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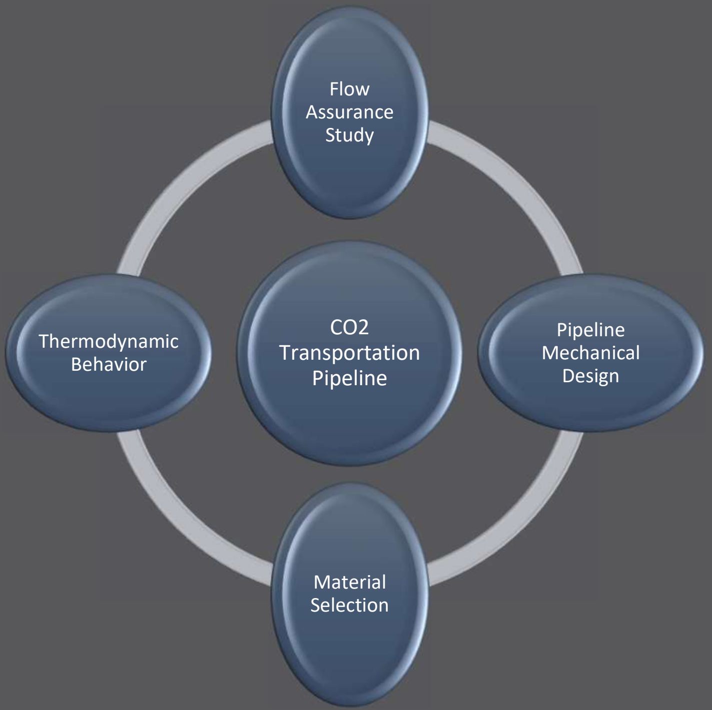

Agenda

- Overview of CO_2 Pipelines for CCUS
- CO_2 Transportation Challenges
  - Flow Assurance Study
  - Mechanical Design
- Requalification of Existing Pipelines
- Conclusions

Overview of CO2 Pipelines for CCUS

Carbon Capture Utilization and Storage (CCUS) is claimed as a solid climate mitigation strategy, in particular for the most challenging decarbonisation projects.

- **According to the International Energy Agency (IEA), CCUS accounts for 15% of the cumulative emissions reductions needed globally by 2050.**

- **An essential role in blue hydrogen production and energy transition.**

- **CO2 transportation methods:**
  - ✓ **Pipeline**
  - ✓ **Truck**
  - ✓ **Ship transportation**

  Pipeline transportation has several advantages over the other means of transportation.

Overview of CO2 Pipelines for CCUS

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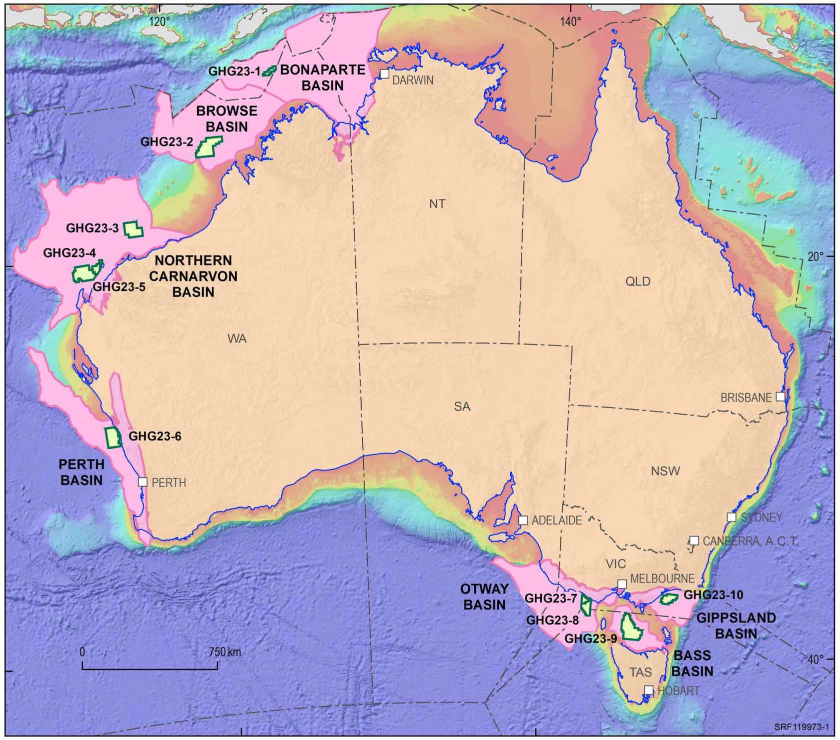
Australia is well positioned to be at the forefront of the global scale-up of CCUS projects:

