cools* upon expansion
- If μ=0, gas temp does *not change*
- If μ<0 (ie, –ve), gas *warms up* with expansion
- Loci of maxima of isenthalpic curves (μ=0) known as inversion curve



Expansion from 1470 psia (101 bar) to 14.5 psia (1 bar)

	Initial Temperature °F (°C)	Final Temperature °F (°C)	$t_{final}-t_{initial}$ °F (°C)
Methane	80 (27)	–4 (–20)	–44 (–47)
Nitrogen	80 (27)	46 (8)	–34 (–19)
Helium	80 (27)	91 (33)	11 (6)
Methane	–10 (–23)	–125 (–87)	–115 (–64)
Nitrogen	–10 (–23)	–60 (–51)	–50 (–28)
Helium	–10 (–23)	1 (–17)	11 (6)
Methane	–46 (–43)	–215 (–137)	–169 (–94)
Nitrogen	–46 (–43)	–107 (–77)	–61 (–34)
Helium	–46 (–43)	–35 (–37)	11 (6)

Joule-Thomson expansion

- Components of an NG J-T (Joule-Thomson):
  - Compressor
  - Air cooled heat exchanger
  - Counter-flow (NG-NG) heat exchanger
  - J-T valve
  - Liquid-gas separator
- Initially NG compressed, cooled & allowed to expand thru J-T valve
- Initial pressure drop to T=47°C
- Process is repeated until liquefaction temp. is reached
- Critical: make-up gas closely controlled

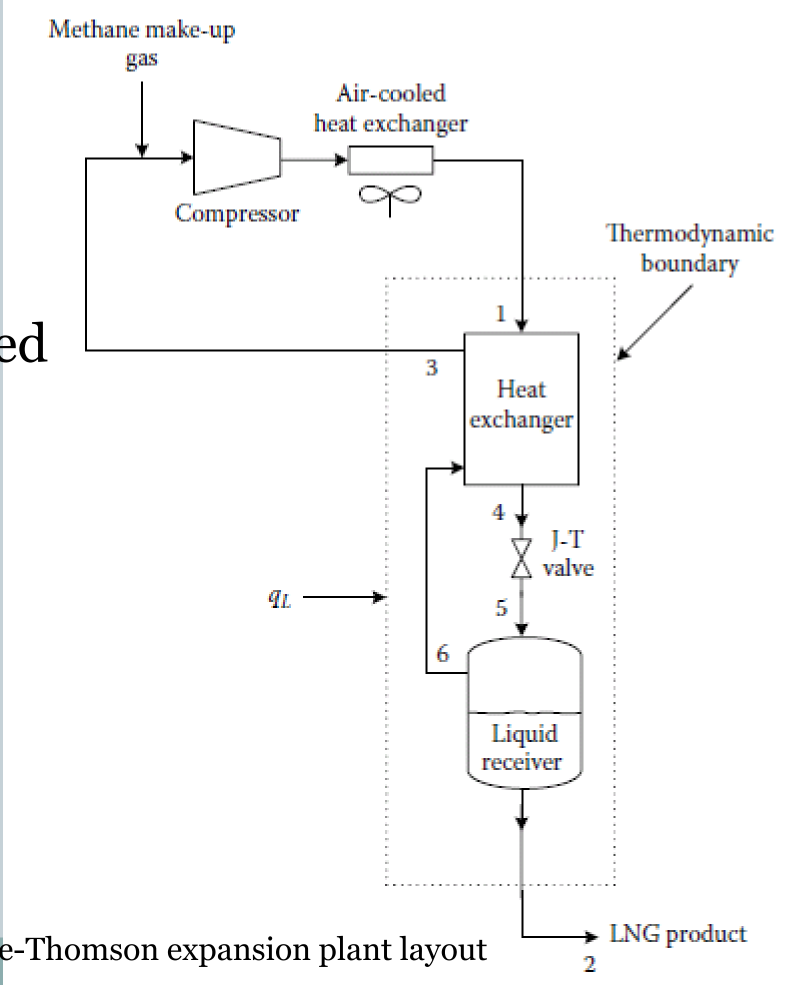


Fig.1: Joule-Thomson expansion plant layout

Joule-Thomson expansion (2)

- 1st Law of Thermodynamics:

  "Energy is conserved & *heat* and *work* are both forms of energy."

