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FLNG – The FPSO for Gas Operational Risks

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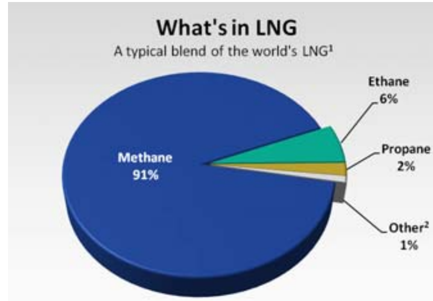
Floating Liquefied Natural Gas Vessels FLNG Activities

- **Marine Operations**
  - Control of vessel stability & safety etc – *akin to FPSO but extra slopping risk etc*
- **Subsea Operations**
  - Control of wells & receipt of gas – *akin to FPSO*
- **Gas Initial Processing**
  - Gas/liquid separation & gas treatment – *potentially akin to FPSO*
- **Gas Liquefaction**
  - Progressive cryogenic gas liquefaction & separation – *changes from onshore LNG*
- **LNG Storage**
  - Cryogenic storage of LNG at <25kPa (4psi) pressure – *akin to LNG carrier/tanker*
- **LNG Offloading**
  - Discharge into an LNG tanker – *potentially akin to LNG terminal or changes*
- ***Floating Storage & Re-gasification Units – FSRU***
  - *Proven technology & possibly 10% of global re-gasification by 2015*

Natural Gas Composition

- **As Extracted - Methane plus Other Species – *Location specific***
  - Some heavier alkanes, eg. Ethane: 0-20%
  - Carbon dioxide: 0-8%
  - Nitrogen: 0-5%
  - Hydrogen sulphide: 0-5%
  - Mercury: Significant traces



[1] Each country's mix is a little different. Methane content last year (2011) ranged from 83% in Libya to 99.7% in Nikiski, Alaska.
[2] Mostly butane

- **As Exported – Mainly Methane plus**
  - Some Ethane, to regulate combustion eg. Wobbe index
  - Odorant for leak detection

Natural Gas Properties - 1

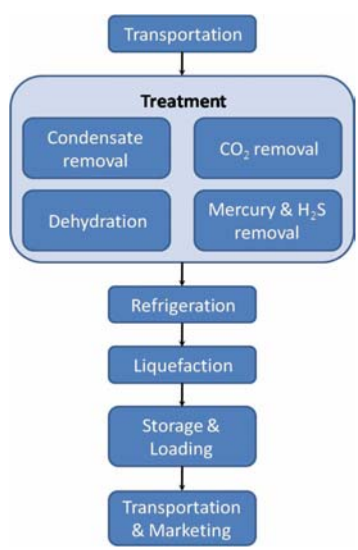
- **Liquid**
  - Colourless, odourless, non-toxic, non-corrosive, non-polluting
  - Non-explosive & non-flammable
  - Circa 600 times denser than natural gas & 60% of energy density of diesel
  - Causes cryogenic embrittlement of many materials
- **Vapour**
  - Flammable Limits: Lower (LFL): 5% NG to Upper (UFL): 15% in the air
  - Can be explosive within flammable range
  - Density relative to air: At ambient temp ~ 47%, but just above boiling point ~ 140%
  - Can cause asphyxia

Natural Gas Properties - 2

Species	Boil °C	Melt °C	Formula	Mol Wt
Nitrogen	*-196*	*- 210*	*N_2*	*28*
Oxygen	*- 183*	*- 219*	*O_2*	*32*
Methane	-162	- 182	CH_4	16
Ethane	- 89	- 183	C_2H_6	30
Propane	- 42	- 188	C_3H_8	44
n-Butane	0	-138	C_4H_{10}	58
n-Pentane	36	- 130	C_5H_{12}	72
Water	*100*	*0*	*H_2O*	*18*

Natural Gas Processing - Typical

- **Separation – removal of:**
  - Bulk of water, any oil/condensate, mud or sand
- **Scrubbing – removal of:**
  - Carbon dioxide & H_2S, via closed circuit amine wash
- **Dehydration – removal of:**
  - Water vapour via glycol scrubber & then via molecular sieve (regenerated beds)
  - Mercury via expendable active bed in mol. sieve *(to avoid amalgam damage to aluminium plant)*
- **Refrigeration, Liquefaction & Separation of:**
  - Heavier hydrocarbons - alkanes > LPG
  - Nitrogen to 4-5% for gas supply or <1% for LNG, via NRU at –140°C to –180°C
- **Treatment of LNG:**
  - Adjust ethane level to control combustion
  - Add oderant, eg. a mercaptan



