SINTEF

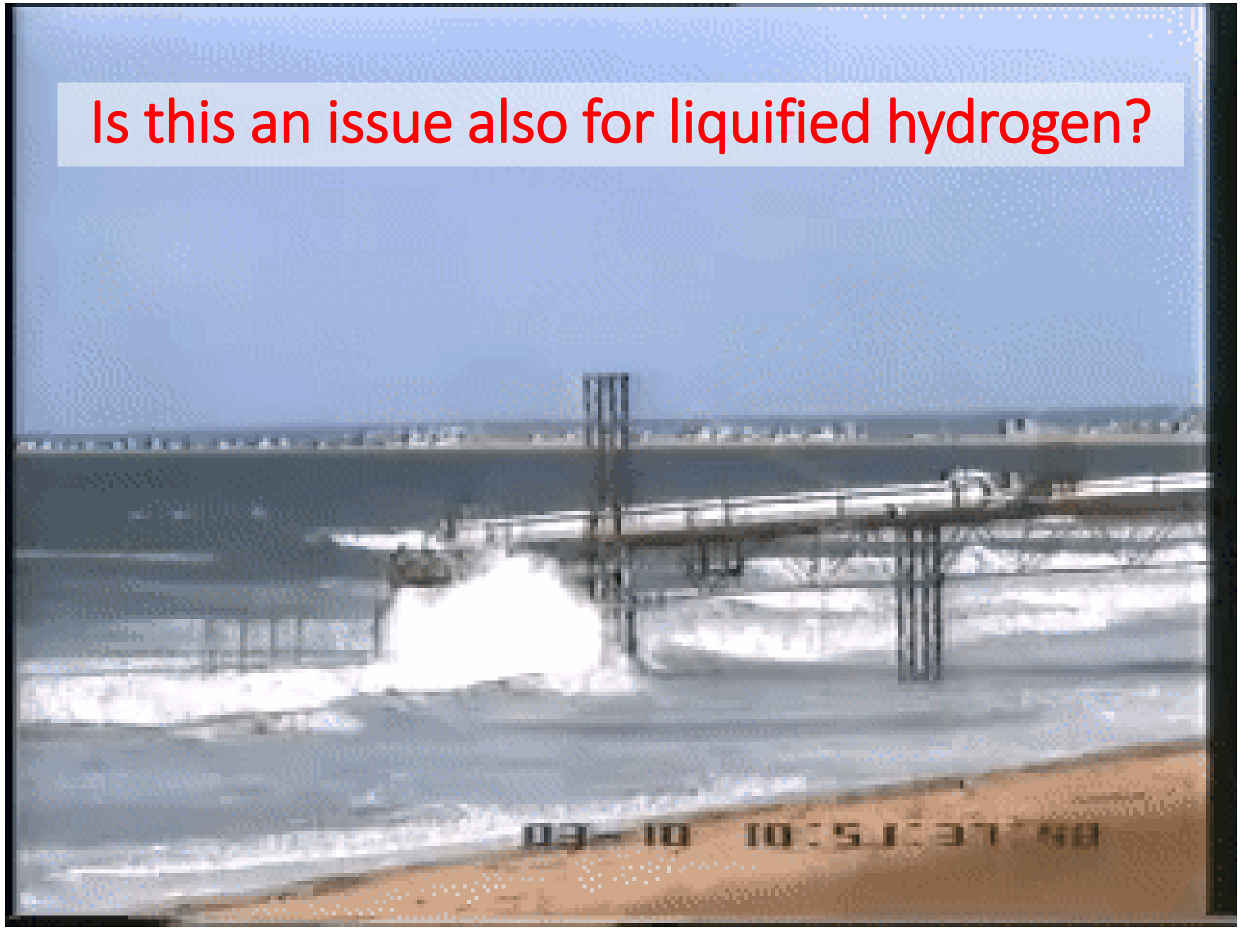
Liquid hydrogen RPT modelling

Final project workshop SH_2IFT, 2022-05-03

Lars Hov Odsæter, SINTEF Energy Research

Technology for a better society

Rapid phase transition (RPT)

