Project: Cryogenic Spill Protection Design Guidance

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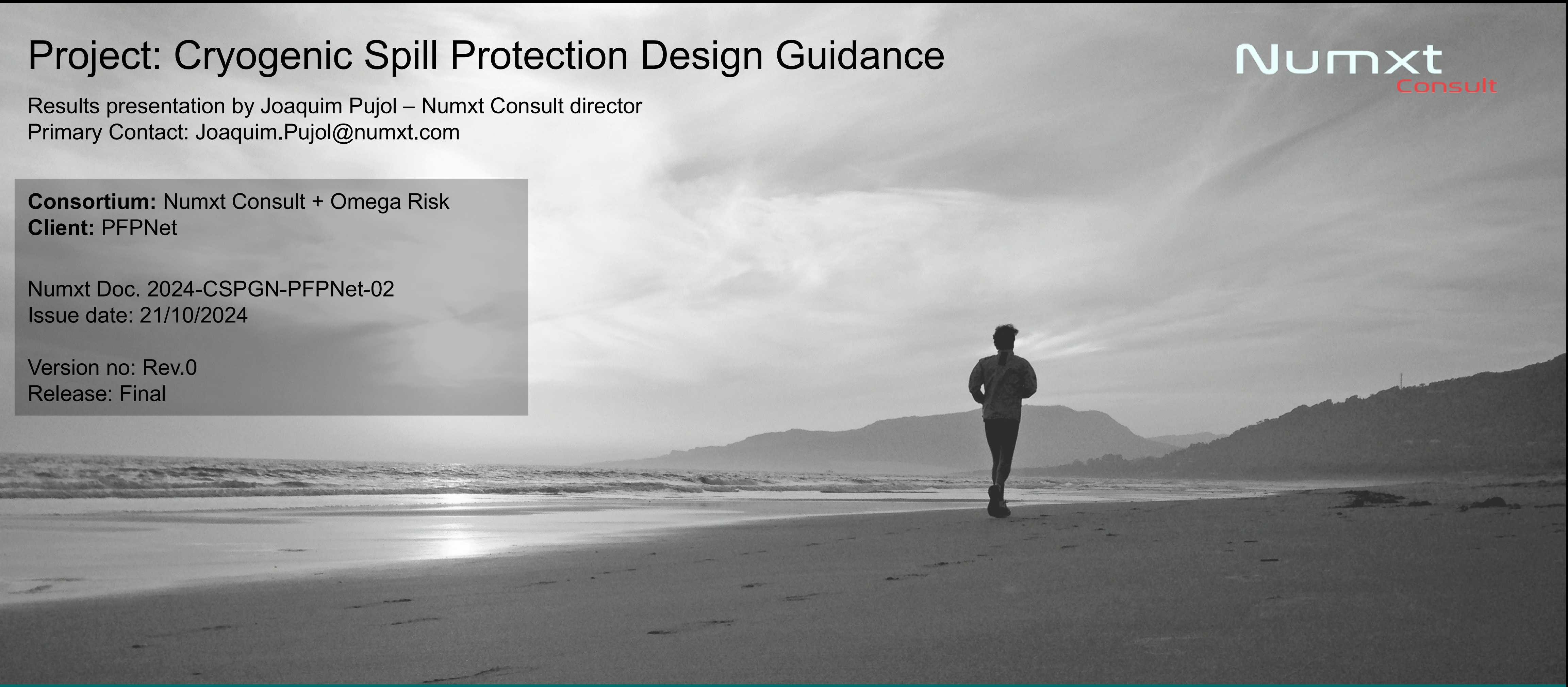

...The Industry can't afford to be complacent!

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Ship Operator: Analysed + Shared lessons

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LATEST JOBS Dry cargo Shipbrokers-Senior Dry cargo Shipbrokers-Dry cargo Junior Shipbroker

LNG industry 'can't afford to be complacent'

Mitsui OSK Lines (MOL) chose not to make a press statement regarding the Fuwairit's cargo release in June 2015.

21 July 2016 17:00 GMT UPDATED 21 July 2016 17:00 GMT

By Lucy Hine London

AHJ, Terminal Operator, Terminals Society: *...we don´t have information to share*

Telegraph article (Sept 2015)– nautilusint.org:
"...complex fracture of the port upper deck walkway and extended overside to the hull"

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BARCELONA: LNG vapour released from the Fuwairit at Engas' terminal.

MOL outlines lessons learned from LNG ship cargo release

Outfit speaks about year-old incident at Barcelona terminal after details permeate out to wider industry

21 July 2016 17:00 GMT UPDATED 21 July 2016 17:00 GMT

By Lucy Hine London

Audience poll

Question: Would you consider these type of events a …?

A) Major incident

B) Near Miss

There are other cases…

Presentation status

<u>CSP Design Guidance document:</u>

- Introduction
- Cryogenic hazards
- Literature survey update
- Cryogenic spill releases
- CSP design methods for SCEs
  - Cryogenic impact zone
  - Simplified Cryogenic Risk
  - Detailed Cryogenic Risk
- Structural mechanics and materials
- Specific aspects

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- Omega Risk

Goal of the document:

- Provide guidance on cryogenic hazards and risks (focus on brittle fracture)
- CSP design specification

Approach followed:

- Be comprehensive without being exhaustive (nerdy)
- Cover wide range of aspects, methods and key factors in cryogenic spill risk analysis
- Document audience: Operators, EPCs, AHJs, CSP Manufacturers, Insurers, ...

