6th Annual LNG TECH Global Summit 2011
De Doelen, Rotterdam 3rd-5th October

Liquefaction of Natural Gas – How can fundamental R&D help the industry? Case studies from GTS

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Trondheim, Norway

Content of the presentation

- The Gas Technology Centre at NTNU - SINTEF
  - What is GTS
  - Research areas and capabilities
- Case Studies:
  - LNG Heat Exchanger Studies
    - Multilevel experiments and modelling
  - Small scale LNG systems
    - From laboratory experiments to installation onboard a gas carrier
  - LNG and Low temperature Energy chain
  - Future research tasks within LNG at GTS

http://www.ntnu.no/gass/

Gas Technology Centre NTNU - SINTEF

Cooperation

- Virtual organisation
- Tight links to industry
- International network

Strategic partners

- Statoil

Researchers

NTNU

- 75 professors
- 135 Ph.D. researchers
- 30 post.doc. researchers

SINTEF

- 200 research scientists

Mission:

- To act as a common interface in gas technology R&D between NTNU-SINTEF and the marked:

Students

- Award 75% of all M.Sc. in Norway’s gas-related industry

The Norwegian University of Science & Technology (NTNU) - and The SINTEF Group

Number of employees (2010):

NTNU	4.700
(Scientific	60%)
SINTEF	2.145
(Scientific	73%)
Students:	18.500

10.000 in Engineering & Science

A technological cluster with education, basic & applied research, innovations and business developments
- of large importance for Norway

SINTEF is a multidisciplinary research organisation with international top level expertise in specific fields

SINTEF Building and Infrastructure

SINTEF ICT

SINTEF Materials and Chemistry

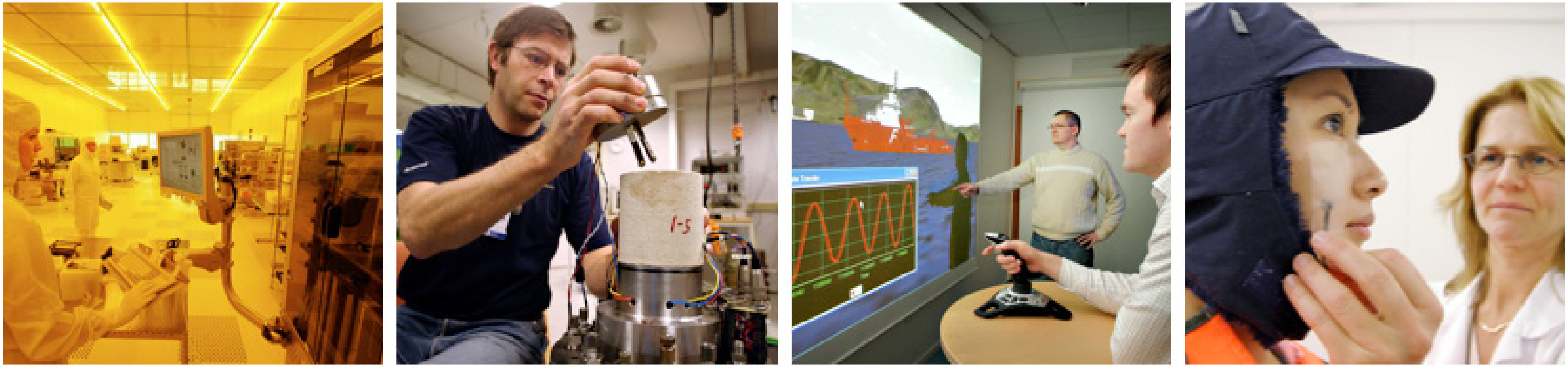
SINTEF Technology and Society

SINTEF Energy Research

SINTEF Fisheries and Aquaculture

SINTEF Petroleum Research

MARINTEK



Disciplines around Gas Technology Centre

SINTEF NTNU

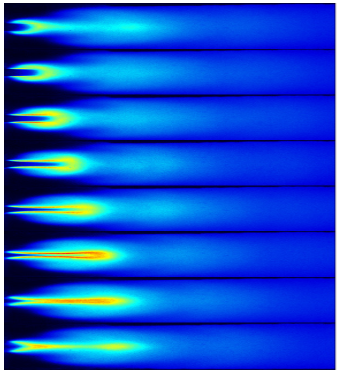
Gas Technology Centre

- Environmental Impact
- Society and Ecology
- Chemical conversion
- Combustion
- Carbon Capture Storage
- Energy Economics
- System Analysis
- Thermodynamics
- Liquified Natural Gas
- Hydrogen

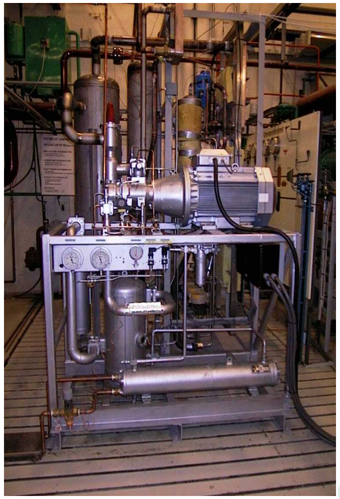
R&D along the Natural Gas value chain

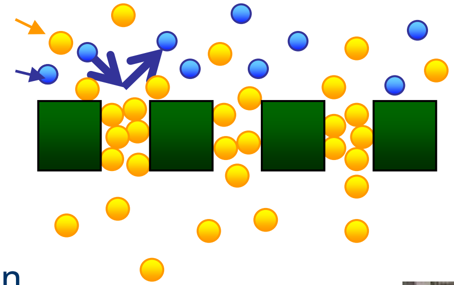
- Reservoir technology (including CO_2-injection)
- Gas transport (multiphase pipelines, LNG, LPG, energy markets)
- Chemical conversion
- Gas processing
- Gas transport infrastructure and techno-economic optimisation
- Fossil fuel hydrogen production, storage and usage

Laboratory facilities

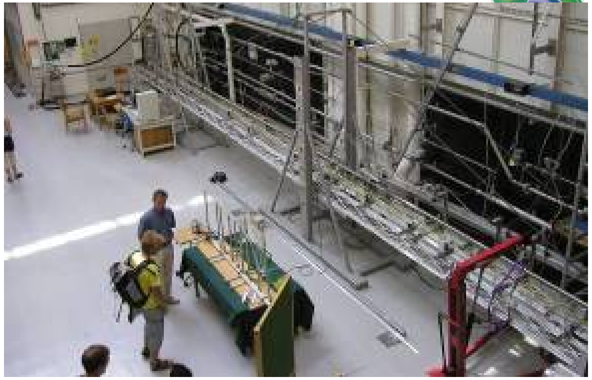


- Refrigeration and Combustion Technology LAB
  - Multiphase flow of oil and gas
  - Heat transfer and pressure drop for gas mixtures in compact geometries
  - Small scale laboratory prototype for liquefaction of Natural gas
  - Oxy-fuel Combustion for Gas Turbines





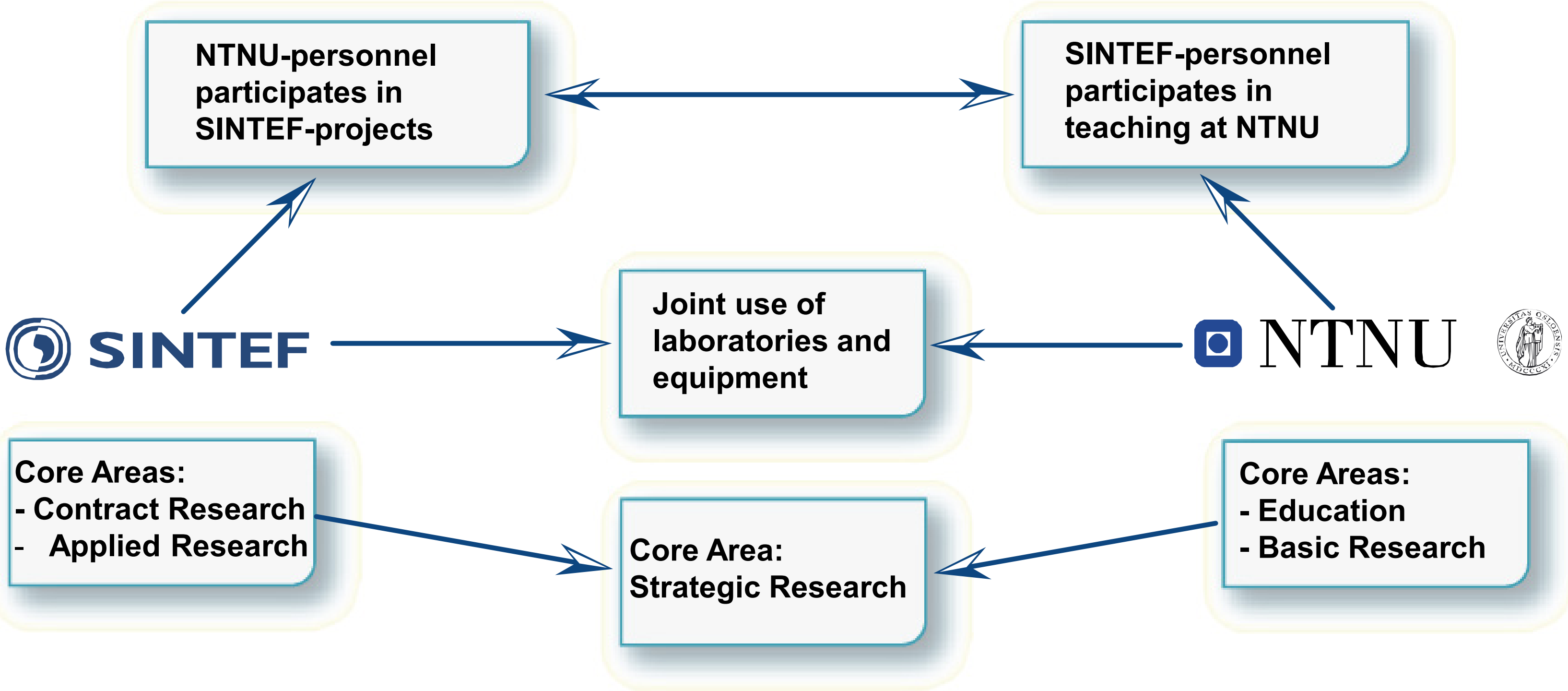
- Absorption LAB
  - Absorption of CO_2, H_2S and NO_x
  - Catalysts and absorbents
- Membrane technology LAB
  - Membranes for hydrogen and CO_2 separation
- Hydrogen production, liquefaction and storage
- Fuel cell technology



NTNU & SINTEF

A Strategic Model of Cooperation:

1. Common strategies
2. Industrial relevance and involvement
3. Basic scientific methodology



NTNU-personnel participates in SINTEF-projects

SINTEF-personnel participates in teaching at NTNU

Joint use of laboratories and equipment

Core Areas:
- Contract Research
- Applied Research

Core Area:
Strategic Research

Core Areas:
- Education
- Basic Research

Strategic Research - Competence Building Projects for the Industry

Some key characteristics:

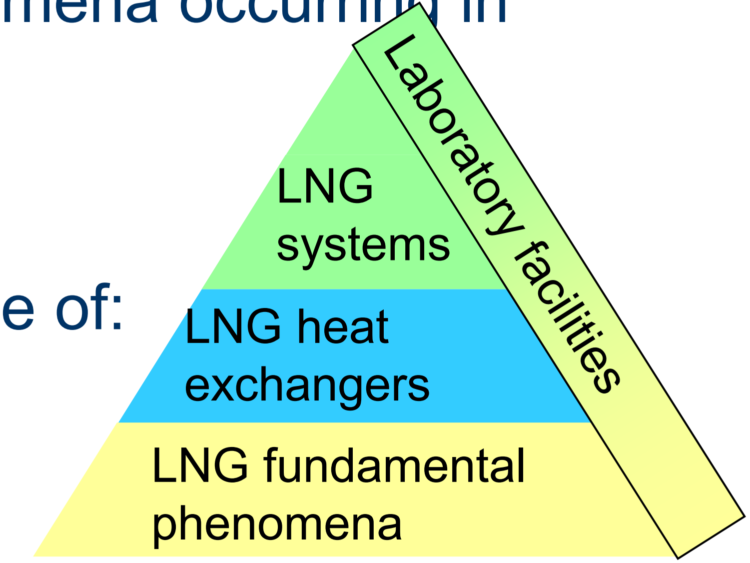
- Long term projects 3-5 years
- Cooperation with leading international research partners and includes PhD education
- Results are to be published in open scientific journals
- Minimum industry funding of 20% of total budget
- The industry is represented in the steering committee of the project

"Enabling Low Emission LNG-systems"

- Project figures:
  - Duration 2009-2014
  - Total budget: 44 million NOK (With 61% from the research council)
- 2 industry partners and support from the Gas Technology Centre
- Educate 3 PhD candidates and 1 postdoc candidates within the field

Enabling low-emission LNG systems
Fundamentals for multilevel modelling

- Focus towards fundamental phenomena occurring in LNG equipment
  - Experimentally
  - By modeling
- Unit design/operation in perspective of:
  - Fundamental phenomena
  - Robust modeling approach
  - Integration with the process
- Process design and system analysis including:
  - LNG process optimizing taking into account detailed unit models
  - LNG process dynamics
  - Process evaluation methodology


