

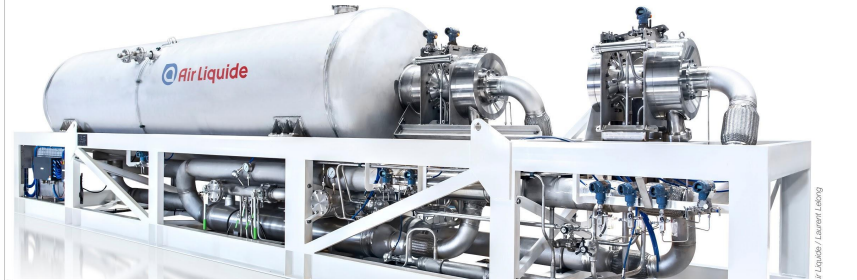
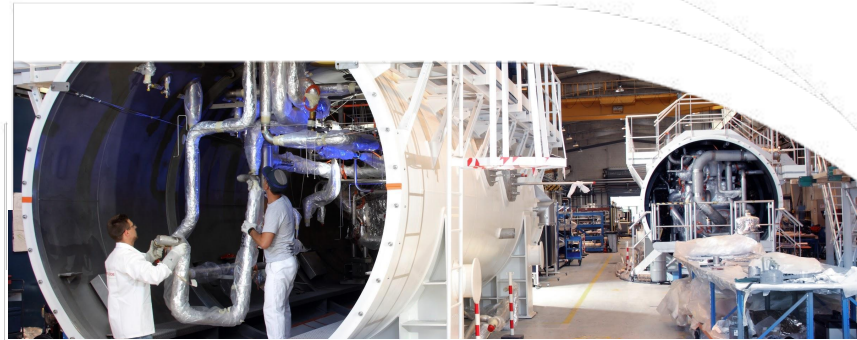
# Subcooling of Liquid Hydrogen with a Cryogenic Refrigerator

ICEC 27 - Oxford 2018

THIS DOCUMENT IS PUBLIC

Oxford • 05 September, 2018 •  
J.M: BERNHARDT, P. DE MAEYER  
Gas & Cryogenics • ALat Sassenage

GLOBAL MARKET  
& TECHNOLOGIES



# Subcooling of Liquid Hydrogen with a Cryogenic Refrigerator

## Outline of the presentation

- Air Liquide Advanced Technologies (AL-aT)
- The customer requirement of subcooled LH2
- The Sabre Test Facility TF1
- Cryogenic Requirement
- AL-aT Cryogenic System
- CFD Simulation Results
- Conclusion



# Air Liquide Advanced Technologies

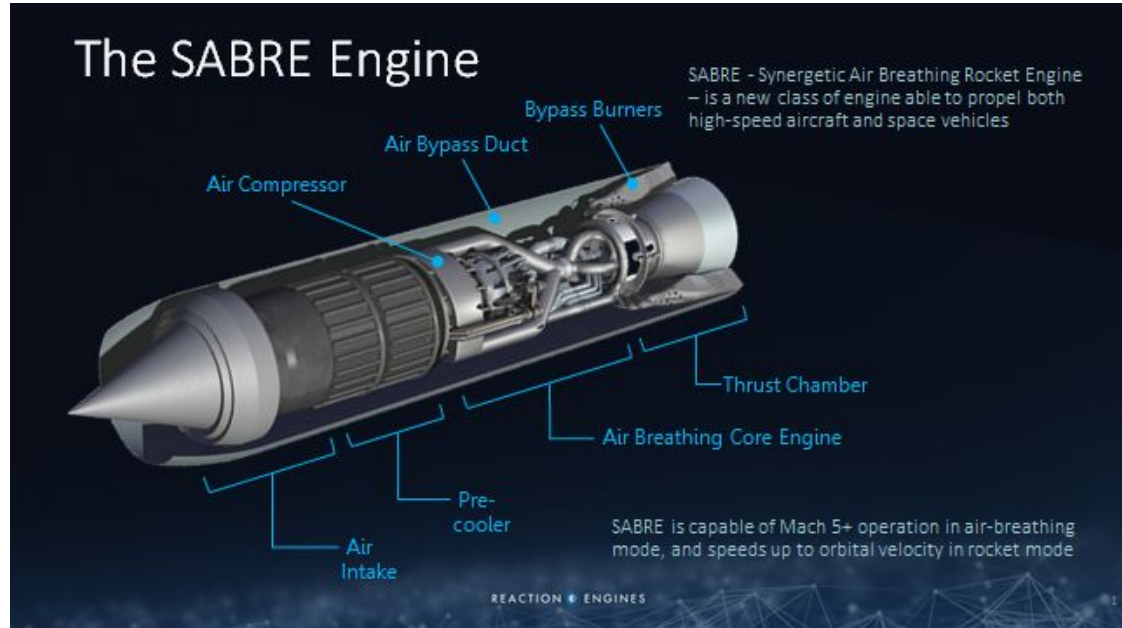
- Founded 1962,  
at present 700 people on Site
- Located in Sassenage, near Grenoble  
in the French Alps
- Advanced technologies in the  
Cryogenics field:
  - Design, Testing and  
Manufacturing Facilities



