

Natural Gas Liquefaction & Storage



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UNIVERSITY *of* NICOSIA

Overview

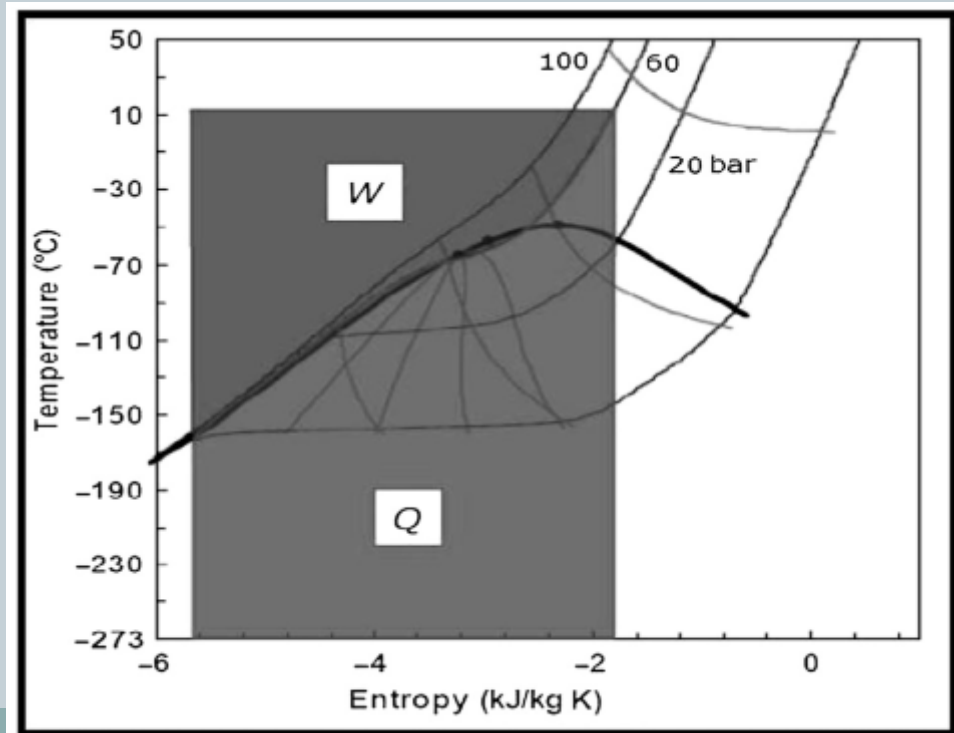
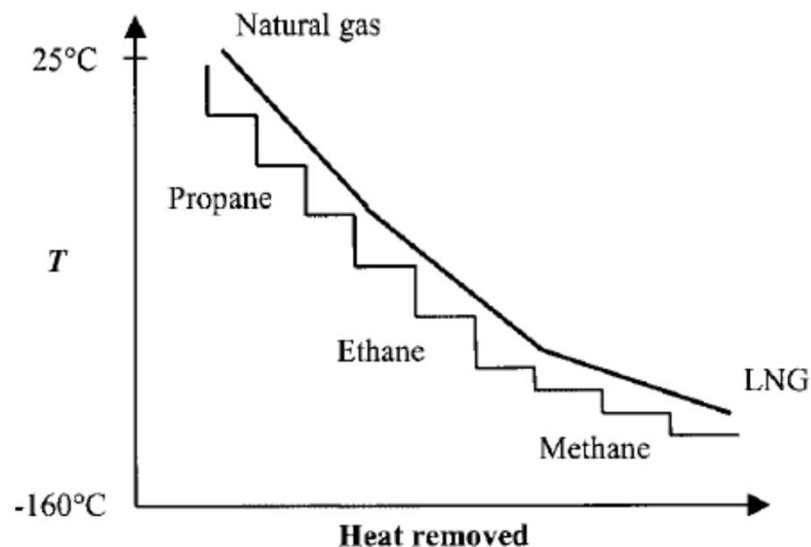
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- Liquefaction cycles:
 - 1) Propane pre-cooled Mixed Refrigerant Cycle (C3MR)
 - 2) Optimized cascade LNG process (POCLP)
 - 3) Mixed refrigerant cascade: closed cycle
- Heat exchangers
- LPG & NGL storage
- LNG storage
- LNG storage facilities:
 - 1. Aboveground double skinned metal tanks
 - 2. Pre-stressed concrete tanks
 - 3. Inground frozen earth storage
 - 4. Mined caverns

Effect of pressure on liquefaction W & Q

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- At low P, W & Q increase
- Thermodynamically, higher pressures are better
- Limitations: operate within the HE design pressure



Recap on cryogenic refrigeration

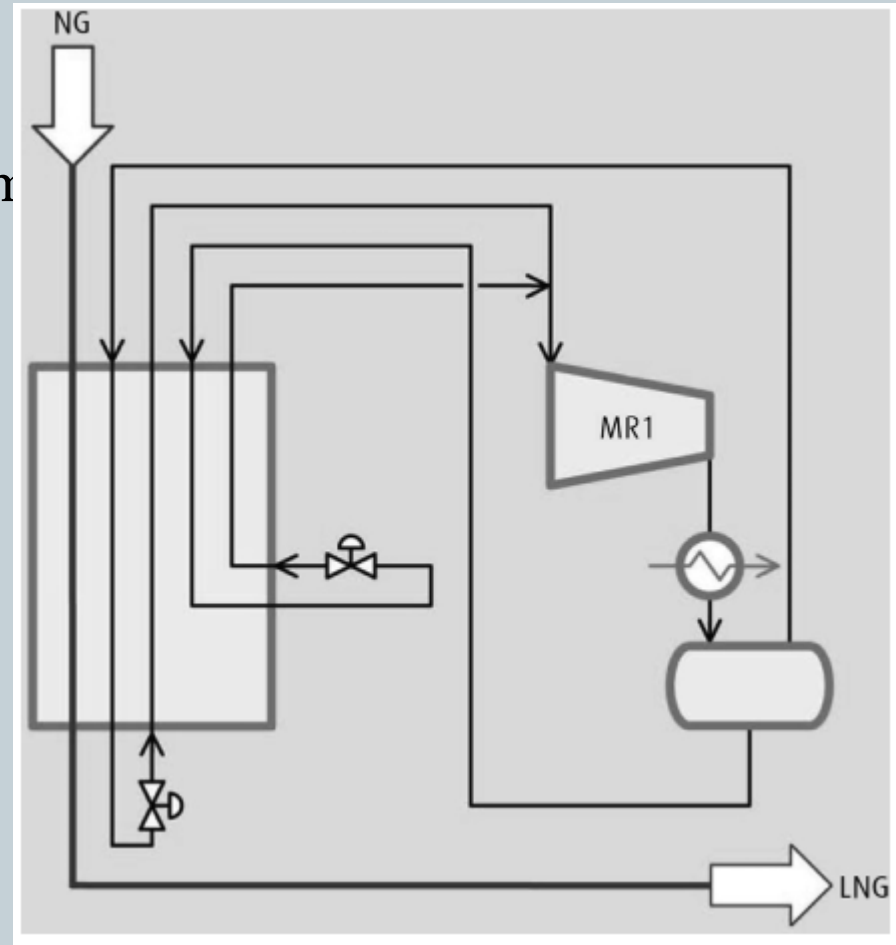
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- Previous lecture:
- 1. Classical cascade cycle
- 2. Mixed-refrigerant cascade cycle
 - Closed cycle (C3MR)
 - Open cycle
- Today:
 - 1) Propane pre-cooled Mixed Refrigerant Cycle (C3MR)
 - 2) Phillips Optimized Cascade LNG Process (POCLP®)
 - 3) Mixed refrigerant cascade: closed cycle