LNG systems

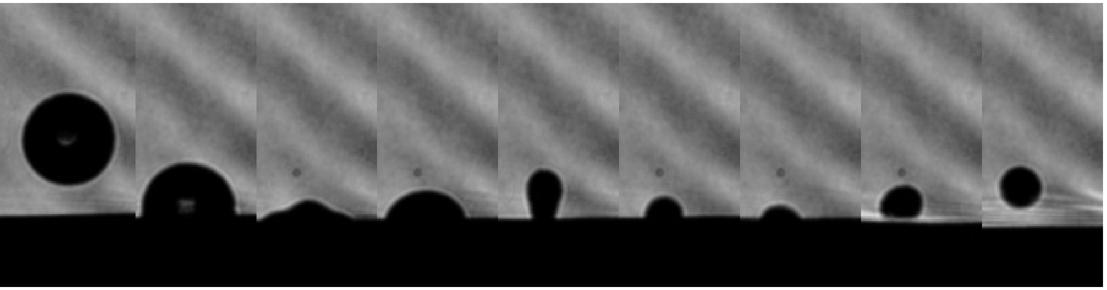
LNG heat exchangers

LNG fundamental phenomena

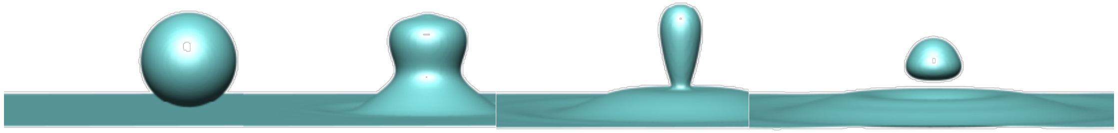
Laboratory facilities

Droplet and film phenomena (PhD and PostDoc)

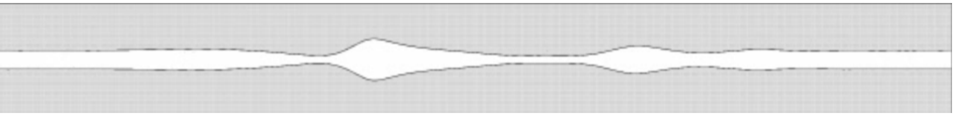
- To be able to model and predict heat exchanger shell-side flow, droplet and bubble and film interaction needs to be better understood, hence both experiments and numerical analysis is required.



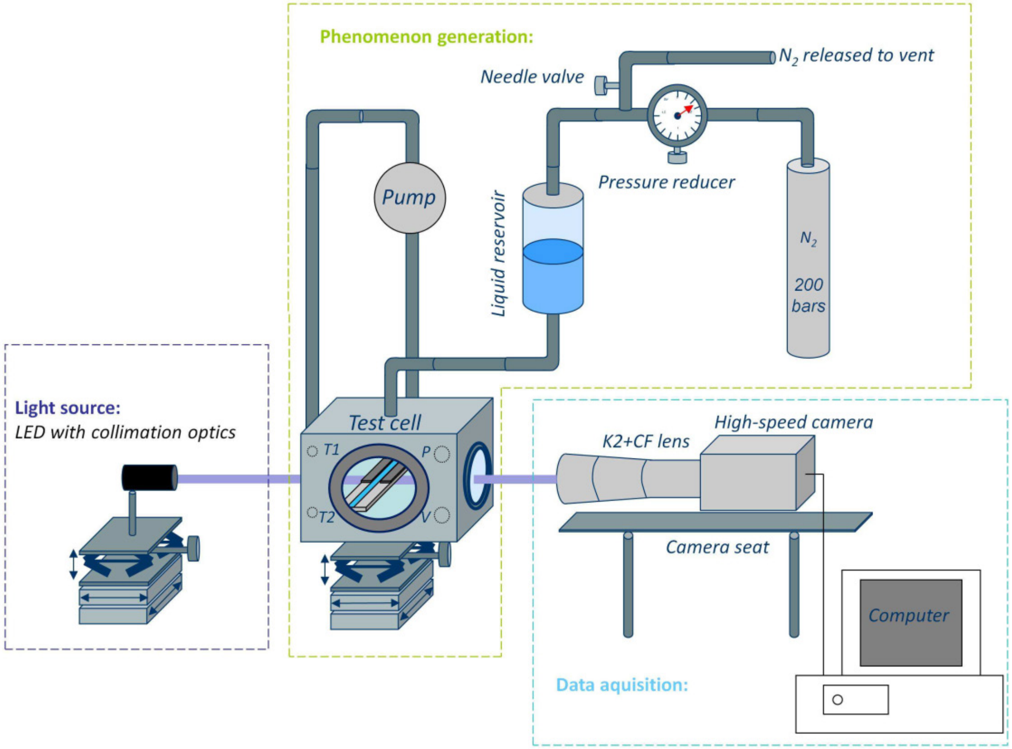
- Fundamental knowledge can be applied to build more accurate engineering models.



- instabilities and heat transfer for two-phase flow in confined geometries representing heat exchanger tube side phenomena.



Droplet and film phenomena – experimental setup



Splashing.

Jetting.

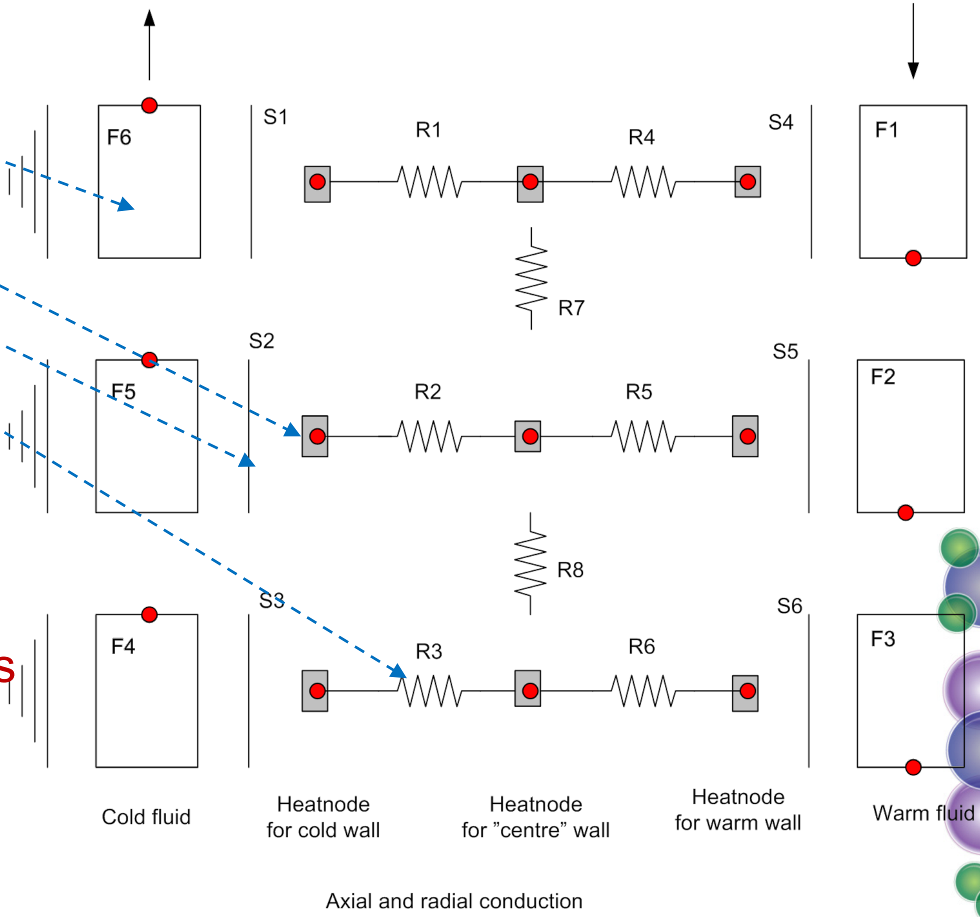
Coalescence.

Bouncing.

Partial coalescence.

Experiments conducted with water and with n-Pentane on a horizontal or a tilted flowing film

General and modular heat exchanger modeling framework



Generic tool with building blocks of:

- fluid nodes
- heat nodes
- surfaces
- thermal resistors

- splitters
- mixers
- flash units
- flow restrictions

Surfaces:

- geometry models
- heat transfer/pressure drop models

Fluid nodes:

- thermodynamic model
- numerical and physical flow model

Example:
Counter-flow HX with wall heat conduction

Use of detailed heat exchanger simulation models in an engineering flow-sheeting environment for static instability analysis

Process optimisation

- Heat exchanger representation in process simulation and optimisation are most often:
  - Black or grey boxes that provide the process input/output states
  - Some degree of ”zone-analysis” in a simplified manner
  - Using lump, composite warm and cold streams

- Using a detailed heat exchanger model, a chosen design can be validated and the process operability can be investigated in a more complete way

- The focus of this presentation is to investigate heat exchanger design in terms of steady state instability, also referred to in literature as: Ledinegg type instability.

Industrial relevance

- Increased focus on compact and energy efficient solutions
- Compact, optimized LNG processes using are proposed and presented in literature are often based on using brazed aluminum heat exchangers (BAHX) only
- A recent example:
  - The ExxonMobil EMR process.
  - About 30 parallel cores
    (Denton 2010)
- The issues of potential instability need to be addressed

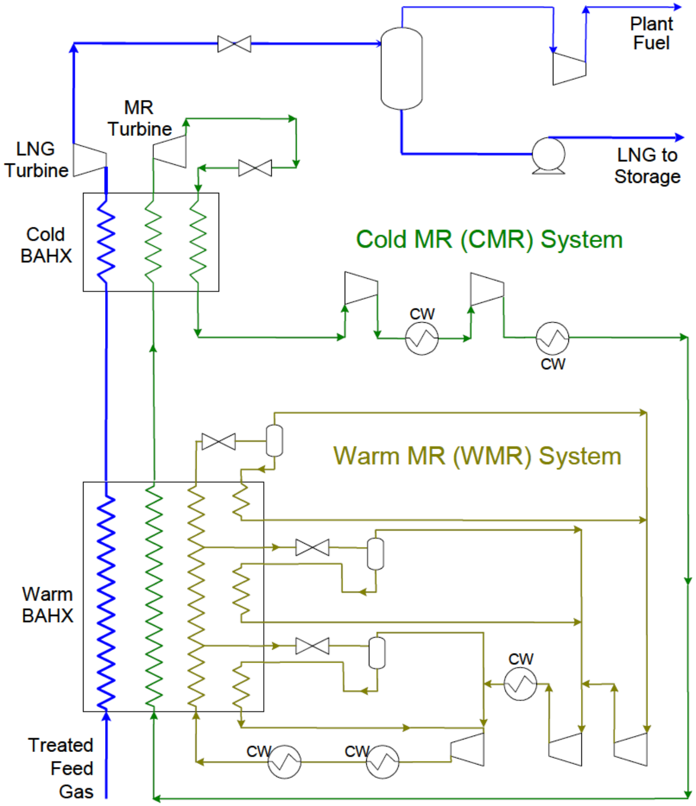


Figure 2 - ExxonMobil EMR Process Schematic

Presented at: 89th Annual GPA Convention, 21-24 March 2010, Austin , TX (Denton et.al)

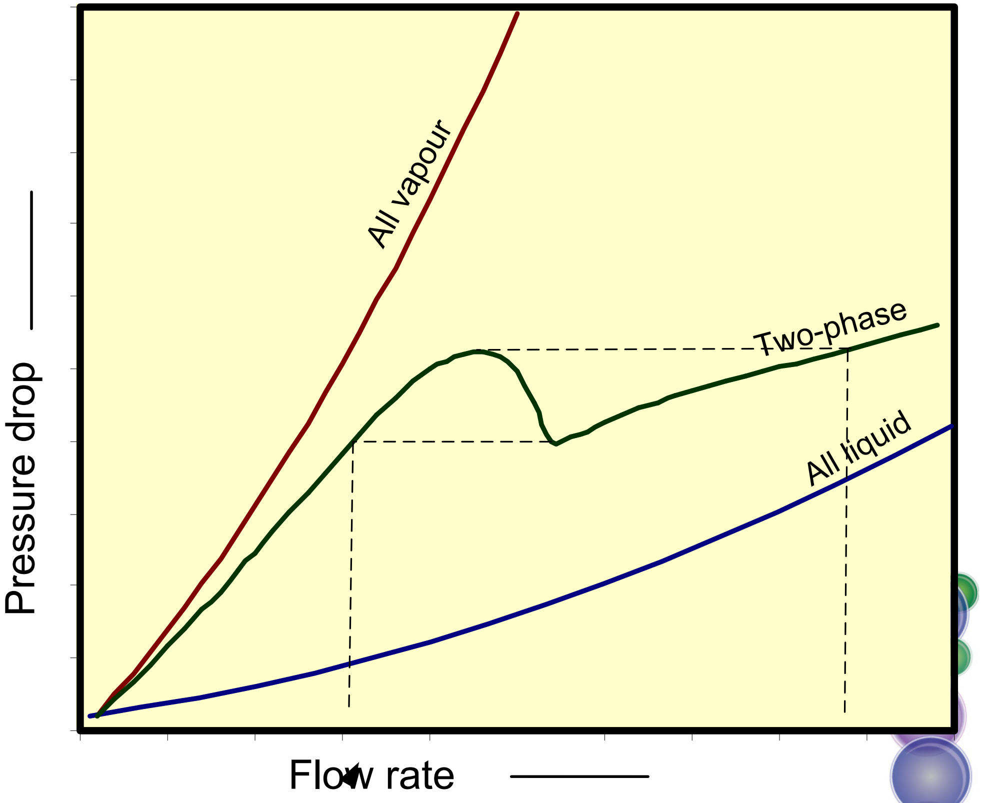
Ledinegg instability in boiling services