- In differential form the 1st Law of Thermo:

$$dQ = dW + dU \qquad (1)$$

where: U = internal energy, W = work, Q = thermal energy

- Application of eqn (1) to thermodynamic boundary yields:

$$\Delta h = q_L \qquad (2)$$

where change in *enthalpy* (Δh) equals the *heat leak* (q_L) on mass basis.

Throttling devices

- Theory #2

Joule-Thomson expansion (3)

- Applying the principle of mass conservation & taking h into account (Fig 1.) eqn (2) yields:

$$q_L = f h_2 + (1-f) h_3 - h_1 \qquad (3)$$

where $f = \frac{\dot{m}_1}{\dot{m}_2}$ is the mass fraction

- Re-arranging eq (3):

$$f = \frac{h_3 - h_1 - q_L}{h_3 - h_2} \qquad (4)$$

- How can we increase f?

Problem #9

Temperature(°C)	Pressure (bar)	Enthalpy (kJ/kg)	Entropy (kJ/kg-K)
25	40	870.93	4.673
–75	4	688.76	5.065
–100	4	634.39	4.772
–150	4	40.90	0.342

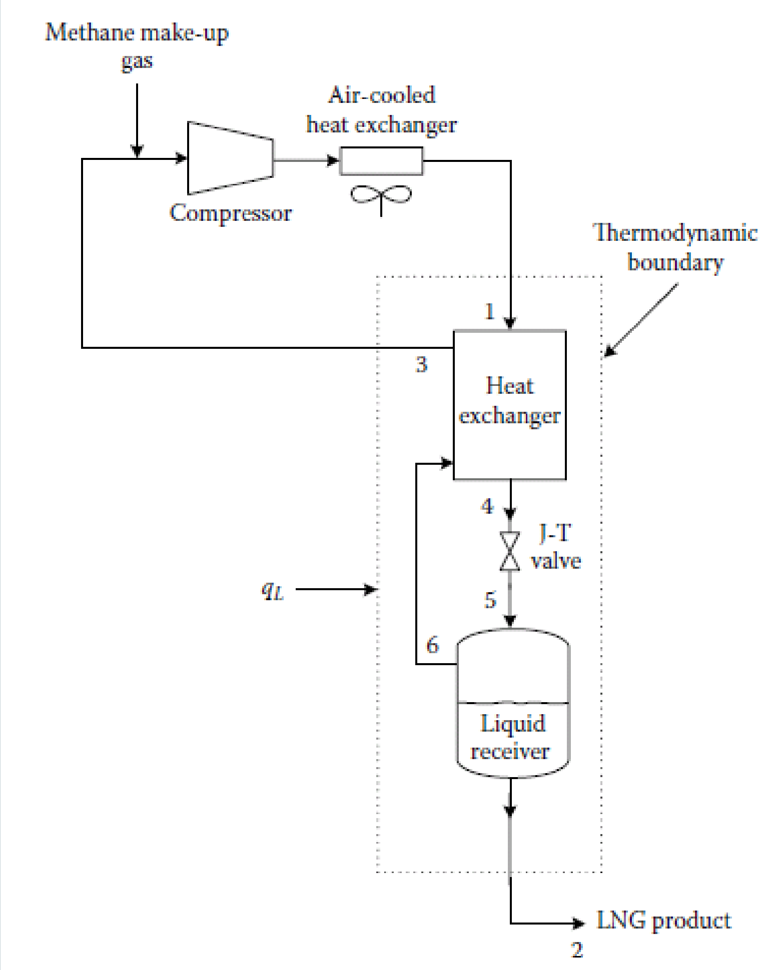


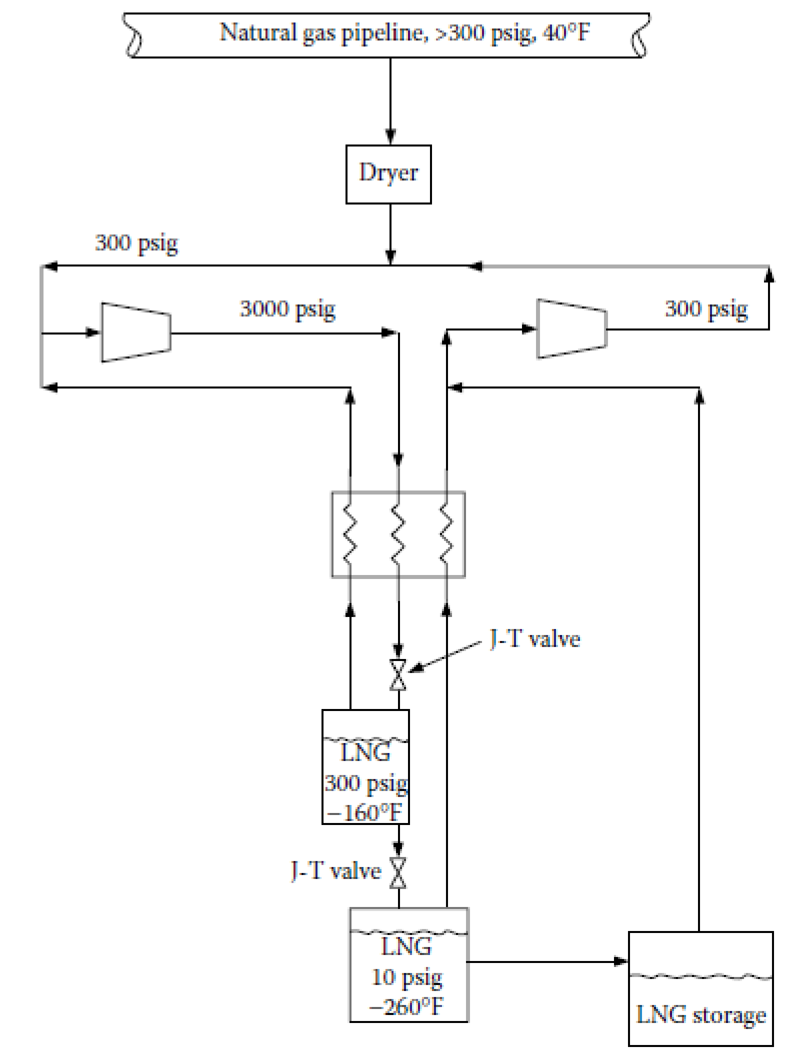
Fig.2: J-T process

J-T efficiency & application

- Use double stage expansion
- Add external source of refrigeration
- Only double stage valve found beneficial for LNG production
- Low capital costs & simplicity make J-T plants ideal for small NG volumes
- However, the higher thermodynamic efficiency of *cascade* & *expander* cycles render J-T unpopular

Small J-T LNG plant

- Simplicity and low costs make this LNG plant attractive
- Suitable for small volumes
- LNG transported via LNG trucks