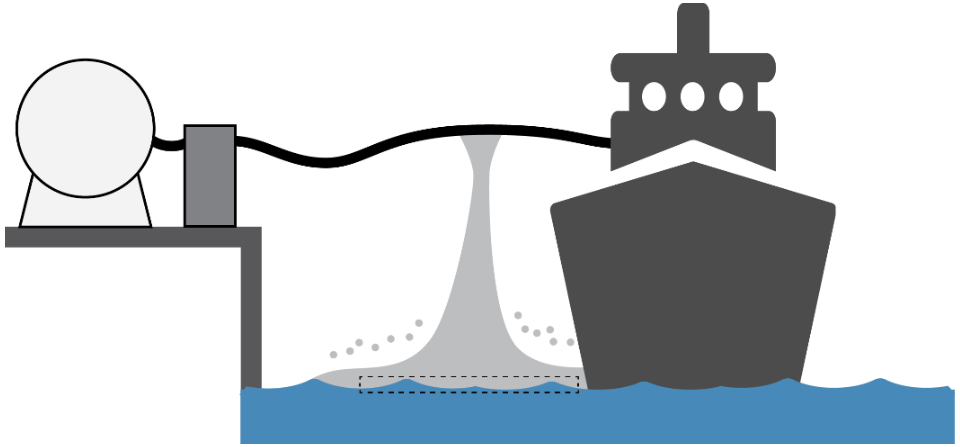


- Sudden and explosive phase transitions
- Explosive expansion due to large density difference between liquid and gas
- Not due to combustion
- LNG spill on water

The Lorient field tests,
Gaz de France

Outline

1. Introduction to LH2 spills and RPT
2. Modelling activity
   - Triggering
   - Consequences
3. Main results and conclusions



Collaborators

Hans L. Skarsvåg (SINTEF ER)

Petter Nekså (SINTEF ER)

Eskil Aursand (SINTEF ER)

Gunhild Reigstad (SINTEF ER)

Federico Ustolin (NTNU)

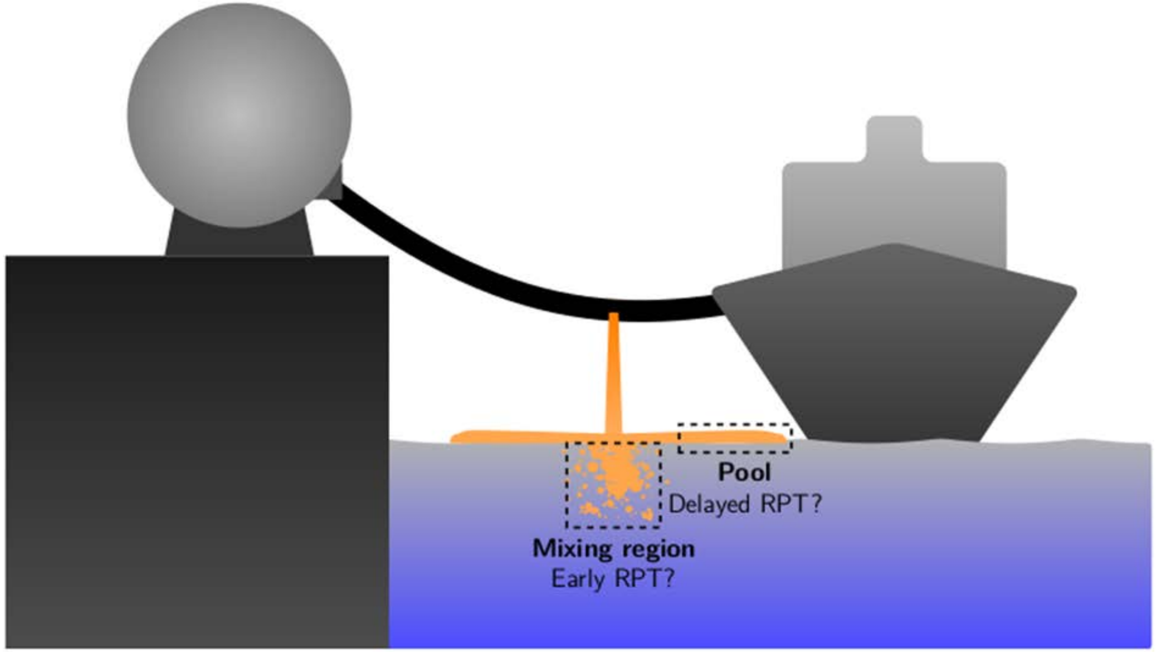
Nicola Paltrinieri (NTNU)

Liquid hydrogen

- Hydrogen is potentially a zero-emission energy carrier
- Distribution:
  - small quanta → compressed gas
  - large quanta → liquid form
- Heavy-duty transportation foreseen to run on LH2
- Comparable to LNG, but
  - Low normal boiling point, T_{sat} = 20 K = -253 ^{o}C (LNG: -161 ^{o}C)
  - Low density, ρ = 71 kg/m^3 (LNG: 438 kg/m^3)

Cryogenic spills onto water

1. Containment breach
2. Flash-vaporization
3. Jet impacts water
4. Droplet-water mixing -> Early RPT?
5. Pool formation and spreading
6. Film boiling
7. Film boiling collapse -> Delayed RPT?