- An *N*-shape may occur in boiling services if an increase in flow rate results in a decrease in pressure-drop

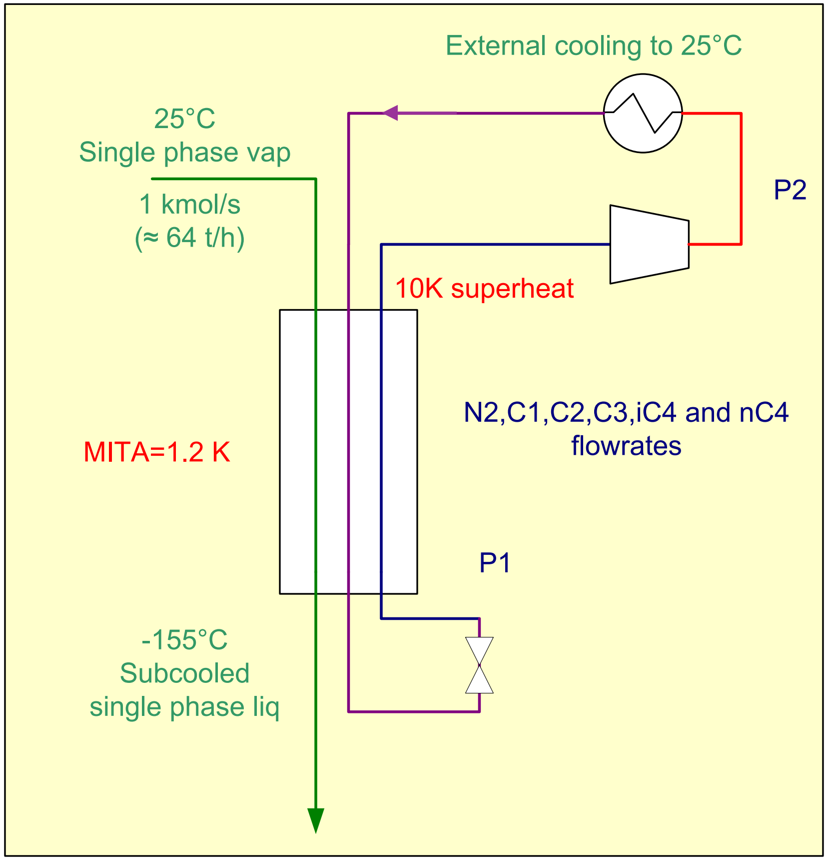
- Counteracting effects:
  - Increase in flow -> higher pressure drop
  - Decrease in average void fraction -> lower pressure drop

- Combination: increased flow -> decrease in average void fraction may give an *N*-shape

N-shape for upward boiling in a heat exchanger



Case: Optimised SMR process for liquefaction of natural gas

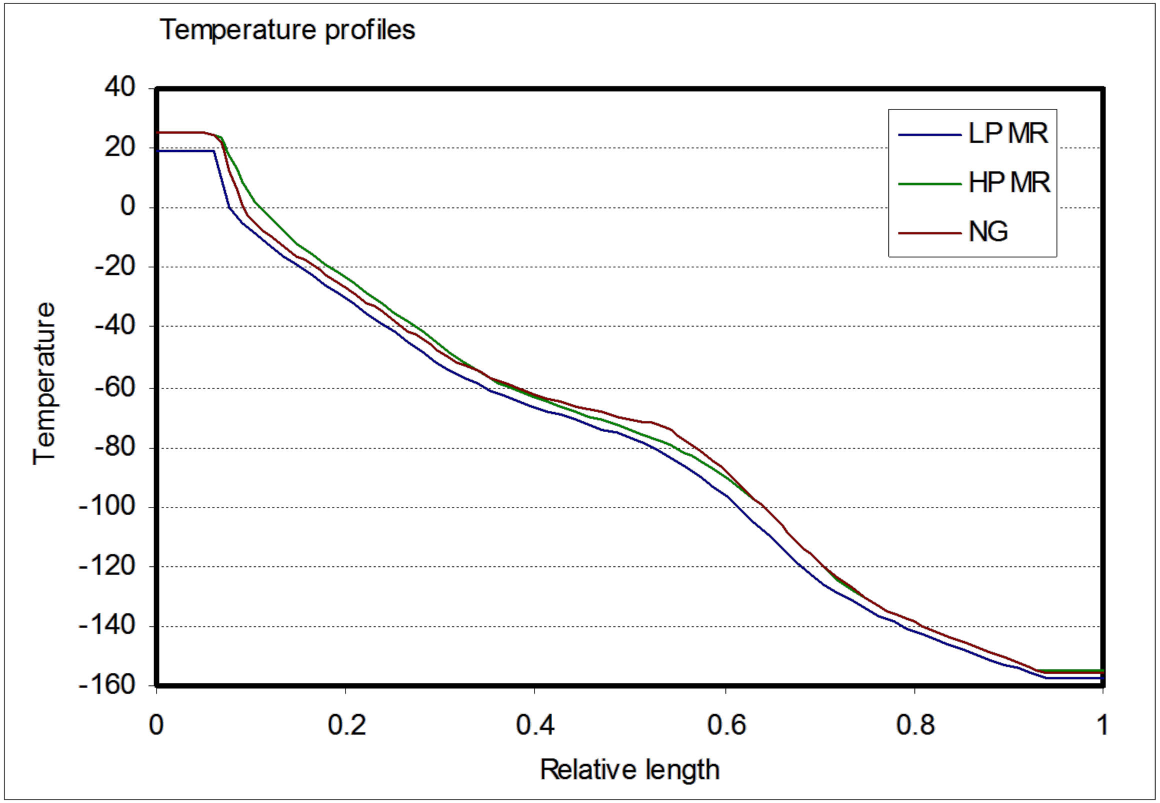


- Cooling and liquefaction of 1 kmole/s NG from 25 to -155 °C
- Optimisation of flow-rate, composition, and pressure levels to obtain minimum energy consumption with restrictions:
  - 10 K superheat
  - 1.2 K minimum temperature approach (MITA)

With specifications:

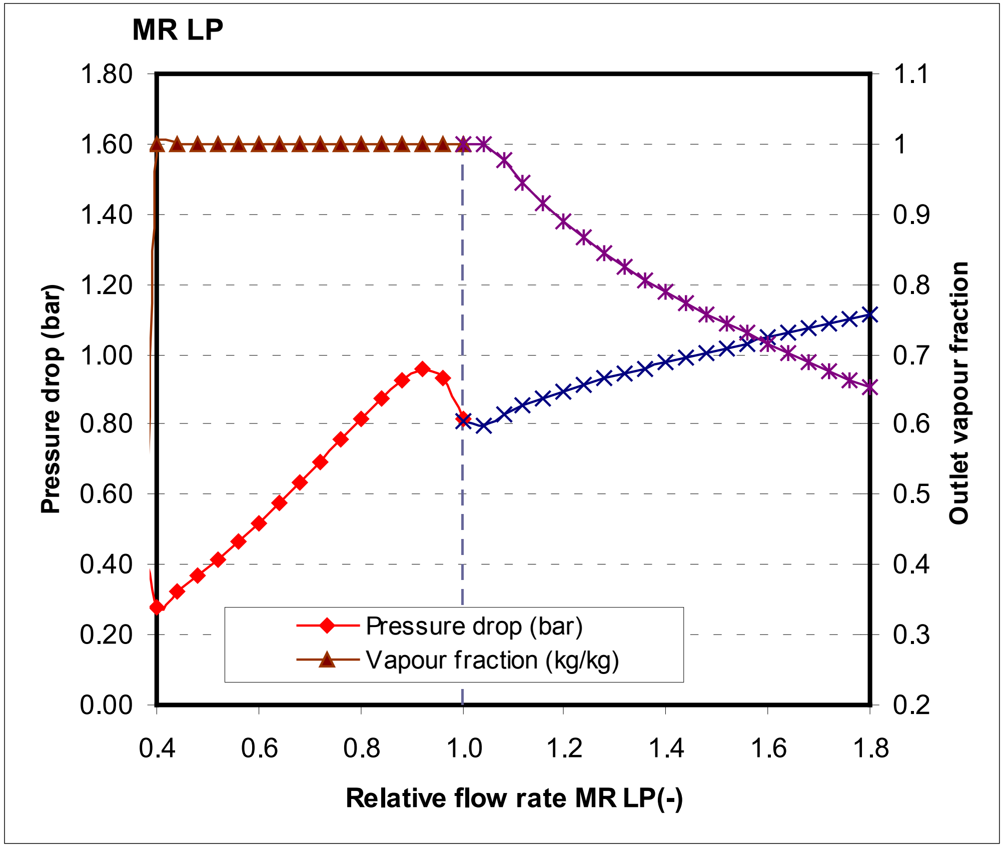
- External cooling to 25°C

Optimised process design with a fully designed heat exchanger



T NG	-155
T LP	-157.1
P LP	5.34
P HP	25.88
N2	0.0929
C1	0.2913
C2	0.3887
nC4	0.2271
MREFR (kmol/s)	3.15
MNG	1

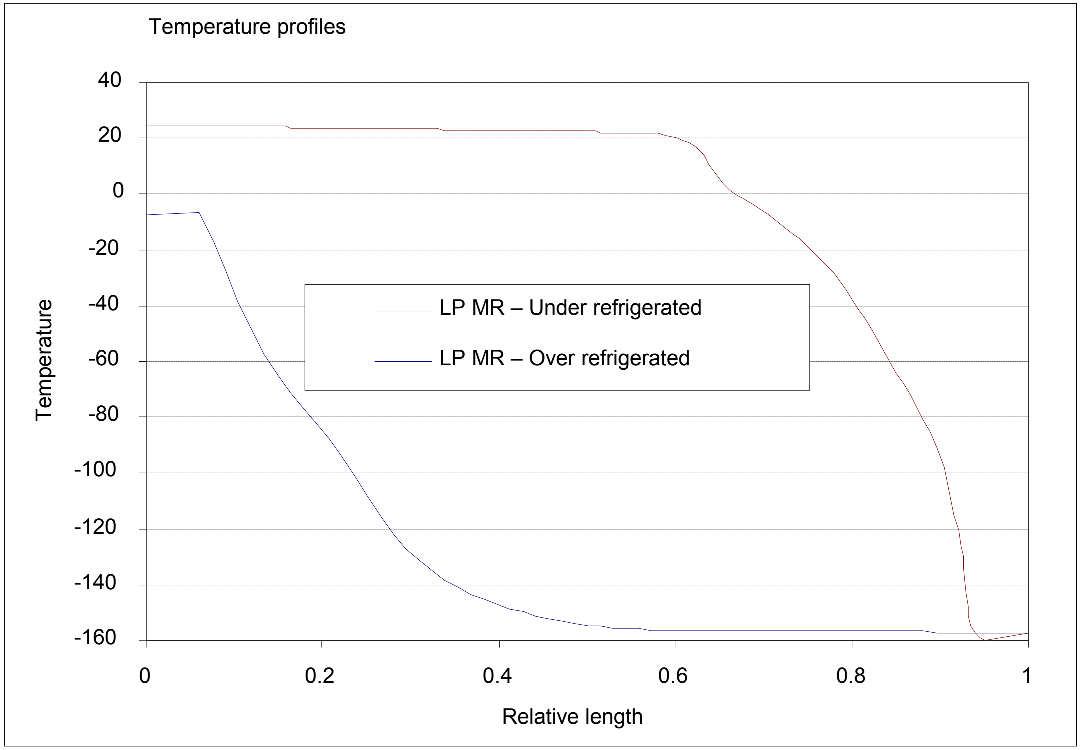
Check for operability -
Pressure drop vs. flow rate for the evaporating stream



Assumption for this simulation:
Constant warm stream flow rates

Consequences of Ledinegg instability

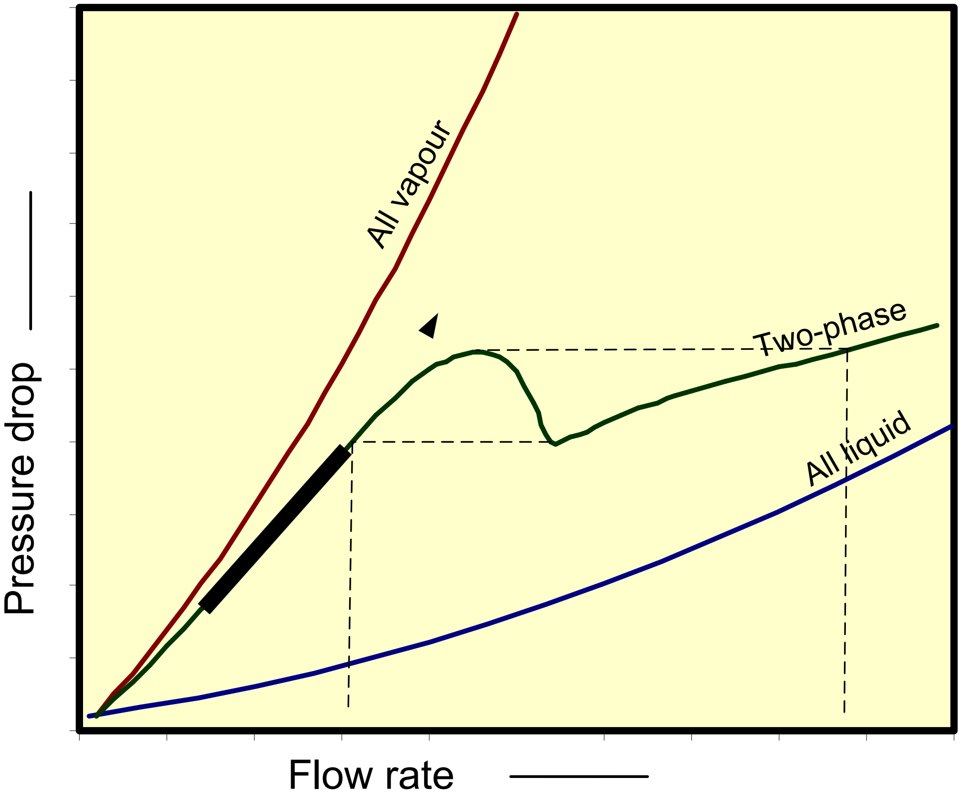
Equal cold stream pressure drop with flow-rate split 42/58 (+/- 8%)



