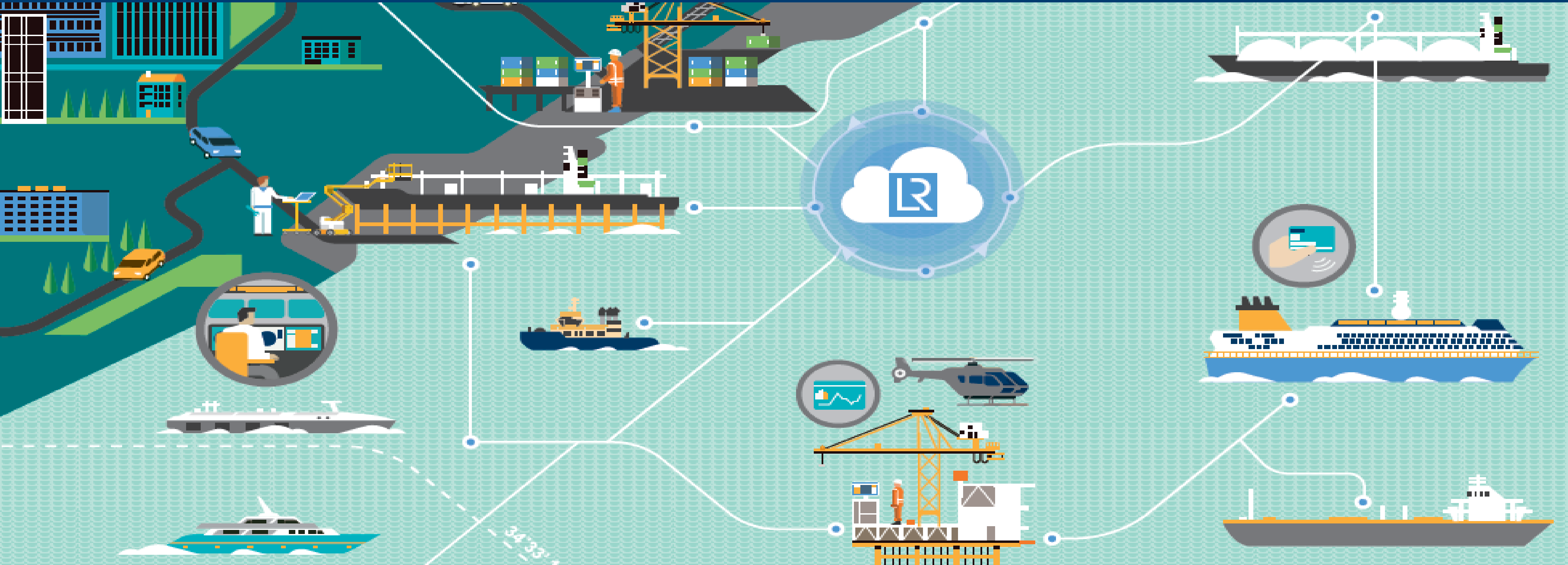
Lloyd's Register

Working together
for a safer world

Hydrogen – Safety Considerations and Future Regulations

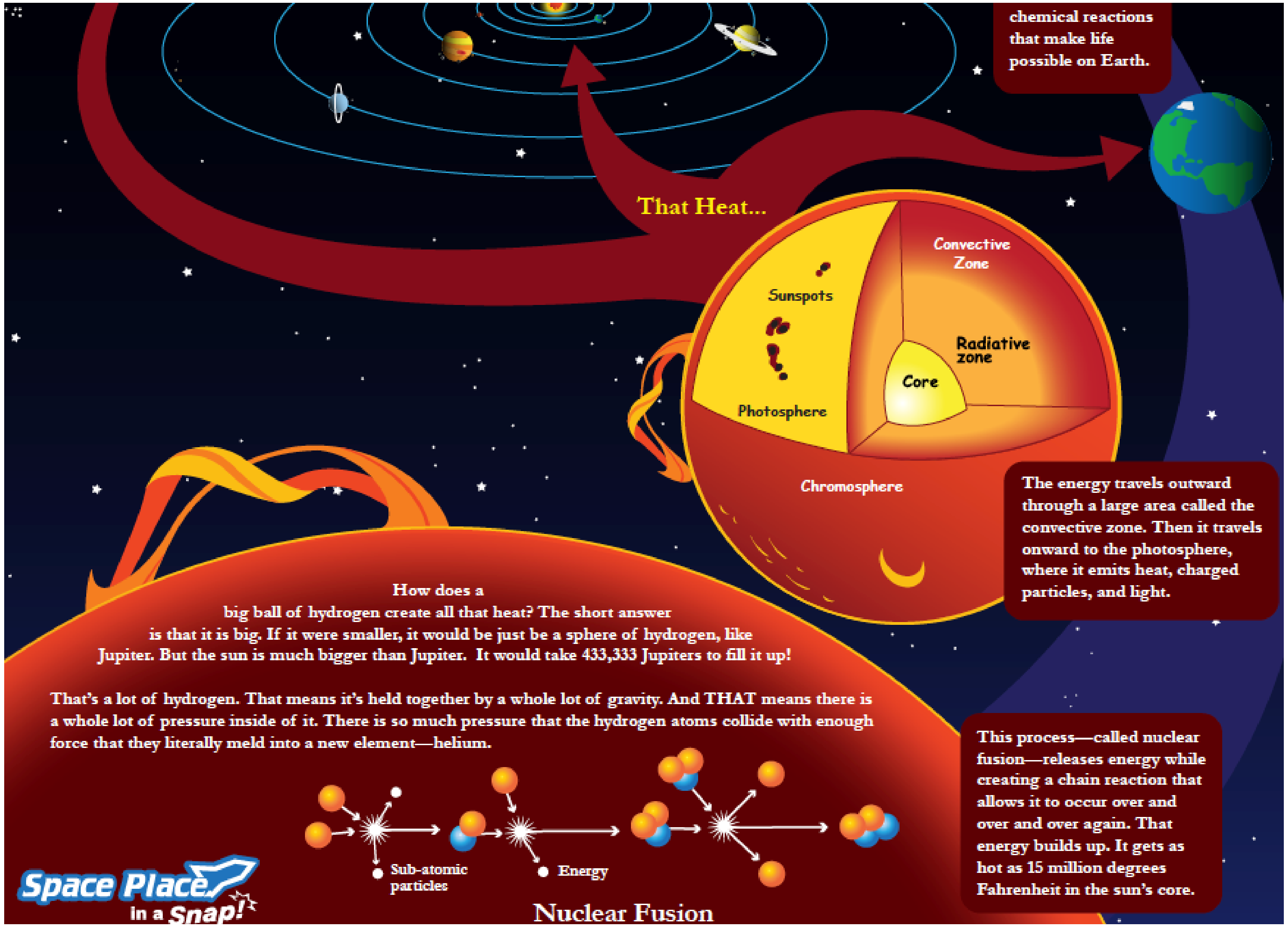
June 2017



Hydrogen in the Marine Industry

1. Why Hydrogen?
2. Lloyds Register Experience with Hydrogen
3. Safety Considerations and Risks
4. Historical Safety Incidents and Accidents
5. Status of Marine Regulations
6. Lloyd's Register's Approach
7. Conclusions