Cryogenic substances

- Cryogenic fluids are substances processed, handled or stored below their boiling point at low temperatures.
- Can be hazardous to People, Asset and Environment

Table 1: Example of common cryogenic fluids

Cryogenic Fluid	Boiling Temperature [ºC] @ 1atm	Maximum DTBTT Carbon Steel [ºC]
CH_4	-161	-40
LN_2	-196	-40
LH_2	-253	-40
LOX	-219	-40
C_2H_6	-88.3	-40
CO	-192	-40
CO_2	-78.5	-40

Cryogenic spill hazard

- This guidance focuses on Cryogenic Risk to the Asset:
  - Cryogenic brittle fracture of carbon steel and
  - Estimation of CSP specs for exposed SCE (Design stages)

Cryogenic hazard to Asset:

When a sustance can locally *drop the temperature of the steel of a structure, pipe, equipment, vessel and/or deck below the steel's characteristic Ductile To Brittle Transition Temperature (DTBTT)*

Safety Critical Element (SCE)

Defined as "any part of the facility, plant or computer program, the failure of which could cause or contribute substantially to a Major Accident Hazard (MAH) or the purpose of which is to prevent or limit the effect of a MAH" (Energy Institut 2020)

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Regulations, Codes and Standards (examples)

In some standards, the cryogenic spill hazard is *explicitly mentioned (e.g. cold burns and/or brittle fracture)* but in some others, needs to be considered *implicitly through the accident escalation potential* requirements.

Regulations	Code and Standards: Risk Management	Code and Standards: Offshore and Onshore assets	Code and Standards: LNG Marine and Bunkering	Code and Standards: Cryogenic Spill Insulation	Code and Standards: Structural Design
Seveso Directive 2012/18/EU	ISO 31000	ISO 20257	IGC	ISO20088-1	Eurocode 1990
PHMSA 49 CFR Part 193	ISO 31010	ISO 16901	IGF	ISO20088-2	Eurocode 1991
COMAH	ISO 17776	ISO 28460	ISO 18683	ISO20088-3	Eurocode 1992
SOLAS	NORSOK Z013	ISO 16903	ISO 20519	...	Eurocode 1993
...	...	BS EN1473	...		...
		IEC 61511			
		NFPA 59A			
		CSA EXP276.2:19			
		...			

Safety Agencies, Class rules and Recommended Practices (Similar comments)

Cryogenic test programmes and JIPS (examples)

Even though LNG has been around since 50-60s, and major LNG experimental activities were run, only recently test programmes focussing on near field source term models, cryogenic spill hazard and brittle fracture have been conducted (Energy and Marine sectors)

References are mainly LNG, but be aware of other cryo substances (e.g. LCO2, LH2, LN2)

LNG hazards understanding	Cryogenic + near field focus
Avocet series (1978)	SAND2011-3342 (2011, Kalan & Petti)
US Burro (1980)	JIP FLNG Cryogenic Spillage Protection (2013-2015)
Shell's Maplin Sands (1980)	JIP on liquid jets and 2-phase droplet dispersion (2002-2009)
US Coyote (1981)	HSL LH2 (2012)
US Falcon (1987)	JIP Sparcling (2020)
MKOPSC (2009)	PHMSA (2022-2026)
DNV small scale LNG (2016)	Shell LH2 (2023)
...	...

SAND2011-3342 (2011, Kalan & Petti) – Test 16

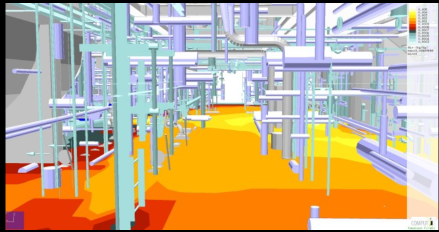
For the privately sponsored tests (e.g. JIPs), one needs to contact the programme lead to discuss access to the data (some of these JIPs led also to ISO standards e.g. ISO20088 series).

Cryogenic Guidance notes, technical papers and focus groups (examples)

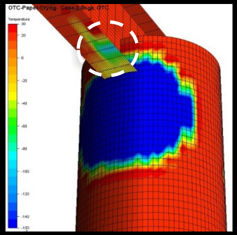
The LNG industry, specially the FLNG projects, spurred developments in the cryogenic spill risk management. Guidance notes, technical papers, focus groups were created in the 2010s to provide engineering guidance and risk-based solutions that would meet the AHJ, International/National regulations and specific Clien requirements.

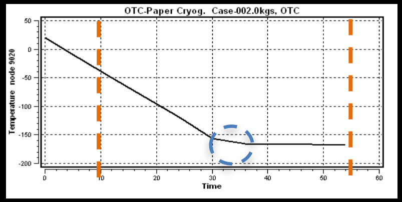
Some references here:

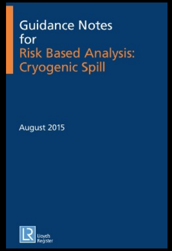
Cryogenic spill guidance notes	LR's Guidance Notes for Risk Based Analysis – Cryogenic spill (2015) PFPNet Cryogenic Spill Protection Requirements Part 1 (2023)
Cryogenic technical papers	Advanced Cryogenic Structural Collapse Analysis I and II, *Design for protection from cryogenic releases, Safety improvements in FLNG, How to estimate performances of cryogenic spillage protection materials, Simplified method to define the cryogenic Spill Hazard, Optimisation of Cryogenic Spill Protection Insulation Thickness, New approaches for testing and predicting structural integrity, Advanced Methodology of Structural Redundancy Analysis for Optimizing Passive Fire Cryogenic Spill Protection, Case study of structural redundancy analysis for optimising cryogenic spill protecton, Validation of KFX, Liquefied Natural Gas as a New Hazard, Cryogenic spill protection and mitigation ...*
Technical Meetings & Focus groups	FABIG TM92 - Design against cryogenic releases