- Some of the world's best deep sedimentary basins
- Blue hydrogen production capability



Overview Maps Showing the 2023 Offshore Greenhouse Gas Storage Acreage Release Areas [1]

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CO2 Transportation Challenges

CCUS pipelines are different from EOR pipelines:

- Transport at lower costs
- Transport in the presence of impurities

Impurities are due to:

- Capture and separation technology used in the CCS chain.
- Fuel used as the CO2 production source.

- **H2O, H2S, CO, O2, CH4, N2, Ar, H2, SOx, NOx are common impurities expected in CCUS CO2 pipelines.**
- Impurities cause challenges in: **Pipeline design**, **Flow assurance**, **Material selection**, **Corrosion prediction**, **Pre-commissioning**, **Operation and Maintenance**, **Compression performance**, **Distance between booster stations**, **HSE**, ...

Impurities	Post-Combustion	Oxy-fuel Combustion	Pre-Combustion
CO_2	> 99%	> 90%	> 95.6%
O_2	< 0.1%	< 3%	trace
H_2O	0.14%	0.14%	0.14%
H_2	trace	trace	< 3%
H_2S	trace	trace	< 3.4%
CH_4	< 0.01%	–	< 0.035%
N_2	< 0.8%	< 1.4%	balance
Ar	trace	< 5%	< 0.05%
SO_x	< 0.001%	< 0.25%	–
NO_x	< 0.001%	< 0.25%	–

Expected Impurities from Different CO2 Capture Technologies [2]

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Importance of Flow Assurance

Removing impurities down to very low concentrations creates significant energy requirements and cost penalties.

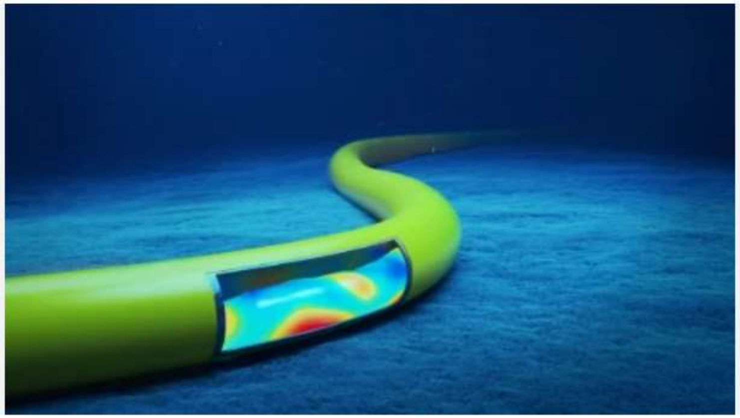
↓

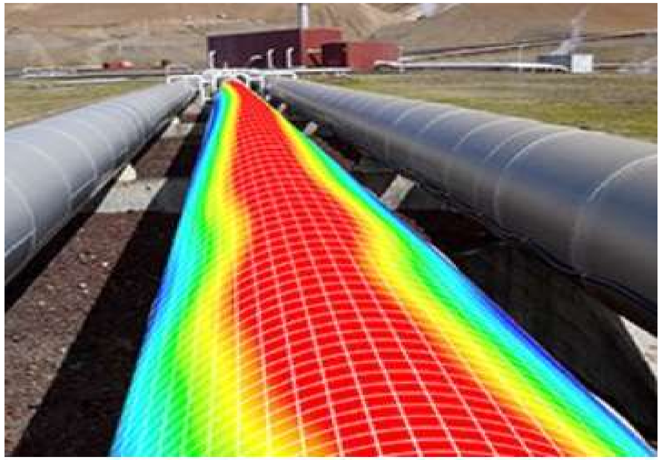
Impurities like N2, O2, H2, and CH4 change the properties of the stream, system bubble point, viscosity, pipeline size, pipe WT, compression performance and distance between booster stations.

