Innovations in Natural Gas Liquefaction Technology for Floating LNG

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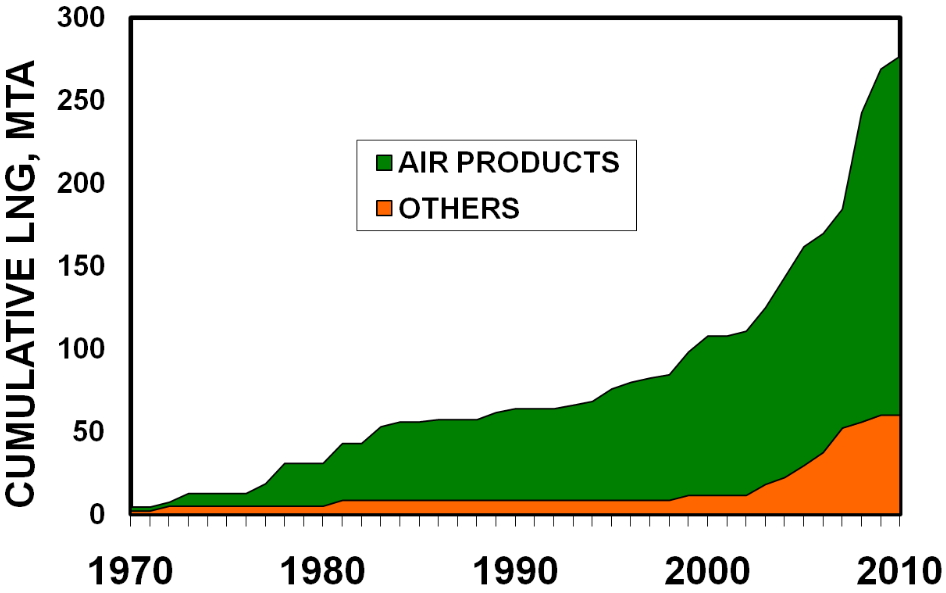
LNG Prospects

Air Products LNG Technology and Equipment

- 85 LNG heat exchangers / 40 years
- 24 turboexpanders
- Integrated offering with several high efficiency refrigeration process cycles



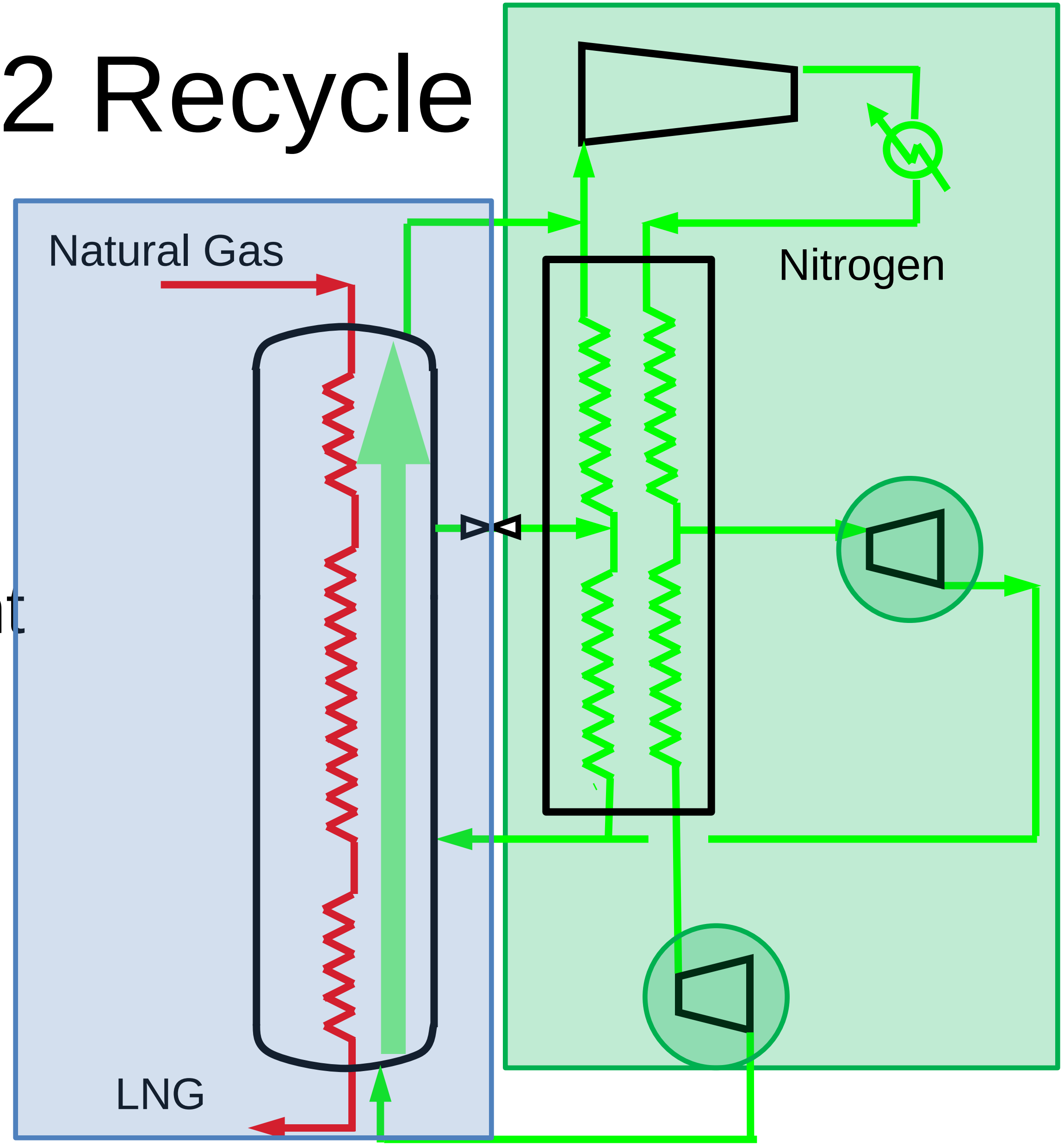
Air Products Liquefaction Processes for FLNG Applications