J.Pujol, R. Kleiveland (ESREL2015): 3D cryogenic risk analysis







FABIG TM92 and Cryo presentations

J.Pujol et al (OTCAsia 2016): 3D cryogenic spray and 3D cryogenic heat loading of structure. Cooling time

Cryogenic Brittle Fracture incidents (search: LNG)

Minerva (2018):
Freezing effects of an LNG leak caused numerous 300-2700mm cracks in carbon steel outer tank walls. Suspected of 11 similar incidents since 2008

Tradewinds article (July 2016):
(LNG spill) ….incident resemblance with 2001's GolarLNG "Khannur"

Telegraph article (Sept 2015)–
nautilusint.org: "...complex fracture of the port upper deck walkway and extended overside to the hull"

Milford Mercury (Apr 2011):
'Minor' LNG leak confirmed…cracks and damage on deck…
(MCA): There is a responsibility of the master to inform the port authority- on this occasion it did not happen and we only became aware of this event after. "

Report for LIPA (2007) :
"...Cargo tank overflow due to valve failure caused severe cracking of steelwork"

Aria database:
(LN2 plant, 2004) …Cold gaseous or liquid nitrogen entered into the buffer tank made of carbon steel, which did not withstand the cold and bursted (cryogenic embrittlement of metal).

Port Delfin report :
(LNG Aquarius, 1977) …Overflowing of cargo tank. LNG overflowed through vent mast.

Port Delfin report :
(Jules Verne, 1965) … Overflowing of cargo tank. Tank cover and adjacent deck fracture

SIGTTO - LNG spillage: fracture of 16mm thick deck stiffener

Roue (2011)- Steel fractures on actual LNG assets due to cryogenic spills

Cryogenic Brittle Fracture incidents (search: LNG)

- **Public domain sources (only)**
  - 62 cryogenic spill incidents (LNG) identified: from East Ohio Gas LNG (1944) to Hammerfest LNG (2023-2024). The incident descriptions are short (sometimes few words)
  - 17 incidents (25%) reported explicitly carbon steel brittle fracture due to cryogenic load
  - Mostly at LNG terminals: Terminal-Ship interface (Marine + Energy AHJs)
  - Largest property damage (cause cryogenic brittle fracture): 1007 MUSD (natural gas plant)
    - Escalation of brittle fracture event: 2 killed + 8 injured
- Other sources (private):
  - Aware more information is in private industry organisations. Upon request, the feed-back was: *"we do not have information to share".*

Esso's Longford natural gas plant (1998):
Failure of lean oil pump leads to heat exchanger experiencing temperatures as low as -48C. Ice formed on the unit due to cryogenic liquid arriving in a section of the plant not intended to contain cryogenic fluids. Decided to resume pumping heated lean oil into the exchanger at 230C. Temperature differential caused brittle fracture in an exchanger and immediate release of 10m3 of HC vapour which ignited and killed 2 people and injured 8 more.

Source: Minerva + Marsh

Types of cryogenic spill releases – CSP specs

- Pressurised cryogenic liquid or 2-phase jets (sprays)
- Cryogenic pools (low pressure liquid)
- Cryogenic vapour releases

Why important to differentiate:

- The strength of the heat transfer to the asset for cryogenic liquefied substances depend on whether a vapour phase release, a jet release (pressurised liquid or 2-phase) or low pressure liquid spill contacts the unprotected SCE. Releases with liquid content will cool down faster the steel than vapour.

- Cryogenic liquid (pressurised or not) and 2-phase releases are prioritised. For cryogenic asset risk management, calculating **the liquid fraction is a cryogenic risk governing factor.**

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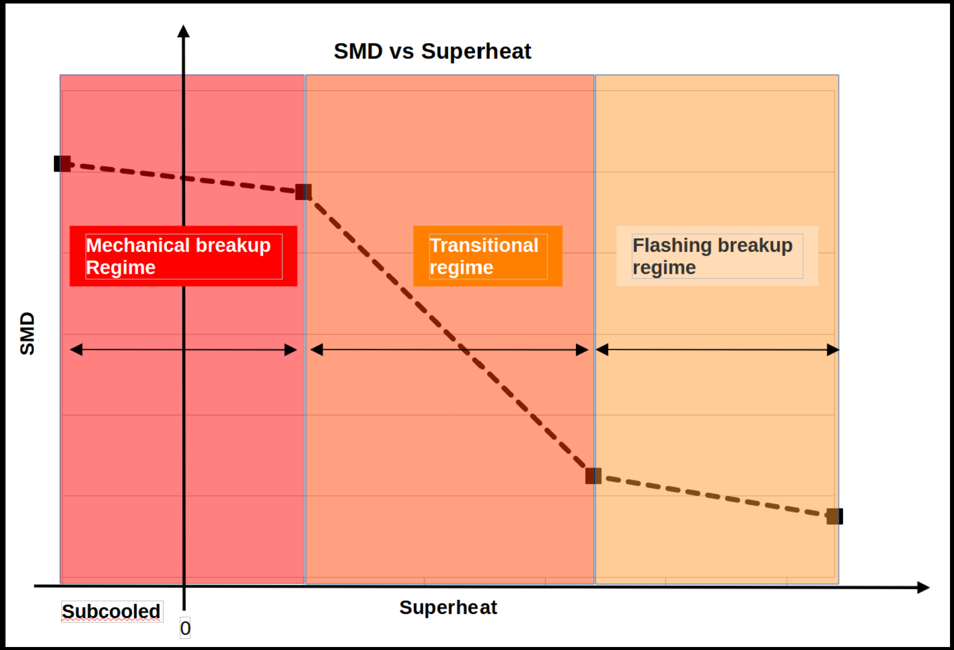
Cryogenic jets: liquid or 2-phase