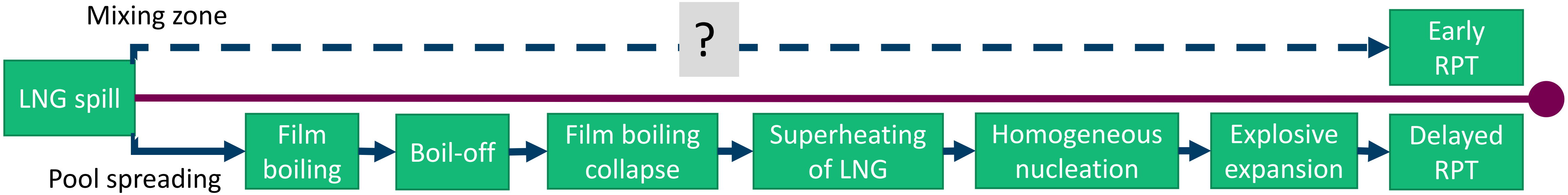


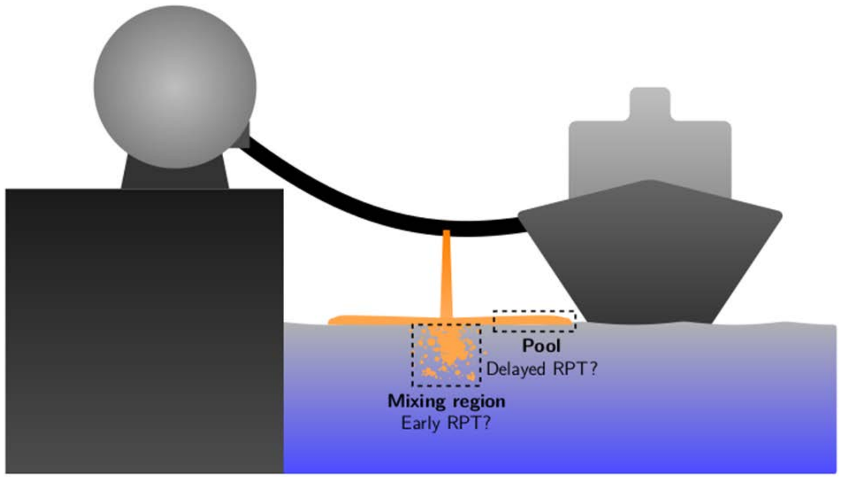
Research overview

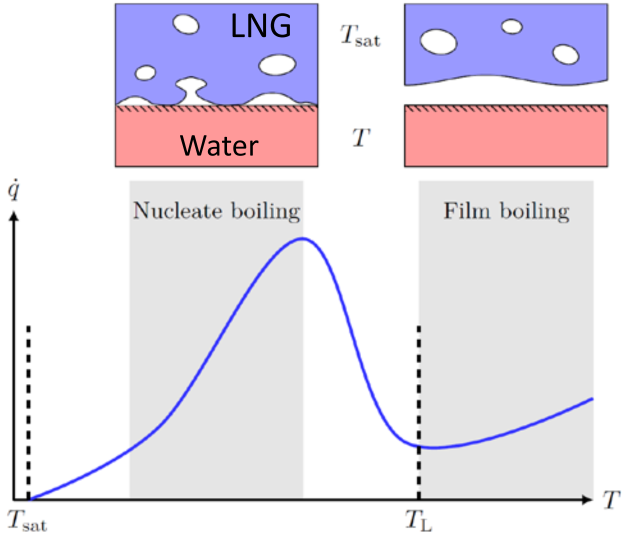
- LNG RPT
  - Observed in industry and experimental programmes
  - Devastating consequences (displace and damage equipment and structures)
  - Randomness in triggering and size
  - Established theoretical framework during 1970s
- LH2 RPT
  - No records from industry
  - Verfonderen and Dienhart (1997)[1]: Low momentum releases
  - SH2IFT experiments: High momentum releases
  - Limited theoretical/modelling studies
- Our models are built on established theory from LNG research