0 1 2 3 4 5+

Train Capacity, MTA

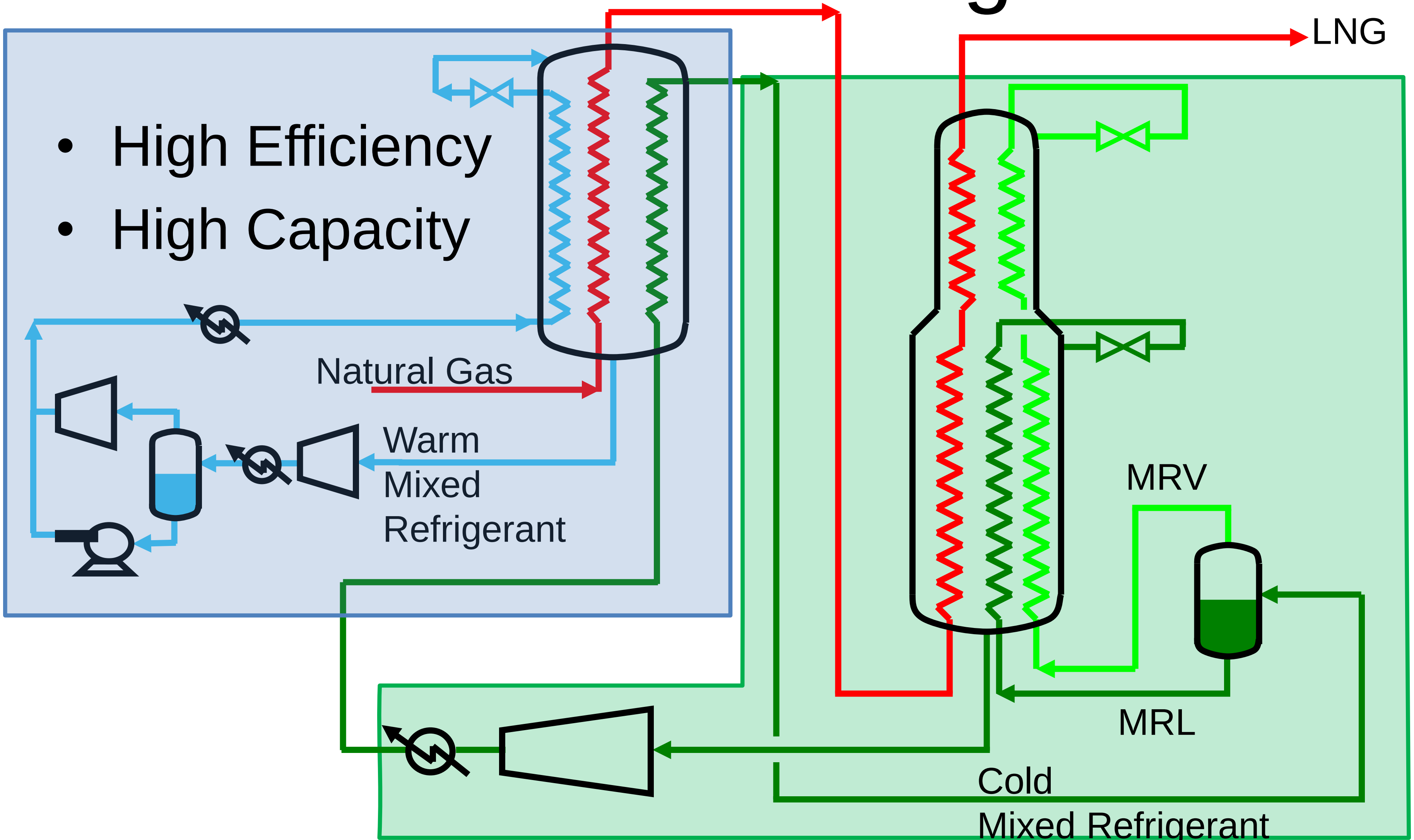
N2 Recycle

- ~ 1 MTPA
- No HC refrigerant
- All Vapor

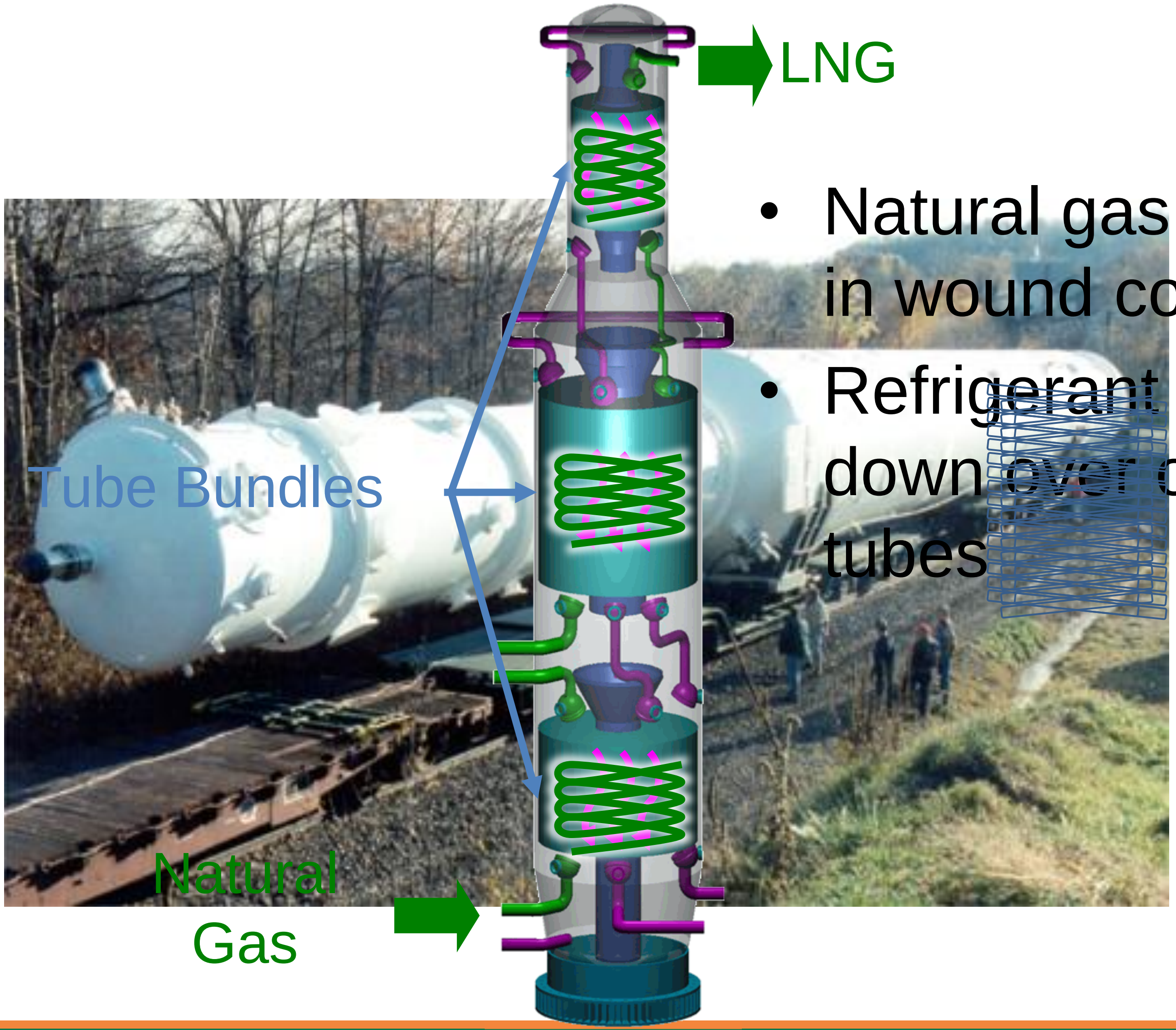


Dual Mixed Refrigerant

- High Efficiency
- High Capacity



Wound Coil Heat Exchanger



- Natural gas liquefied in wound coil tubes
- Refrigerant flows down over outside of tubes

Wound Coil Exchangers for Safety and Reliability

- Liquefying hydrocarbons can cause high thermal stresses due to inherent refrigerant/load imbalances
- Wound Coil Exchangers proven to withstand thermal stresses
- Dual containment – high pressure hydrocarbons contained in tubes within a pressure vessel shell. Containment important to FLNG safety