# Subcooling of Liquid Hydrogen with a Cryogenic Refrigerator

## The Customer Requirement

Reaction Engines Ltd (REL) of Culham, Oxfordshire, are developing the SABRE air-breathing rocket engine, which is **fueled by Liquid Hydrogen**.



# Subcooling of Liquid Hydrogen with a Cryogenic Refrigerator

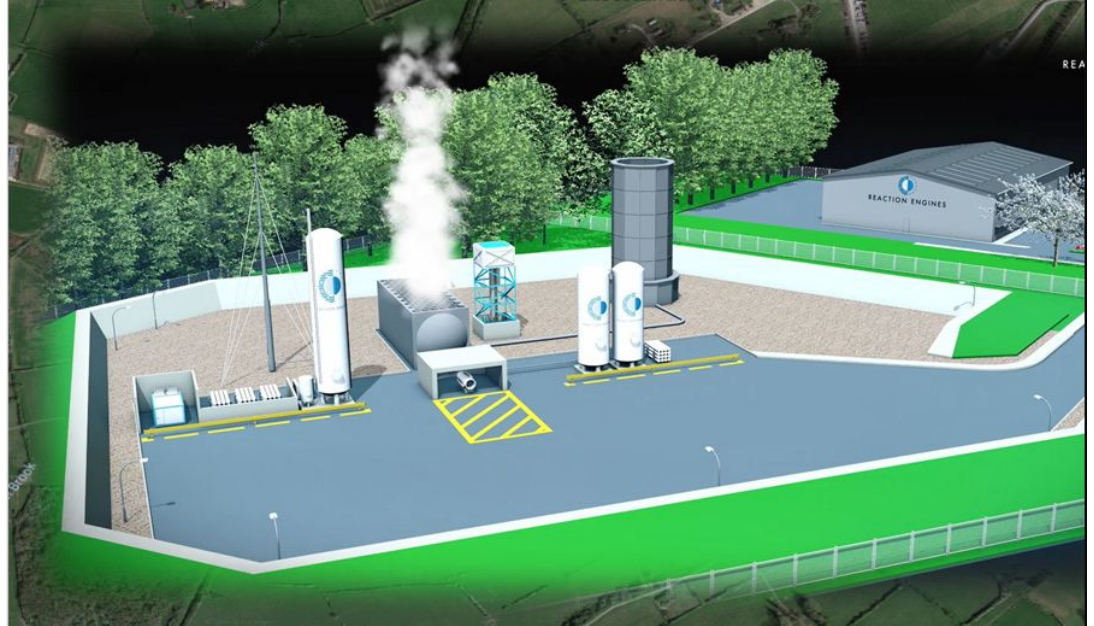
## The Customer Requirement

### Reaction Engines Ltd (REL)

of Culham, Oxfordshire, are developing the SABRE air-breathing rocket engine, which is fueled by Liquid Hydrogen.

#### SABRE Test Facility (SABRE TF1):

- under construction in Westcott, Aylesbury, UK
- to Supply SABRE with
  - 5 kg/s of Liquid hydrogen (LH2) at 20 K (At 18 K at a later stage)
  - 6 kg /s of Gaseous Hydrogen (at 75 barg)