Recap basic LNG process

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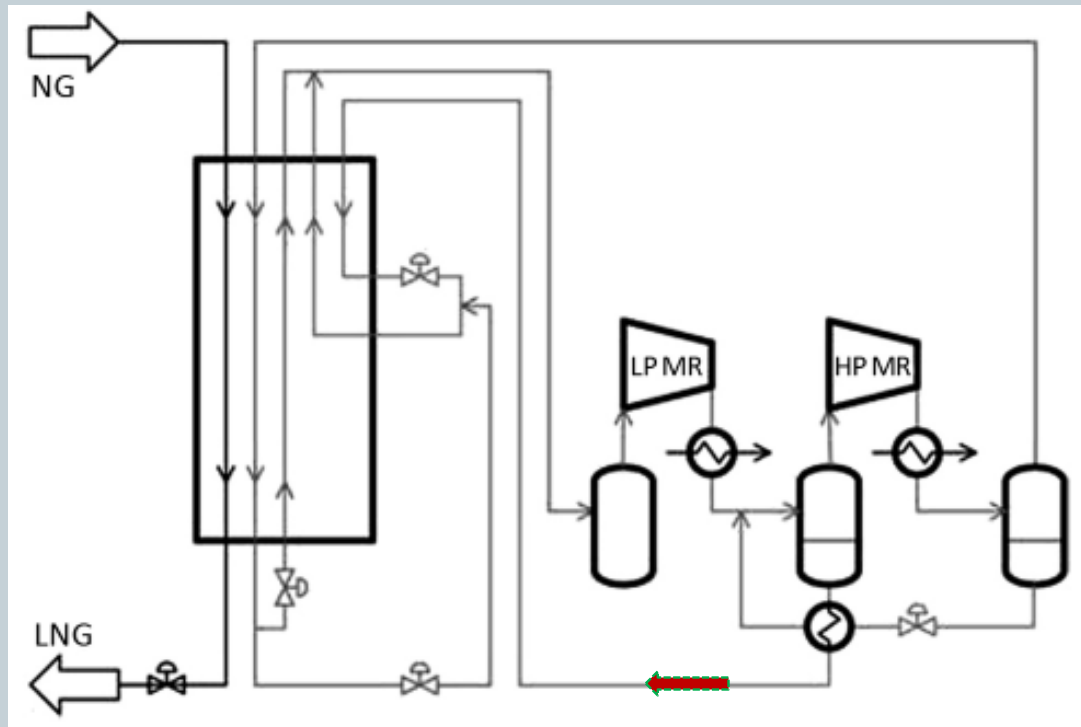
- Mixed refrigerant cycle (MRC)
- Separation vessel separates gas from liquid fraction
- J-T valves
- Air or water cooler
- Cold box includes PFHE



Multi-stage MR process

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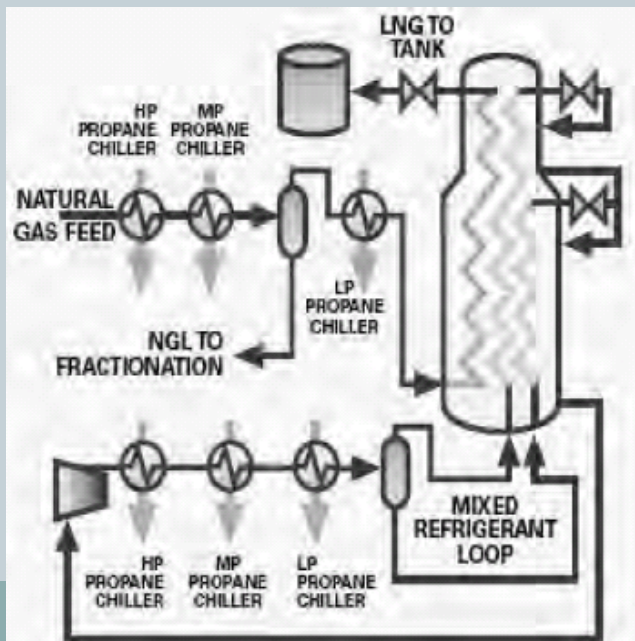
- Heat exchanger type: coil wound
- Utilizes medium-P refrigerator system



Propane pre-cooled mixed refrigerant (C₃MR)

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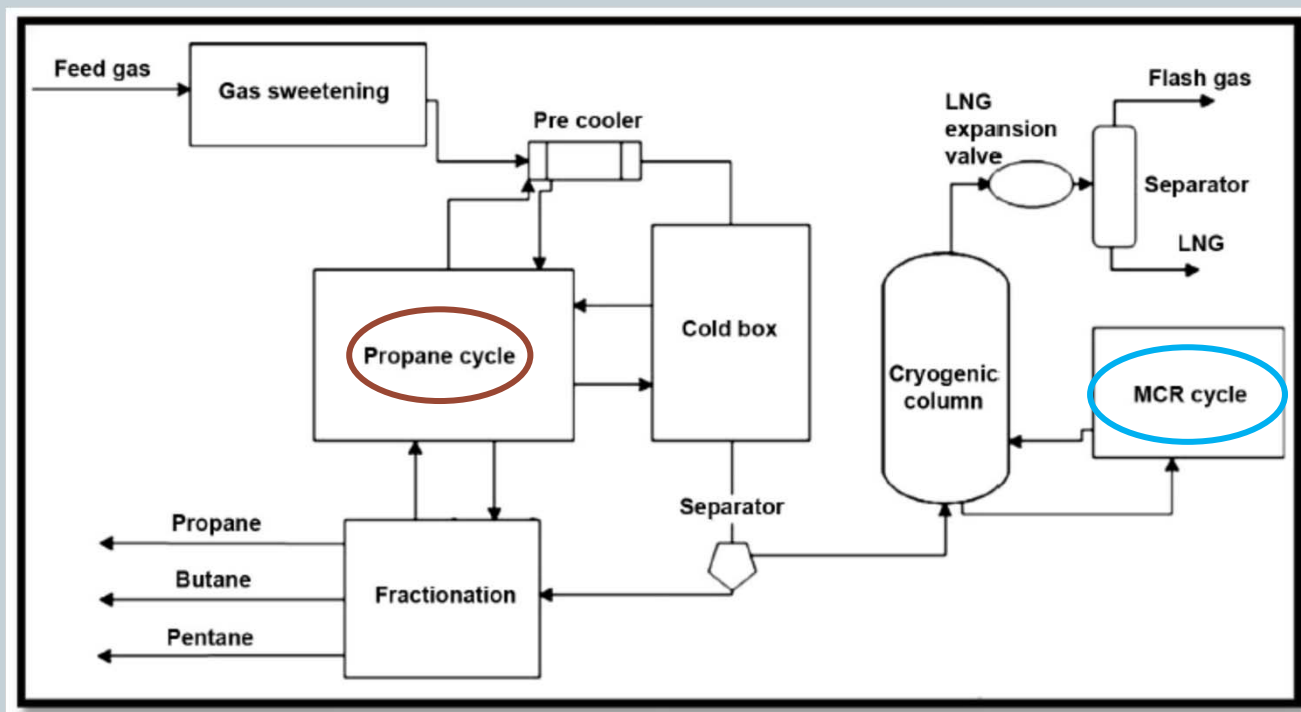
- Popular ever since late 1970s
- Train capacity max. 4.5 mtpa
- Mixed refrigerant: nitrogen, methane, ethane, & propane
- Coil wound HE: small diameter spiral wound tube bundles
- Addition of N₂ expander possible 8 mtpa



Multi-component refrigerant (MCR)

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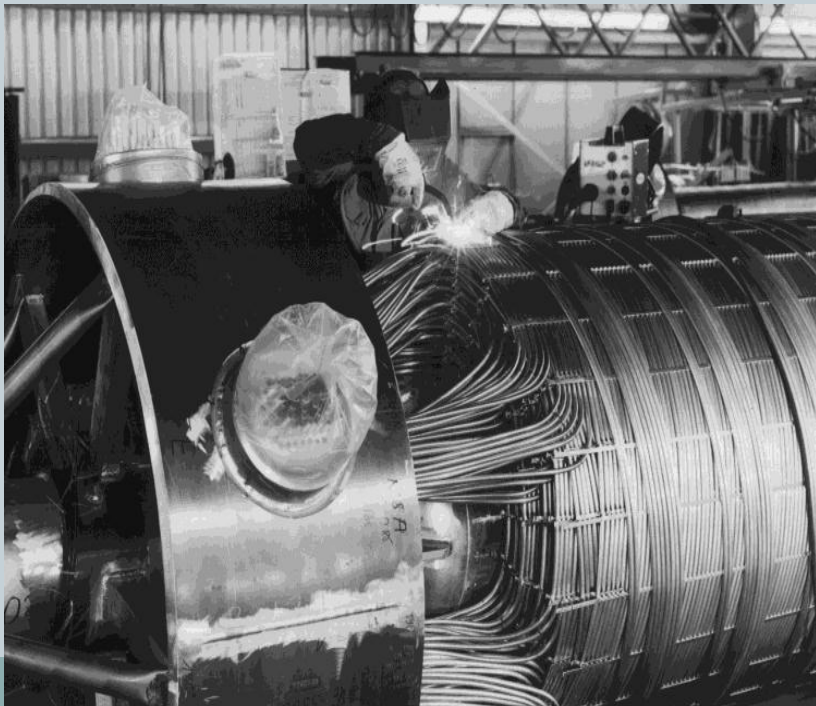
- ~75% of LNG plants use propane precooled (*Air Products & Chemicals*)
- Cold box lower temp. to -30°C
- LNG expansion valve brings press. to atmospheric