WCHE for Floating LNG

FLNG vessel subject to motion

Exchanger design verification

- Mechanical strength
- Process flow effects

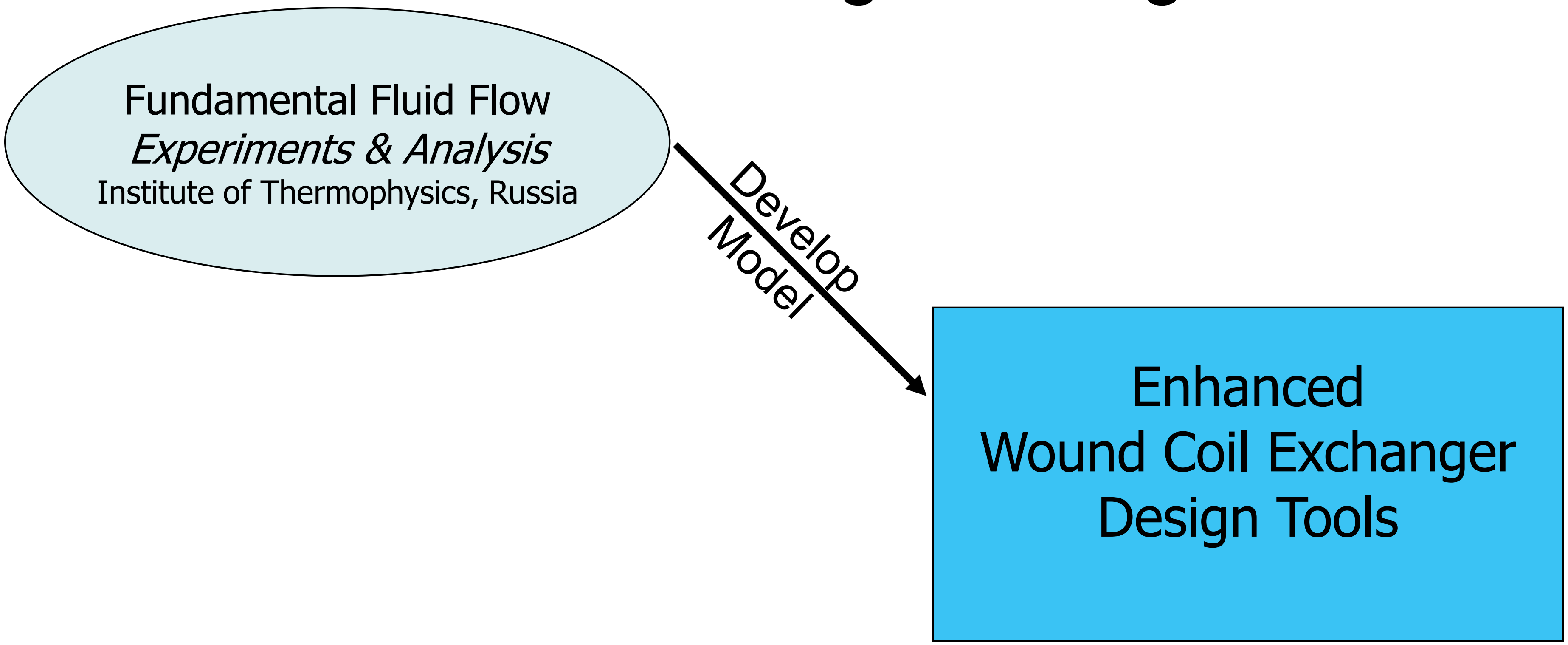
WCHE Mechanical Design Verification for FLNG

- Pressure vessel design
  - Considered North Sea 100 year storm conditions for strength, with 25 year service life for fatigue
  - Exchanger design meets fatigue criteria set by DNV
  - Design method certified by DNV
- Internal bundle support system
  - Tested cyclic loads due to wave motion, based on North Sea 100 year storm conditions
  - Demonstrated resistance to wear or distress that would impair function

Wound Coil Exchangers for FLNG: Process Effects

- Flow through tubes
  - Pressure driven, not affected by ship motion
- Liquid flow through shell-side distributors
  - Performance insensitive to motion, as verified by computational fluid dynamics and experimental testing
- Flow on shell-side of exchanger
  - Motion may affect how liquid flows over the tube bundle
  - Liquid distribution may affect heat transfer performance
  - Effects are mitigated by proper bundle design, using Air Products’ enhanced design tools

Development of Enhanced Wound Coil Exchanger Design Tools



Fundamental Fluid Flow

Experiments & Analysis

- Laboratory measurements provide inputs to hydraulic flow model
  - Experiments performed with water, water- surfactant mix, and hydrocarbons
  - Experiments give hydraulic behavior under tilt conditions