# Subcooling of Liquid Hydrogen with a Cryogenic Refrigerator

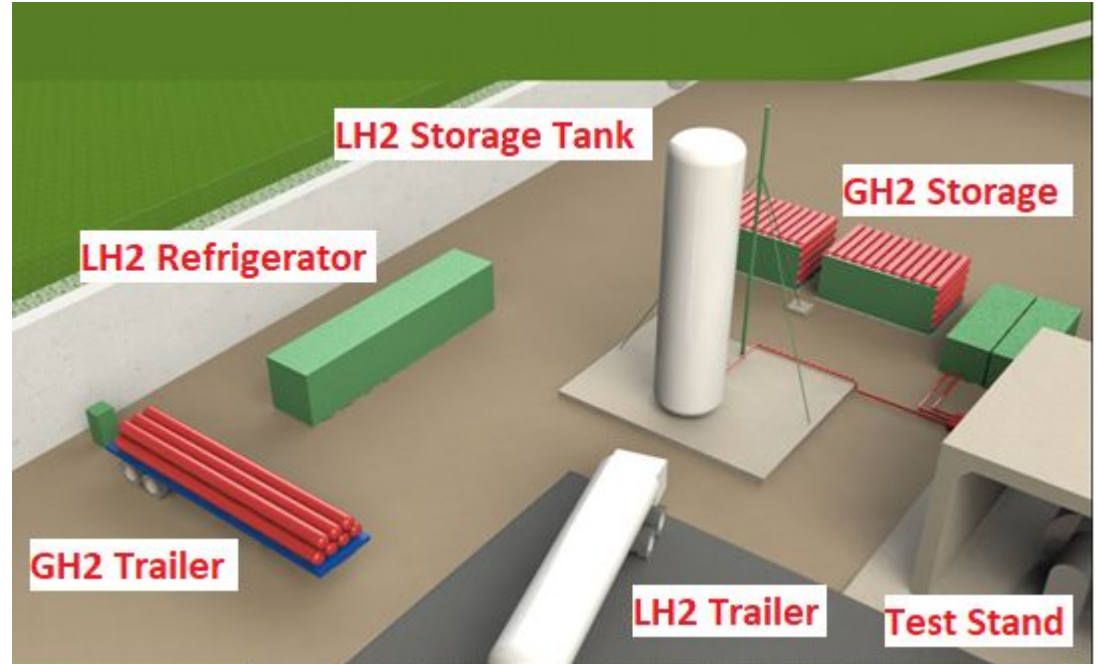
## The Customer Requirement

### SABRE Test Facility (SABRE TF1):

- to Supply SABRE with
  - 5 kg/s of Liquid hydrogen (LH2) at 20 K (At 18 K at a later stage)
  - 6 kg /s of Gaseous Hydrogen (at 75 barg)

### LH2 Storage Tank Requirement:

- Supply Two 210 second Test-Runs at 48 h interval (~ 1000 kg per run):
  - LH2 at 20.5 K, 7 barg
  - LH2 at 18.0 K, 7 barg
- LH2 Temperature Control +/- 0.5 K



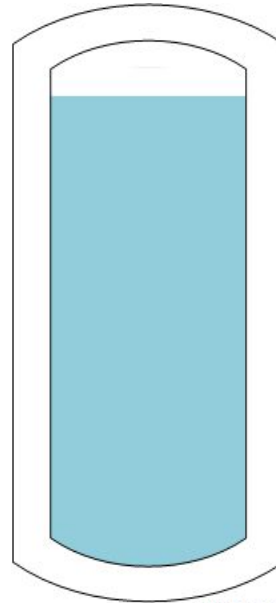
# Subcooling of Liquid Hydrogen with a Cryogenic Refrigerator

## Cryogenic Requirement

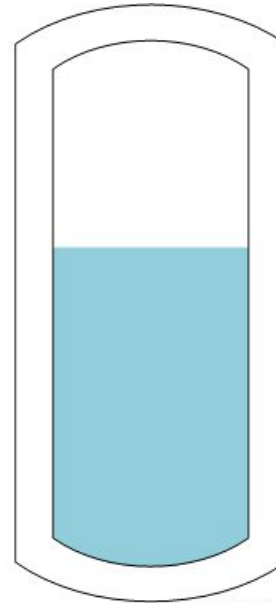
- Supply Two 210 second Test-Runs at 48 h interval (~ 1000 kg per run):
  - LH2 at 20.5 K, 7 barg
  - LH2 at 18.0 K, 7 barg
- LH2 Temperature Control +/- 0.5 K

## Air Liquide's Solution

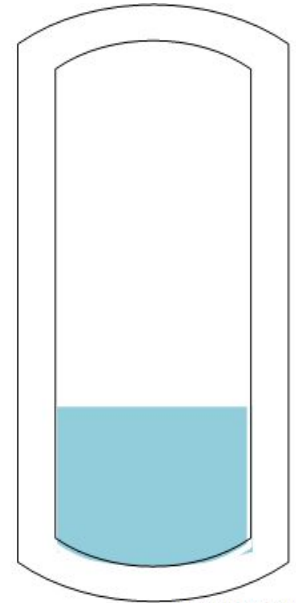
- LH2 consumption per run (18 m3):
  - 14 m3 to fuel SABRE
  - 4 m3 to cool down system
- Storage Tank Volume:  
56 m3 of LH2,  
i.e. two test -runs + margin
- Tank Dimensions:
  - 62 m3 Water Volume
  - 17 m High, 3.2 m Outer diameter