Natural Gas Liquefaction

- **LNG History & Basis**
  - LNG patent filed in 1914 & first commercial production in 1917
  - Repeated NG compression, cooling with various refrigerants & adiabatic expansion
- **Liquefaction – Main Onshore Processes**
  - **C3MR (Mixed Refrigerant) or APCI – *by Air Products & Chemicals***
    - Most common with ~86 of ~100 process trains onstream or under construction
  - **Cascade – *by Conoco Phillips***
    - Second most common with ~10 of ~100 process trains
  - **Dual Mixed Refrigerant (DMR) – *by Shell***
    - Only ~3 onshore plants (inc. Sakhalin) – will be used for Shell 'Prelude'
  - **Linde/Statoil**
    - Only ~1 plant at Snohvit
- **Liquefaction for FLNG – new Nitrogen Based Tricycle – by Technip & Air Products**
  - Safer (limited or no C2-C5 refrigerants), small footprint & less motion sensitive

Onshore LNG & NG Accidents - 1

- **1944 – East Ohio Gas LNG Plant, Cleveland , Ohio**
  - Brittle fracture of low nickel tank (no bund wall)
  - ~ 1.2M gallons of LNG into sewers, exploded, burnt & killed 128 & 30 acres destroyed
- **1979 – Cove Point LNG Plant, Maryland**
  - Pump seal failed, NG into electrical conduit, exploded & killed worker & plant damage
- **2004 – Sonatrach NG Liquefaction Plant, Skikda, Algeria**
  - Steam boiler exploded, after ingesting refrigerant hydrocarbon leak
  - Boiler explosion damaged ethane & propane storage, causing major gas explosions
  - 27 killed, 56 injured, 3 LNG trains destroyed, marine berth damaged – cost USD900M
- **2012 Pemex NG Plant in Reynosa, Mexico**
  - 'Sabotage' initially suspected, then attributed to ruptured pipe/duct near pipeline metering point, but explosion severity not compatible with open nature of plant - TBC
  - 30 killed & 46 injured
- **Various Dates & Locations**
  - Brittle fracture of carbon steel plating via spills & 2,000t of vapour from rollover in tank

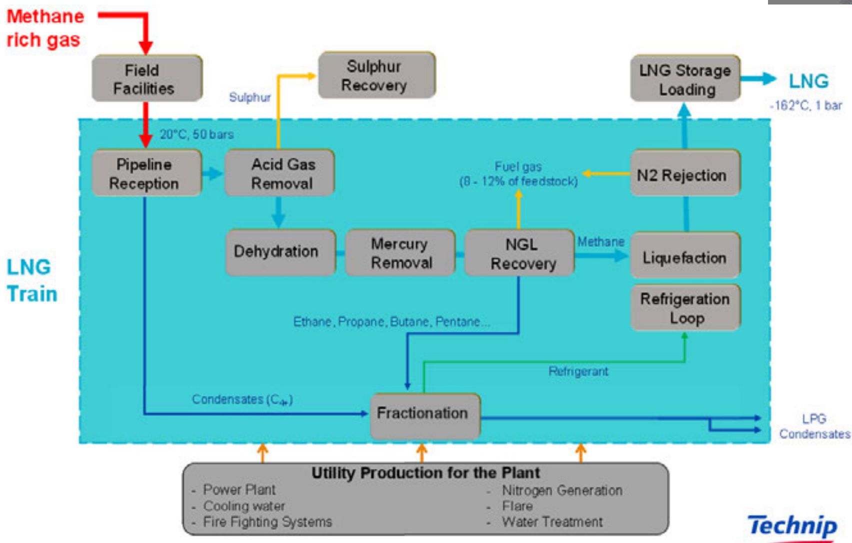
Onshore NG Accidents - 2

2012 Pemex NG Plant – *Alternative Views*

FLNG Marine Environment Challenges - Technip

- **Mechanical**
  - Offloading LNG between two vessels on the high seas
  - Importing large quantities of high pressure feed gas onto a floating facility
  - Equipment and piping loads generated by motion
  - LNG tank sloshing over 25 years without dry docking
  - Maintenance
  - Marine environment – salt & humidity – *replace aluminium by stainless & Ni steels*
- **Process**
  - Gas processing facilities to be adapted to marine environment
  - Compact design - weight and volume
  - Designing for motion compared to static onshore plan
- **Proposed Liquefaction Development**
  - Technip + Air Products: Nitrogen based Tricycle, using coil wound heat exchanger (CWHE) for strength, safety (any leak inside pressure vessel) & performance