Individual temperature profile

Remedies for avoiding Ledinegg instabilities

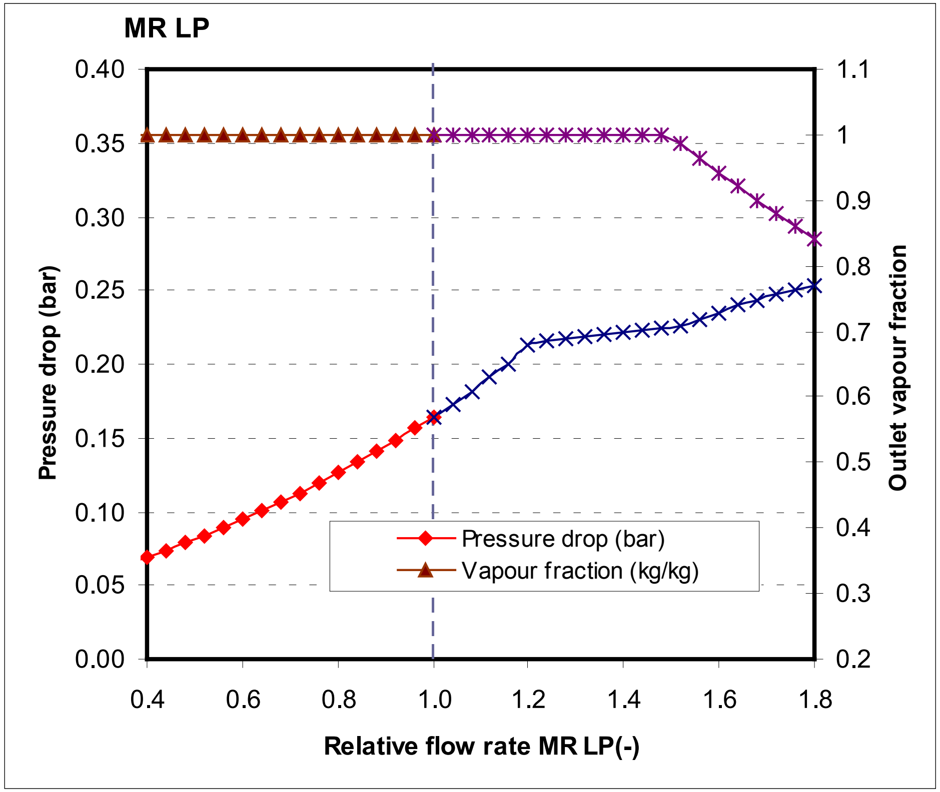
N-shape for upward boiling in a heat exchanger



- Move the operating point within the blue line.
- Get rid of the *N*-shape
  - Modify HX design,
  - Reduce outlet resistance
  - Increase inlet resistance
  - Avoid cold end pinch
  - (Reduce the heat load)

Example on modified design

- Reduced heat flux for cold channels – increased surface while maintaining - or reducing the pressure drop…



	HX 1	HX 2
Core volume (m3)	31.7	107.0
Heat transfer surface (m2)	26502	70255
Average heat flux (W/m2)	2911	1073
Mass flux (kg/m2 s)	62.7	19.4
Design pressure drop (bar)	0.82	0.17
N-shape	Yes	No

Summary – on heat exchanger / process analysis

- In cryogenic processes using fluids with low density and low latent heat, instabilities are more likely to occur

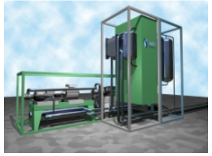
- The risk of ending up with a design operating point in an unstable region is high, if
  - processes are optimised based on composite curves and minimum temperature differences,
  - the pressure drop vs flowrate curve exhibits an N-shape

- When equipment with a high degree of parallelism is used, this could have serious consequences in terms of thermal stress or inefficient operation

- There are currently 3 PhD studies on the topic of instability in heat exchangers at NTNU.

Small Scale LNG production – The SINTEF Mini-LNG concept – from laboratory to installation onboard a gas carrier

- The Mini-LNG technology
  - General characteristics
- Re-Liquefaction plant, application example
  - Full scale plant analysis



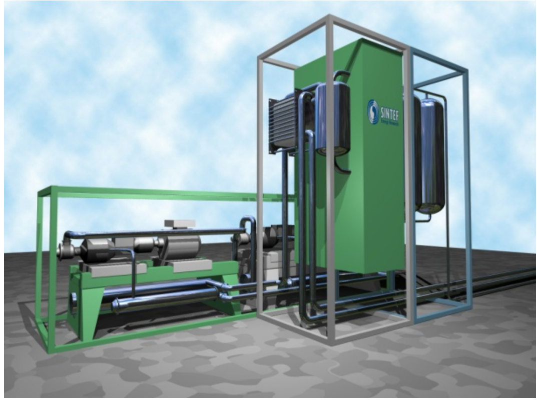
Contact person on Mini LNG: Petter Nekså

(petter.neksa@sintef.no)

NG liquefaction plants, capacity range

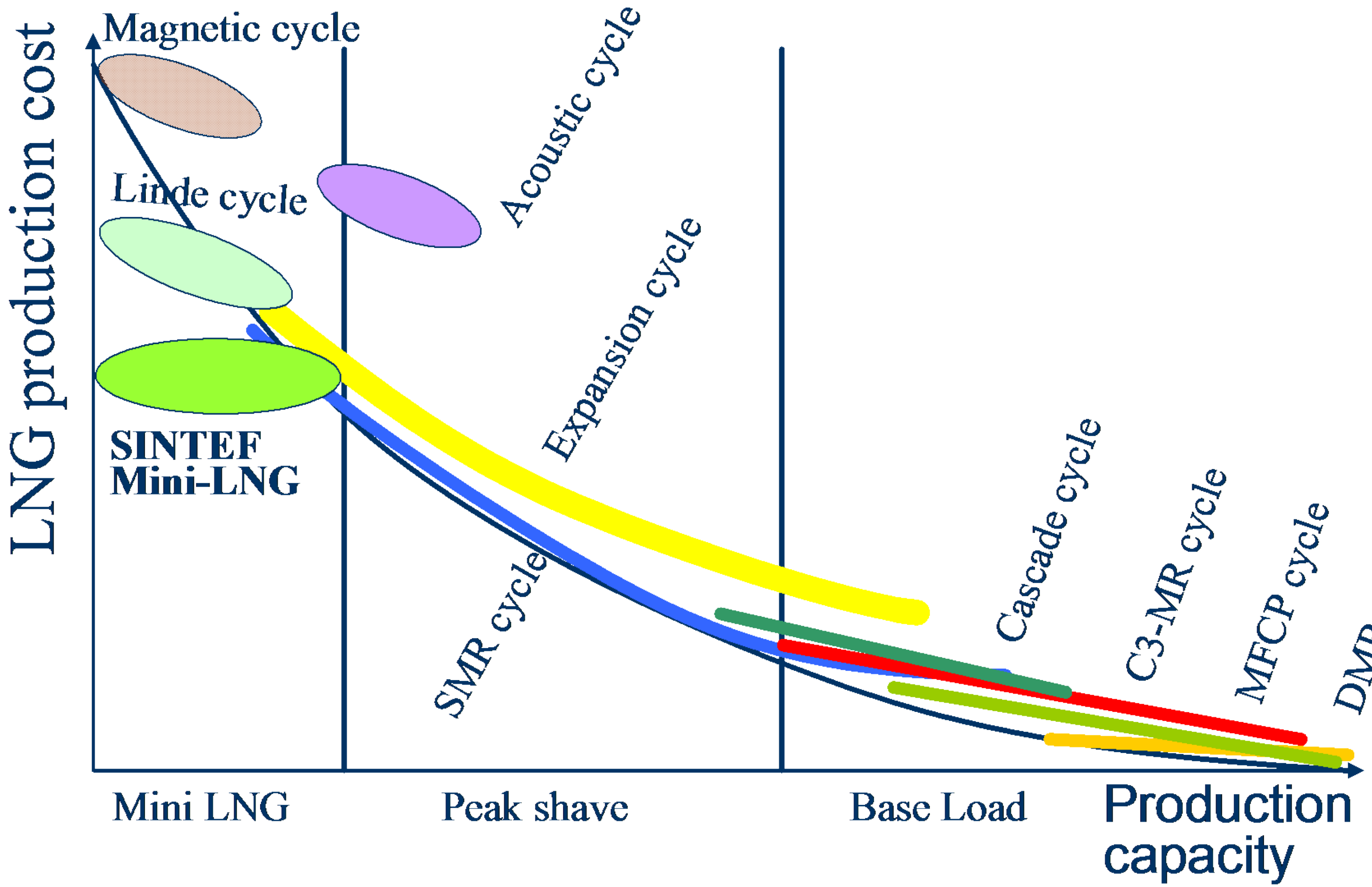
Base-load
LNG production: 1500 – 5000 kT/year
Hammerfest/Snøhvit 4300 kT/year (12500T/day)

Peak shaving
LNG production: 35 – 150 kT/year

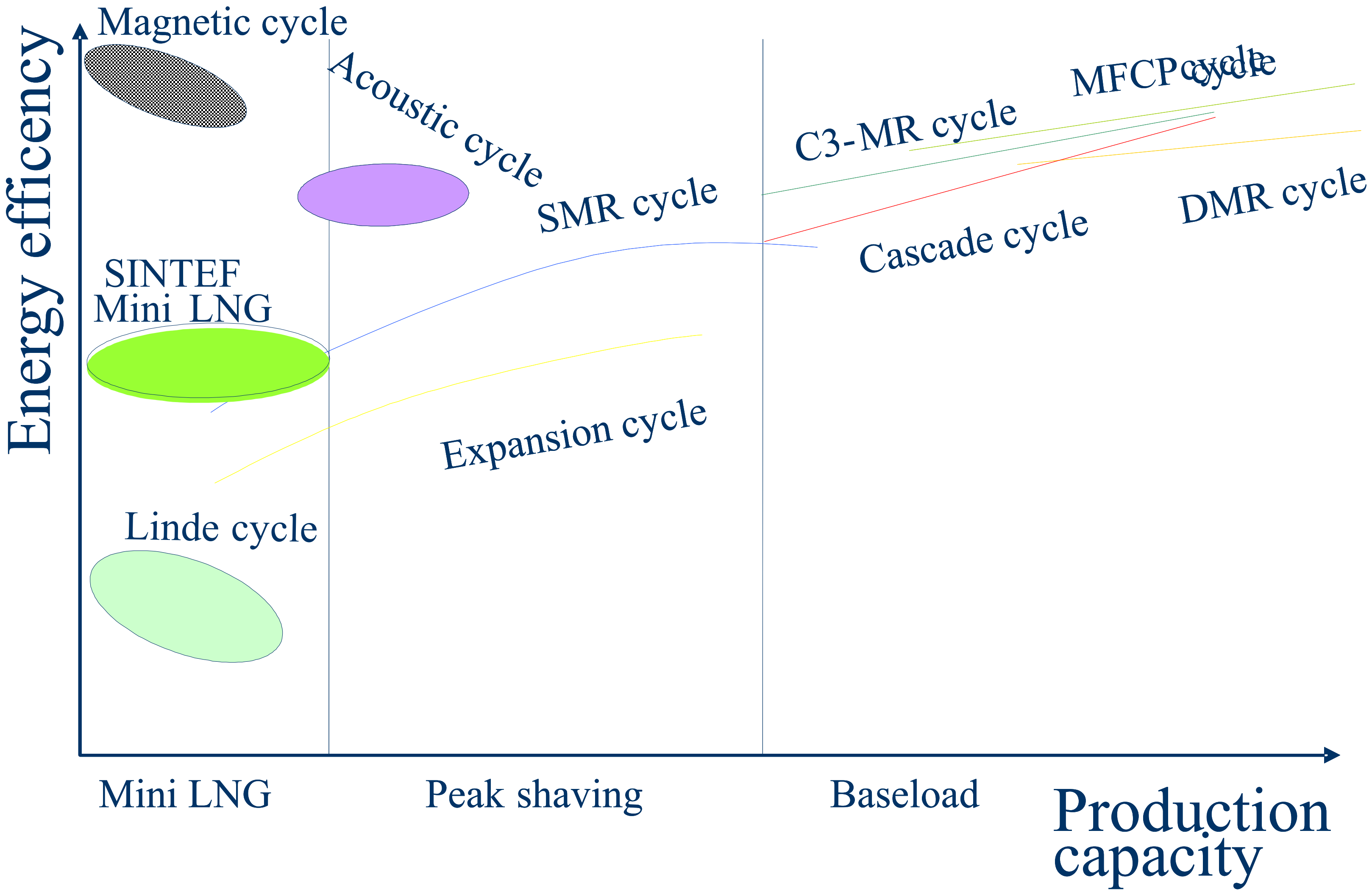


Mini-LNG
LNG production: 3.5 – 35 kT/year
(10 – 100 T/day)