1. Why Hydrogen?

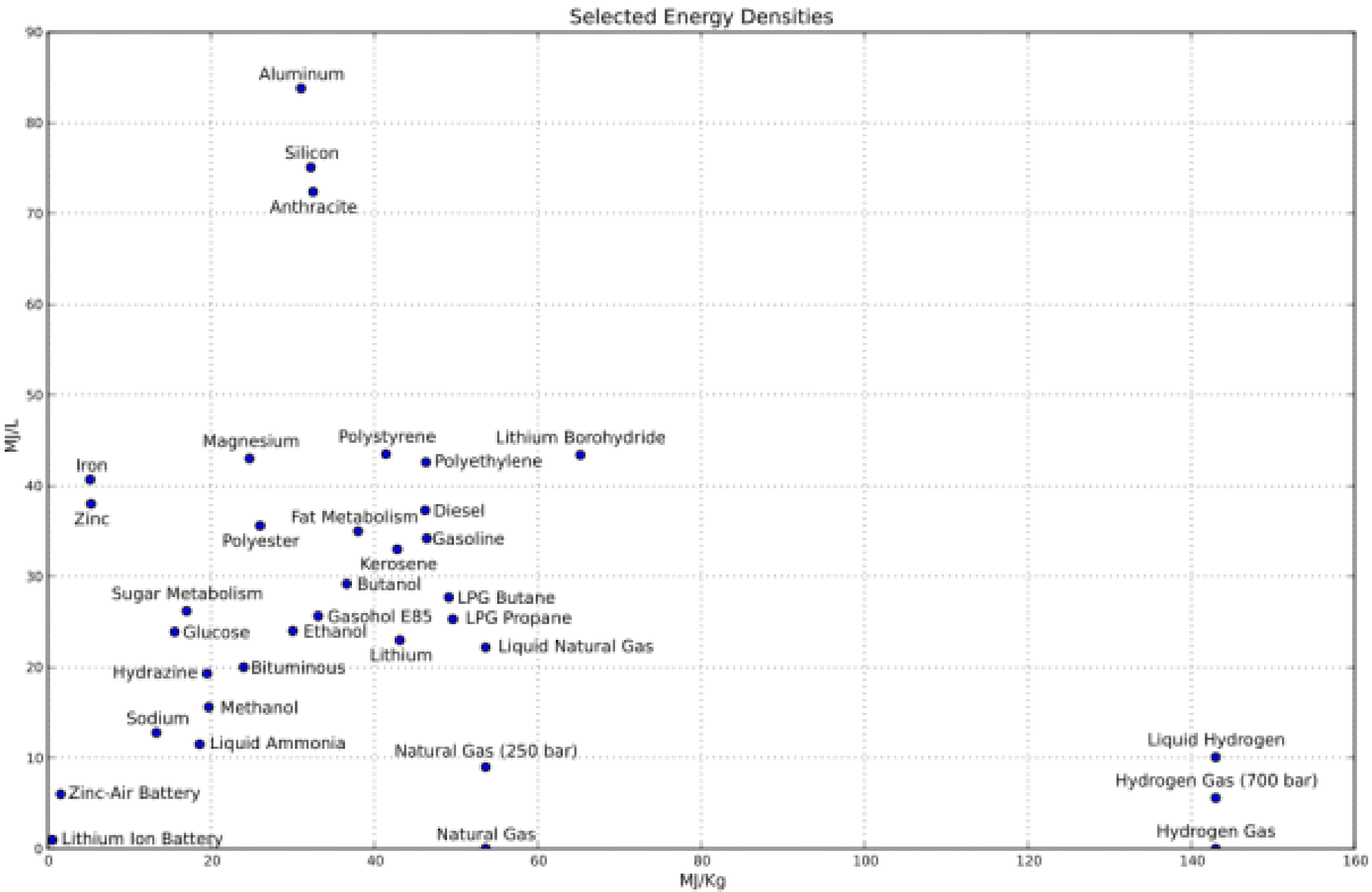


-The most common element in the universe.

-Among the most important elements for sustaining life on earth.

Image source: NASA

1. Why Hydrogen?



-Great Energy Density on a mass basis resulting in minimal weight considerations (lightweight).

-Poor energy density on volumetric basis requiring increased space requirements.

2. Lloyds Register's Experience

Projects

-Numerous Hydrogen Installation Risk Assessments
-Consultancy on 7 hydrogen refuelling stations
-Safety Assessment of hydrogen production facility
-Hydrogen Fuel Cell powered ships
-Dual fuel vessels (hydrogen/fuel oil ICEs)

Hydrogen Working Groups

-FLACS dispersion/explosion consequence modelling
-IEA Hydrogen Safety Working Group 2004-2012