Phase behaviour and the impact of impurities on thermo-physical properties affect OPEX and CAPEX.

Accurate Flow Assurance study and identification of operating envelops to assess the potential upsets triggering:

- Drop out of water
- Corrosive liquids
- Temperature drop





Importance of Flow Assurance

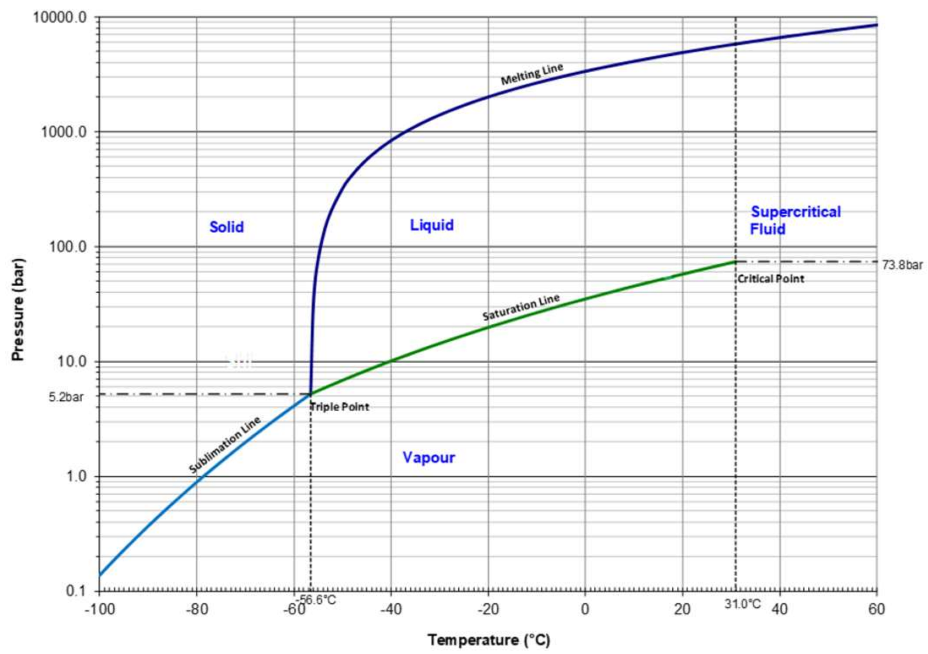
CO2 can be transferred as:

- **<u>Gas</u>** ➡ Large Pipe Size Requirement
- **<u>Liquid (Low Pressure)</u>** ➡ Equipment for Cooling the CO2 and pipeline Insulation Requirement
- **<u>Supercritical or Dense</u>**

The supercritical phase is the most cost-effective method of CO2 transport.

100 t/h (20 barg @ 30 °C) ~ 58000 m^3/day

100 t/h (100 barg @ 30 °C) ~ 3400 m^3/day



Phase Diagram for Pure CO2 [5]

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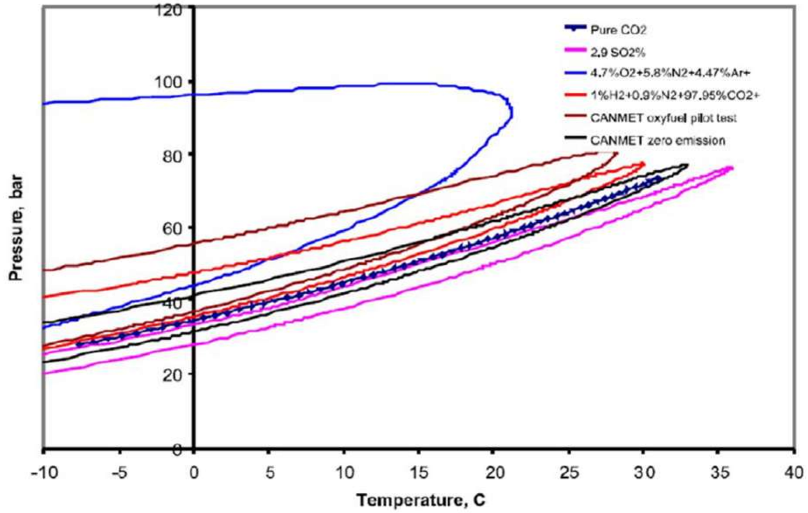
Importance of Flow Assurance

Effect of Impurities on Thermodynamic Behavior

<u>Impurities change the critical pressure of CO2</u>

To reduce the impact of impurities on the possibility of a two-phase flow, the operating pressure of the CO2 transport pipeline needs to be increased.