The cost challenge of small scale LNG

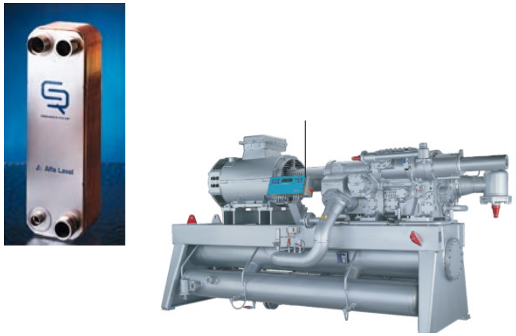


The energy efficiency challenge of small scale LNG



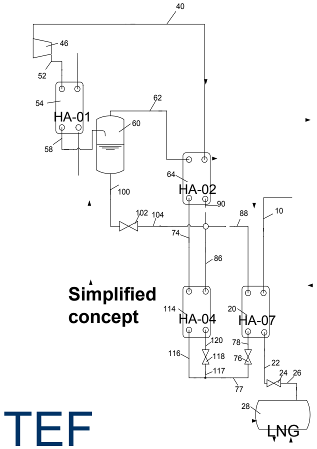
The SINTEF mini-LNG concept - Liquefaction Unit

- Using standard equipment for low investment cost and fast manufacture of the liquefaction unit
  - Copper brazed plate heat exchangers, withstands rapid temperature changes
  - Lubricant injected screw compressors
  - Proven robust oil/lubricant management
- Construction in steel frames:
  - Lower manufacturing cost
  - Faster manufacture time
  - Modular movable plant elements
- Refrigeration cycle with mixed refrigerant (N_2,C_1,C_2,C_3,C_4) for low energy demand
- Adaptation of selected equipment, MR and operational conditions to given application and NG composition

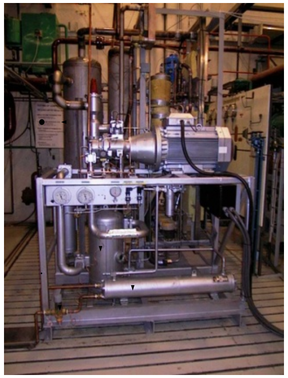


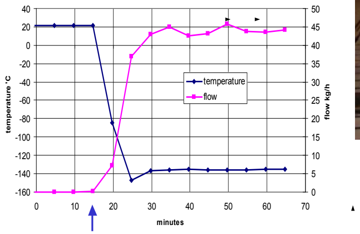
From theory – laboratory - full scale

- Theoretical
  - Process development and simplification
  - Analysis
- Laboratory plant 1 tonnes$_{LNG}$/d
  - Fully instrumented closed loop lab plant at SINTEF
  - Operation since 2003, 2000 h (500 continuous)
  - Lubricant tests, various operating conditions, rapi start-up
- Full scale test, 20 tonnes$_{LNG}$/d
  - Design and construction
  - FAT test at SINTEF Tiller lab in Trondheim 2008
  - Analysis of results
  - Installation onboard a gas carrier 2009

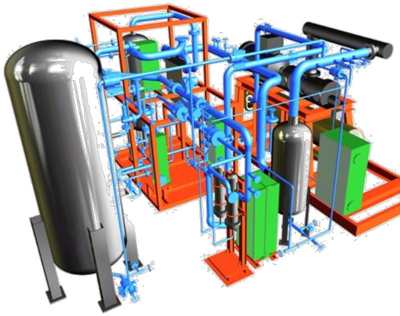


Simplified concept

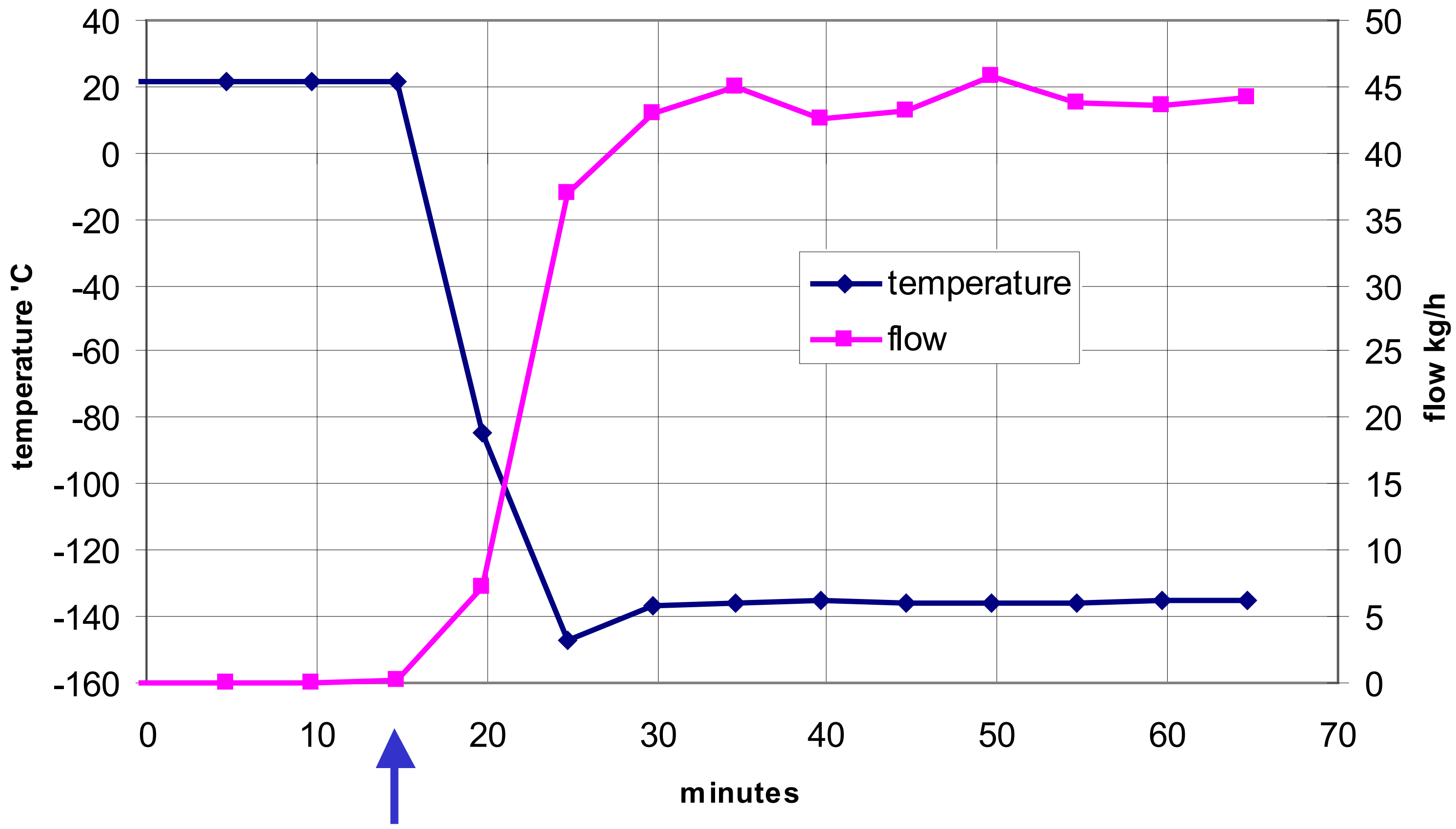




start



Mini-LNG liquefaction unit
Rapid start and stop
Reading from laboratory plant 1 tonnes/d

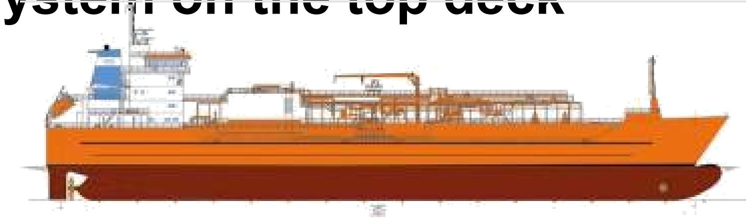


start

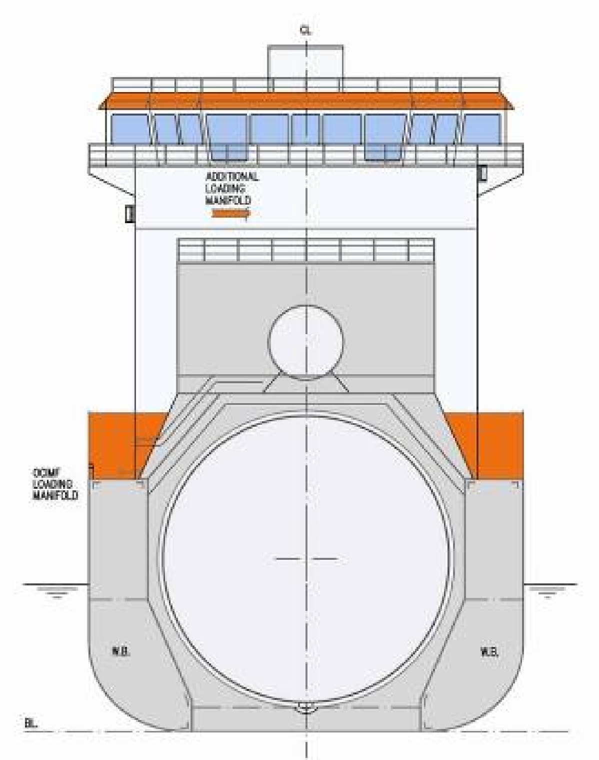
Application example SINTEF Mini-LNG

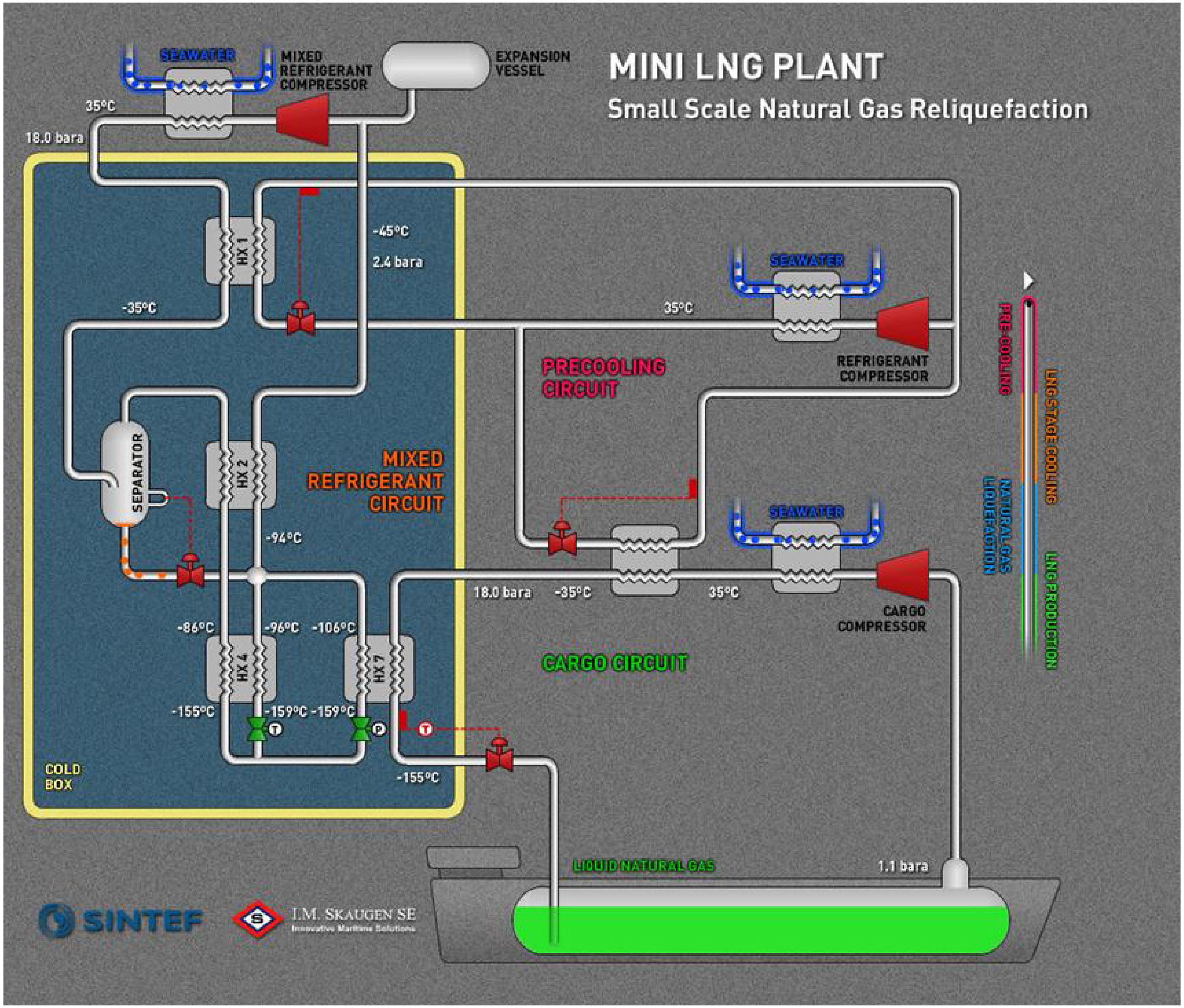
Reliquefaction of boil-off gas from a small IMS Multigas carrier using the Mini-LNG Techology