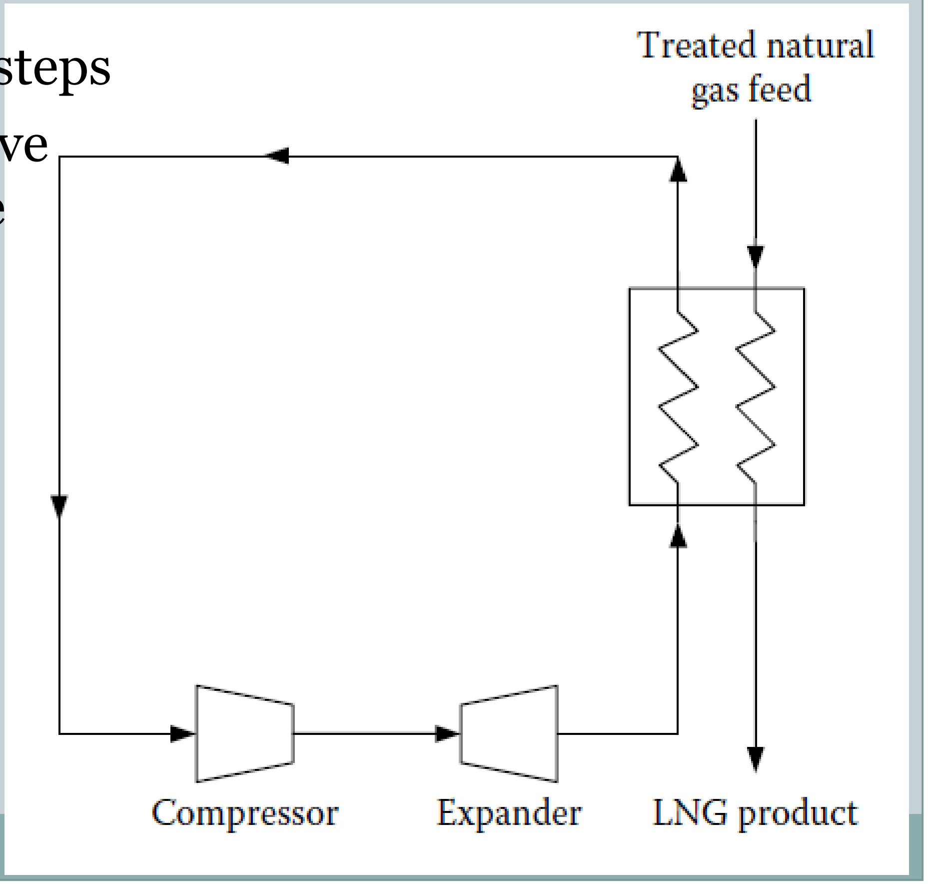


2. Expander cycles

- Remember: J-T expander cycle is thermodynamically irreversible
- Reversible or nearly reversible gas expansion offers 2 advantages vs JT:
  - A large amount of compression work can be recovered → higher η
  - Reversible process attains larger cooling effect
- Reversible, adiabatic *expander cycle* temp drop for CH_4: (75psia, 80˚F) to −94˚F
- J-T: $\Delta T = 4$˚F
- Expanders are compressors with their flow reversed
- Work performed by an expander needs to be removed. Thus couple:
  - Turboexpander → centrifugal compressor
  - Reciprocating expanders → reciprocating compressors (rarely used)
- Expander cycles:
  - (a). Closed cycles
  - (b). Open cycles

(a). Closed LNG cycles

- Working fluid is not natural gas, could be N_2
- N_2 expansion cools NG
- N_2 & NG do not directly mix
- Nitrogen is a safe gas, ensures few steps
- Cycle requires fewer & less expensive shutdown procedures vs open cycle
- Relatively complex machine