-HySafe NOE 2004-2012

3. Safety Considerations and Risks

Image source: Linde

Hydrogen storage can be challenging as a result of unfavourable volumetric energy density resulting in

-High Pressures (up to 700 bar-g) or

-Extremely Low Temperatures (-253C)

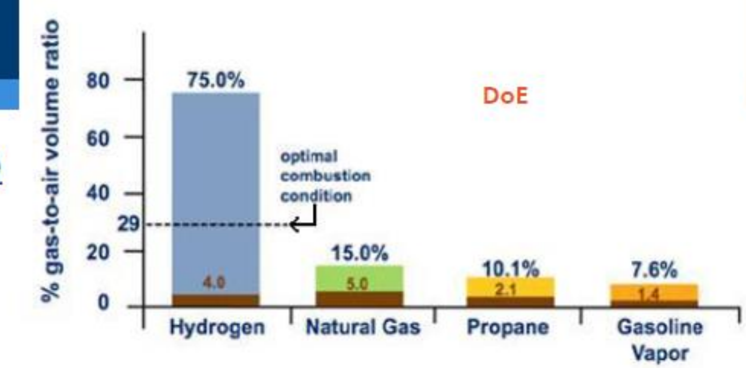
Indirect storage via hydrogen carriers poses challenges in volume, H2 liberation processes and cost.

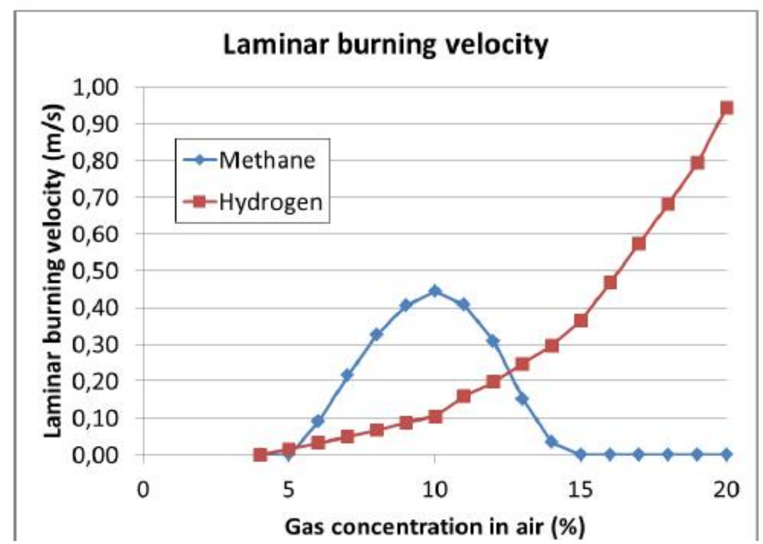
Furthermore hydrogen given its minimal molecular size is very leaky, diffusing through containment materials.

3. Safety Considerations and Risks

Hydrogen properties- reactivity

Property	Hydrogen	Methane (NG)
Flammability in air	4 to 75%	5 to 15%
Burning velocity	~3 m/s	0.45 m/s
Detonation energy	1 g TNT	1 kg TNT





Explosion pressure P ~ S_L^2 i.e.