3D illustration of the tanker with the refrigeration system on the top deck



10.000 m^3
Multigas



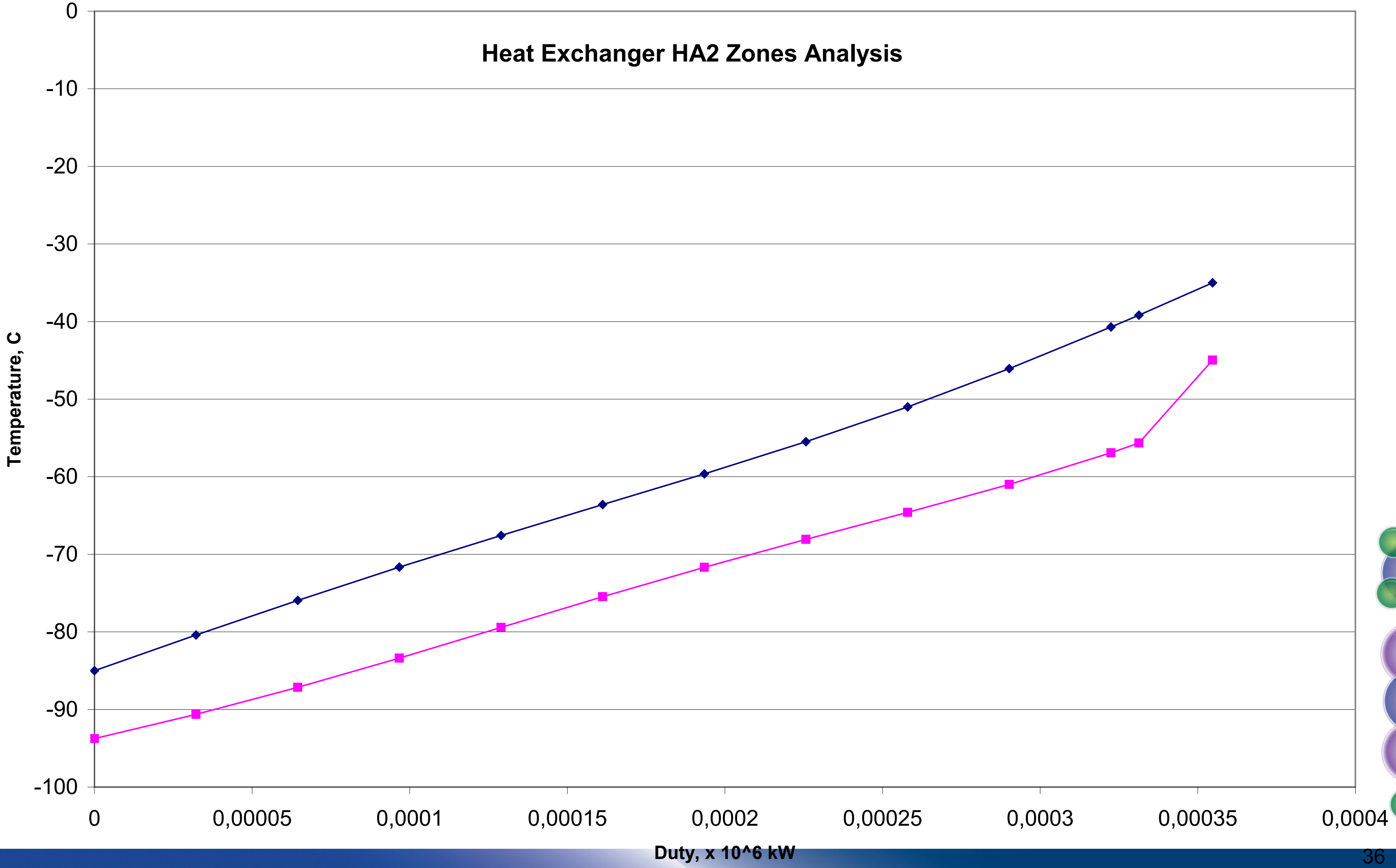

MINI LNG PLANT
Small Scale Natural Gas Reliquefaction
SEAWATER
MIXED REFRIGERANT COMPRESSOR
EXPANSION VESSEL
35°C
18.0 bara
HX 1
-45°C
2.4 bara
-35°C
35°C
SEAWATER
REFRIGERANT COMPRESSOR
PRECOOLING CIRCUIT
SEPARATOR
HX 2
MIXED REFRIGERANT CIRCUIT
-94°C
SEAWATER
18.0 bara
-35°C
35°C
CARGO COMPRESSOR
-86°C
-96°C
-106°C
HX 4
HX 7
CARGO CIRCUIT
-155°C
-159°C
-159°C
T
P
T
-155°C
COLD BOX
LIQUID NATURAL GAS
1.1 bara
PRE-COOLING
LNG STAGE COOLING
NATURAL GAS LIQUEFACTION
LNG PRODUCTION
SINTEF
I.M. SKAUGEN SE
Innovative Maritime Solutions

Plant design simulation results (mini-LNG)

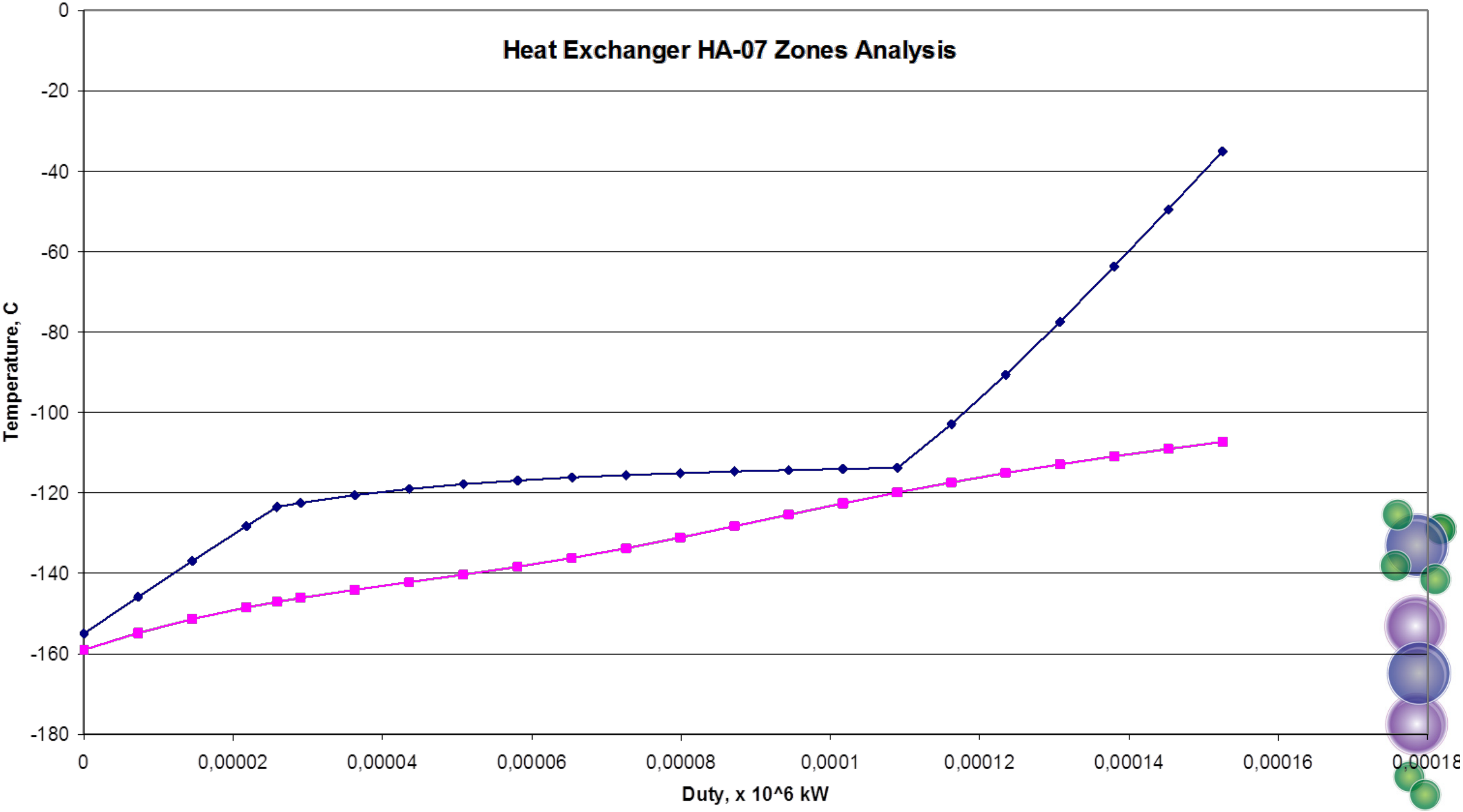
BOG NG with 89 mol% CH4, 11 mol% N2 (18 bara)

Boil-off gas liquefaction capacity	20 tonnes/d
LNG exit temperature (before throttling to tank)	-155 ^{o}C
MR (at first vapour-liquid separator inlet) and NG pre-cooling temperature	-35 ^{o}C
Mixed refrigerant compressor pressure ratio	9.3 -
Mixed refrigerant compressor power consumption	395 kW
Estimated compressor isentropic efficiency	0.65 -
Mixed refrigerant actual suction volume	1520 m^{3}/h
Specific suction volume	1.8 m^{3}/kg LNG
Specific power consumption mini-LNG	0.47 kWh/kg LNG

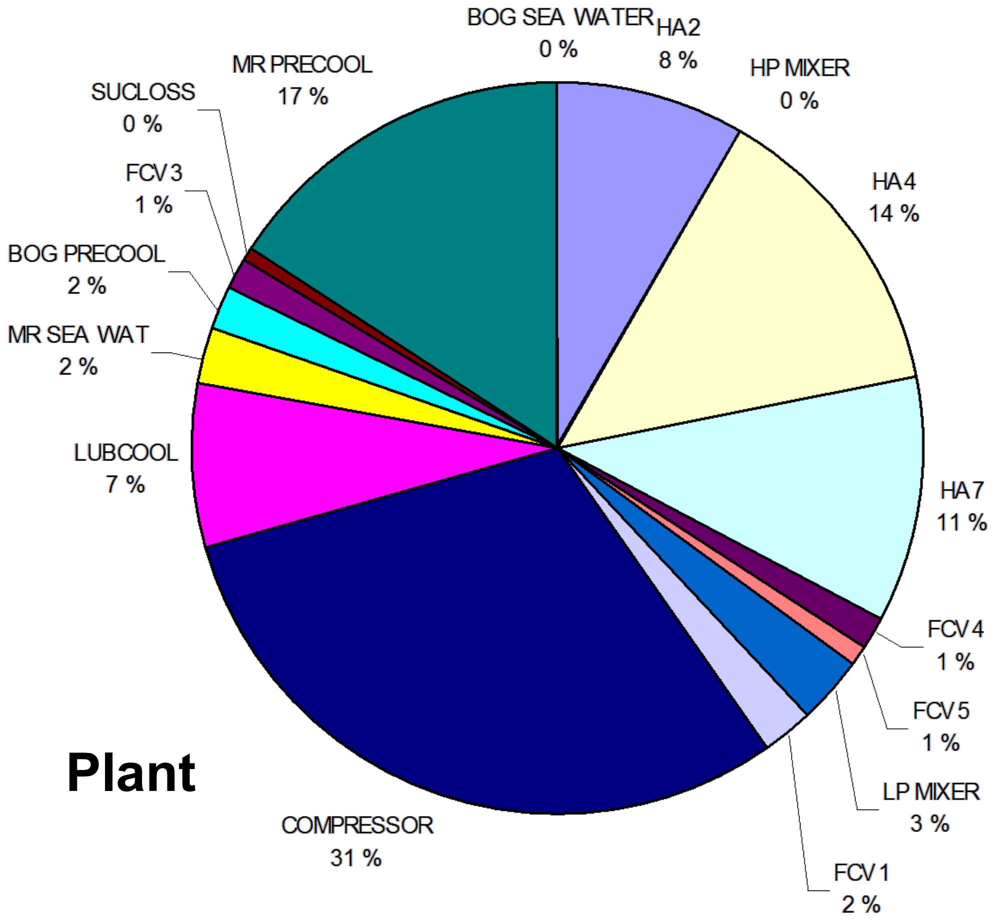
Heat Exchanger HX 2, MR-HP/MR-LP, high temp
Duty vs. Temperature