FULL TANK  
56 m3 LH2



TANK AFTER ONE RUN  
37.5 m3 LH2



AFTER TWO RUNS  
18.5 m3 LH2

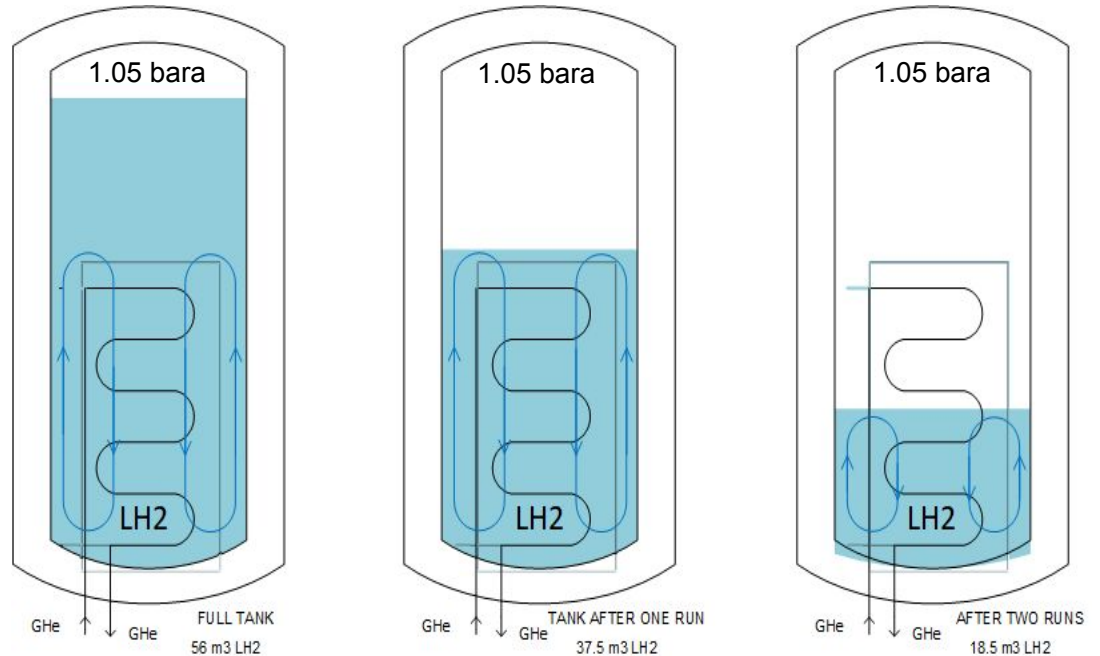
# Subcooling of Liquid Hydrogen with a Cryogenic Refrigerator

## Cryogenic Requirement

- Supply Two 210 second Test-Runs at 48 h interval (~ 1000 kg per run):
  - LH2 at 20.5 K, 7 barg
  - LH2 at 18.0 K, 7 barg
- LH2 Temperature Control +/- 0.5 K

## Air Liquide's Solution

- Heat-Exchanger Coil immersed in LH2, entering tank at the bottom
- Cold Helium Gas Fed to Top Coil Spiral Circulating Downwards
- LH2 Cool Down stage at 1.05 bara, to avoid sub-atmospheric conditions
- Cold Helium Gas Supplied by standard Air Liquide **HELIAL** Cryogenic Refrigerator