Coil wound heat exchanger (CWHE)

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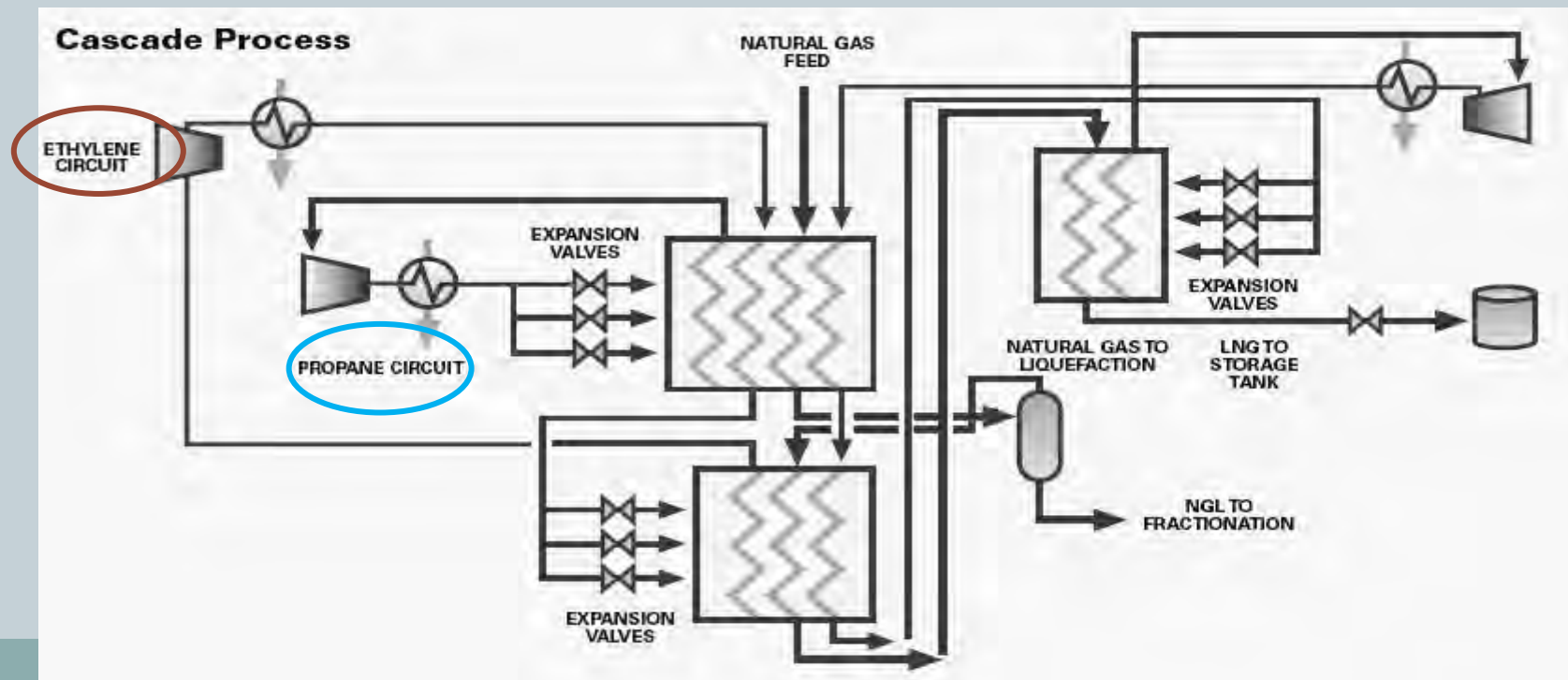
- Main cryogenic heat exchanger
- Small diameter spiral wound tube bundles
- Permit very close heat exchange btw refrigerant & methane stream



Optimized cascade LNG process (POCLP)

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- POCLP LNG plant of 3 mtpa LNG built in Trinidad
- Refrigerants: propane & ethylene circuits
- POCLP offers high thermal efficiency
- Design optimized for project economics & operational flexibility

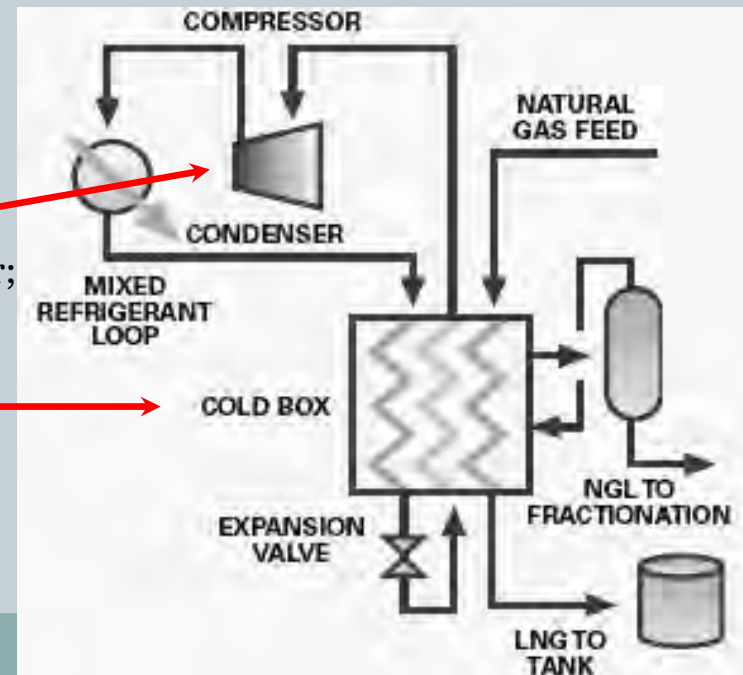


Mixed refrigerant cascade: closed cycle

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- Process equipment can be **reduced** by single refrigeration stm
- Note the '**cold box**' of the propane precooled mixed refrigerant stm
- Cold box consists of: plate fin heat exchanger cores
- Heat exchanger almost matches temp of gas stream to refrigerant temp
- Refrigerants: propane & mixed refrigerant
- Simplification results in 30% lower capital costs
- Configuration not very efficient as multi-stage systems
- Peak-shaving use only

Note only 1 compressor;
Before we had 2



Black & Veatch Pritchard PRICO process

Heat exchangers: plate-fin HEs

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- **Advantages:**
 - Low cost per unit area
 - Complex stream arrangement possible
 - Readily available from many qualified suppliers
 - Cool down more quickly and start-up faster
- **Disadvantages:**
 - Expensive manifolding for larger plant capacities
 - Limited acceptable temperature gradients



Video

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- LNG 101 - Pt. 5 Heat Exchangers

Heat exchangers: Spiral wound HEs

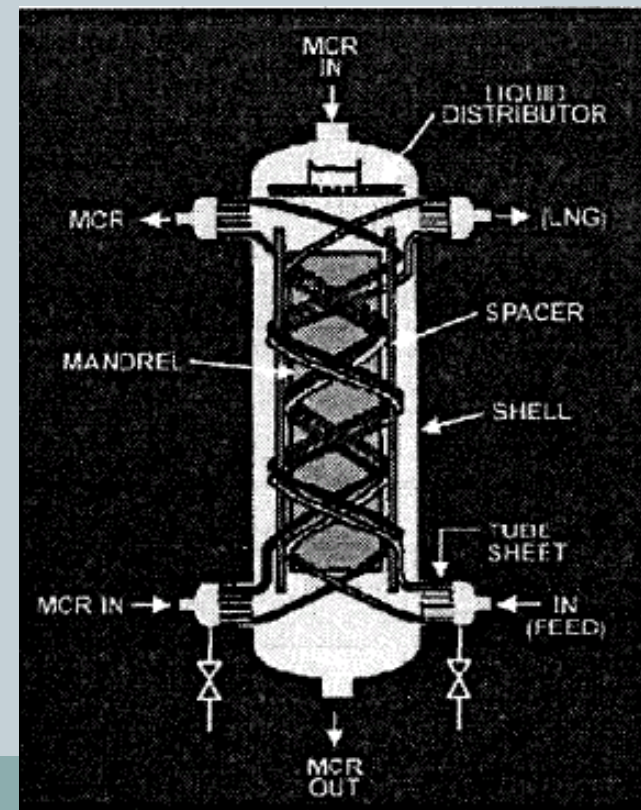
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- **Advantages:**