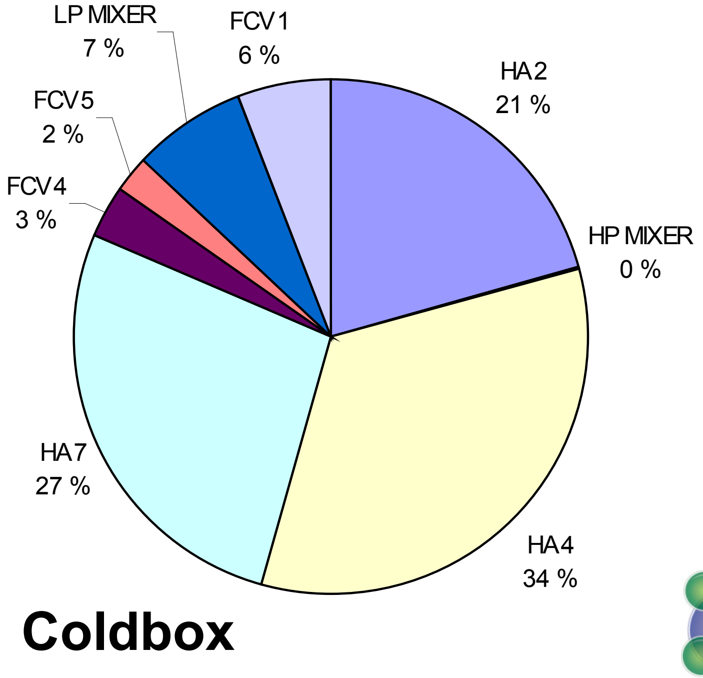


Heat Exchanger HX 7, NG/MR-LP
Duty vs. Temperature



Plant exergy loss analysis





- Still considerable potential for reducing losses
- Especially for compressor and heat exchangers
- Dependent on component availability

Full scale test results

Results from full scale tests and simulation model verification

Including simulation results for future plant operating conditions (corrects for off-design conditions at full scale tests)

Parameter	Unit	Measured	Simulation	Simulation corrected [1)] (dp and leak)	Simulation corrected [2)] (precooling t)
Liquefaction capacity	tonnes/d	14,4	14,4	17,1	18,8
LNG exit temperature before throttling to tank	°C	-154,1	-154,1	-155	-155
MR precooling temperature at vap-liq separtor	°C	-24,9	-24,9	-24,9	-35
NG precooling temperature	°C	-31,7	-31,7	-35	-35
Refrigerating capacity	kW		70,7	84,3	93,2
Volume flow LP MR out of coldbox	m^3/h		1436	1512	1517

- Capacity difference relative to nominal (18.8 tonnes/d)
  1) Corrected for leak in safety valve by-pass from high p to low p and undersized stop valve in suction tube
  2) Corrected to nominal precooling temperature (-35°C)

~ 14 %-points

~ 9 %-points

- Some maldistribution in first secondary hx (HX 2) observed
  - Estimated influence on capacity 5 - 7 %

Constraints and possible improvements

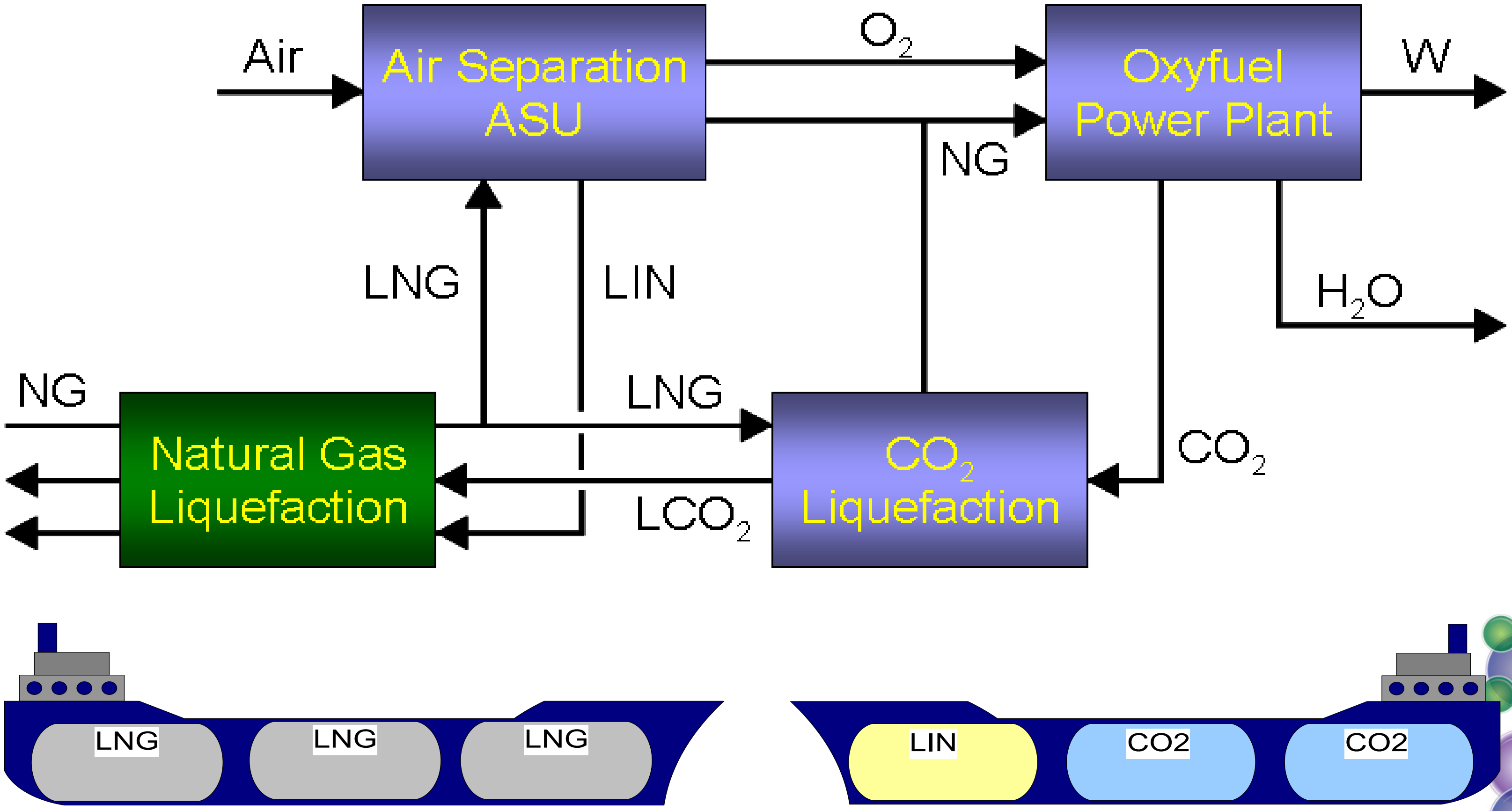
- Some constraints today
  - NG pressure from BOG handling system 18 bar (balance BOG compr./Mini-LNG)
  - Storage pressure in chain, carrier tanks can handle 5 bara
  - Design for high ambient temperatures - Sea water temperatures in north of Europe relatively low
  - Availability of components
- Efficiency improvements
  - Improved compressor efficiency
  - Reduced temperature differences in hx
  - Optimisation of MR composition
- Plant operation without pre-cooling could be possible
  - Existing refrigeration system on-board is used for precooling today

Liquid Energy Chain Optimization

Contact person: Prof. Truls.Gundersen
(truls.gundersen@ntnu.no)

Aspelund A. and Gundersen T. ”A Liquefied Energy Chain for Transport and Utilization of Natural Gas for Power Production with CO_2 Capture and Storage – Part 1”, ***Journal of Applied Energy***, vol. 86, pp. 781-792, 2009 .

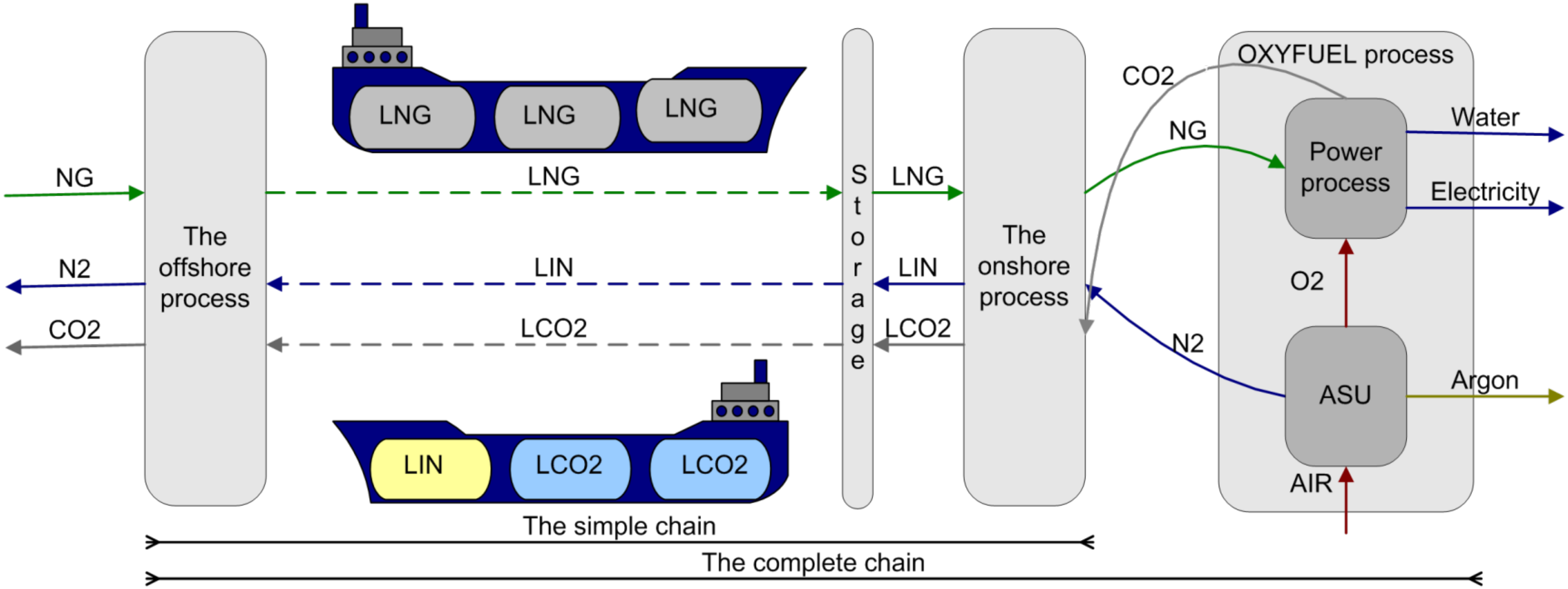
A Liquefied Energy Chain (LEC)



Aspelund A. and Gundersen T. "A Liquefied Energy Chain for Transport and Utilization of Natural Gas for Power Production with CO_2 Capture and Storage – Part 1", ***Journal of Applied Energy***, vol. 86, pp. 781-792, 2009 .

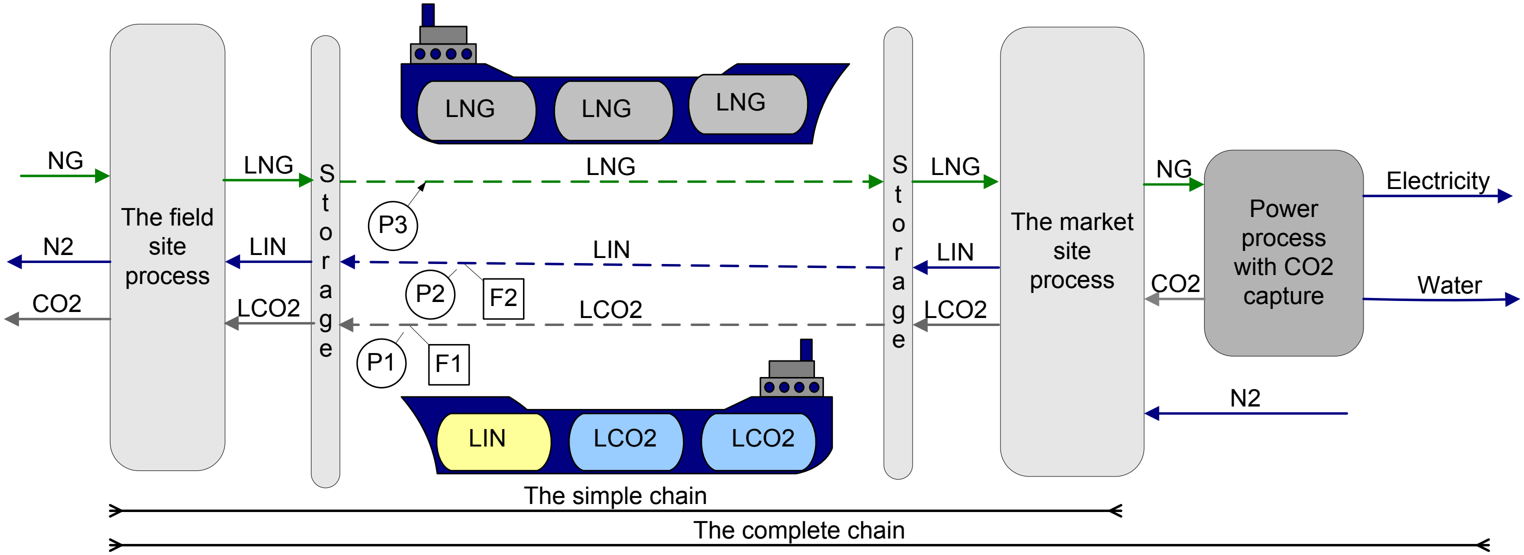
T. Gundersen

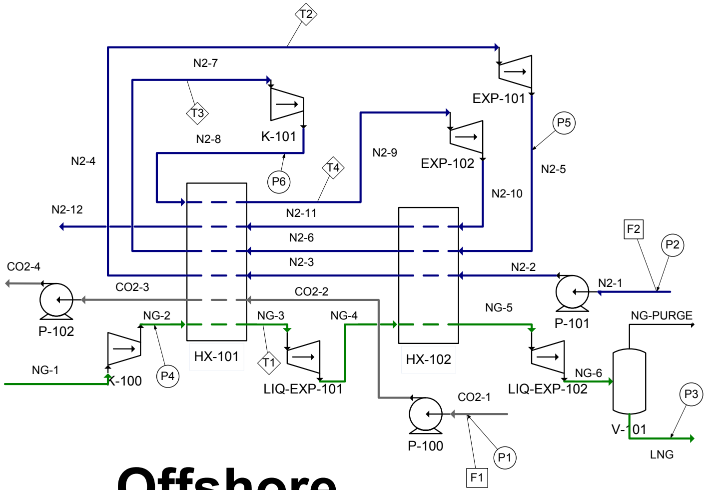
A Liquefied Energy Chain (LEC)