Development of Enhanced Wound Coil Exchanger Design Tools

Fundamental Fluid Flow
Experiments & Analysis
Institute of Thermophysics, Russia

Develop Model →

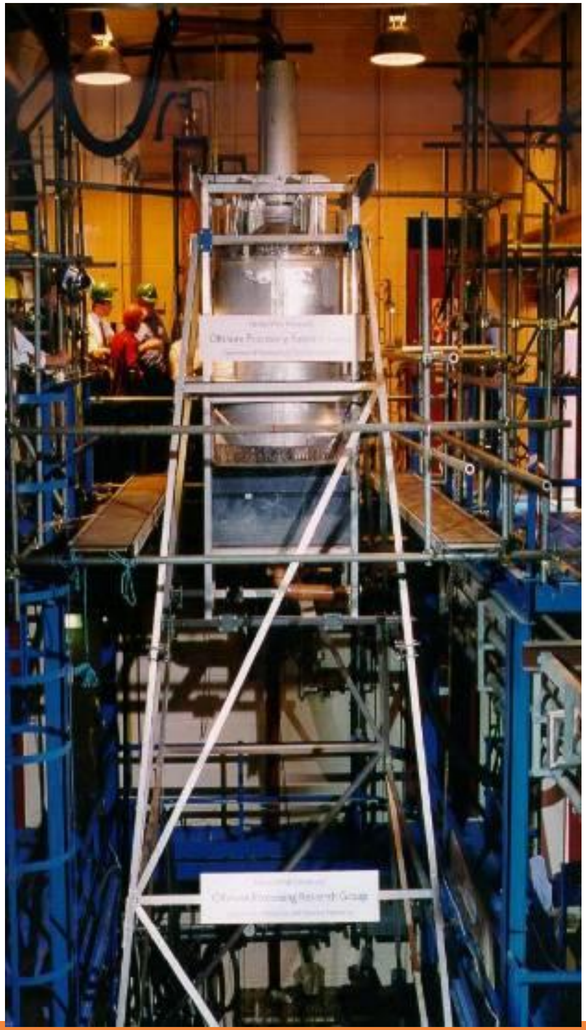
Pilot Plant Test Bundle
Liquid Flow with Bundle Oscillations
Heriot-Watt University, Scotland

Verify Model →

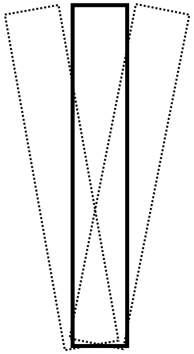
Enhanced
Wound Coil Exchanger
Design Tools