- Large heating surface per shell. The largest single shell exchangers
- Robust when exposed to thermal stresses during start-up or misuse
- Fixing of single tube leakages within moderate down time

- **Disadvantages:**

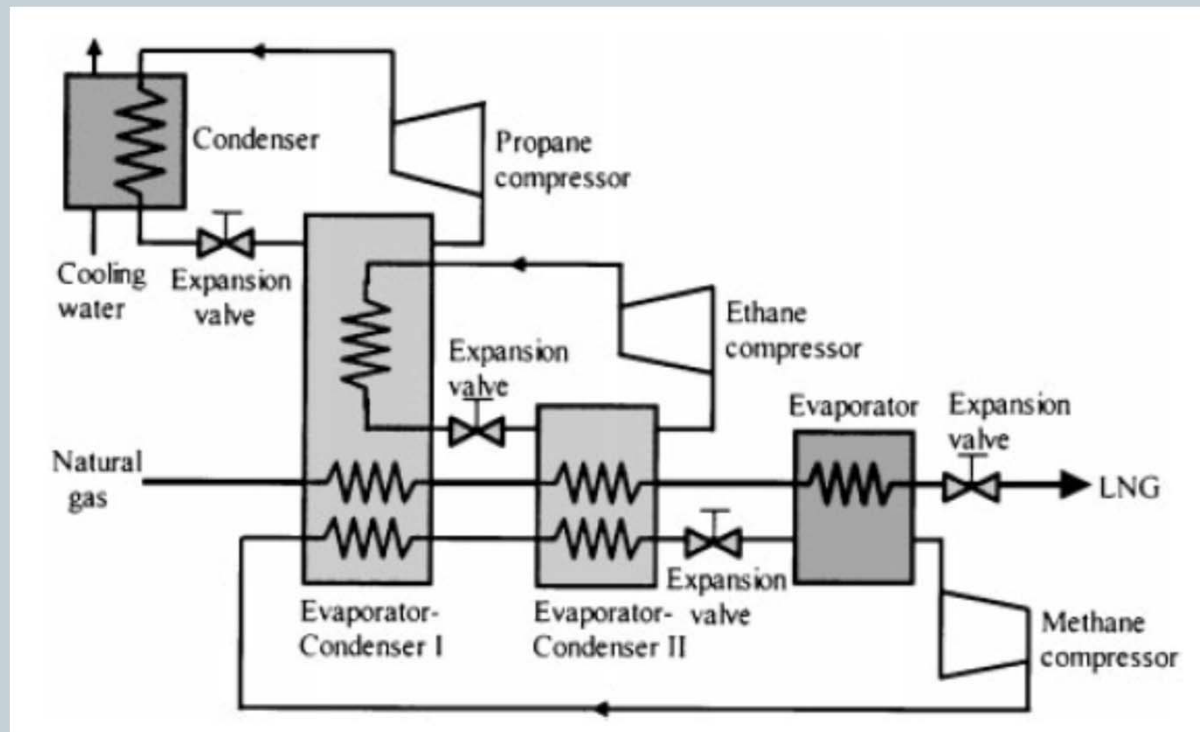
- Proprietary equipment (APCI & LINDE)
- LNG stream sourced only from one shell side



Example

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- Exercise #10



Selection of liquefaction technology

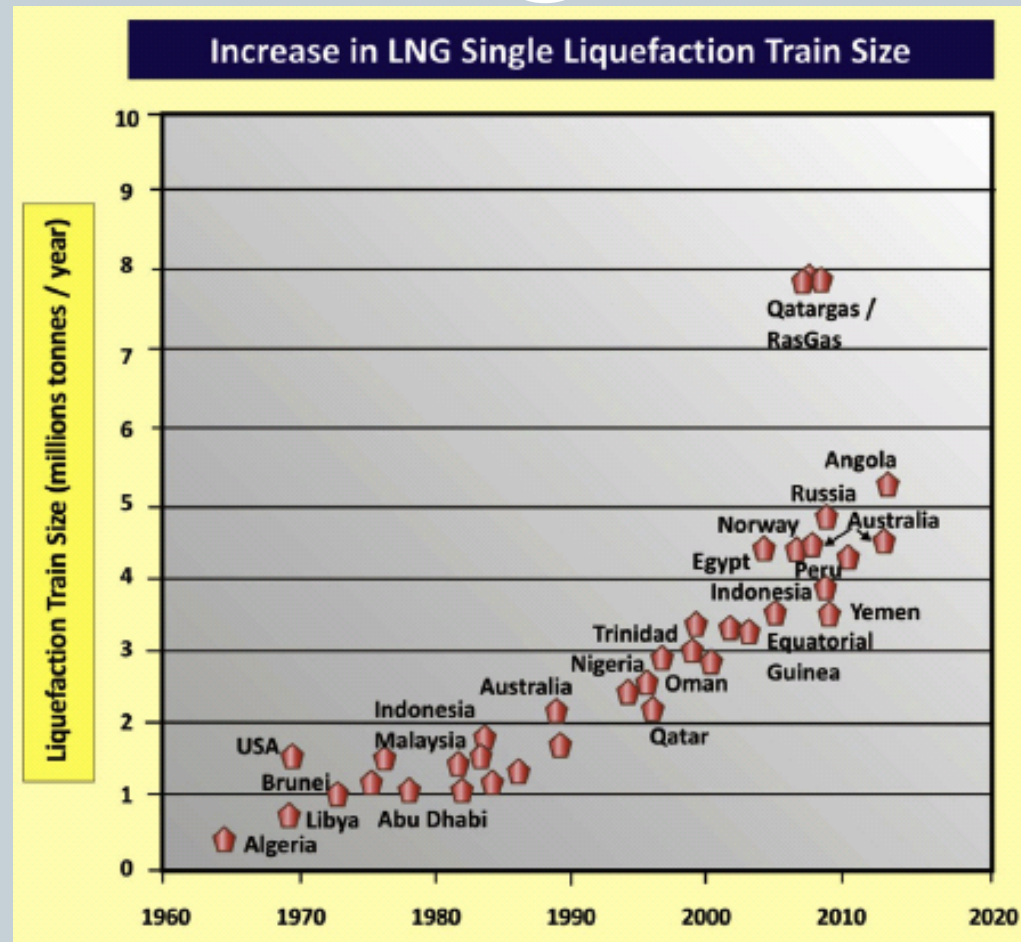
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- Capital cost (\$/t)
- Equipment selection
- Capacity
- Thermal efficiency
- Proven operability and reliability
- Operating flexibility
- Process simplicity
- Available area (plot)
- Efficiency
- Refrigerant make-up
- Cooling medium
- Project schedule
- Type of heat exchanger(s)
- Compressor & driver type and size



LNG train sizes

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LPG & NGL Storage

LPG & NGL storage

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- NGL: low-molecular weight H/Cs i.e., CH_4 , C_2H_6 , C_3H_8 , & C_4H_{10}



NGLs are also stored underground

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Why store compressed gas in spherical tanks?

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- **Robust design.** If shaped correctly a spherical structure is robust.
- **Even stress distribution.** Even stresses on sphere's internal & external surfaces externally eliminate weak points (or uneven stress variations)
- **Spherical shape of water droplet.** A droplet when under free fall assumes a spherical shape. Reason: it does so because all the resultant stresses neutralize in the absence of any external force (i.e., gravity)
- **Smaller surface area.** A sphere has a smaller SA per unit volume than any other vessel shape (rectangular, cube, cylindrical).
- **Large volume for least surface area.** Therefore, efficient shape.
- **Less wall thickness.** Less pressure implies less structural rigidity.
- **Smaller weight.** Compared to cylindrical vessels, for example.
- **Less heat flux.** Smaller SA means less heat influx into the pressure vessel when fluid is at lower temp. than surroundings compared to cylindrical or rectangular storage vessels. Hence, less pressurization.

Why store compressed gas in spherical tanks?

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- **Costs.** Spheres are more expensive to fabricate.
- **Diameter.** Their size (volume) is limited by fabrication costs.
- **Use.** Spheres are use mostly for storage rather than processing because their floor plan exceeds vertical cylindrical vessels & connecting nozzles are more expensive.
- **Double wall design.** Usually, spherical tanks are double walled with intermediate insulation.
- **Sizes.** Typical, sizes could store 35,000 m³.



