Thrust Vector Control System for solid propellant de-orbit motors

IMAGE: ESA

almatech

ESA Clean Space Industrial Days 26 May 2016

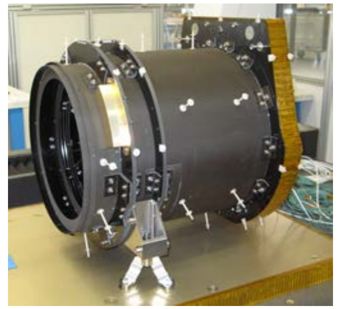
PRESENTATION OUTLINE

1. Introduction	A few words about Almatech
	Project objectives
	Baseline scenario
2. Conceptual design	Identified design drivers
	Concept tradeoff
	Jet Flap Mechanism
	Vectoring performance – SRM in space
3. Validation	Cold flow testing
	Test facility limitations
	Validation of vectoring performance
	Challenges of testing
4. Way forward	Prospective way forward

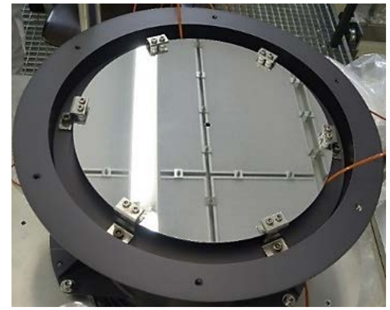
ALMATECH IS A SPACE ENGINEERING COMPANY WITH ESTABLISHED EXPERTISE IN FOUR MAIN FIELDS

- **Integrated Systems**
- **Ultra-stable structures**
- **High precision mechanisms**
- **Thermo-optical hardware**

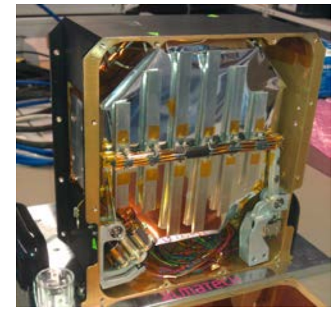
- CHEOPS
- Solar Orbiter
- BepiColombo
- ExoMars 2018
- Sentinel-5



OPTICAL TRAIN ASSEMBLY (OTA) FOR CHEOPS

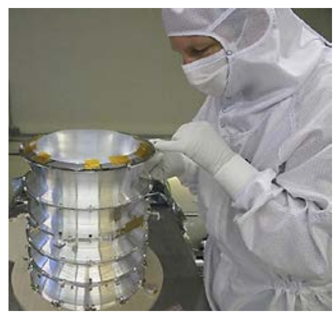


STIX WINDOWS FOR SOLAR ORBITER

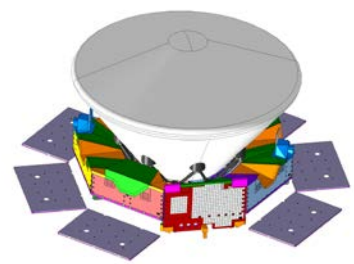


DETECTOR ELECTRONIC MODULE (DEM) FOR SOLAR ORBITER

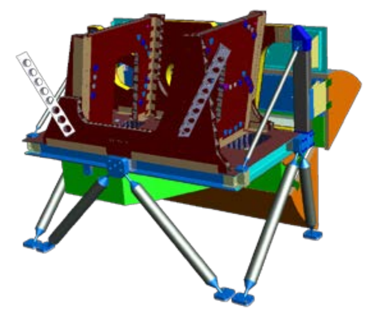
SLIT-CHANGE MECHANISM (SCM) FOR SOLAR ORBITER



RECEIVER BAFFLE UNIT (RBU) FOR BEPICOLOMBO



MLI OF THE CARRIER MODULE OF EXOMARS 2018



OPTICAL STRUCTURE AND RADIATORS (IOMSR) OF SENTINEL-5

Objectives

- Almatech was selected for the ESA Clean Space initiative to develop and test a Thrust Control Vector (TVC) mechanism for de-orbiting purposes

  (ESA Contract No. 4000112746/14/NL/KML)