[1] doi.org/10.1016/S0360-3199(96)00204-2

RPT triggering for LNG



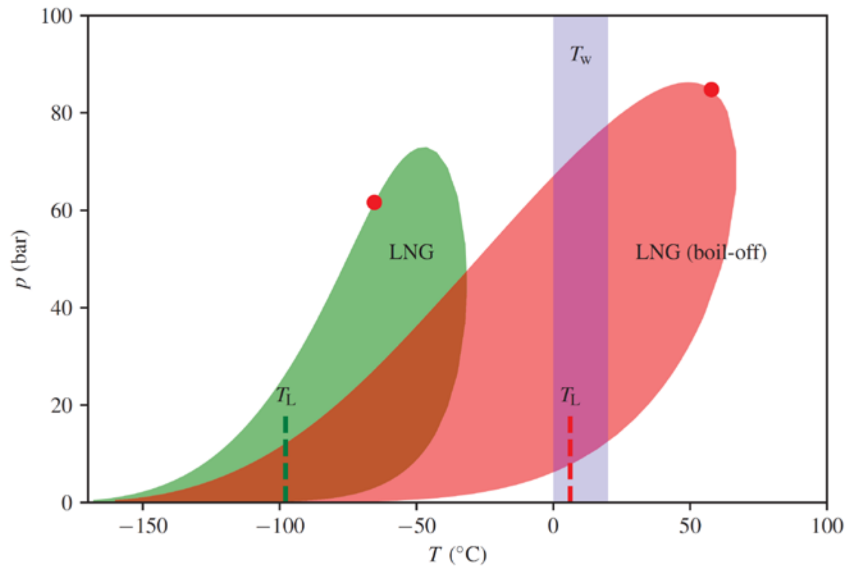




SINTEF

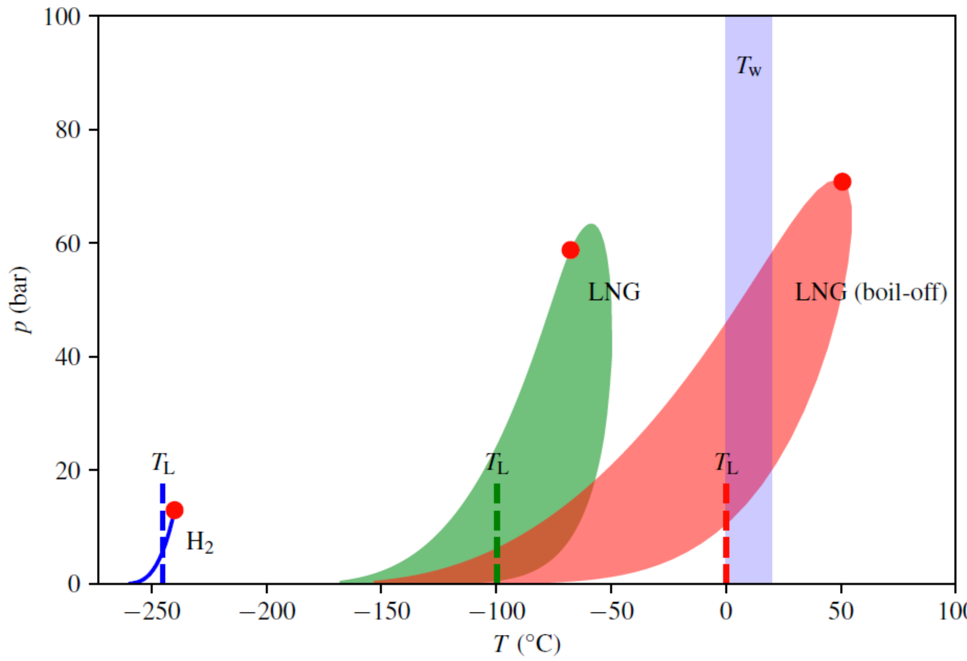
RPT triggering for LNG

- Leidenfrost temperature determines risk of triggering
$$T_L > T_w$$
- Estimate of LNG Leidenfrost temperature:
$$T_{\mathrm{L}} = \frac{27}{32} T_{\mathrm{crit}} = -102^{\circ}\mathrm{C} \ \text{vs} \ \ T_{\mathrm{water}} \approx 0^{\circ}\mathrm{C}$$
- When 30-50mol% methane concentration is reached:
$$T_{\mathrm{L}} = T_{\mathrm{water}}$$
- LNG becomes enriched on heavier components as it boils
- Triggering! But only 10-20% of original LNG remains