Pilot Scale Experiments

Liquid Flow with Bundle Oscillations

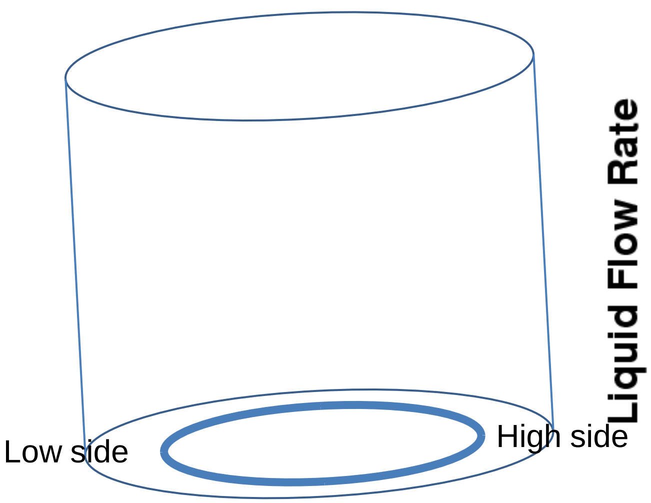


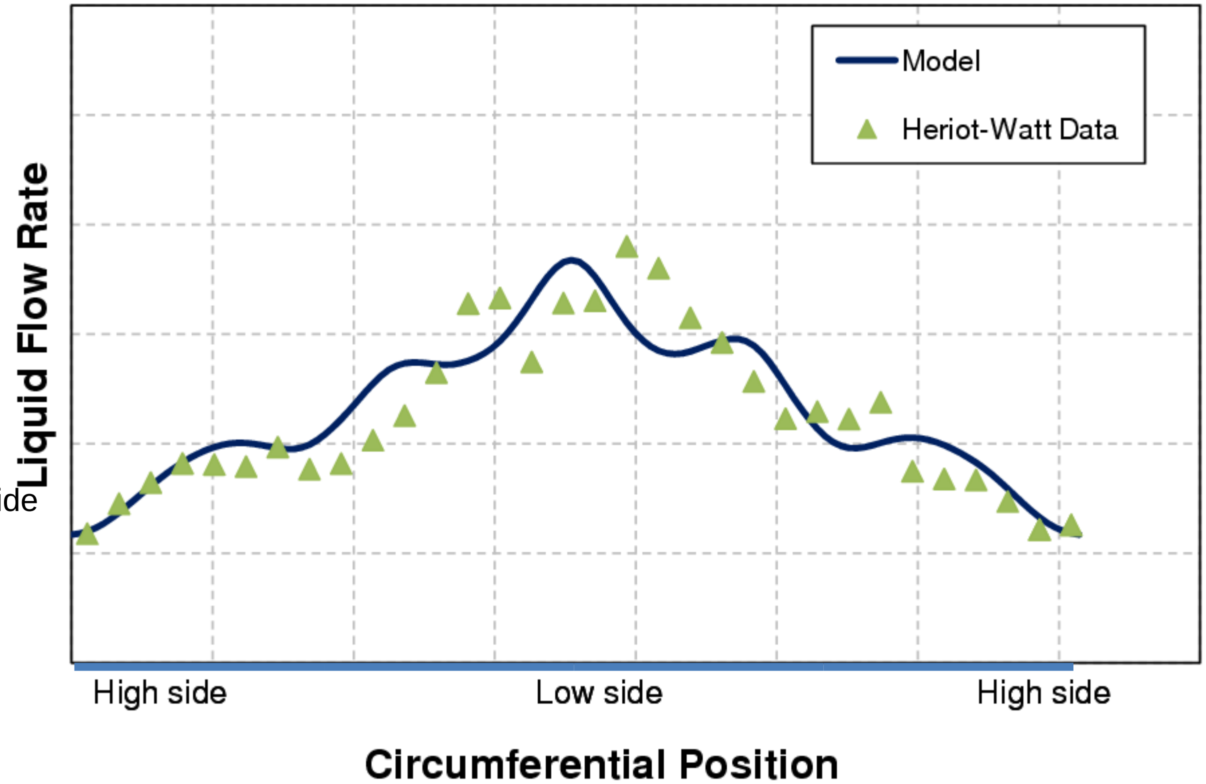
- Testing performed at Heriot-Watt University in Scotland
- Flow distribution data under static tilt and oscillation (pitch/roll)