Hydrogen < 10% - limited reactivity

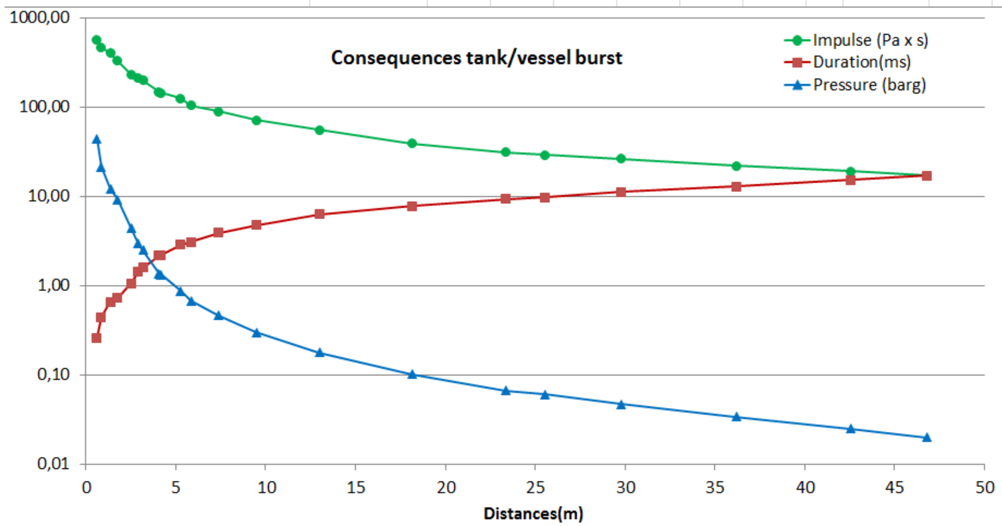
Hydrogen >15% - reactivity worse than NG

Hydrogen Releases – Compressed Hydrogen

Input in orange cells only		
Tank temperature	323	K
Pressure in tank	700	bara
Volume of tank	100	litre

With too high risk level or non-tolerable consequences it is recommended to perform CFD calculations to evaluate and optimize mitigation measures, e.g. installing barrier walls.

	Distance to pressure level						Pressure level			Distance	
Safety distances and loads	**1 barg**		**0.2 barg**		**0.05 barg**		0,14	**bar**		10	**m**
Distance	5,07	m	12,65	m	29,25	m	16,16	m	Pressure	0,287	barg
Pressure impulse at this distance	128,2	Pa s	57,0	Pa s	26,69	Pa s	45,6	Pa s		69,3	Pa s
Pressure duration	2,75	ms	6,13	ms	11,01	ms	7,16	ms		5,00	ms
Reflected loads									**Reflected**		
Reflected pressure	2,00	barg	0,40	barg	0,10	barg	0,28	barg		0,57	barg
Reflected impulse	256,4	Pa s	114,1	Pa s	53,4	Pa s	91,2	Pa s		138,6	Pa s
Reflected pressure duration	2,75	ms	6,13	ms	11,01	ms	7,16	ms		5,00	ms