Phase Envelopes for Pure CO 2 and CO2 Mixtures [4]

Any uncertainties in thermodynamic behaviors have technical and cost implications on the hydraulic system of CCS pipeline systems.

Importance of Flow Assurance

Equation of State and Thermodynamic Modeling

Span & Wanger is the most acknowledged EOS for pure CO2.

Peng Robinson and Span & Wagner:

- For rich CO2 streams
- High accuracy for mass density prediction

GERG-2008:

- High accuracy for gas-phase and supercritical
- Deficiencies in phase equilibrium and gas solubility

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Importance of Flow Assurance

Impurities and CO_2 Transportation

In cases with significant levels of impurities, the applied EOS should be tuned using experimental data, particularly for:

- Water solubility prediction
- Water dropout prediction
- Hydrate formation evaluation

Importance of Flow Assurance

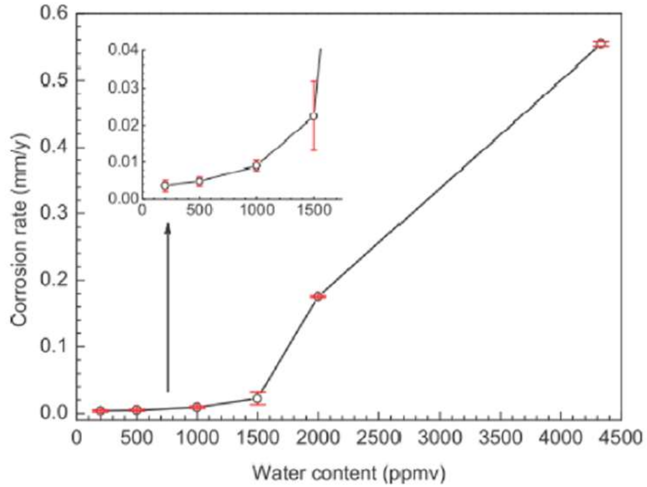
Impurities and CO2 Transportation

Free water (H2O) is the most undesirable of impurities. It can result in:

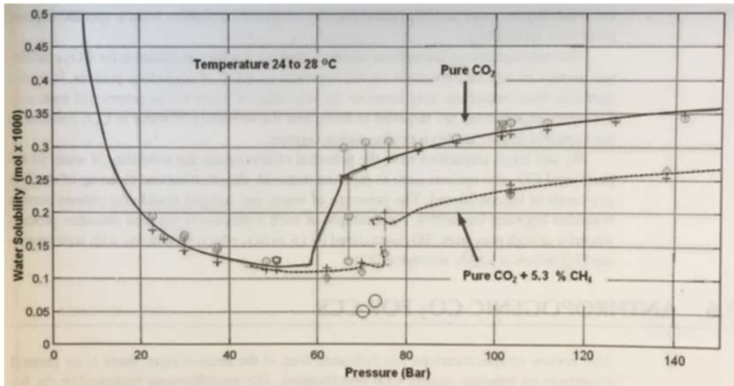
- Hydrate formation,
- Corrosion problems.

Water solubility in CO2 is affected significantly by the fraction of different chemical components.

- CH4, N2, H2O and amines.



Variations of Corrosion Rate with Water Content Exposed [10]



Solubility of Water in Pure CO2 and a Mixture of CO2 and 5.31% CH4 at 25°C [5]

Importance of Flow Assurance

Hydrate Formation

- Operating away from the hydrate formation zone is essential.

- In situations of extremely rapid depressurisation, even a low water content level could be enough for hydrate formation.