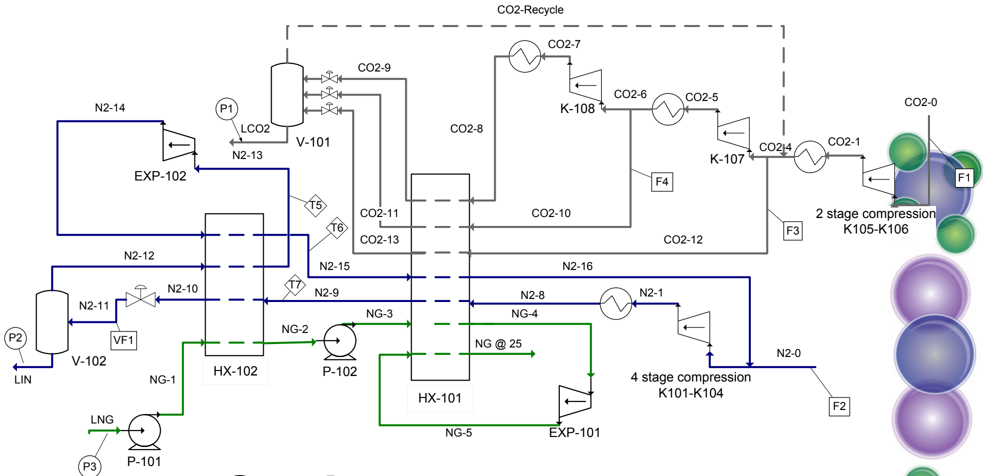
- **Key Features of the "LEC" Concept**
  - Utilization of **Stranded** Natural Gas for Power Production
  - High Exergy **Efficiency** of 46.4% (vs. 42.0% for traditional)
  - Elegant and Cost Effective solution to the **CCS** Problem
  - CO_2 replaces Natural Gas injection for **EOR**
  - **Combined** Energy Chain (LNG) and Transport Chain (CO_2)

Simulation-Optimization of the entire LEC





Offshore

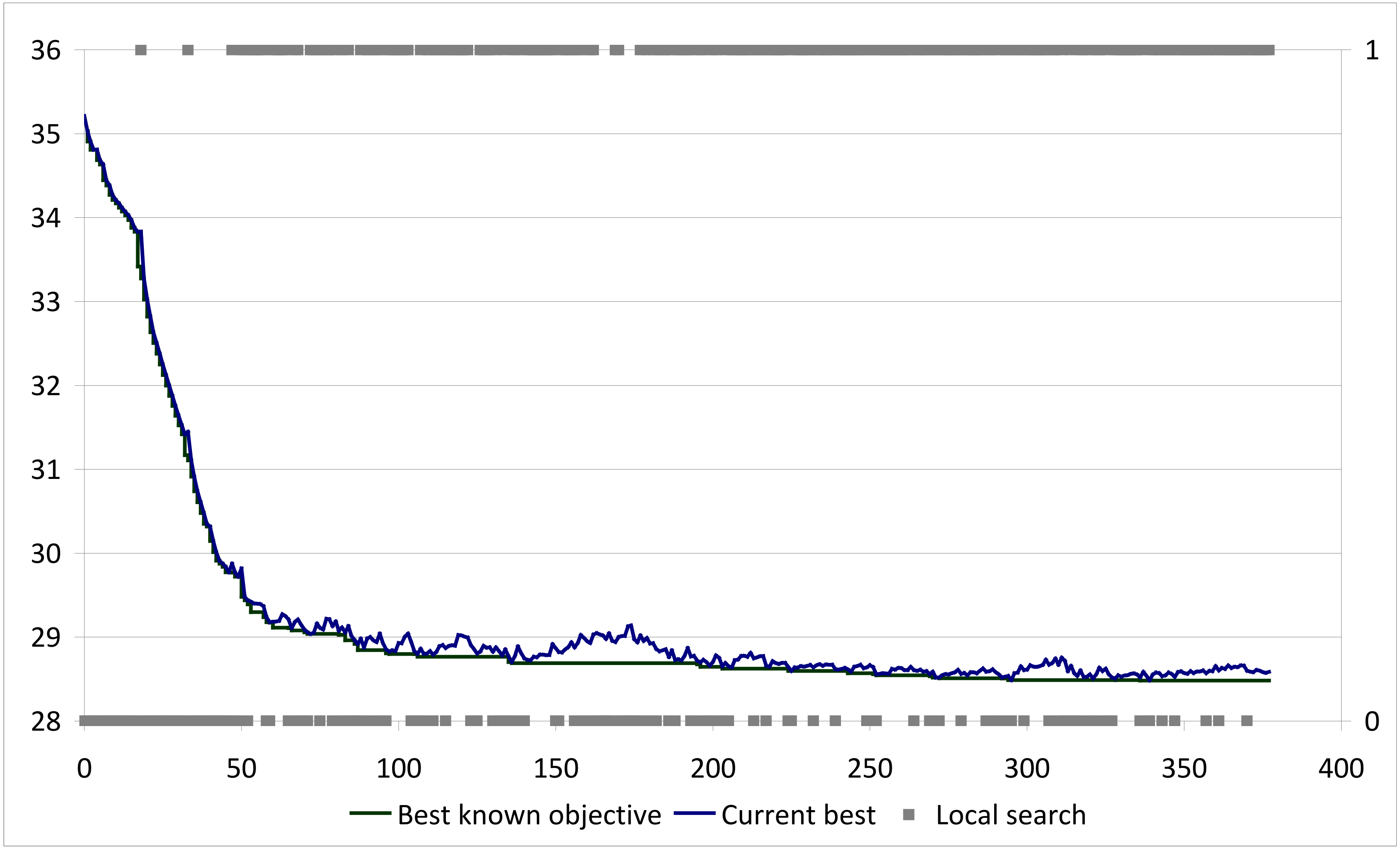


Onshore

Optimizing the Liquefied Energy Chain

- **First: Near-Optimal Design established by**
  - Domain Knowledge related to LNG
  - Heuristic Design rules (new and old)
  - Pinch Analysis (the Composite Curves)
  - Exergy Analysis (calculating η_{Exergy})
  - Rigorous Simulation by HYSYS (testing the Concept)
- **Second: Mathematical Programming and a novel (and innovative) Superstructure**
  - Offshore and Onshore Processes Optimized separately
- **Third: Stochastic Search with Rigorous Simulation**
  - Referred to as “Simulation–Optimization”
  - Taboo Search (global) and Nelder Mead (local)
  - HYSYS providing Objective Function Values
  - Applied Simultaneously to the entire Chain

Progress of the Optimization



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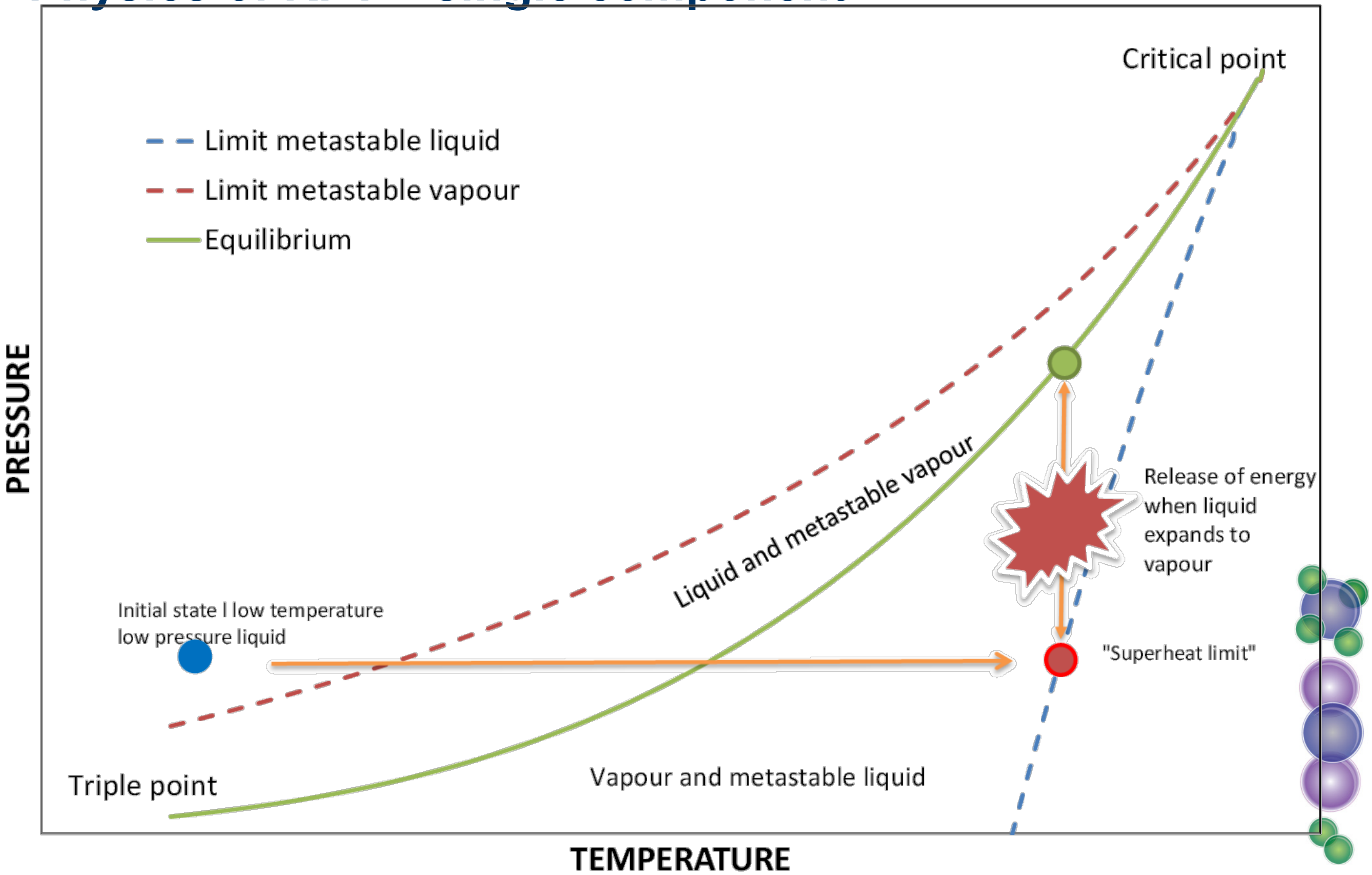
Future research tasks – Rapid Phase Transition (RPT)

- What is RPT?
  - can occur if liquid natural gas is spilled on / and mixed with water
  - a physical explosion where unstable, superheated liquid instantaneously expands to vapour phase and creates overpressure and pressure waves
  - explosion impact often converted to tons of TNT

- Increased attention in recent safety studies
  - increased use and transport of LNG
  - well researched, but still difficult to predict
  - complex chain of various physical phenomena
  - challenging in terms of scale-up from laboratory tests

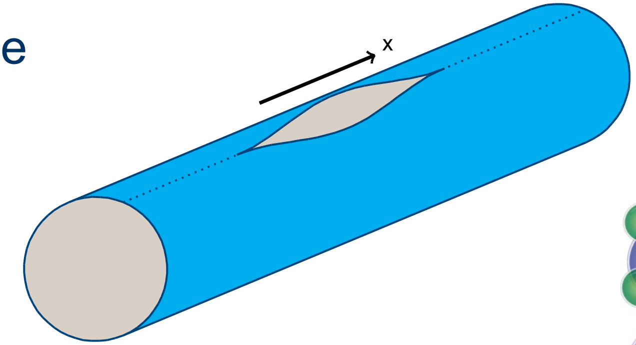
Physics of RPT – single component



Future research tasks – Rapid Phase Transfer (RPT)

- Plan to start up new 3 mill EUR project in 2012 – awaiting governmental financial support – still open for industry participation
  - Both experimental and modelling approach are planned

- 2 PhD from NTNU from the mid 90's
  - pool boiling of hydrocarbon on water surface
  - mixing of cryogenic jet in water
  - fragmentation
  - modelling
  - spreading



- Now: Utilize advances in measurement and visualization techniques and advances in modelling experience on fast transients on pressure wave propagation

Thank you for your attention!

Gas Technology Centre:

www.ntnu.no/gass

www.sintef.no

Some selected references

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