LNG Storage

LNG storage

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- LNG storage facilities need for:
 - Meeting baseload export needs
 - Winter peak loads
- LNG storage facilities are divided into:
 - Aboveground
 - Inground
- Main types of LNG storage facilities:
 - 1. Aboveground double skinned metal tanks
 - 2. Above or belowground prestressed concrete tanks
 - 3. Inground frozen earth storage
 - 4. Mined caverns
- What is a **membrane**? It is a sheet of impervious material, typically metal, that prevents the LNG & gas vapors from contacting the tank walls. Thickness: ~1.2-2 mm

LNG storage facilities

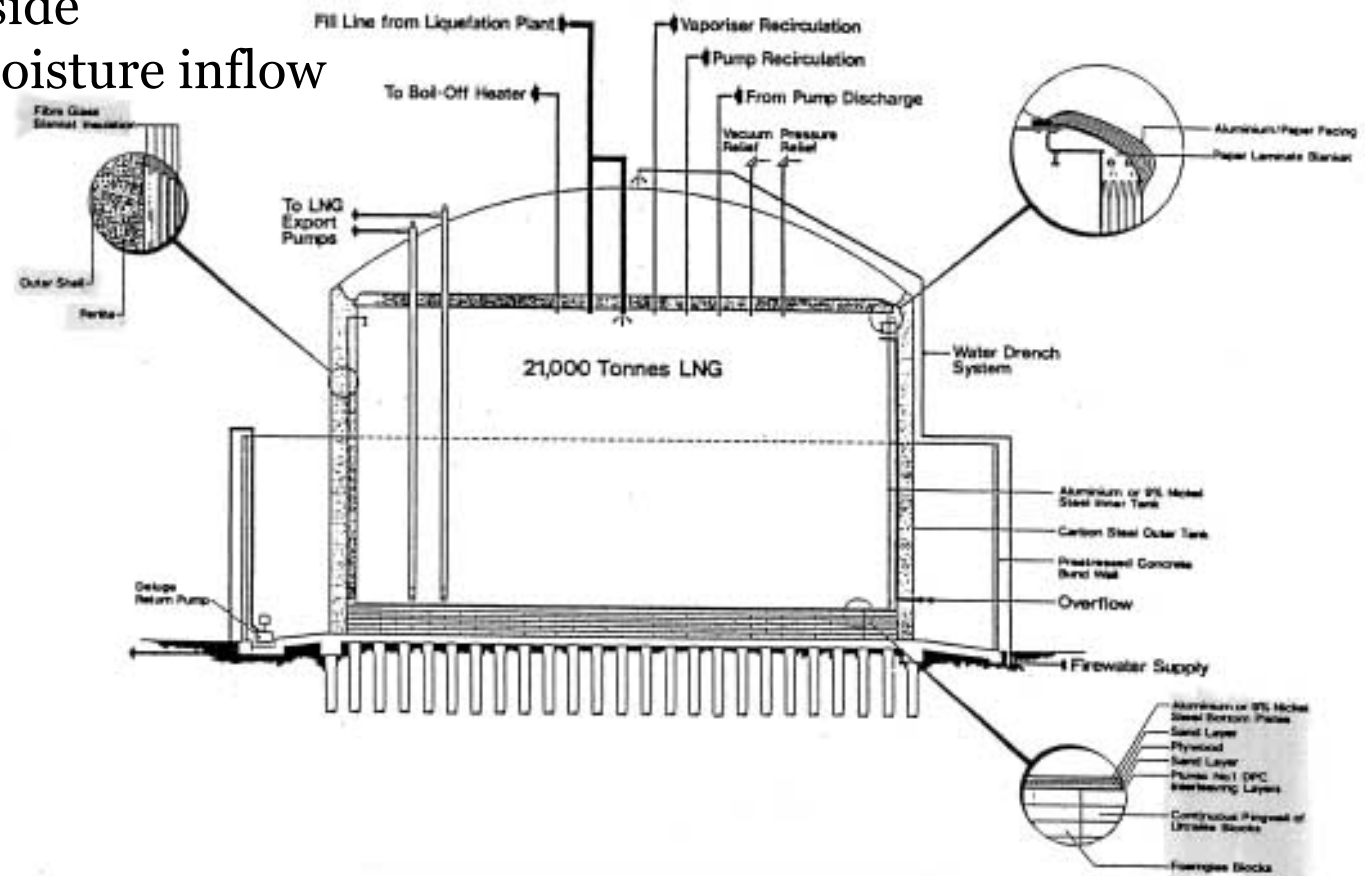
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- Defining factors: cost, safety, reliability, efficiency, duty, aesthetics
- Insulation (& ambient conds) dictate heat influx & boil-off rate
- **1.** Aboveground double skinned metal tanks
 - ✧ Most reliable & predictable for heat influx
 - ✧ Fire and explosion resistant, no geological constraints
 - ✧ Materials: Al, s. steel, 9% nickel steel
- **2.** Above/below ground pre-stressed concrete tanks
 - ✧ Reinforced pre- or post-stressed rods prevent cracks
- **3.** Inground frozen earth storage
 - ✧ **A:** Bigger tanks;
 - ✧ **D:** Costly excavation, structural stability, heat loss
- **4.** Mined caverns
 - ✧ Rarely located close to demand

1. Aboveground double skinned metal tanks

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- Originally used for liquid O₂ storage.
- Wealth of experience exists on these tanks
- Vapor tight outside skin prevents moisture inflow



1. Aboveground double skinned metal tanks

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- To date they remains the most predictable & reliable storage tanks
- Tanks are fire resistant (due to tank insulation)
- Tanks not subject to geological constraints for siting
- Most predictable system in terms of heat influx

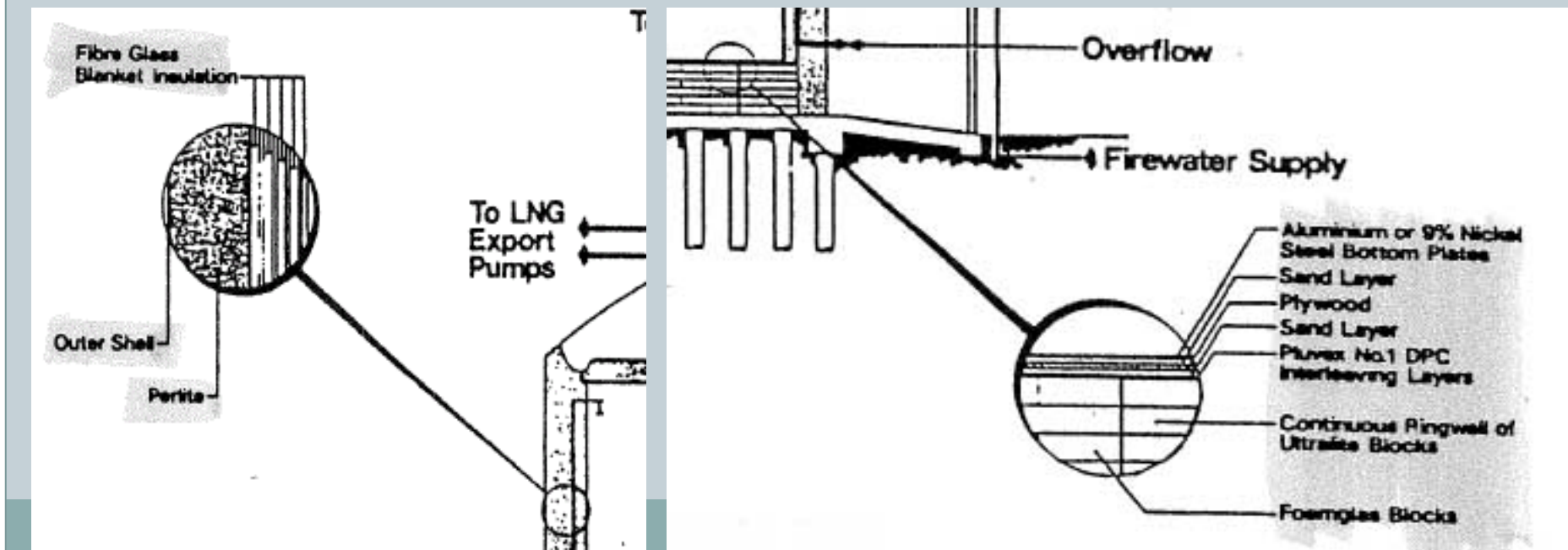


- Since 1950s size of tanks increased from 5,000 to 50,000 tonnes
- Typical size: 50,000 m³