- Almatech is Prime with 2 Italian partners: D-ORBIT SITAEL

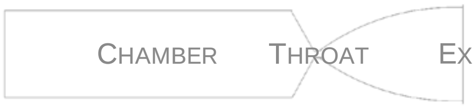
  Other project participants are: CFS Engineering von KARMAN INSTITUTE FOR FLUID DYNAMICS

- **The objective of the activity** is to
  - identify vectoring solutions
  - trade-off of vectoring concepts
  - design
  - manufacture and
  - test a breadboard of a TVC mechanism

TRP under ESA Clean space initiative

BASELINE SCENARIO

- **Large spacecraft** ~ 1500 kg
- **LEO** ~ 800 km altitude
- **Rocket motor clustering** 4 motors required for deorbit
- **Rocket motor thrust level** – 3 classes, nominal 250 N
- **Long burning time** ~ 4.75 min, cigarette burning
- **Bell shaped nozzle**
- **High expansion ratio** ~ 450



$$Expansion\ ratio = \frac{Area_{exit}}{Area_{throat}}$$

Identified design drivers

Performance
- thrust deflection angle > +/-5 deg
- thrust deflection rate > 10 deg/s

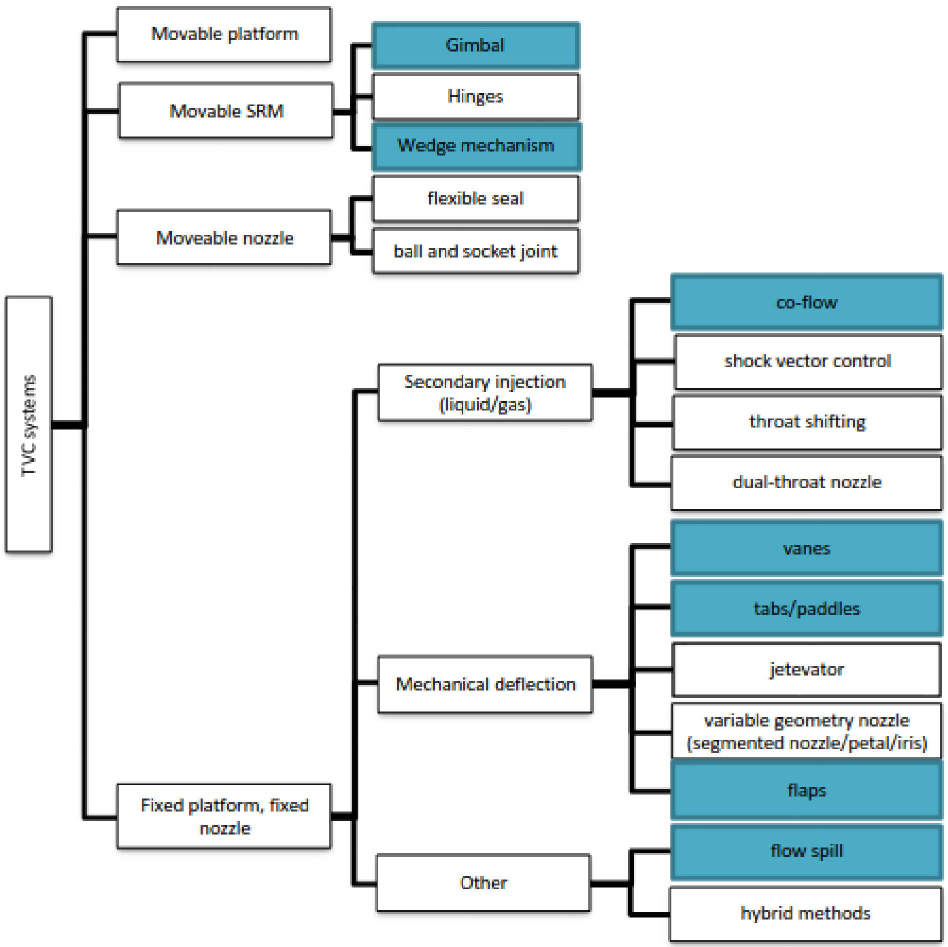
Cost-effectiveness
- minimized complexity
- standardized components and processes
- manufacturing and assembly reproducibility