- The cryogenic hazard length of the liquid droplets will depend on the strength of the liquid atomisation.
- Both operating pressure and temperature drive the breakup regime of the spray:
  - Mechanical regime
  - Thermodynamic (flashing) breakup.
- The Sauter Mean Diameter (SMD) represents the droplet size
  - The smaller the SMD, the shorter the travel distance
- This has implications on the potential SCEs impacted.



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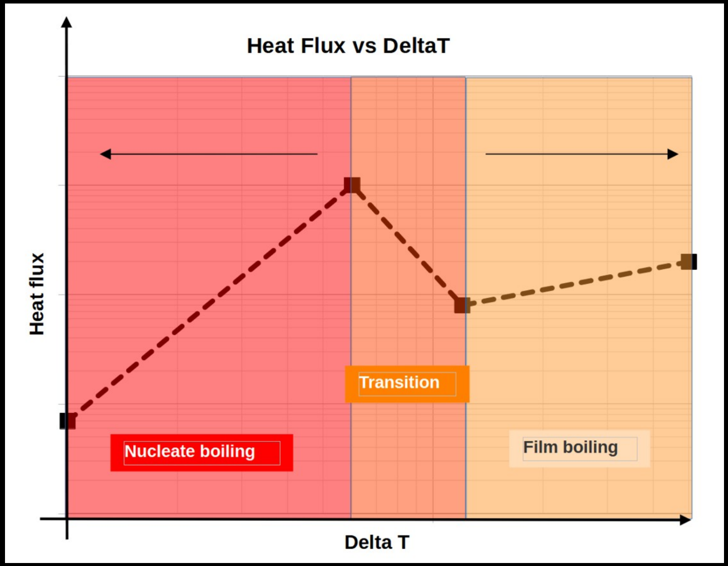
Cryogenic pools

- Cryogenic spills at very low operating pressures, which create a cryogenic running pool on horizontal plated surfaces (e.g. main deck).
- The potential exposed surfaces will be below the leak point (layout implications)
- The cryogenic liquid spread is gravity driven rather than directional jet (layout implications)
- Boiling regimes:
  - Film boiling: high temperature differential between the cryogenic liquid and the carbon steel. Boiling creates a thin layer of cryogenic gas reducing the heat transfer to the steel (slower cooling)
  - Nucleate boiling: cryogenic vapour layer has collapsed, more direct contact liquid vs steel, leading to a quicker approach to DTBTT
- The film boiling layer is an unstable equilibrium mode, can get unstable quickly



Cryogenic vapour

- Normally omitted in early stages, as the cooling is slower than liquid (ref previous figure)
  - → The SCE needs to be exposed for a minimum duration to be at risk of brittle fracture
- Lower vapour cooling rates mean emergency safety measures can help mitigating the cryognic vapour risk
  - Fast detection, fast activation of ESDs, BD activation will reduce exposure time
- External wind will heat the cryogenic vapour
- A deterministic approach might be used to assess relevance for the design. If yes, include in the probabilistic analysis, if not, discard.
- Note: all cryogenic liquid leak will generate cryogenic vapour

Deterministic approach: Cryogenic impact Zone

Risk = consequence x frequency

Introduction:

- Becomes available when the jurisdiction or industry sector *prescribes the design accidental release* (e.g. 1-2 inch hole diameter leak) or accepts the asset to be *designed against "credible" accidental releases*.
- The CSP analysis is then simplified to a **cryogenic spill consequence analyses.**

Approach:

- Characterise the spill: pressure, temperature, leak composition, single phase or two-phase, inventory, mass flow. Based on the targeted SCE, define leak location, direction (if jet) and ambient wind conditions.
- Transient leak profile: calculate the accidental leak rate vs time (incl. emergency systems activation).
- Advanced 3D consequence: liquid/2-phase jet, pool or vapour CFD modelling of the spill vs time (include fluid-structure interaction).
- Identification of the SCEs impacted (yes/no) and their exposure duration (min).

Different areas/modules (hence SCEs) will have different prescribed loads, and if the ACH approves "credible" releases, discussions about what "credible" will come in.

Deterministic approach: Cryogenic impact Zone

Risk = consequence x frequency

Outcome:

- For each leak location, check if the SCE is reached and based on the leak profile for how long.
- Each SCE would be protected against its longest cryogenic spill duration per spill type (jet, pool, vapour).
- The conservativeness of the approach is reduced by modelling advanced consequence: 3D CFD models.