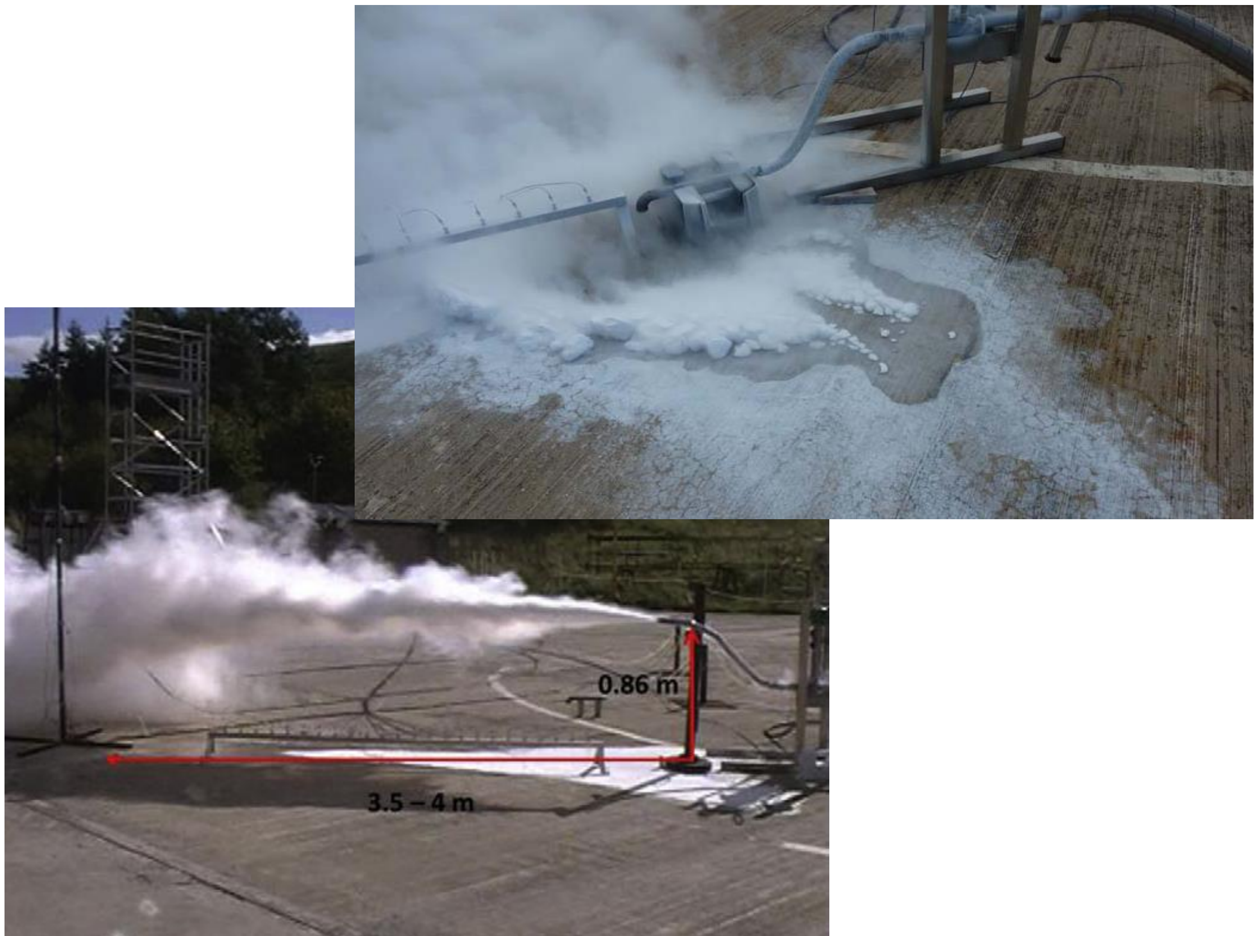


Catastrophic rupture of 700 bar-g storage tanks will release tremendous energy.

- The consequence can be limited by location and choice of tanks.
- Sonic release – speed of sound 1270 m/s (2.8 x methane)
- Rapid dilution in air for free jet
- Open installations with sufficient distance away from structure/obstructions may limit gas concentrations to < 15% H2 in air.

3. Safety Considerations and Risks

Hydrogen Releases – Liquefied Hydrogen



Leakages from liquefied hydrogen storage can be catastrophic within enclosed steel structures.

- Immediate loss of toughness and embrittlement of carbon steel.
- H_2 vapours can remain denser than air for prolonged periods.
-Given the very low temperature release it can lead to liquefaction and freezing of air in way of the leakage.
-O_2-doped air will further increase H_2 reactivity