Reliability
- non-operational lifetime of 15 years in-orbit
- long SRM burn time

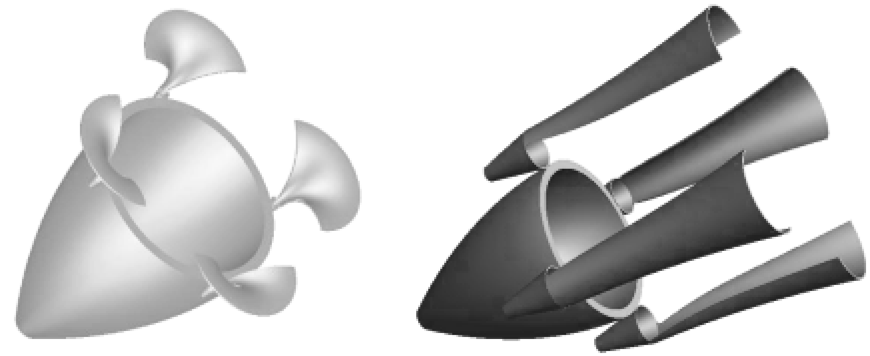
Integration
- interfaces
- ease of access and installation
- AIT activities
- cleanliness

Compactness
- low mass, volume
- low encumbrance for clustering

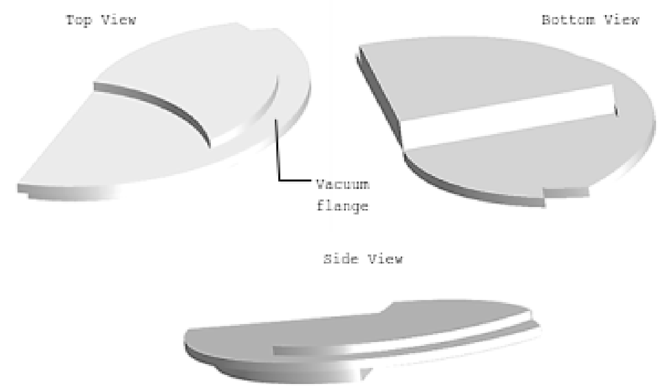
CONCEPT TRADE-OFF



CO-FLOW CONCEPT



JET TAB IRIS MECHANISM



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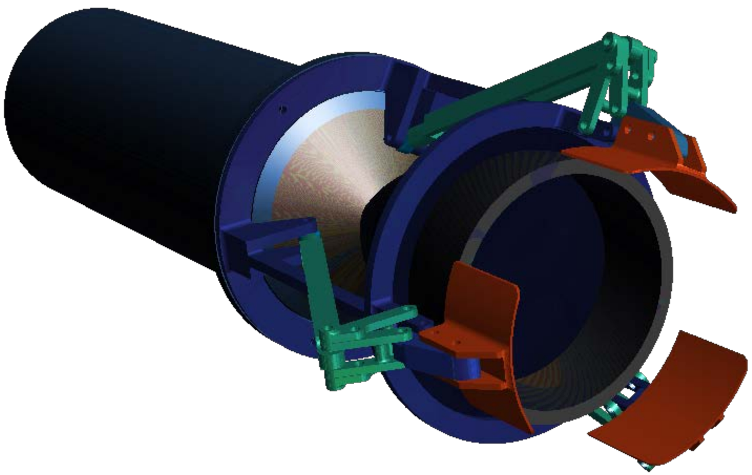
JET FLAP VECTORING MECHANISM