Prescribed leak (P, T, Comp, Hole,...)	Leak location	Type of release	Jet direction	Wind (direction, speed)	SCE1 exposed (Y/N), Duration	SCE2 exposed (Y/N), Duration	...
Leak 1	Loc_A	Jet	East	North, 5m/s	Yes, 5min	No, -	...
…	…	…	…	…	…	…	…
Leak 2	Loc_B	Pool	NA	West, 2m/s	No, -	Yes, 20min	…
…	…	…	…	…	…	…	…

- Knowing the cryogenic impact zone and the exposure duration through 3D CFD consequence, enhances the effectiveness of the cryogenic mitigation measures, e.g. areas with stainless steels, location and sizing of drains, CSP materials, specs…

Deterministic approach: Cryogenic impact Zone

Risk = consequence x frequency

Application:

- Assets that fall outside the Major Accident Hazard regulations (e.g. Seveso and the likes) could prefer this deterministic approach more often (e.g. marine assets, refuelling operations).
- In the energy sector, when the jurisdiction prescribes the accidental release, the cryogenic spill analysis is followed by deterministic structural redundancy studies. Common seeing the duty holders going beyond regulatory compliance and topping up with additional risk studies for internal purposes. If an accident occurs, their business is damaged.
- New industry sectors with limited certainty about their operational frequencies may choose to conduct a deterministic consequence study for design purposes. Too much uncertainty on the leak frequencies to conduct a probabilistic risk study.

Recommendation:

- Risk is the combination of frequency x consequence . By understanding 3D CFD consequence, one of the risk drivers is mastered.
  - More robust design (risk mitigation measures). At early stages: layout redesign, segregation by walls,…
- If jurisdiction requires this approach and proves to be too conservative (frequency is to be factored in), the 3D CFD consequence is reused and the design has already learnt.

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Deterministic approach: Cryogenic impact Zone

Risk = consequence x frequency

Factors to control:

- Representative leak:
  - When the design spill is pre-defined, not uncommon to focus on the same failure cases for Explosions as for Cryogenics.
  - Focus on very high pressure LNG releases will generate large explosions but will likely miss the cryogenic brittle fracture risk
- Ignition probs and ignition times:
  - Current cryogenic spill risk studies provide CSP specs (e.g. exposure durations) assuming no ignition to ensure SCE functional integrity regardless of ignition time.

Probabilistic approach: Simplified cryogenic risk

Risk = consequence x frequency

Introduction:

- Quick screening methodology aiming at giving answer to the following questions:
  - Which SCEs are at risk of cryogenic brittle fracture? Potential escalation?
  - What governs the cryogenic risk: consequence or the likelihood?
  - What is the most effective risk mitigating measure (from a cost-benefit analysis)?
- Uses preliminary inputs and simplified models,
- One screening method for cryogenic risk is described next.
  Note: variations exist even within simplified cryogenic risk analysis (e.g. hybrid models).
- Common approach for early design: Concept, (FEED)

Both risk drivers estimated: a) Frequency and b) Consequence (simplified)

Being a simplified approach → Be aware of the boundaries of the method

Probabilistic approach: Simplified cryogenic risk

Risk = consequence x frequency

Study basis:

- Project acceptance: Cryogenic brittle fracture impairment criterion:
  - Definition: *Unprotected carbon steel would be at risk of brittle fracture if an accidental spill drops the steel's temperature below its DTBTT (e.g. -29C).*
  - Simplified cryogenic risk implementation:
    - **Liquid or 2-phase cryogenic spills**: Immediate impairment of the SCE is assumed if unprotected steel is reached by a spill below the steel's DTBTT.
    - **Vapour spills:** If unprotected steel is reached by a vapour release below DTBTT, a minimum exposure duration required (project assumption)

  Note: If cryogenic solid particles are leaked, start assuming immediate impairment (TBD): solid impact + cryogenic

- Project acceptance: Cryogenic frequency impairment criterion:
  - The frequency criterion defines cryogenic specs the teams are going to design against: 10E-4/yr, 10E-5/yr,…

Probabilistic approach: Simplified cryogenic risk

Risk = consequence x frequency

Study basis:

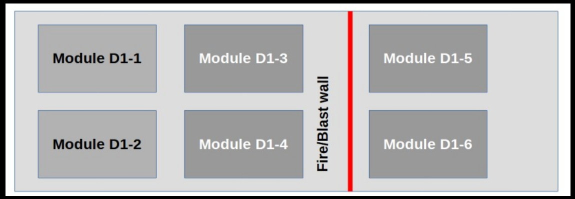
- Accident statistics: select leak frequency databases
  - Several sources are available for project leak frequency: UK's HCRD, PARLOC, OGP LNG, …
  - Provide leak frequency distribution per asset type, equipment type, hole size based on past incidents (statistics).
    - Could be discrete, e.g. leak frequency for predetermined hole size ranges (e,g [2'' to 4''], [4'' to 8''],…)
    - Given as a continuous distribution function
  - UK's HSE HCRD is the most complete and detailed accident statistics database.
  - For cryogenic risk: some use HCRD (full data set - warm and cold), some use OGP LNG

Probabilistic approach: Simplified cryogenic risk

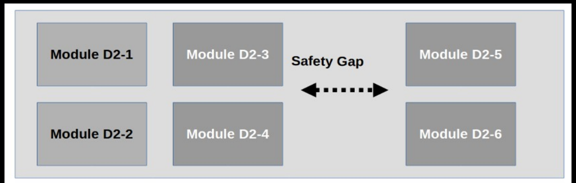
Risk = consequence x frequency

Input data: for each concept

- 2D layout drawings: Understand the basics of each concept
  - Location and size of each area/module
  - Location of plated/grated decks, walls, safety gaps, loading arms,
  - Location of SCEs: TR/LQ, large equipment/vessels, control rooms,…
  - Drawings at different elevations



Example: Design Concept X



Example: Design Concept W

- Process data: The essential process info for each concept
  - Early stage PFDs
  - Early stage stream data

Concept Design	Stream description	Area/Modules	Fluid composition	Operating Pressure	Operating Temperature	Liquid fraction	Other
Design 1	S1	A1	(CH_4, C_2H_6,..)	P1	T1	[0,1]	...
Design 1	S2	A2	(CH_4, C_2H_6,..)	P2	T2	[0,1]	…
...	...	...	...	...	...	...	...