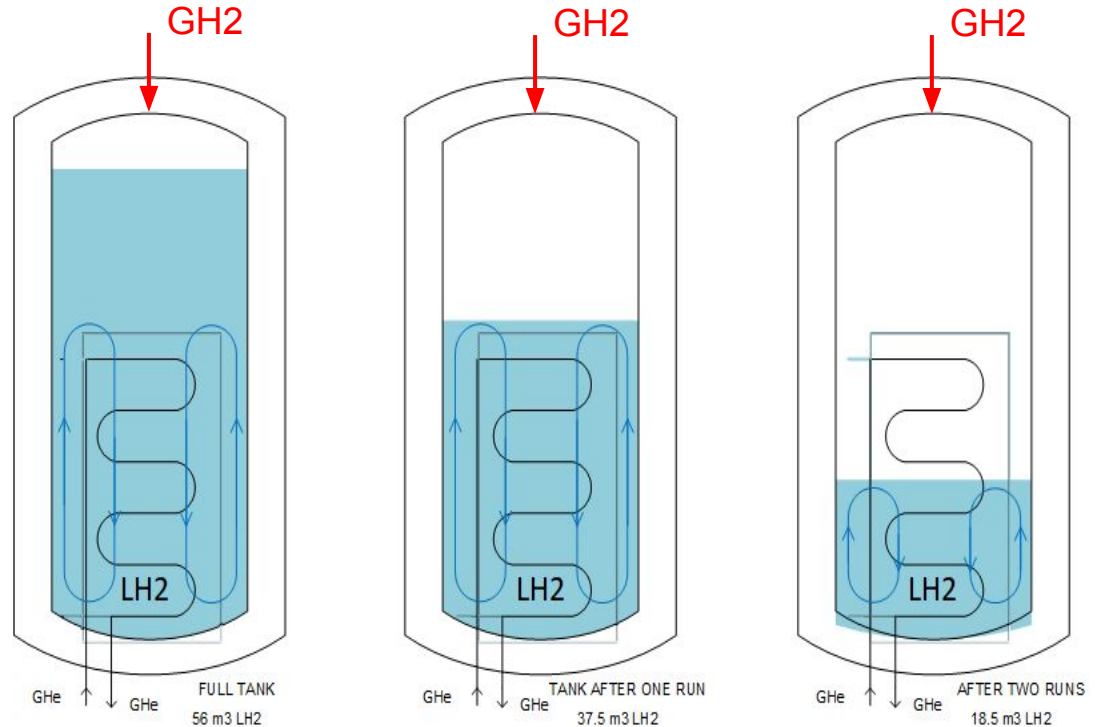
# Subcooling of Liquid Hydrogen with a Cryogenic Refrigerator

## Cryogenic Requirement

- Supply Two 210 second Test-Runs at 48 h interval (~ 1000 kg per run):
  - LH2 at 20.5 K, 7 barg
  - LH2 at 18.0 K, 7 barg
- LH2 Temperature Control +/- 0.5 K

## Air Liquide's Solution

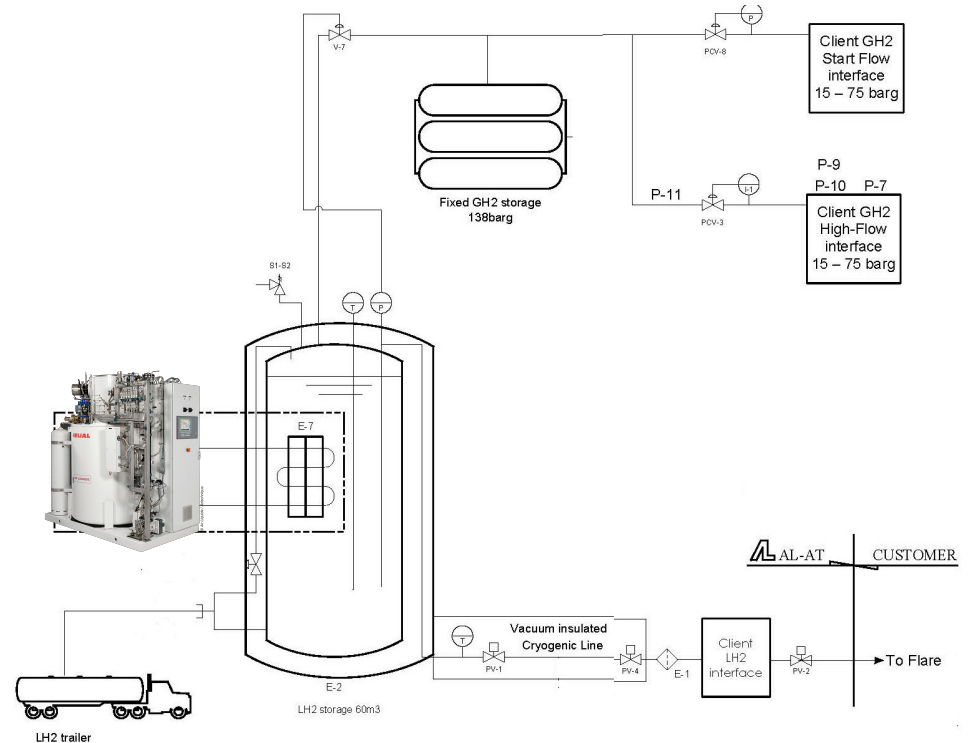
- During the Test -Run, Room-Temperature GH2 is fed to the LH2 tank vapour dome in order to:
  - Pressurise LH2 Tank up to 7 barg
  - Drive out LH2 at 5 kg/s
- GH2 stored in High-Pressure Cylinders



# Subcooling of Liquid Hydrogen with a Cryogenic Refrigerator

## Air Liquide's Solution Description

- **HELIAL** Cryogenic Refrigerator, including:
  - Helium Cycle Compressor and Oil Removal System (ORS)
  - **HELIAL** Cold Box
  - Cryogenic Feed Lines to Heat-Exchanger Coil
- 62 m3 Water Volume LH2 Storage Tank, including:
  - Filling Panel
  - Safety Panel
  - Cryogenic Feed Line To SABRE Test-Stand with Purge and Cooldown Systems
- 900 kg of High-Pressure GH2 Storage