FLNG
Process Schematic



Technip

LNG Carriers
Storage & Handling Options

- **Storage**
  - **Moss Spherical Tanks**
    - Initially 9% nickel-steel, but subsequently 29>57mm thick aluminium
    - Insulated by glass fibre, aluminium foil & expansion foams
    - Overtaken by Membrane, *but use for SBM double tanker FLNG with Linde train*
  - **Membrane Tanks**
    - No. 96: Dual layer 0.7mm Invar (36% Ni steel) in plywood boxes filled with perlite
    - Mark III: 1.2mm low temp. stainless + fibreglass reinforced polyurethane foam with Triplex plastic secondary barrier
- **Temperature Control**
  - Latent heat absorption from low boil-off rates (~0.15%>0.10%/day) maintains LNG temperature
  - Boil-off gas either burnt to generate power &/or steam or re-liquefied (newer vessels)

FLNG
Storage & Handling Options - 1

- **Storage Challenge – with part filled tanks**
  - Reducing sloshing & impact on stability & tank & insulation integrity for 20+ years
- **Storage Tank Options**
  - Self supporting prismatic, eg. Daewoo Aluminium Cargo Tank Independent Type B
  - Two-row membrane tanks, either side of central cofferdam, eg. by Höegh LNG
  - *'Prelude' will have 6 LNG & 2 LPG tanks – type TBA*
- **Temperature Control**
  - As per carriers/tankers
- **Offloading**
  - Mechanical arms (*'Prelude': 4*LNG & 3*LPG)*: parallel offloading (*'Prelude' conclude insignificant spill risk, due to double hulls, fenders, tugs, thrusters, weather limits etc*
  - Cryogenic hoses: tandem offloading – *increase vessel separation & weather window*

FLNG
Storage & Handling Options - 2

Concept: Dual floating cryogenic LNG offloading hoses & dual cryogenic boil-off return hoses

DNV has qualified Technip hose for Amplitude LNG Loading System (ALLS) at GdF site

Also Trelleborg-Saipem offshore development

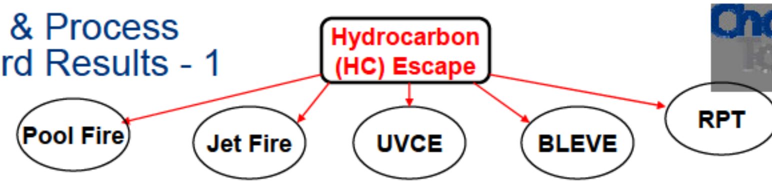
ALLS - Disconnection and storage after LNG transfer

16" ID cryogenic flexible pipe
Connection system covered in ice

Platforms, FPSO & FLNG
Hazard Factors - Plant, Process & People

- **Layout & Arrangements**
  - Failure to locate by risk & consequence
  - Inadequate protective barriers, evacuation & rescue systems
  - Congestion & lack of venting &/or pressure relief facilities
- **Mechanical**
  - Risk level of process selected
  - Inadequate component strength
  - Material degradation failures in service or brittle fracture during LNG spillage
  - Connection leaks – process plant or offloading
- **Control**
  - Electrical & electronic system failures – initial & response
  - Procedure & communication system deficiencies
  - Operator errors – initial & response
- **External**
  - Vessel impacts
  - Terrorist action
- ***Piper Alpha** – many above applied & 165 died > Safety Cases & integrated approach*

Plant & Process
Hazard Results - 1



- **UVCE: Uncontained Vapour Cloud Explosion**
  - In open spaces if obstructions/congestion create enough turbulence for flame front speed to generate sufficient pressure *(pressure increases with square of speed)*
  - Caused major damage at Flixborough & Buncefield etc with other HC – see later
  - DNV et al consider NG UVCE not feasible over open water, due to low flame front speed & condensed fog in the gas cloud
- **BLEVE: Boiling Liquid Expanding Vapour Explosion**
  - In confined spaces, eg. tanks & vessels, leading to rupture & container etc destruction
  - Need external heat to generate vapour & influenced by fluid level & relief valves etc
  - Can occur without combustion, eg. with water
- **RPT: Rapid Phase Transformation**
  - Cold explosion via rapid liquid to vapour phase change, eg. LNG into water or reverse
  - Potential local structural damage to hull & equipment