Probabilistic approach: Simplified cryogenic risk

Risk = consequence x frequency

Input data: for each concept

- Parts count: Basic information about the equipment in each module/area
  - EPCs might provide coarse estimates of equipment parts count (re-use past project experience)
  - If not available, the risk discipline will make assumptions (to be approved by the project).

Concept Design	Area/Module	Flanged Joints valves	Piping	Process vessels	Heat Exchangers	...
Design 1	M1	M1-CatX_k	M1-CatY_k	M1-CatZ_k	M1-CatW_k	...
Design 1	M2	M2-CatX_k	M2-CatY_k	M2-CatZ_k	M2-CatW_k	…
…	…	…	…	…	…	...

  - The combination of leak frequency database, parts count and leak categories → Leak frequency per cryogenic spill
- List of SCEs (targets): Ensuring integrity of the SCEs throughout a cryogenic spill is main goal.
  - Main barriers (e.g. decks), escape and evacuation means (e.g. lifeboats, TR), critical control rooms, large vessels, special equipment (e.g. loading arms),...

Probabilistic approach: Simplified cryogenic risk

Risk = consequence x frequency

Simplified Cryogenis Risk

1) Faiulre Case Definition
2) Release modelling
3) Simplified consequence
4) SCEs impairment curves

Main activities: for each concept

- Failure Case Definition: List of accidental events to be modelled
  - The risk discipline estimates the inventory, allocates the leak category and calculates the leak frequency
    - **Leak category:** a) defines the range of hole sizes that will be used for leak frequency estimation. b) defines the representative hole size that will represented the category. Common to have 3-4 leak categories analysed
    - **Failure frequency:** The result of the combination of leak frequency database, project specific parts count and the project specific leak categories.

Failure Case	Area/Module	Pressure [barg]	Temperature [ºC]	Composition	Jet Direction	Inventory	Leak Category	Leak Frequency
FC1	M1	8	-162	CH4	N	450	**S**	**5.4E-5**
…	…	…	..	..	...	…	**M**	**2E-5**
…	…	…	..	..	...	…	**L**	**7E-6**
…	…	…	..	..	...	…	**R**	**1E-8**
FC93	M2	20	-90	C2H6	E	220	**M**	**4E-5**
…	…	…	..	..	...	…	**…**	**...**

Probabilistic approach: Simplified cryogenic risk

Risk = consequence x frequency

Main activities: for each concept

- Release modelling and cryogenic leak durations:
  - Thermodynamic analyses to identify which failure cases will result in exit temperatures (at 1atm) below DTBTT and the phase being released. The evolutions of the leak rate vs time are also estimated in this task.
  - Advanced process simulators able to model phase changes during the release are commonly used. Depending on the substance released, vapour, liquid or solid particles could exit the orifice.
  - **Drop**: Any failure case leading to exit temperatures *above DTBTT* or *vapour releases lasting less than the defined impairment duration*

Simplified Cryogenis Risk

1) Failulre Case Definition
2) Release modelling
3) Simplified consequence
4) SCEs impairment curves

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Probabilistic approach: Simplified cryogenic risk

Main activities: for each concept

- Simplified cryogenic consequence modelling:
  - 2D ***integral consequence models*** are common tool for consequence modelling in a simplified cryogenic risk analysis.
  - Important factor: the consequence model is able to track the vapour fraction of cryogenic spill vs distance
    - **Pros**: Integral models are fast. Simplified consequence results in short timeframes.
    - **Cons**: speed at the expense of reduced physics (→ understand the model's battery limits).
  - Conservative project specific assumptions are needed, e.g. liquid fraction travel distance in congestion, max size of cryogenic pool spread, SCE shielding…

Risk = consequence x frequency

Simplified Cryogenis Risk

1) Failulre Case Definition
2) Release modelling
3) Simplified consequence
4) SCEs impairment curves

Probabilistic approach: Simplified cryogenic risk

Main activities: for each concept

- Simplified cryogenic consequence modelling: Report for each failure case:

  1) Which SCEs are reached by liquid/2-phase and/or vapour releases

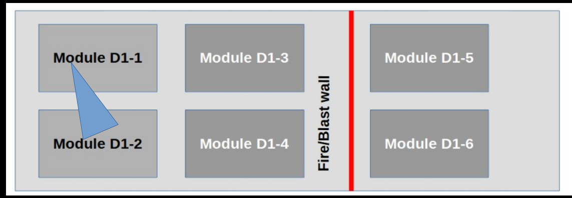
  2) The duration of the exposure shall be reported.

Risk = consequence x frequency

Simplified Cryogenis Risk

1) Faiulre Case Definition
2) Release modelling
3) Simplified consequence
4) SCEs impairment curves

			SCE impairments: type and exposure duration (min)						
Failure Case	**Area/Module**	**Jet Direction**	**SCE1 Jet Time**	**SCE1 Pool Time**	**SCE1 Vapour Time**	**SCE2 Jet Time**	**SCE2 Pool Time**	**SCE2 Vapour Time**	**SCE3 ...**
FC1	M1	Up	10	-	15	5	10	20	...
…	…		…		..	…	..	…	...
FC93	M2	-	-	-	-	-	25	30	...
…	…		…	..	..	…	…	…	...