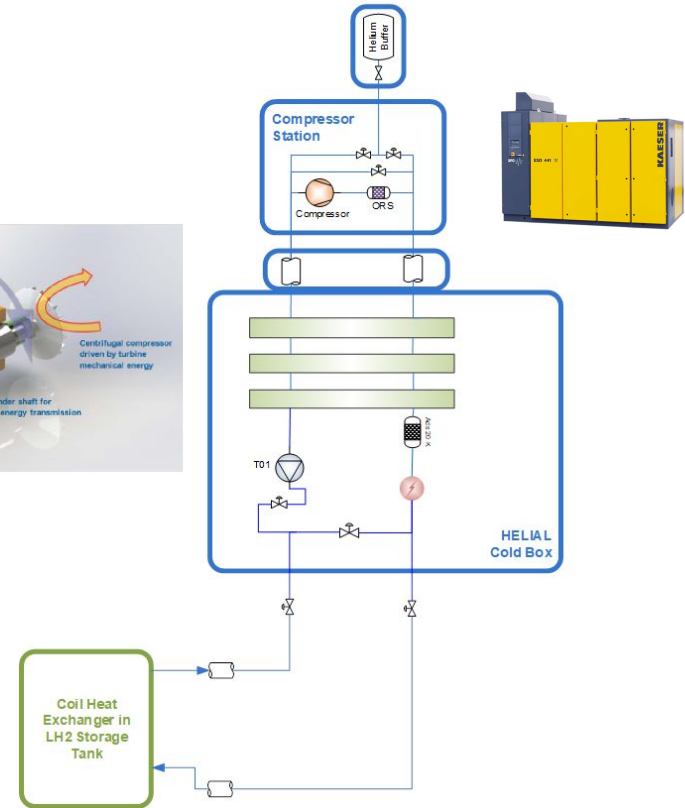
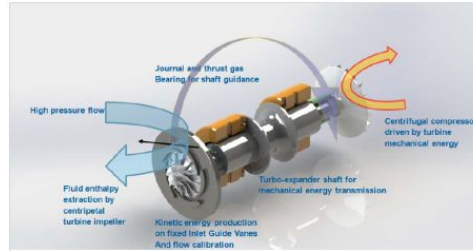


# Subcooling of Liquid Hydrogen with a Cryogenic Refrigerator

## Air Liquide's Solution Description

### **HELIAL** Cryogenic Refrigerator Main Characteristics

- One static gas bearing expander
- Cooling Power (with  $\Delta T = 5$  K):
  - 1200 W at 20 K
  - 700 W at 18 K
- Power Consumption 160 kW