Hydrogen Releases – Ignition

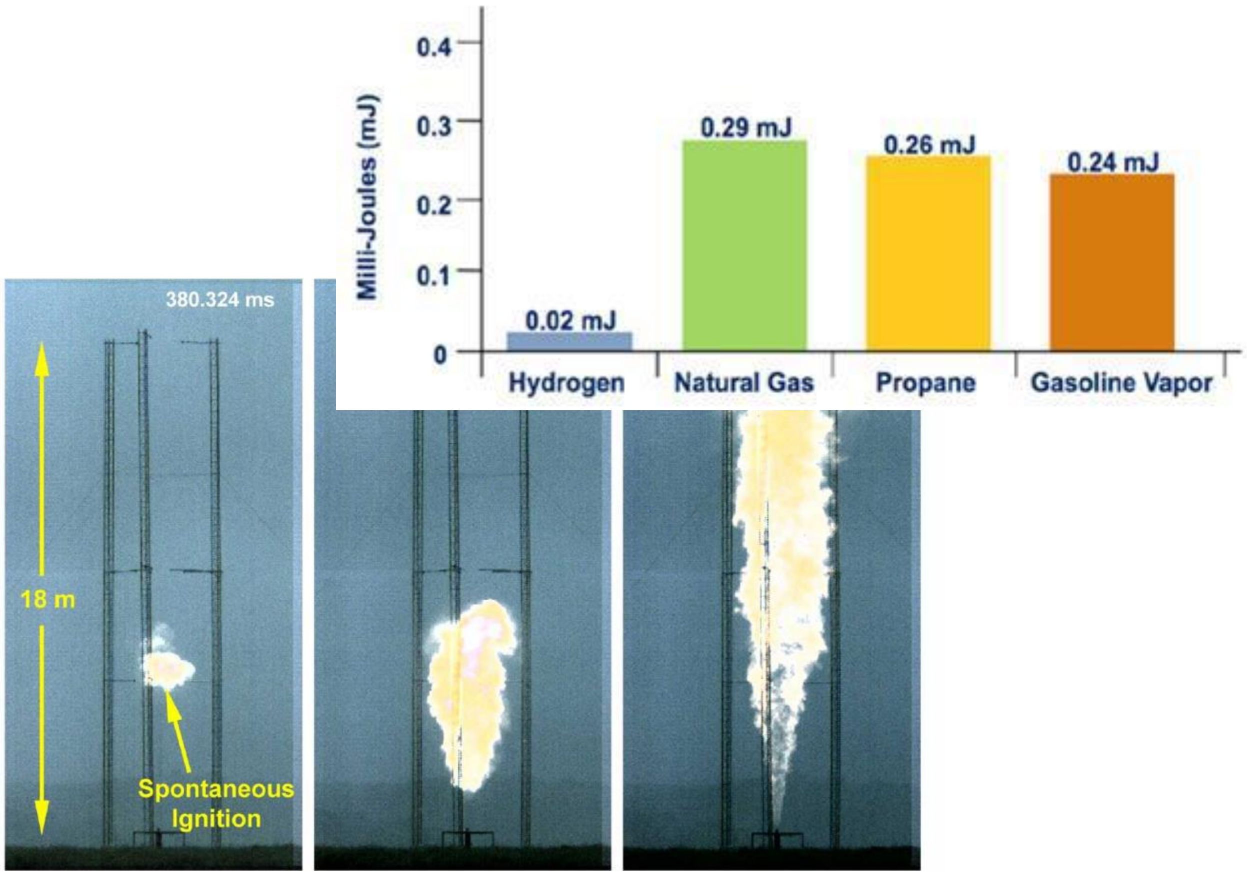


Image sources: DOE and Sandia

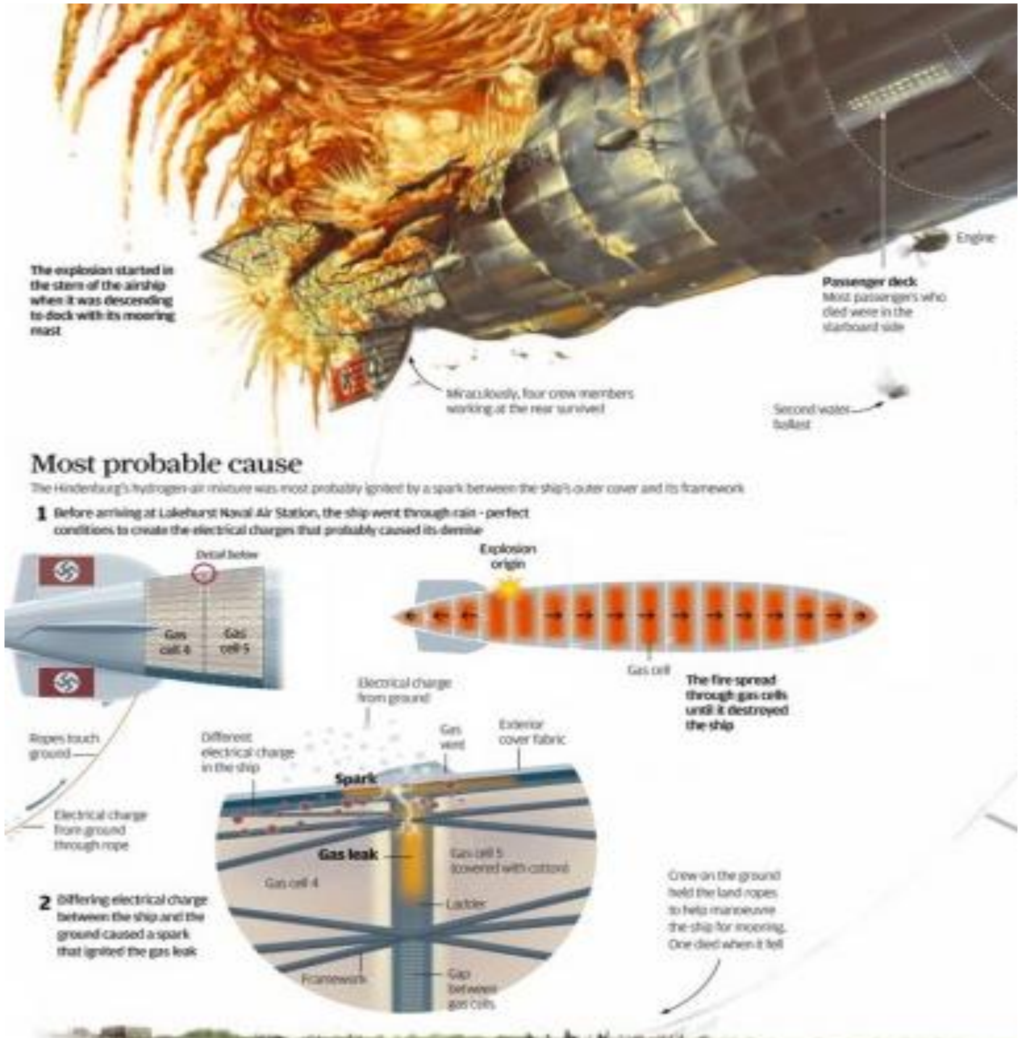
Minimum ignition energy 0.019 mJ (methane 0.29 mJ)
Static electricity sparks ~1 mJ

Ignition phenomena often hard to explain and may include but are not limited to:

-Equipment/component static electricity and discharges
-Sparks from dust/particles in a jet
-Shockwaves heating pockets of H2 and air above AIT

Resulting jet fire will be noisy, invisible, very hot flame, limited radiation.