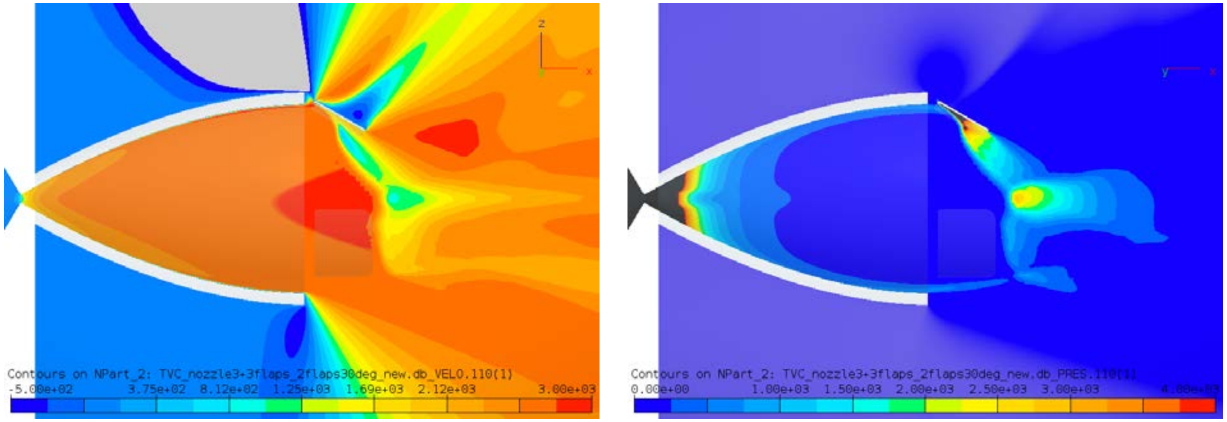


- **Linkage mechanism** - relative simplicity
- **Good performance characteristics**
- **Protected from environment** with possibility to retract to the spacecraft
- **No need for high temperature sealing** due to structural decoupling of SRM nozzle from the TVC system, thus reduced thermal loading
- **Mechanism jamming risks greatly reduced** with use of metallic flex pivots including custom-designed large angle flexures (patent pending)

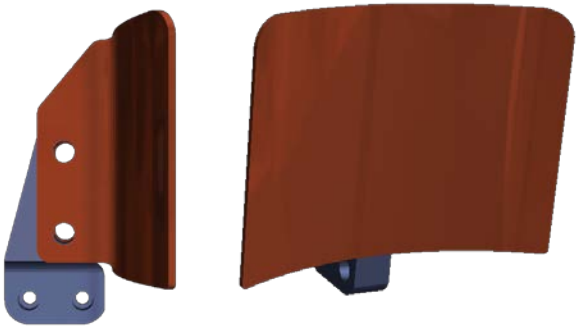
VECTORING PERFORMANCE – SRM IN SPACE

- **Vectoring** - 5 degree thrust vectoring with 45 degree flap deflection
- **Plume profile** - under-expanded
- **Exit pressure** – 193 Pa
- **Backflow** is generated in axial gap between nozzle exit plane and flap
- **Flap deflector** – curved following the curvature of the nozzle exit, providing a smooth continuation of the nozzle to avoid generation of strong shock waves
- **Force on flaps** – max. ~ 18 N