RPT triggering for LH2

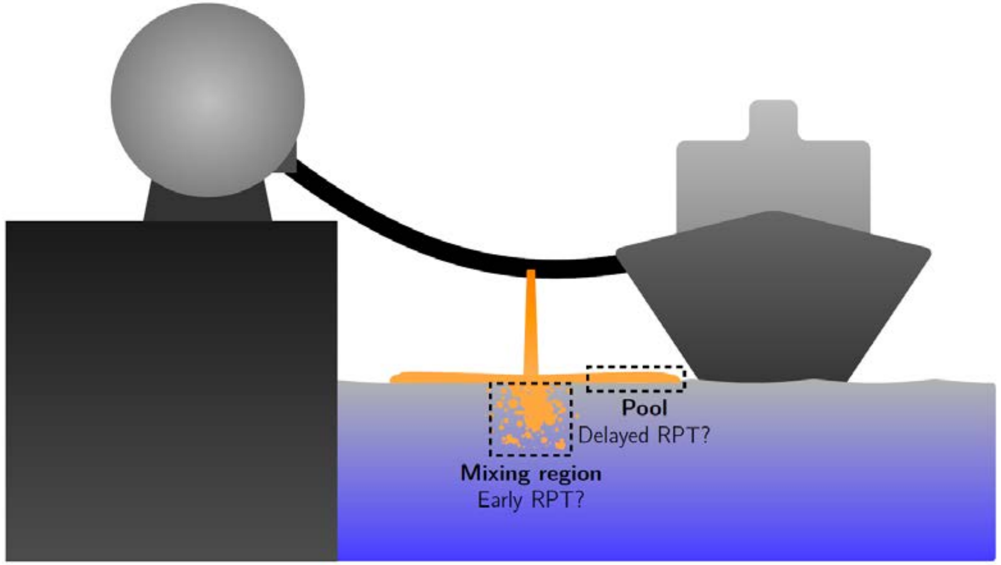
- Triggering criterion: $T_L > T_w$
- Estimate of LH_2 Leidenfrost temperature:
  $T_\mathrm{L} = \frac{27}{32} T_\mathrm{crit} = -245°\mathrm{C}$ vs $T_\mathrm{water} \approx 0°\mathrm{C}$
- No boil-off effect
- T_L will never exceed T_w
- No known pathways to late RPT



SINTEF

Triggering of early RPT

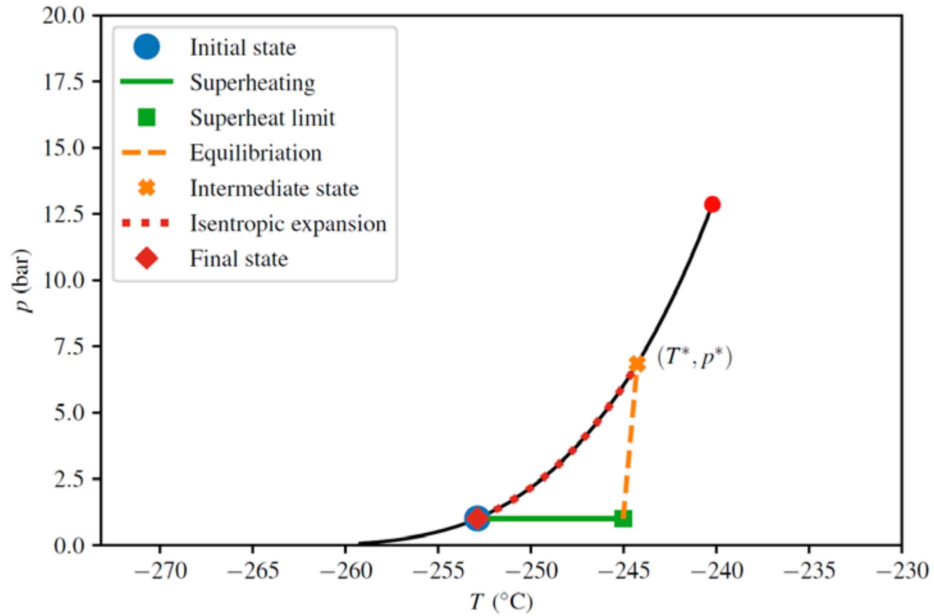
- RPT in the mixing zone
- Film boiling stability for high impact and high pressure?
- Early RPT unlikely due to
  - Extremely low density of liquid hydrogen (70 kg/m3)
  - Stable film-boiling (low Leidenfrost temperature)
- Potential triggering mechanisms
  - External forces
  - Ice formation