1. Aboveground double skinned metal tanks

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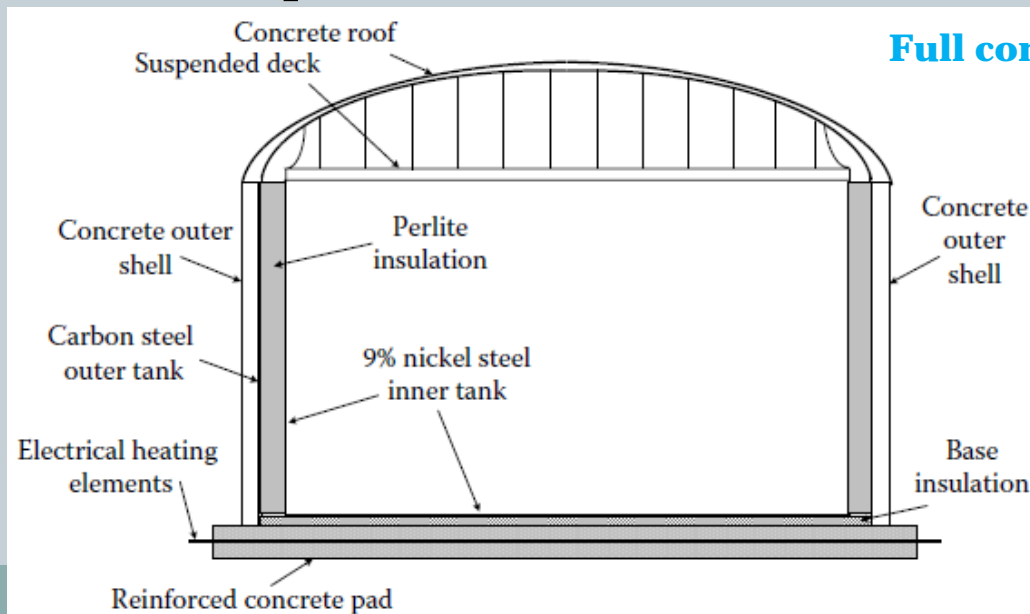
- Material required to maintain their ductility & strength at -168°C
- Materials: 9% nickel steel (popular), Al, austenitic stainl. steel (small)
- Material availability, weldability workability, economics, workshop quality dictate material selection
- Electrical base tank heating prevents ground freezing



1. Aboveground double skinned metal tanks

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- LNG stored at 140mbar
- Acceptable boiloff rate: 0.03-0.06% (peak shaving), 0.08-0.2% (base load)
- Extraction of LNG from tank done via deep well pumps
- Connections enter from tank top to ensure integrity of the side walls
- Tanks fitted with process, emergency & vacuum relief valves
- Sensors (pressure, temp.) ensure continuous monitoring of tank & LNG

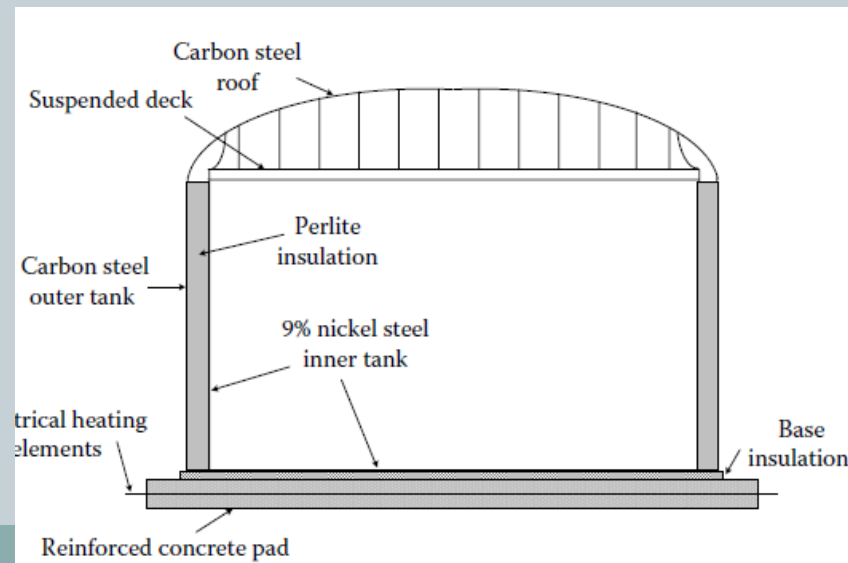


Full containment LNG system

Why heat the ground?

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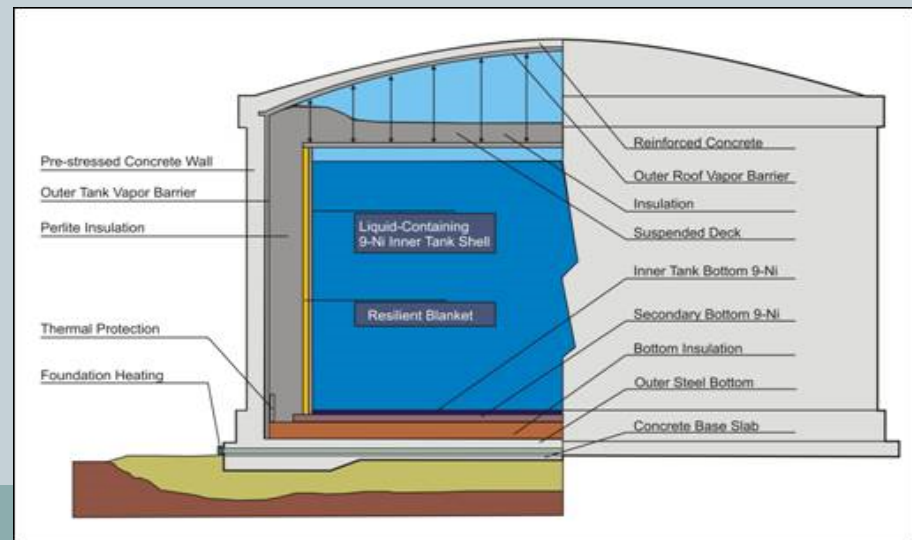
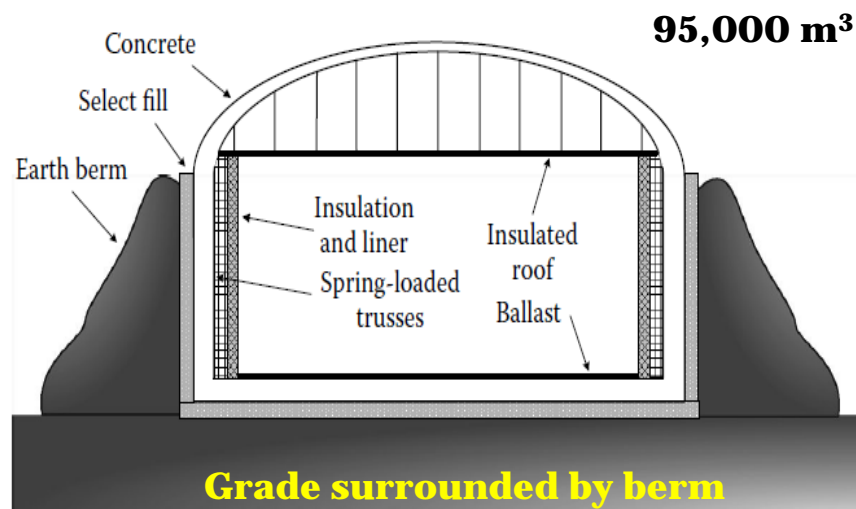
- An electrical ground heater maintains soil $T > 0^{\circ}\text{C}$
- Prevents ground freezing & freeze-heave
- Ice forms in direction of heat flux (vertically upwards; **capillary action**)
- Ice crystals (lenses) require water content to develop
- Force of crystals is sometimes powerful that it lift soil layers by 30cm
- Frost-heave can cause damage tank foundations, crack pavement, etc.