Probabilistic approach: Simplified cryogenic risk

Main activities: for each concept

- Impairment curves for SCEs:
  - Impaiment curves for each SCE generated through combination of the failure cases, the release modelling and the consequence data.
  - The cut-off of the calculated impairment curve and the cryogenic frequency criterion will define the SCE's cryogenic risk load
  - In simplified cryogenic risk studies, the impairment curves should be used to screen concepts and capture the main cryogenic spill bottlenecks. Update Simplified Cryogenic Risk or extend to Detailed Cryogenic Risk study at Detailed Design

Risk = consequence x frequency

Simplified Cryogenis Risk

1) Faiulre Case Definition
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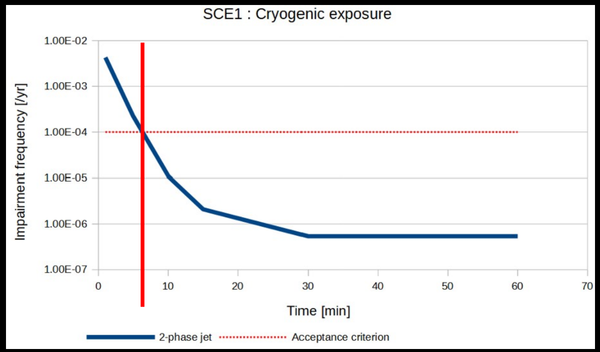
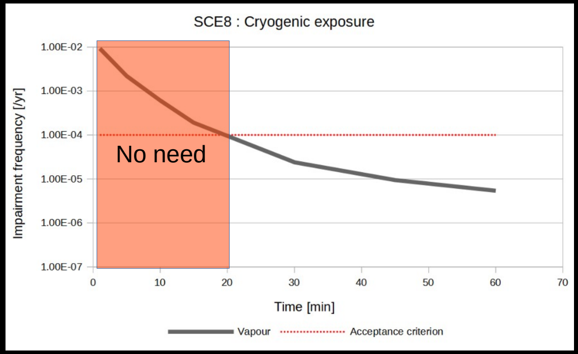




Probabilistic approach: Simplified cryogenic risk

Risk = consequence x frequency

Some battery limits of the approach

- Simplifications in the 2D integral models
  - Omit presence of structures, equipment, vessels, pipes, walls, plated decks (e.g. free jets)
  - Miss the enhanced heat transfer from impinged structures to the cryogenic spill
  - If cryogenic jet impinges, it could create liquid accumulation/pool (missed by the simplified model)
- Simplifications in process models
  - Regardless of using advanced process simulators, simplified process models are used to calculate the leak profiles in the simplified cryogenic risk analysis.
- Safety factors applied for part counts and/or worst case process operating conditions
- Leak, gas detection and emergency system response times conservatively assumed

CSP design methods: Detailed cryogenic risk analysis

Probabilistic approach: Detailed cryogenic risk

Introduction:

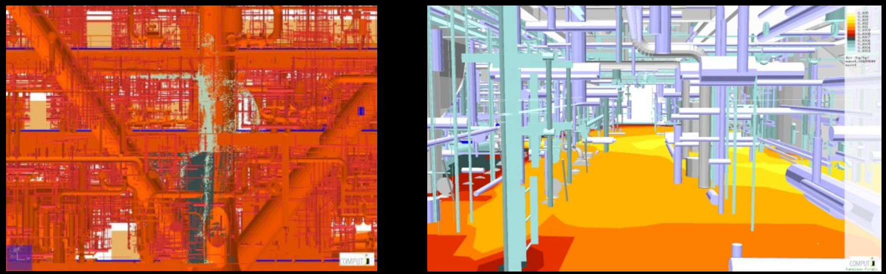
- Method for CSP optimisation or specific cryogenic bottlenecks
    - The most accurate: coupled 3D CFD + 3D Heat transfer + 3D Structural response
    - Allows verification/correction of simplified method assumptions
    - Detects secondary cold spots and possible collapse of structures (coatbacks...)
    - Simplifies redundant structures (steel) and weight.
    - Detailed inputs and advanced 3D flow, heat transfer and non-linear FEM
- Common approach when weight savings and advanced cryogenics are needed
- The guidance will describes one method, but project variations are possible.
    - Follow the principles in ESREL2015 and OTCAsia 2016 papers

Risk = consequence x frequency

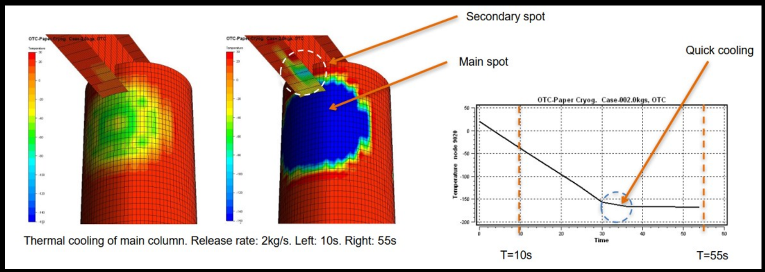
Detailed Cryogenic Risk:

1) Failure Case Definition
2) Release modelling
3) Adv. 3D CFD consequence
4) 3D Cryogenic Risk
5) SCEs impairments

6) Representative load defin.
7) Coupled 3D CFD + Heat transfer (cold spots)
8) + 3D Structural response
9) CSP and structural optimisation



ESREL2015: 3D cryogenic flow + 3D cryogenic risk exposure



OTCAsia 2016: 3D cold spots (3D flow and heat transfer)

Key Factors to consider In CSP Performance Evaluation

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Content

- Explores the critical structural factors influencing brittle fracture in unprotected steel and assesses the performance of CSP (e.g. concrete)
- Aims to guide CSP system design and optimization, ensuring the safety and integrity of structures subjected to extreme conditions.