FLOW VELOCITY AND PRESSURE PROFILE AT 30 DEG FLAP DEFLECTION



CURVED FLAP PROFILE



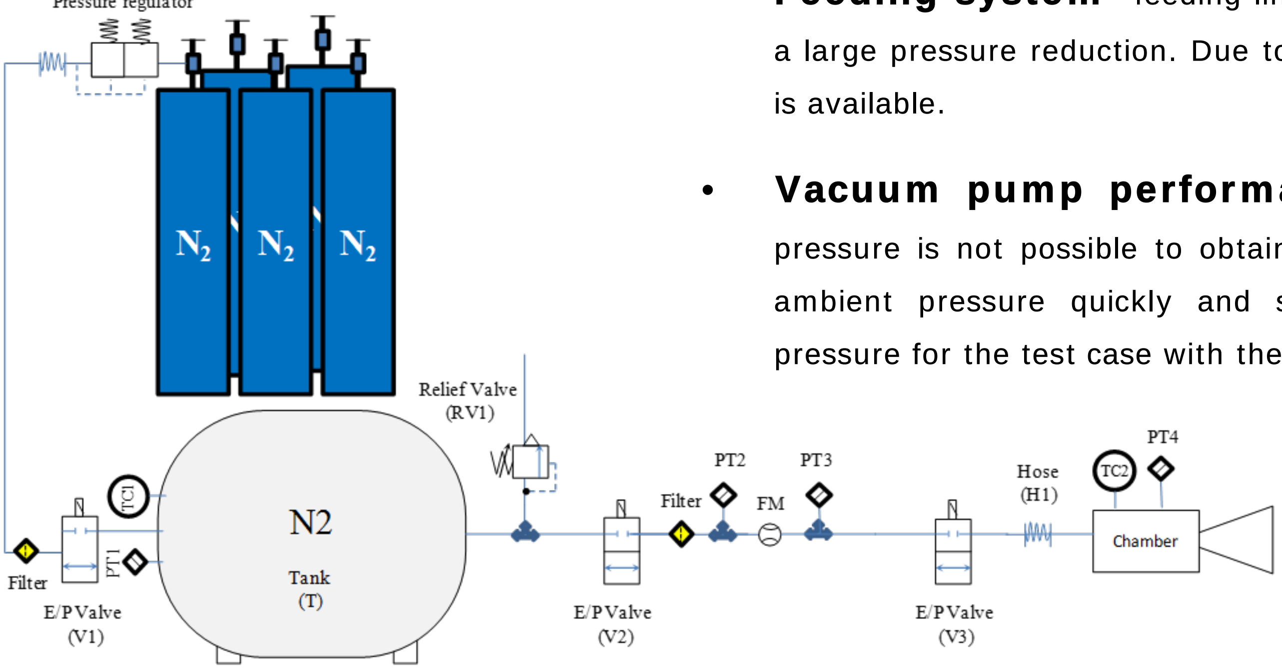
COLD FLOW TESTING

LONGSHOT HYPERSONIC
WIND TUNNEL TEST SECTION

- **Cold gas testing in vacuum**
  - Facility:
    - VKI Longshot Hypersonic Wind Tunnel Test Section
  - Test chamber:
    - diameter: 2.72 m, height: 3.25 m
    - vacuum pump can go down to 1Pa
  - Gas reservoir:
    - 9800 liter
    - maximum service pressure of 16 bars
- **Working medium**: N_2
- **Force balance test stand** – installed in the chamber to measure the trust intensity and direction

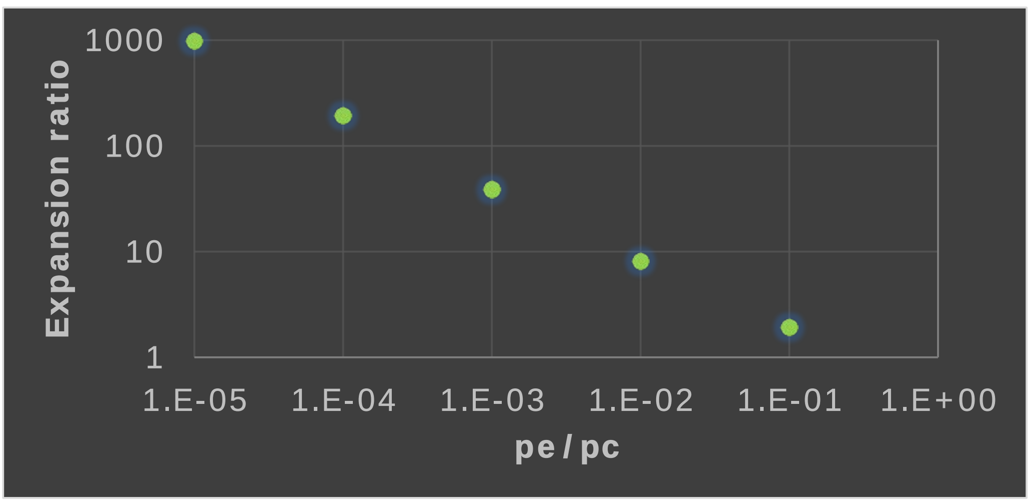
TEST FACILITY LIMITATIONS

- **Thruster performance** – the nominal thrust developed with N_2 is 107 N.
- **Feeding system**– feeding line of 50 m is required which results in a large pressure reduction. Due to losses, only 9 bar chamber pressure is available.
- **Vacuum pump performance** – a continuous, low level of pressure is not possible to obtain and maintain during the firing; the ambient pressure quickly and steadily increases. (The nozzle exit pressure for the test case with the nominal nozzle is 27 Pa.)