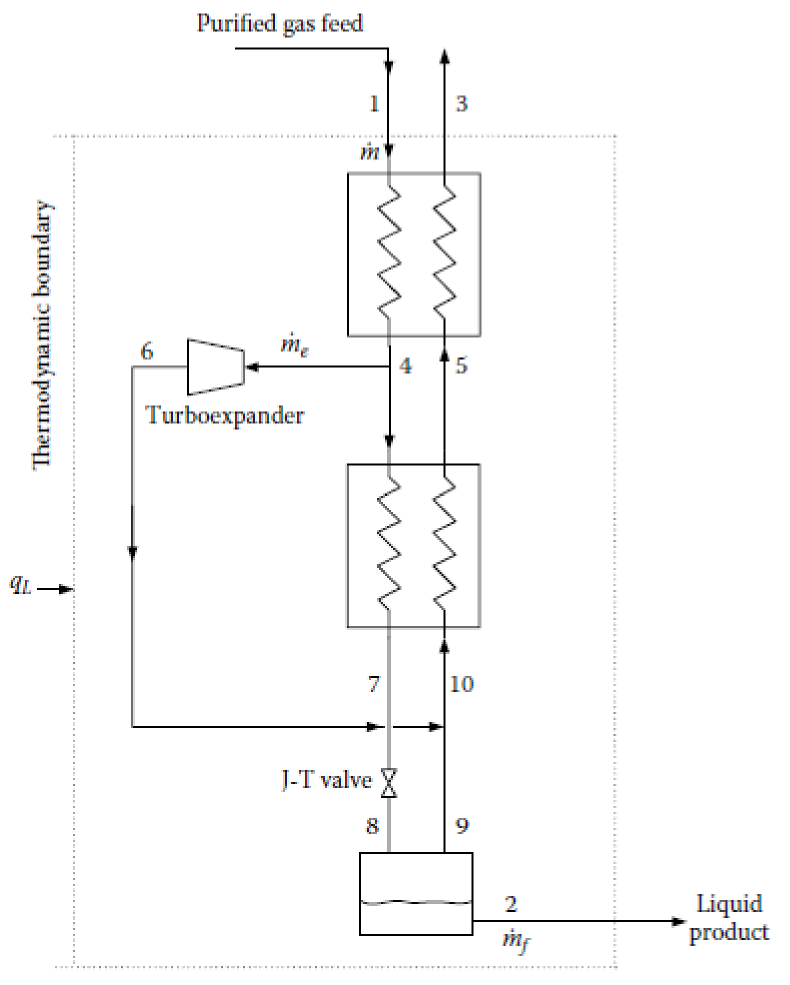
(b). Open LNG cycles

- Simpler than a closed cycle
- NG is the expanding medium
- Application of the 1st law of thermo in the thermodynamic boundary:

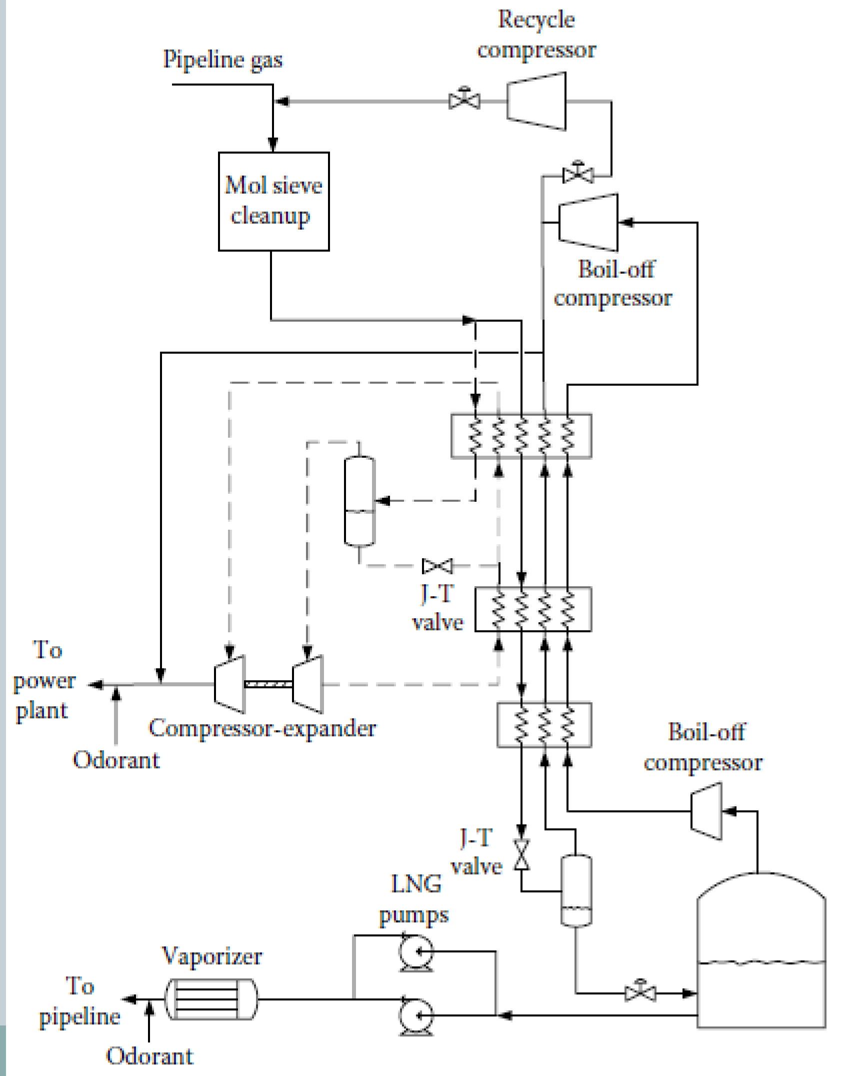
$$f = \frac{h_3 - h_1 - q_L}{h_3 - h_2} + \frac{e(h_4 - h_6)}{h_3 - h_2}, \quad (5)$$

where e = fraction of NG entering the turboexpander; $(h_4 - h_6)$: work done by the expander; $\dot{m}, \dot{m}_f, \dot{m}_e$: mass flow rates into liquefier, of liquefied product, & into turboexpander

- Several variations of open LNG cycles



Open cycle type peak shaving plant



Thanks for your attention!