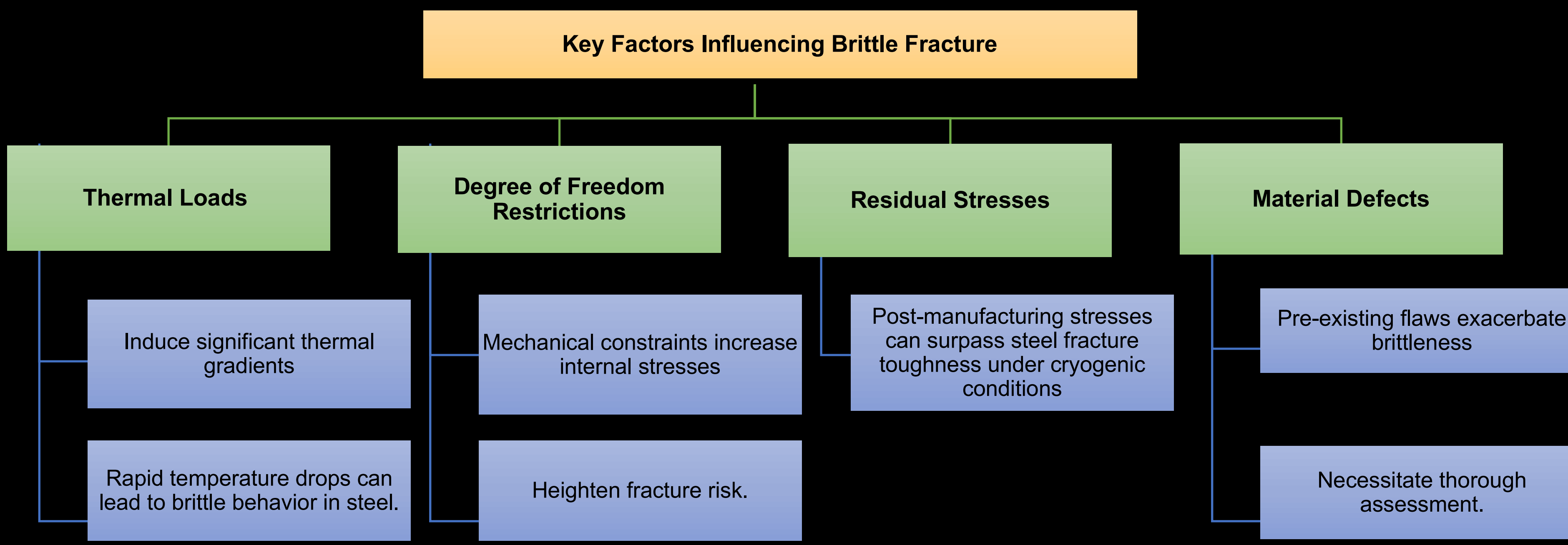
Objective:	**Importance**:	**Scope**:
• Evaluate the structural performance of materials under cryogenic loads.	• Understanding steel and concrete responses to cryogenic spills is vital for safety in industries handling liquefied gases (e.g., LNG).	• Behavior of cryogenic spills. • Structural response of materials to cryogenic conditions.

Key Factors to consider In CSP Performance Evaluation

Structural Response of Steel to Cryogenic Loads

- Mechanisms of brittle fracture at cryogenic temperatures, highlighting:
  - The role of thermal dynamics
  - Material imperfections
  - Specific steel grades suited for cryogenic applications.

- Aimed at assisting the readership in understanding how thermal loads and mechanical constraints affect the structural integrity of steel which is crucial.



Concrete Performance as Cryogenic Spill Protection

- Evaluates concrete's suitability as CSP material, emphasizing:
  - Its thermal and mechanical properties under cryogenic conditions.
- Provides design recommendations to enhance performance, addressing potential risks such as cracking and spalling.

Key Considerations:

Thermal Properties:
- Low thermal conductivity and high heat capacity enable concrete to mitigate thermal shock.

Mechanical Properties:
- Concrete becomes stronger but less ductile at low temperatures, impacting its failure behavior.

Enhancements:
- Use of additives and reinforcements can improve concrete's resistance to cracking and spalling under cryogenic loads.

Design Recommendations:
- Employ high-performance concrete mixtures.
- Implement control joints and select aggregates with low thermal expansion.
- Strategically place CSP in critical structural areas to ensure integrity against cryogenic impacts.

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Overview of one Cryogenic Spill Protection Design procedure

OMEGA RISK

- Define Design Parameters
  - Determine material characteristics of CSP suitable for cryogenic temperatures:
    - Thermal Conductivity
    - Specific Heat Capacity
    - Compressive Strength (increased at cryogenic levels)
    - Tensile Strength (requires reinforcement to mitigate decreases)
    - Modulus of Elasticity (consider brittleness)
- Cryogenic Exposure Characteristics
  - Assess the cryogenic fluid, release scenarios, and steel structure dimensions
- Heat Transfer and Cryogenic Spill Modeling
  - Simulation: Conduct heat transfer simulations to ensure steel temperatures remain above the ductile-to-brittle transition temperature (DBTT).
- Thickness Estimation and Optimization
  - Utilize FEM calculations to determine CSP insulation thickness based on localized thermal performance.
  - Target Steel Temperature: Maintain temperatures above DTBTT (e.g., -20°C).
  - Exposure Type: Consider direct liquid, two-phase flow, or vapor-only exposure.

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Risk Advisory for Safe Operations and Sustainable Environment

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