4. Safety Incidents and Accidents



Prominent accidents

Hindenburg (1937) – traumatic confirmation of hazardous properties of hydrogen

Challenger (1986) – demonstrated the very reactive nature of liquefied hydrogen and oxygen

A number of noteworthy accidents and many smaller incidents are documented within the US DOE database:

h2tools.org/lessons

5. Status of Marine Regulations

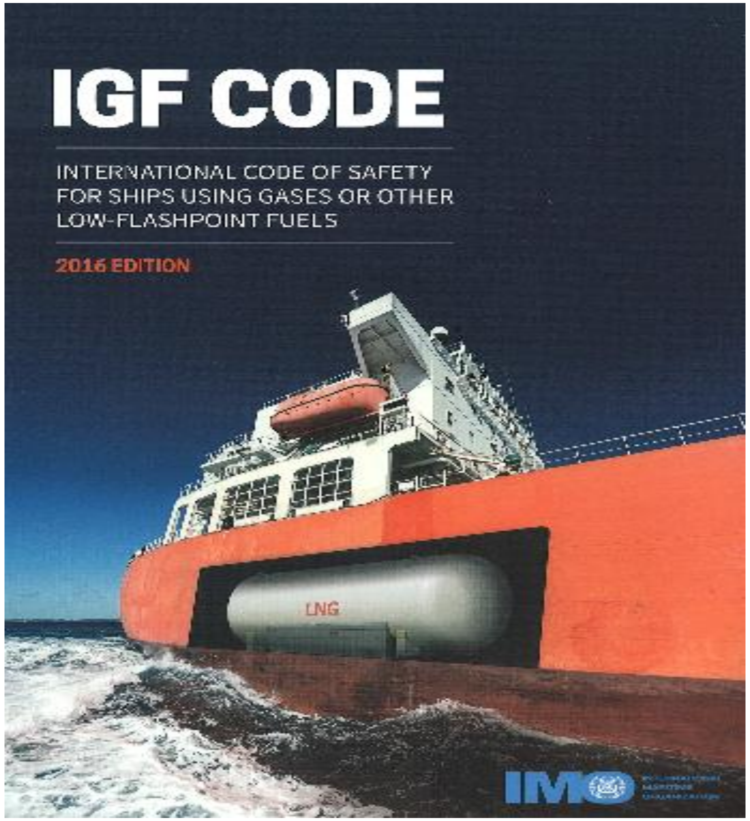
Resolution MSC.420(97) Carriage of Liquefied Hydrogen in Bulk

Issued November 2016, Mitigation of key hazards:

1. Low Temperature
2. Low Ignition Energy,
3. High Permeability, low viscosity
4. Wide flammability limit,
5. Low visibility of flames in case of fire,
6. High flame velocity resulting in detonation with shockwave,
7. Liquefaction/solidification of inert gas and constituents of air (oxygen-enriched atmosphere)
8. Hydrogen embrittlement including weld metals.

5. Status of Marine Regulations

Hydrogen as a Marine Fuel



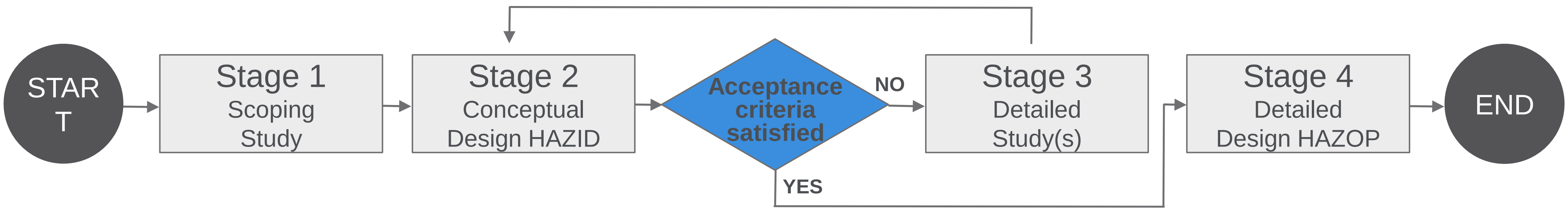
IMO's CCC 4 meeting on September 2017 (Sub-Committee on Carriage of Cargoes and Containers) will tackle fuel cells including sources of hydrogen feed.

The requirements being discussed will cover installation and fire safety as well as fundamental design, operation and core components of fuel cell power systems.

Culminating with the draft part E within the IGF Code.

6. Lloyd’s Register’s Approach

Core Gas Fuelled Ship/Carriage of Liquefied Gas Requirements complimented by Risk Based Design (Structured Risk Assessments)



Risk techniques/workshops - structured discussions of

1. Minimising leakage potential.
2. Where leakage can be expected, holistic design to limit H2 concentration below 10%.
3. Limiting hydrogen storage with respect to room/space volume.
4. Minimising congestion – dilution of pressurised releases and mitigating flame acceleration.
5. Actively designing against detonation
6. And many more………

6. Lloyd's Register's Approach

Stimulating Innovation….encouragement of novel approach through the RBD (Risk Based Design) processes.