SINTEF

Consequence modelling

- Consequences of hypothetical RPT event
- Thermodynamical model
  - Aursand and Hammer (2018)[1]
  - Thermopack[2]
- Peak pressure (max occuring pressure) and corresponding energy yield
- Energy yield on a volumetric basis probably most representative



Consequence	LH_2	LNG	LH_2 Compared to LNG
Peak pressure, p^* (bar)	7	40	17 %
Energy yield, E (kJ kg^{-1})	40	68	59 %
Energy yield, E (MJ m^{-3})	2	39	5 %

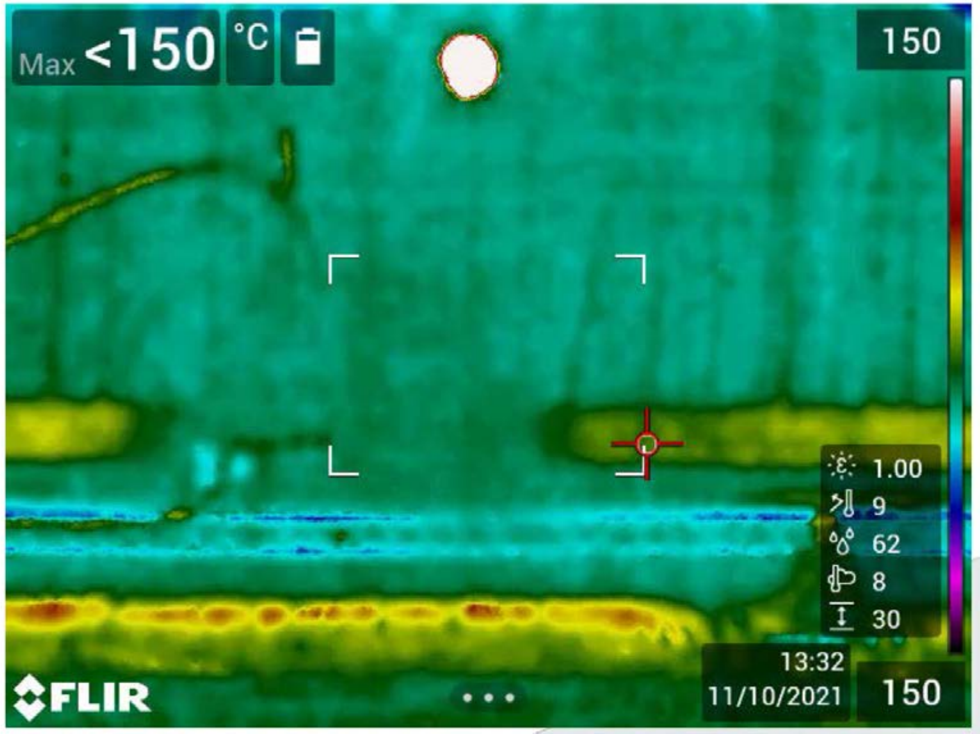
[1] doi.org/10.1016/j.jlp.2018.06.001
[2] github.com/SINTEF/thermopack

SH2IFT

SINTEF

Risks of LH2 spills on water

- RPT is not found to be a major issue for LH2
- Still, spills should be avoided due to
  - Risk of ignition
  - Evaporation and spreading by dispersion
  - Cryogenic hazards
- Open questions from SH2IFT experiments:
  - What are the mechanisms for the ignition phenomena observed in experiments?
  - Thermo- and fluid dynamics modelling combined with experiments



SINTEF

Main results and conclusions

- The probability of an explosive LH2 RPT event for a LH2-on-water scenario seems low
- No RPT events have been reported from reported spills
  - Verfonderen and Dienhart (1997): Low momentum experiments
  - SH2IFT experiments with high momentum jets gave no RPT
  - No records of RPT from industry
- Consequences of hypothetical LH2 RPT are estimated to be relatively low
  - Peak pressure is 17% of that from LNG RPT
  - Explosive energy yield is 5% by volume (or 60% by mass) compared to LNG RPT
- *RPT is not found to be a major issue for LH2*
- Open questions from experiments
  - Need for more research – both modelling and experiments

Odsæter et.al. (2021): doi.org/10.3390/en14164789

SH2IFT

SINTEF

Acknowledgement

Thanks to project partners and the Research Council of Norway for funding

With funding from

The Research Council of Norway

Forskningsrådet

SINTEF

Technology for a
better society