2. Pre-stressed concrete tanks

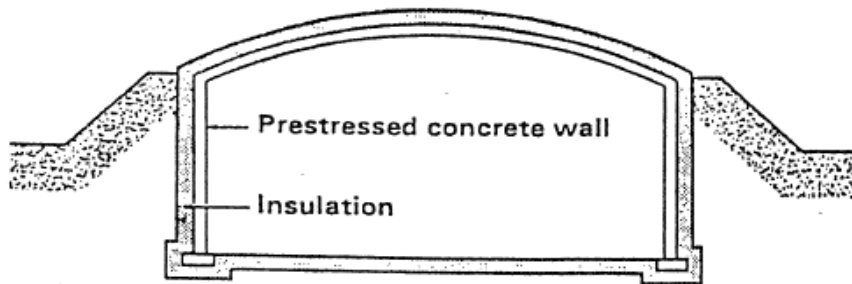
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- Above or below ground tank designs
- Pre-stressed concrete overcomes the concrete's weakness in tension
- Compressive stress (tendons) counterbalances tensile stress
- Possible to create bridges, beams, floors, tanks with longer span
- Capabilities realized using steel tendons (bars or cables)
- Rods or wire prevent formation of cracks from thermal stresses
- Pre-stressed concrete tanks devised in US

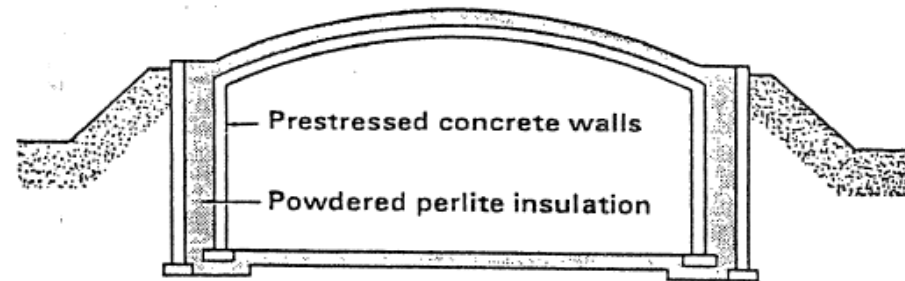


2. Pre-stressed concrete tanks

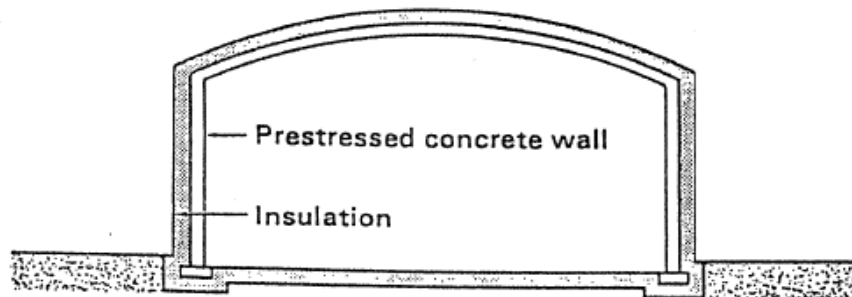
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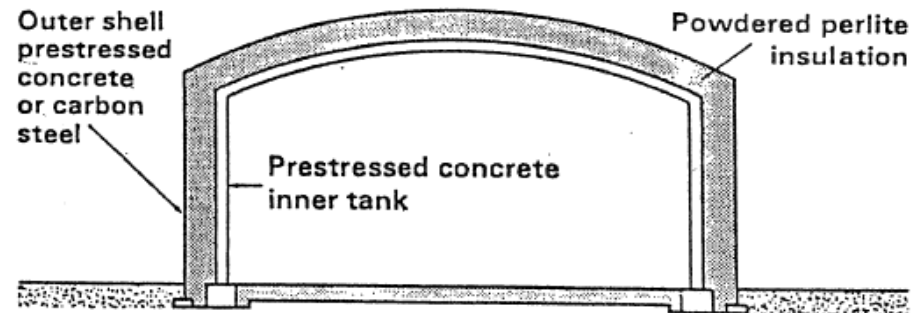
a Belowground, bermed, externally insulated single-shell tank



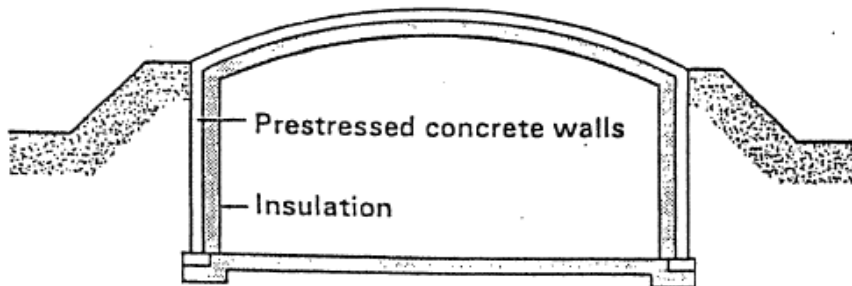
b Belowground, bermed, double-shell tank



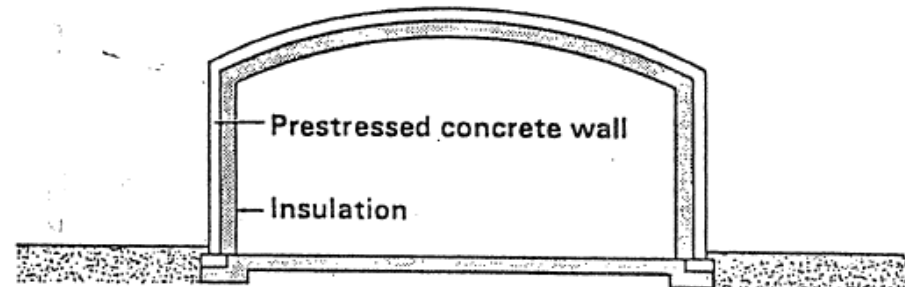
c Aboveground, externally insulated, single-shell tank



d Aboveground, double-shell tank



e Belowground, bermed, internally insulated single-shell tank



f Aboveground, internally insulated, single-shell tank

2. Pre-stressed concrete tanks

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- Insulation depends whether tank is above/underground
- Soil heaters used to minimize soil heave
- Aboveground LNG tanks:
 - Erect vertical pre-stressed concrete panels & form side walls
 - Walls wound circumferentially with high tensile steel
 - Pour concrete
 - Inner plastic membranes are also used & GRP on roof



Flat Roof Tank

3. Inground frozen earth storage

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- Good safety characteristics. Non obstructive view.
- Good security features
- Achilles' heel: roof
- Can be built in large sizes with reduced heat losses
- Drawbacks:
 - Complex excavation procedure:
 - ✦ Freeze ground by circulating brine thru freeze tubes
 - ✦ Bottom of pit refrozen after excavation
 - Lack of detailed info about physical & thermal props of ground make it hard to predict
 - ✦ Heat loss difficult
 - ✦ Structural rigidity of the tank
 - Precision of heat transfer calcs complicated by phase change especially on coasts
 - Thermal expansion & phase change of ground fluids could lead to cracking of rock adjacent to tank
 - Extensive commissioning period: up to 70 days
 - Difficult inspection

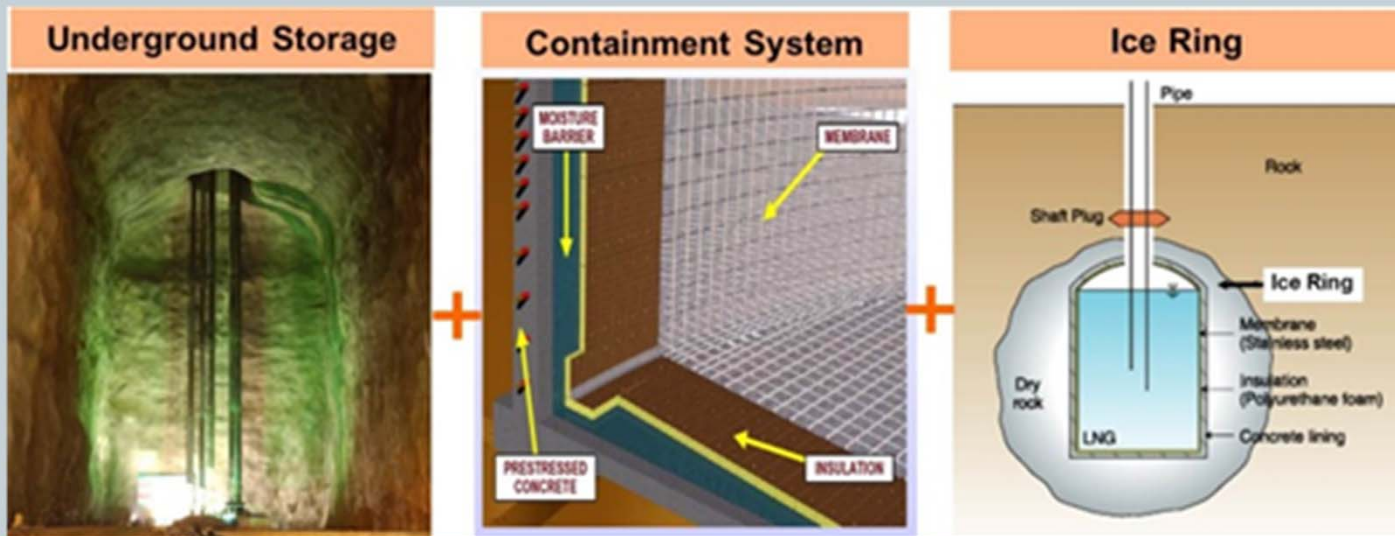
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4. Mined caverns