- In the case of a system shut-in, the risk of hydrate formation is low if the CO_2 stream water content is below 250 ppm.
- Therefore, the specification of the drying condition of CO_2 is important.

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Importance of Flow Assurance

Depressurisation

- Transportation of CO_2 in the dense phase presents low-temperature risks during the depressurisation

    - Risk of pipe fracture
    - Risk of hydrate formation

- During the depressurisation, particularly around the peak elevation point, the presence of localised cold metal temperatures should be considered.

Mechanical Design

DNV RP F104, and ISO 27913 are specific codes for CO2 pipeline. They are applicable for both onshore and offshore pipelines.

ASNZS 2885.1, Part 1 Appendix T is a guidance on CO2 pipeline design.

From the structural and mechanical point of view, CO2 pipelines are largely similar to traditional oil and gas pipelines.

For example, for WT calculation conventional failure modes as defined in DNV ST F101 should be followed, and the required WT should be balanced between:

- ✓Pressure containment,
- ✓Hydrostatic collapse,
- ✓Combined loading criteria.

But there are some points of differences between CO2 and traditional oil and gas pipelines, which need more attention:

- ✓Material selection
- ✓Ductile Fracture Propagation (DFP)

DNV

RECOMMENDED PRACTICE

DNV-RP-F104

Edition February 2021
Amended September 2021

Design and operation of carbon dioxide pipelines

INTERNATIONAL STANDARD

ISO 27913

First edition
2016-11-01

Carbon dioxide capture, transportation and geological storage — Pipeline transportation systems

Captage du dioxyde de carbone, transport et stockage géologique — Systèmes de transport par conduites

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Mechanical Design

Material Selection

Due to the operational condition of CCUS Co2 pipelines, the following subjects need special attention during material selection:

- Fracture toughness (due to the risk of DFP)
- Sufficient low-temperature toughness
- Corrosion model (Due to uncertainty of existing models in predicting the corrosion mechanism in the presence of impurities)
- Effect of rapid gas decompression and potential impurities on internal liners, especially the polymer liners

Running Ductile Fracture in Dense CO2 Pipeline – Experimental Test [9]

Mechanical Design

Ductile Fracture Propagation (DFP)

- **DFP is expected when:**

  Decompression pressure wave speed < crack propagation speed

- **In CCUS CO2 pipelines operating at dense phase, the pressure drop from dense phase to two-phase flow is more onerous than the transition to gas phase.**

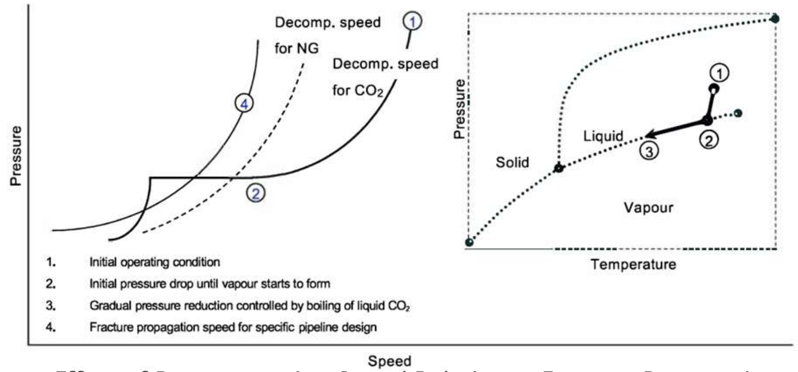
Which causes potentially indefinite cracks, imposes high repair costs, and makes repair not practical in offshore pipelines.

Three possible options to assess this concern:

✓Expensive full-scale tests,

✓Complex CFD/FE analysis,

✓Simplified models and standards.



Effect of Decompression Speed Relative to Fracture Propagation Speed with Inset Showing Phase Envelop for Pure CO2 [5]

Mechanical Design

Ductile Fracture Propagation (DFP)

The available simplified methods to evaluate the potential of running ductile fracture in CCUS CO2 pipelines are:

- Battelle Two-Curve Method (BTCM), ISO 27913 proposes two modifications to BTCM.