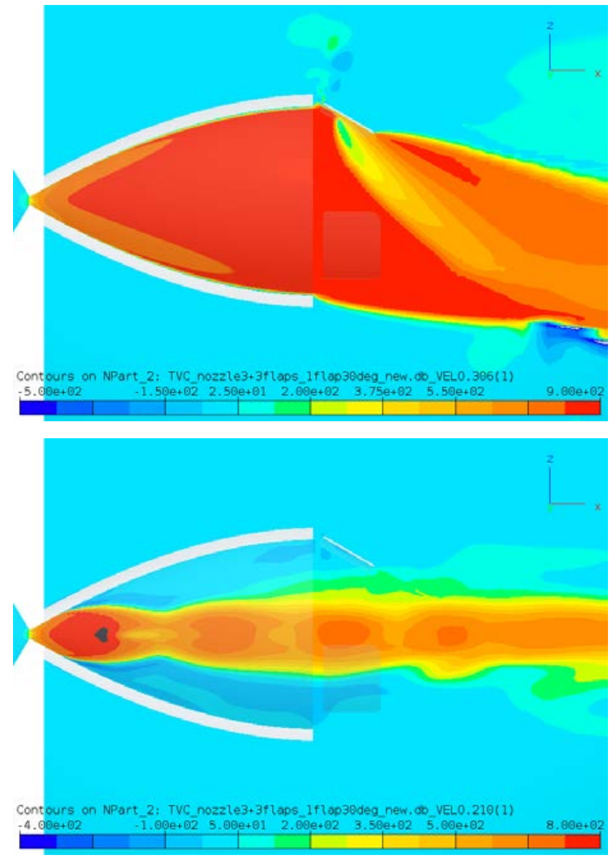


VALIDATION OF VECTORING PERFORMANCE

- **Plume profile (Exit to ambient pressure ratio)**
  - under-expansion can only be reproduced by significantly decreasing the throat diameter, however forces on the flaps become very low
- **Chamber to exit pressure ratio** – large due to very large expansion ratio, challenging to reproduce



FLOW VELOCITY PROFILE AT 30 DEG FLAP DEFLECTION
MODEL WITH 65 PA AND 6500 PA AMBIENT PRESSURE



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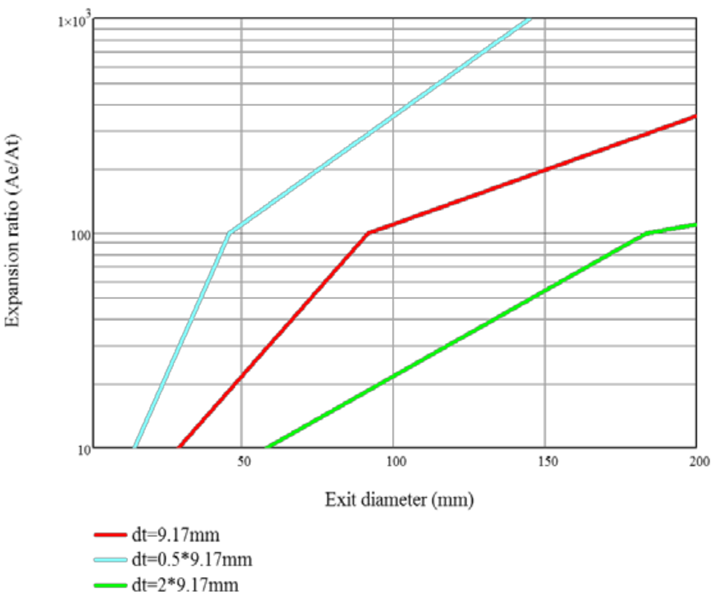
VALIDATION OF VECTORING PERFORMANCE – NOZZLE GEOMETRY



- **Expansion ratio** – can be changed by changing the throat diameter, nozzle diameter or both
- **Nozzle diameter** – decreasing the diameter also shortens the nozzle
- **Throat diameter** - from a force measurement and manufacturing point of view, it is advantageous to upscale the throat diameter; the larger diameter, however, will results in a larger mass flow rate that will have implications on the test time due to the limitations of the vacuum pump.
- **Reynolds number** - the Reynolds number is a function of the nozzle exit diameter, thus the flow Reynolds number and BL thickness are not reproduced when changing the nozzle geometry.