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- Naturally occurring LNG are rarely close to demand
- Lack of detailed geological data is an issue
- Separating the LNG from the cavity walls:
 - Use of concrete cast against the wall
 - Inner wall of Invar steel on insulating panels
- Currently, mined caverns are not used on a commercial basis



LNG storage tanks selection criteria

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- Safety
- Reliability
- Materials
- Costs: capital & running.
- Effect on amenity?
- Location
- Duty

- Large LNG tanks holds some 200,000 m³. Dimensions:
 - Sidewalls' thickness = 2.2m
 - Bottom slab = 9.8m
 - Diameter = 78m
 - Roof thickness = 1m @ center; 2.5m @ circumference

Heat transfer in LNG tanks

Mechanisms of heat transfer

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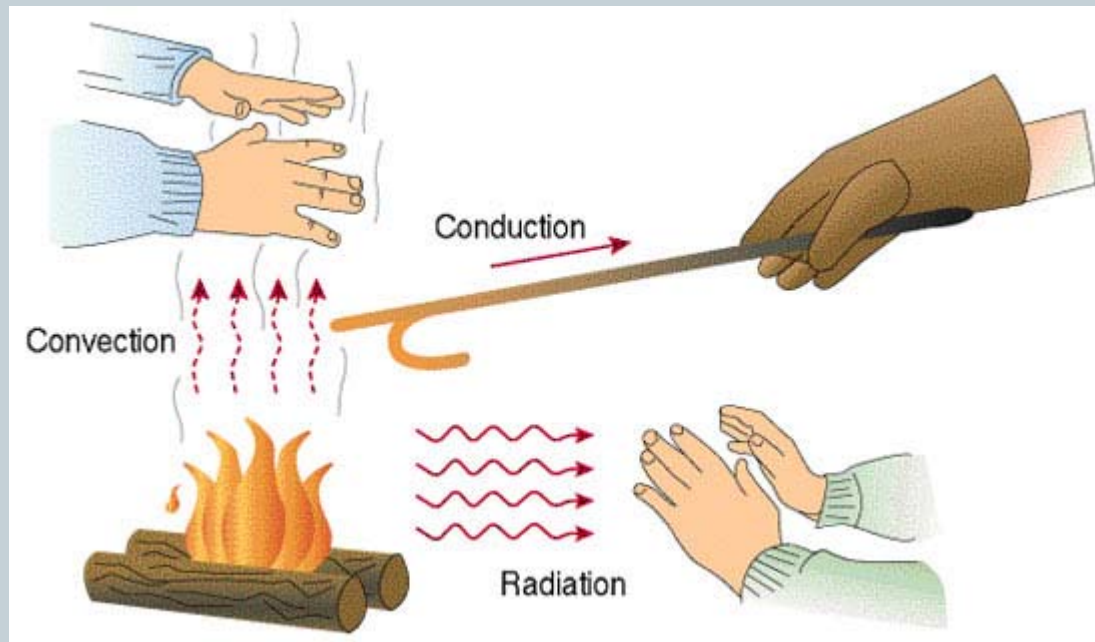
- Thermal science divided into: thermodynamics & heat transfer
- **Heat** can be defined as the degree of hotness of a body
- **Heat**: the transfer of energy btw a system and its environment due to a temp gradient btw them
- Three major mechanisms of heat transfer:
 - 1. **Conduction**
 - 2. **Convection**
 - 3. **Heat radiation**
- For certain applications (eg, heating/cooling a blg, human in water) it is important we know the **rate of heat transfer**



The 3 major heat transfer mechanisms

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- 1. Conduction
- 2. Convection
- 3. Heat radiation



1. Heat conduction

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- Process transfers thermal energy btw objects in physical contact
- Exchange of KE btw particles (atoms, electrons, molecules) @ atomic level
- Temperature difference in a homogeneous medium results in a heat transfer within the body
- Rate of heat transfer = $f(\text{material, geometry, } \Delta T, \text{thickness, ...})$
- Good conductors: Cu, Al, Ag
- Insulators: fiberglass, asbestos, paper



1. Heat conduction (2)

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- Rate of heat conduction thru a plane layer is:

$$\text{Rate of heat conduction} \propto \frac{(\text{Area})(\Delta T)}{\text{Thickness}}$$

or *Fourier's law*:

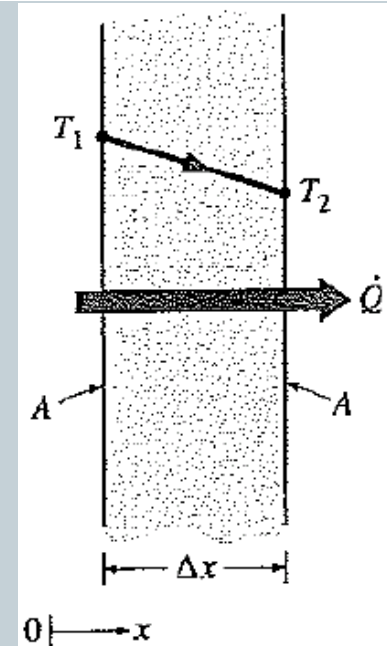
$$Q_c = -kA \frac{\Delta T}{\Delta x} = -kA \frac{T_2 - T_1}{x_2 - x_1}$$

where:

$\Delta T/\Delta x$ (K/m) is the temp. gradient in the dn normal to A
A is the surface area (m²).

k is the material's thermal conductivity

–ve sign indicates heat flows from high to low temp.



Theory

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- Heat flow through cylindrical geometries

Exercise

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- Exercise #11

Guarding against quakes

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The case of Revinthousa LNG regas terminal (Greece)

- Built in 1999; Capacity: 5.5 bcm/y; Tanks (total): 130,000 m³
- Tanks are freestanding in pit & function as aboveground tanks during a seismic event



LNG Marine Transportation

LNG seaborne transport

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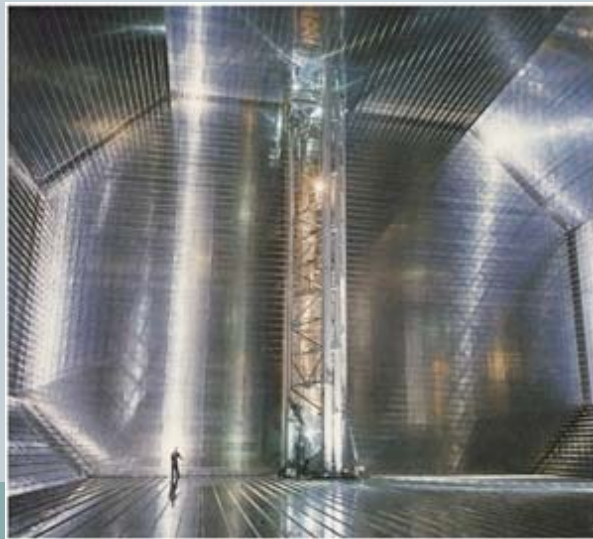
- Ships committed to 15-20 year contracts
- On-board liquefaction (boil off gas)
- LNG stored at atmospheric pressure at -161°C
- Need for regasification terminal
- Q-max: 266,000 m³ (Qatar)



LNG carriers

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- Three containment systems (self-supporting & integral):
 - Prismatic design
 - Spherical type
 - Membrane design
- Materials: aluminum, balsa wood, stain. steel, polyurethane
- Advanced leakage protection systems



Thanks for your attention!