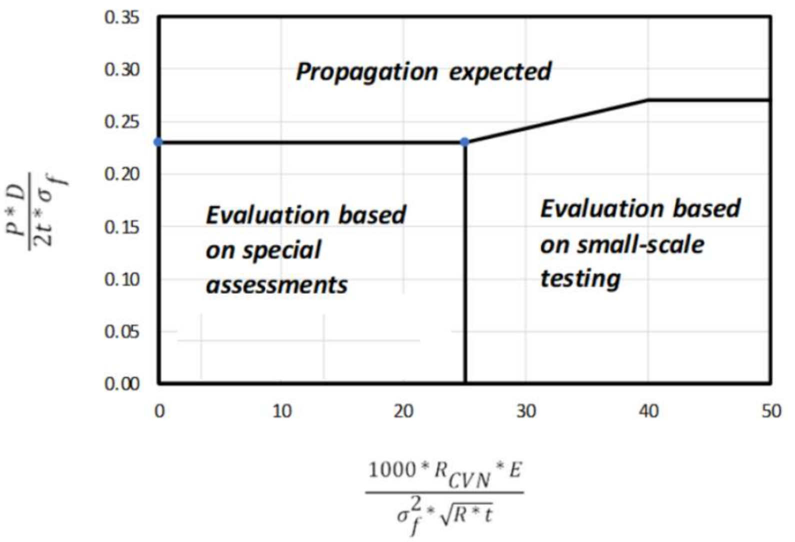
It is only applicable to an upper threshold of 330 J for CVN based on ISO, and less than 150 J based on ASNZ 2885.1

-DNV has used the results of experimental tests on dense phase CO2 pipelines to create this figure to evaluate Running Ductile Fracture potential. Based on its findings, this graph has been categorised into three different zones:

✓Propagation is expected.

✓Evaluation can be expected based on small-scale testing.

✓Evaluation requires further special assessment (full-scale propagation tests)



Scheme for Evaluation of Running Ductile Fracture Arrest in Dense CO2 Pipelines [5]

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Mechanical Design

How to mitigate/control the DFP risk:

- Material properties (CVN)

- Higher CAPEX
- Feasible for new pipelines but less feasible for existing pipelines

- Increase WT

- Higher CAPEX
- Feasible for new pipelines but less feasible for existing pipelines

- Change of operating condition (pressure, temperature, composition)

- Feasible for both new and existing pipelines
- Should be verified by detailed hydraulic analysis (thermodynamic uncertainties)

- Installation of crack arrestors

- Feasible for new pipelines
- Unfeasible for existing offshore pipelines
- Sometimes feasible for existing onshore pipelines

Requalification of Existing Pipelines

Existing gas pipelines may be repurposed for CO2 gas phase transport. But dense phase CO2 requirements in terms of operating pressures and CVN usually make the conversion less feasible.

The existing pipelines shall be assessed against the following criteria:

Life extension assessment:

- The service lifetime of the existing pipelines is uncertain
- ILI and Integration Assessment

Service change effects assessment:

- Material resistance against RDF
- Material compatibility with CO2 transportation (especially for non-metallic components)
- Established operational envelope for intended CO2 fluid characteristics
- Low-temperature exposure effect on the adhesion and durability of external coating
- Compliance with safety regulations to carry CO2

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Conclusions

- CO_2 transmission pipeline has an essential role in the CCUS industry.

- CO_2 pipeline design has a number of challenges, which rely heavily on the thermo-physical properties of the flowing fluid.

- The main concerns associated with the transportation of CO_2 are:

  - Suitable equation of state due to impurities in the CO_2 stream
  - Accurate flow assurance study especially in hydrate formation, corrosion and depressurisation
  - Material selection for corrosion and material selection for ductile fracture
  - CO_2 is an asphyxiant that is heavier than air. It can travel large distances at lethal concentrations from the pipeline after rupture.

- The increasing interest in CCUS is creating momentum around CO_2 properties modelling and the availability of experimental tests and results.

- The availability of more experimental data leads to increasing the accuracy of thermodynamic behaviour prediction and, therefore, more reliable mechanical design.

- CO_2 transportation pipeline CAPEX and OPEX are considerably dependent on thermodynamic behaviour prediction.

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