Plant & Process
Hazard Results - 2: GL-ND Spadeadam Tests

Pool Fire – Kerosene

NG Leak Fire – Valve spindle leak at 30barg

Pool Jet Fire – NG leak from 20mm hole at 70barg

NG Vapour Cloud Explosion - Deflagration

Venting of NG Explosion

Plant & Process
Combustion & Explosion Mechanisms

- **Deflagration – *feasible with NG***
    - Subsonic flame propagation (<100m/s vs ~300m/s) & low overpressure (eg. <0.5 bar)
    - Combustion propagates as flame front moves forward through the gas mixture
    - Requires some congestion to be sustained (eg. pipework or trees)
    - Partial confinement & many obstacles can cause turbulent flow & eddies, which may accelerate flame from subsonic to supersonic & change deflagration to detonation
- **Detonation – *requires containment or long flame path with NG***
    - Supersonic flame propagation (up to 2,000m/s) & high overpressure (up to 20 bar)
    - Pressure shock wave compresses unburnt gas ahead of wave to temperature above auto-ignition temperature & detonation occurs
    - Effects of a detonation are usually devastating
- **Deflagration to Detonation Transition (DDT) – *features in major losses inc:-***
    - 1974 cyclohexane VCE from pipe rupture in Flixborough chemical plant
    - 1989 propane rich VCE from leaking pipeline in Russia
    - 2005 oil spillage VCE at Buncefield Oil Storage Terminal

LNG Carriers & FLNG
Hazard Mechanism - RPT

Rapid Phase Transformation – *Modelling by ioMosaic*

- ***Large hole above water & tank 98% full***
  - LNG discharge onto water
  - RPT near outside of hull & pool forms
- ***Large hole below water & tank 98% full***
  - Initially LNG discharges into water
  - RPT near outside of hull & pool forms
  - Then some water into tank
- ***Large hole just below water but tank 25% full***
  - Water enters tank & mix with LNG
  - RPT inside tank & possibly severe tank damage
  - Water freezes in tank, after heating LNG
- ***The hazard potential of RPT is very localised, but might be severe***
- ***RPT more likely if LNG contains ethane & propane***

Plant & Process
Significant Hazard Investigations

- **Practical Tests**
  - Fire & explosion tests by BG/GL-Noble Denton at Spadeadam:-
    - Explosion severity increases from methane to propane, ethane & ethylene
    - LPG extraction & refrigeration may introduce up to ~ 70% of FLNG process risk
  - LNG onto water tests by GdF, Shell Maplin Sands & Lawrence Livermore in USA
- **Computational Fluid Dynamics**
  - GexCon 'FLACS' – Flame Acceleration Software used to model plant design & major incidents, inc. Piper Alpha & Petrobras 36 platforms & Buncefield
  - DNV 'PHAST' modelling of onshore & on water LNG leaks & fires, inc. flammable atmosphere distances (if no ignition) for different hole sizes above & below water line, eg. ~900m for 750mm hole above water line or up to ~3km for 1500mm terrorist hole

LNG Carriers & FLNG
Hazard Assessment – Chevron 2002

- **LNG carrier incidents:**
  - 8 spillage incidents – some brittle fracture hull damage
  - No cargo fires or explosions
  - 2 grounding incidents – no significant loss of cargo
  - LNG carriers more robust than tankers
- **LNG pools on water:**
  - No BLEVE – only occur with combustible mixtures in confined spaces
  - Can undergo RPT or form pool which burns or evaporates faster than on land
  - Cloud warms, rises &, if ignited, burns until all burnt or concentration below LFL - *can burn (subsonic) back to leak source, via residual spill pool*
  - <u>LFL modelled from 0.5 to 2.5 miles</u> & burn times from 64 to 37 minutes for 25km^3 spill via 1m & 5m holes - *multiple ignitions likely from larger terrorist holes*
- *NB: Addresses LNG Carriers & Spills on Water, but not FLNG Liquefaction train etc*

FLNG
Hazard Avoidance - Layout

SBM

'Prelude'

Concepts