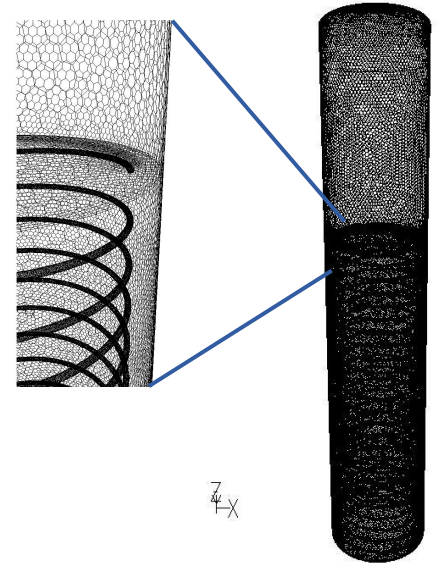


# Subcooling of Liquid Hydrogen with a Cryogenic Refrigerator

## CFD Simulation Results

### Calculation Hypotheses:

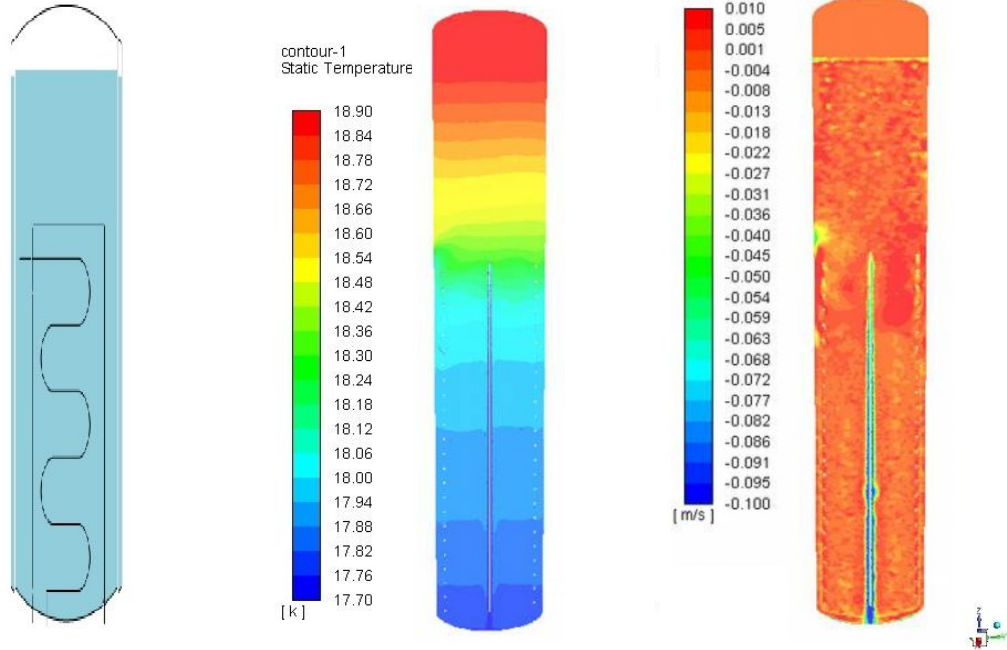
- Coil Fed by line along its centre (two calculation options : with or without heat transfer)
- 3D stationary simulations
- Liquid Phase: Conduction and Natural Convection
- Gaseous Phase: isothermal (No Convection)
- Gas-Liquid Interface Heat Flow 480 W to model GH2 Condensation Heat (No Mass Transfer) .
- Extracted Heat: 600 W Imposed by Heat-Exchanger Coil Surface Temperature
- Initial Uniform Liquid Phase Temperature: 18K
- Heat Inleaks 105 W Uniformly Distributed (Equivalent 0.5 % BOR)



# Subcooling of Liquid Hydrogen with a Cryogenic Refrigerator

## CFD Simulation Results – Full Tank – with cooling on central tube

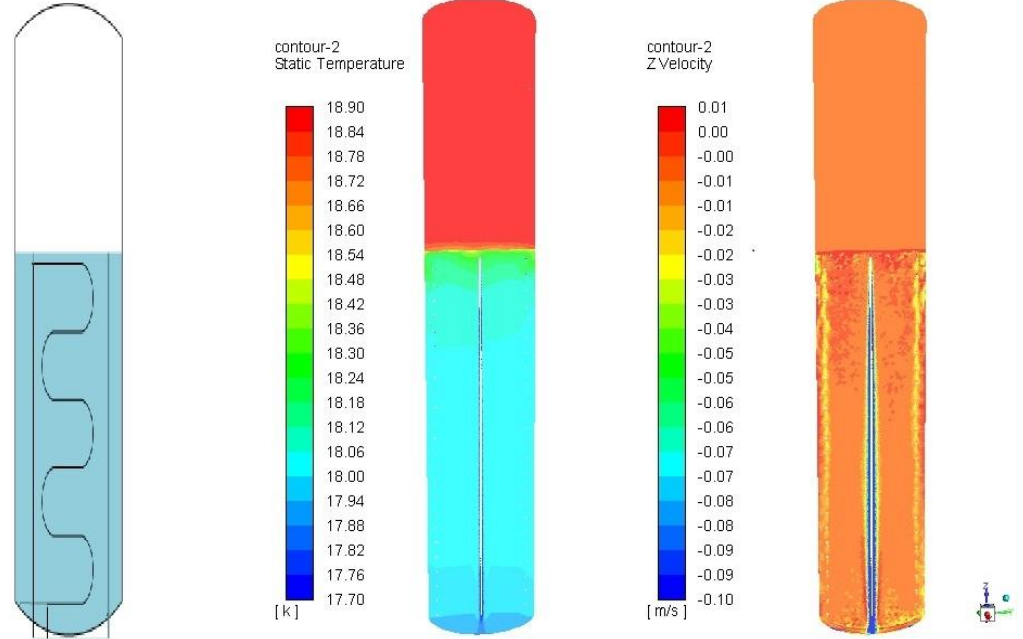
- **Liquid above Coil :**
  - Stratified Temperature Profile
  - Temperature Variation < 0.7 K
  - No Vertical Movement in Liquid
- **Refrigerated LH2 volume:**
  - Stratified Temperature Profile
  - Temperature Variation < 0.5 K
  - Higher Convection Flow  $V_z < 0.2$  m/s
  - Falling along central tube and first tubes of coil
  - Rising along the walls and on vessel section