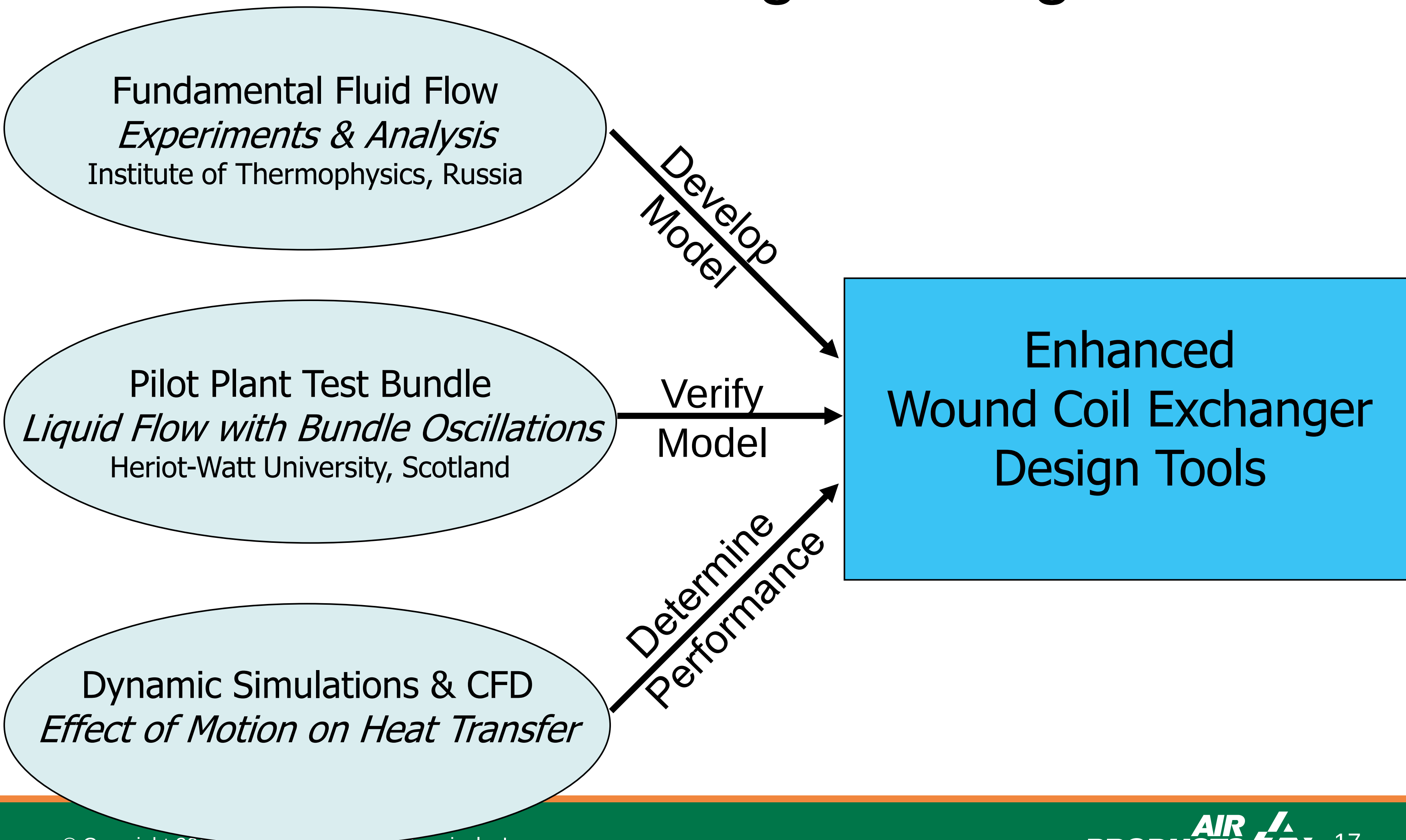
Validation of Model

- Model validated by comparison to Heriot-Watt pilot scale data





Development of Enhanced Wound Coil Exchanger Design Tools



FLNG Exchanger Design

Key Motion Variables

- Static tilt
- Pitch/roll
- Oscillation period
- Exchanger elevation

Key Design Variables

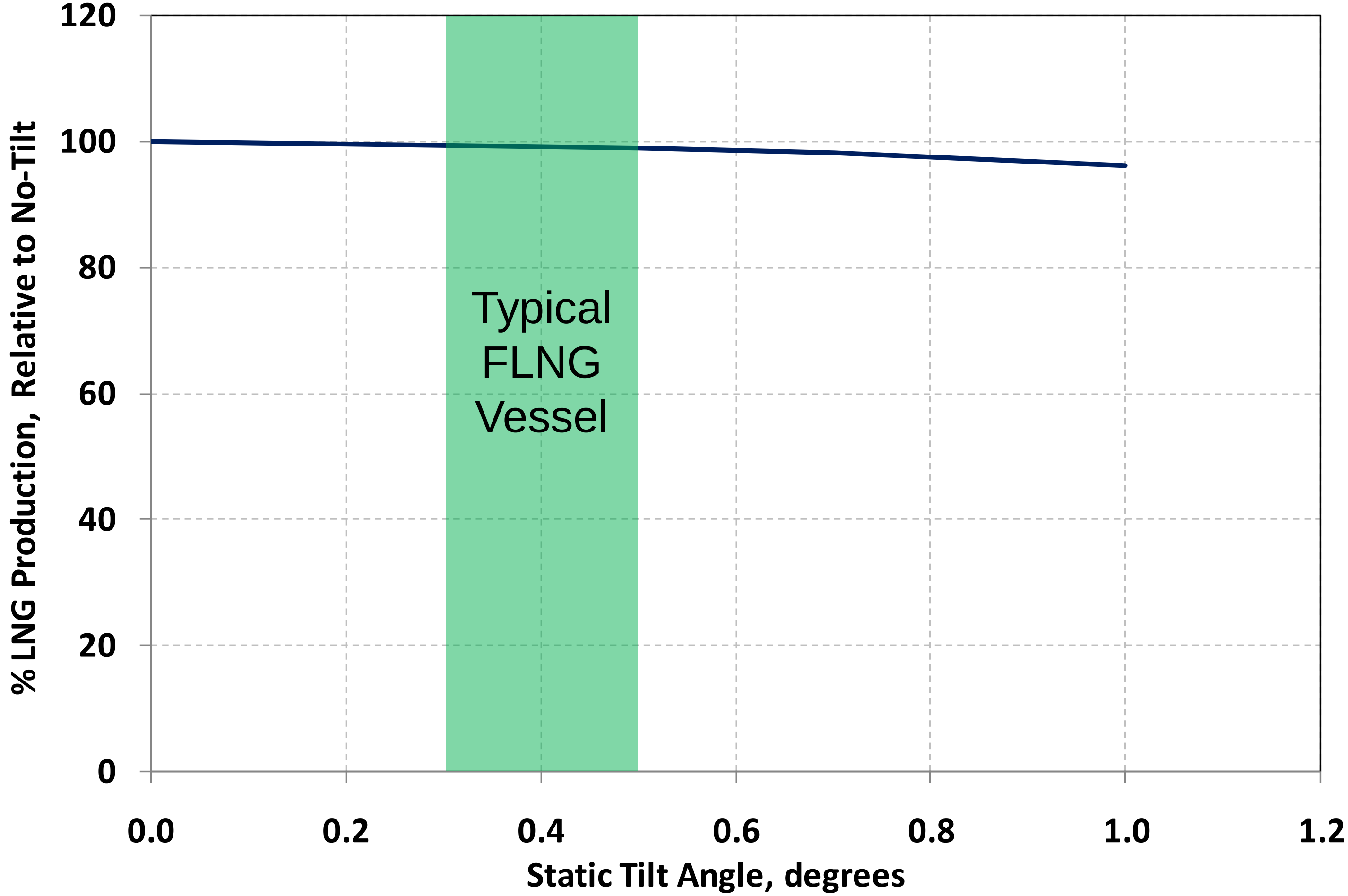
- Duty and temperatures
- Bundle geometry
- Shell-side flow