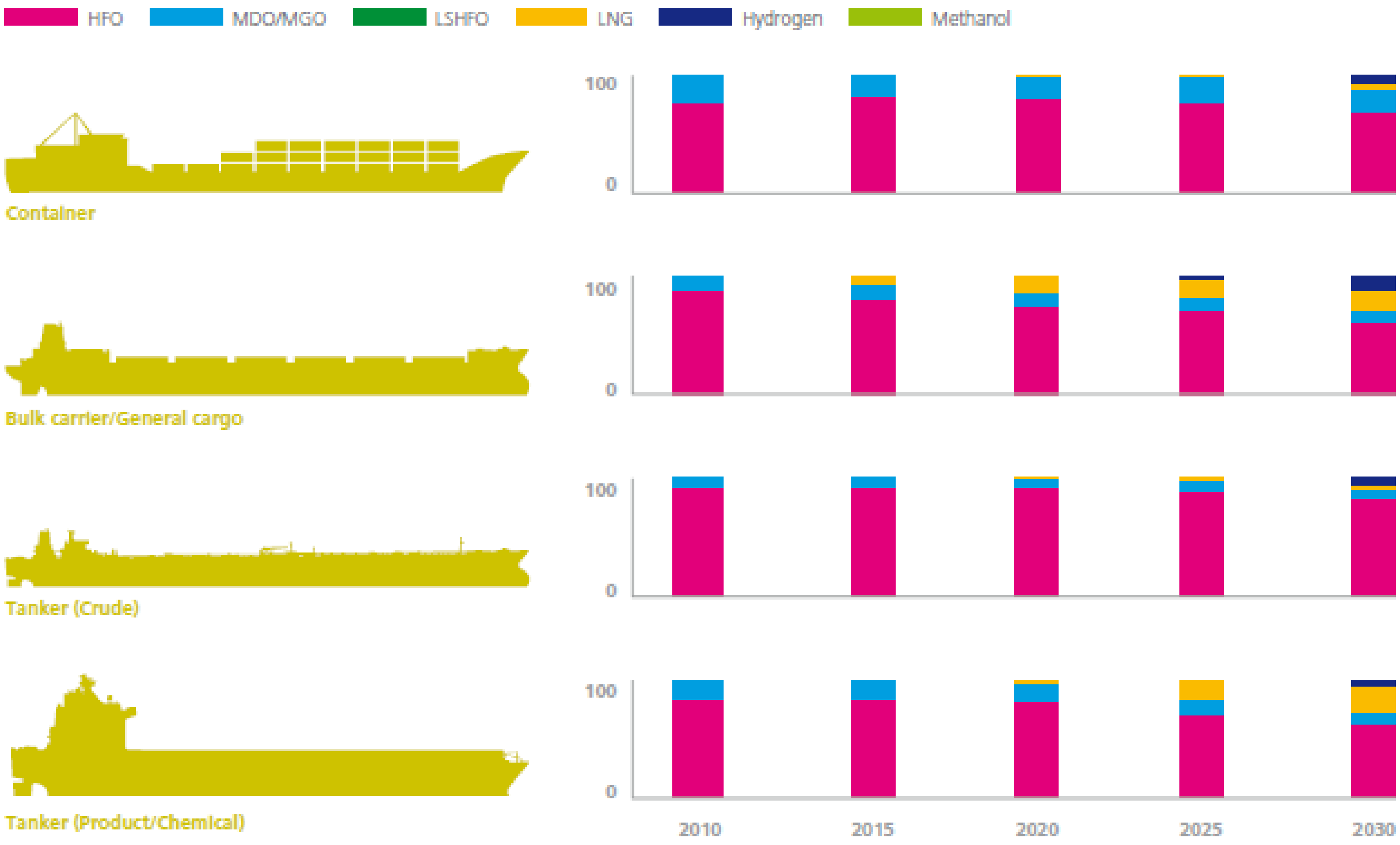
Instead of solely focusing on

1. Qualitative and quantitative assessment of leakage
2. Adverse thermal modelling (cooling)
3. Gas Dispersion modelling
4. Gas ignition and consequence modelling
5. Explosion modelling and Simulations

There maybe scope in considering monitoring techniques to allow diagnostics and prognostics of components, equipment, storage, etc. that receive, store, process hydrogen.

7. Conclusions

Fig. 17 **Fuel mix for containership, bulk carrier/general cargo, tanker (crude) and tanker (product/chemical) fleet (%)**
Source: LR / UCL



LR's Global Marine Fuel Trends 2030 in partnership with UCL (University College London) has identified hydrogen as key resource in the decarbonisation of the marine industry.

LR is focused on enabling innovations on hydrogen safety.

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Thank you for your attention.

www.lr.org

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