# Subcooling of Liquid Hydrogen with a Cryogenic Refrigerator

## CFD Simulation Results - Tank 2/3 Full (After one Test Run) - with cooling on central tube

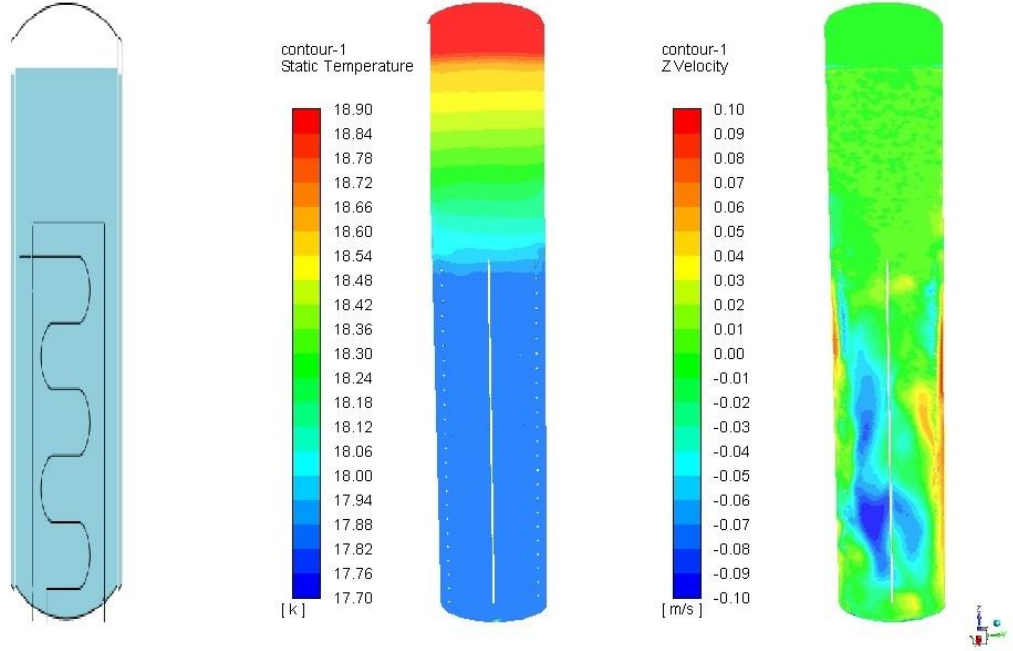
- **Liquid above Coil :**
  - NA
- **Refrigerated LH2 volume:**
  - Stratified Temperature Profile
  - Temperature Variation  $< 0.4$  K
  - Higher Convection Flow  $V_z < 0.2$  m/s
  - Falling along central tube and first tubes of coil
  - Rising along the walls and on vessel section



# Subcooling of Liquid Hydrogen with a Cryogenic Refrigerator

## CFD Simulation Results – Full Tank – no cooling on central tube

- **Liquid above Coil :**
  - Stratified Temperature Profile
  - Temperature Variation  $< 1.0$  K
  - No Vertical Movement in Liquid
- **Refrigerated LH2 volume:**
  - Uniform Temperature 17.9 K
  - Low-Intensity Convection Flow  $V_z < 0.1$  m/s
  - Rising along the walls
  - Falling along first tubes of coil and other structures inside the tank



# Subcooling of Liquid Hydrogen with a Cryogenic Refrigerator

## CFD Simulation Results : Conclusions

### ***Simple model to represent sub-cooled liquid in a LH2 tank***

- Liquid above Coil : Stratified  $\Delta T = 0.7 \text{ K}$  to  $1 \text{ K}$
- Refrigerated LH2 volume : From less than  $0.1 \text{ K}$  to  $0.5 \text{ K}$  gradient on total inventory
- On the useful volume for one test run, the temperature gradient is less than  $0.2 \text{ K}$

***Within the worst condition on flow circulation (downstream on the central tube), the temperature gradient on sub-cooled LH2 is still acceptable for the SABRE project.***

# Subcooling of Liquid Hydrogen with a Cryogenic Refrigerator

## Project Schedule

SABRE TF1 Test Facility Currently Under Construction

- June 2017: REL Request for Proposal
- March 2018: Contract Awarded to ALaT
- May 2018: Project Kick- Off
- **September 2018: Preliminary Design Review**
- November 2018: Final Design Review
- July 2019: Equipment Delivery
- September 2019: Installation & Commissioning
- November 2019: Site Acceptance Tests
- January 2020: Start of SABRE Test Operations





Thank for your  
attention

—  
Questions ?