Design for FLNG Motion

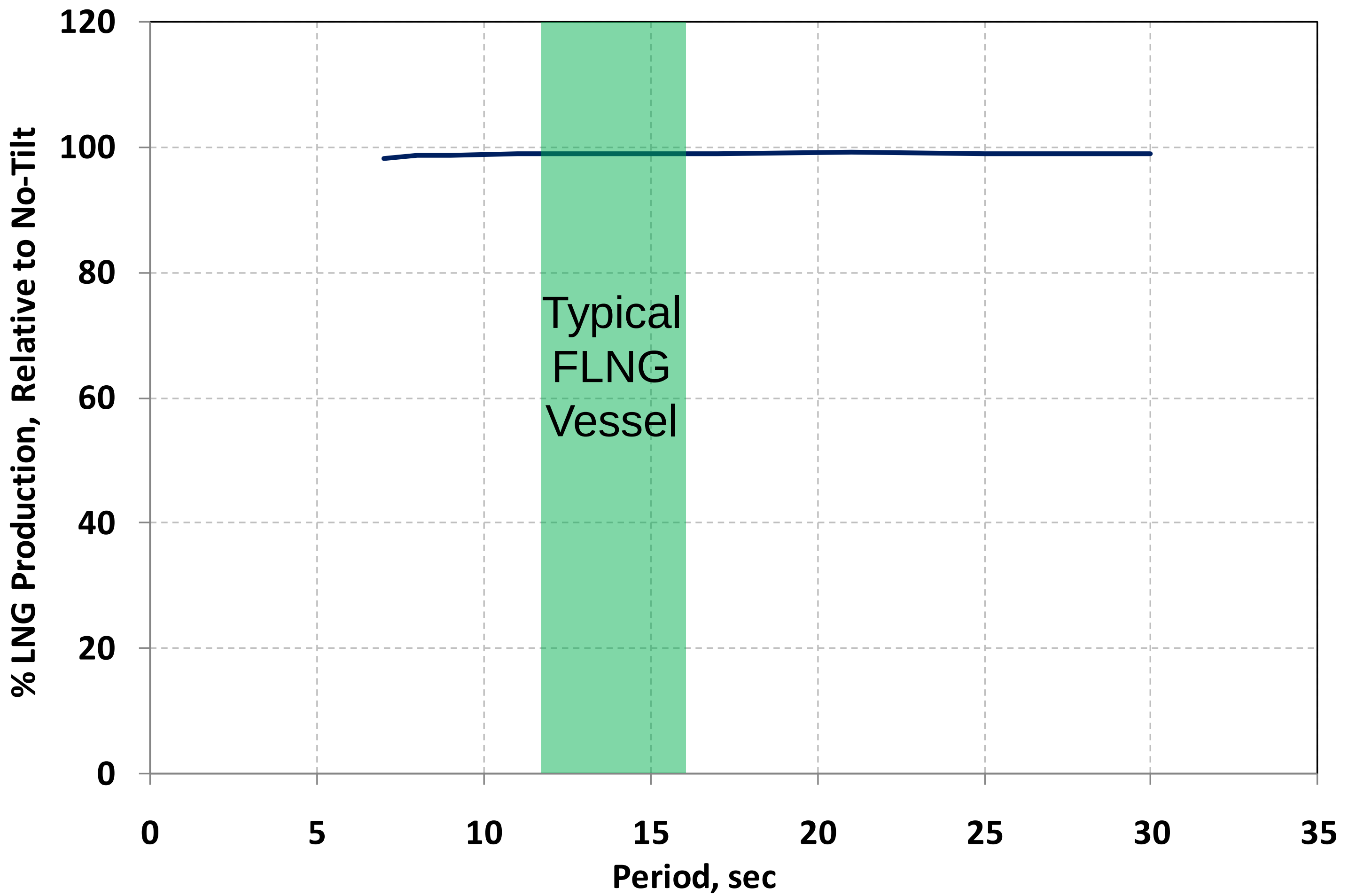
- Exchangers are typically designed for full production at maximum ship motions expected majority of the year (e.g. ~99% occurrence probability)
  - Typical design point: Pitch/roll of 3 degrees or less

- For higher ship motion:
  - Have analyzed for ship motions up to 6 degrees pitch/roll and these can be accommodated with small impact
  - At larger motion, heat exchangers continue to operate with possible reduction in production or increase in power requirement

Sensitivity to Static Tilt



Sensitivity to Oscillation Period



Summary

- Air Products offers a robust wound coil exchanger design and a selection of process cycles for FLNG
- Air Products has developed a detailed approach to understanding impact of motion on the heat exchanger:
  - Both experimental and theoretical
  - Includes the significant inputs and design parameters
  - Effects are quantified
- For typical FLNG motion
  - Effects are mitigated by proper bundle design, using Air Products' enhanced design tools

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Thank You