$d_{throat} = 9.17\ mm$

$d_{nozzle} = 196\ mm$

$Expansion\ ratio = 450$

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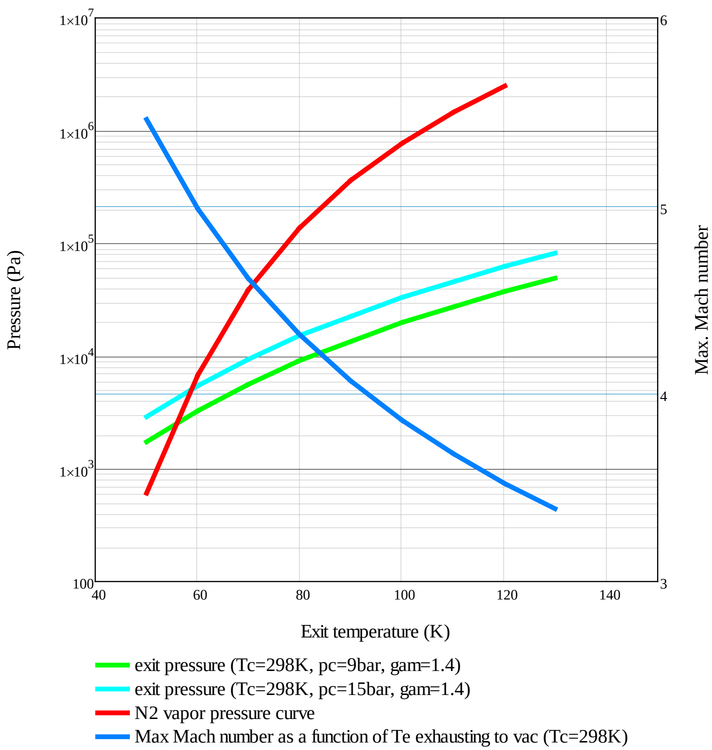
VALIDATION OF VECTORING PERFORMANCE

- **Hypersonic similarity** - a Mach number of 4.88 is required from the cold flow model (SRM exit Mach number: 6).



- Nitrogen can condense in a hypersonic nozzle due to the expansion of the flow. This phenomenon is can significantly affect the accuracy of the experiments.
- For the matched Mach number (4.88) condensation will likely occur, as it the corresponding exit temperature is 51 K.
- To avoid condensation:
  1) an exit temperature of 100 K is chosen. The required Mach number is 3.146 ⇒ No hypersonic similarity
  2) the combustion chamber needs to be heated to ~580 K. ⇒ No cold flow

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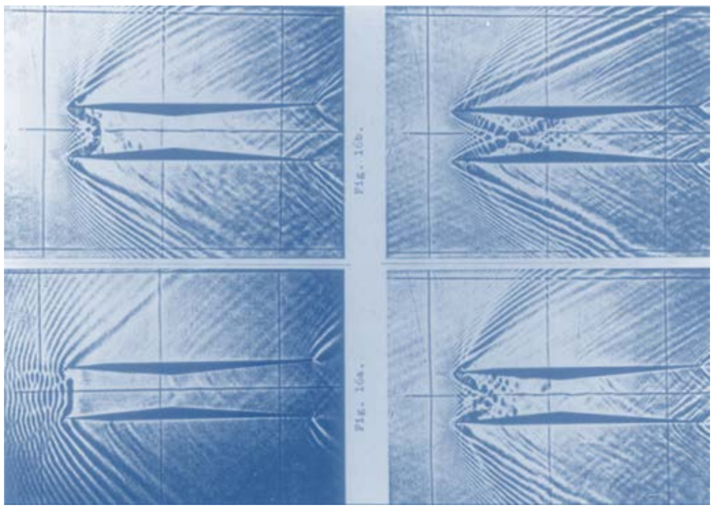
CHALLENGES OF TESTING

HYDRAULIC ANALOGY



- **Cold gas testing in vacuum** - alternative facilities
- **Testing in atmospheric conditions** - cold gas or hot gas (rocket motor firing); while ambient conditions are constant, flow characteristics are not reproduced
- **Pulsed mode testing** - very short test duration to keep the ambient conditions relatively constant, complex and costly measuring equipment
- **Hydraulic analogy** - Mach similarity is possible, but can only visualize flow phenomena
- **Simulations only**
- **In-orbit demonstration**

WAY FORWARD

- **No sufficiently representative test method with cold flow was identified** that could reproduce the SRM flow conditions and provide comparable deflection conditions.
- **Rarified gas dynamics (*DSMC*) simulations** could provide useful and reliable information for further development of the Jet Flap concept.
- **Breadboarding** effort can be put into other high potential concepts not involving cold flow testing (such as gimbal).

THANK YOU!

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