Europe’s Access to Space: Past, Present and Future

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Content

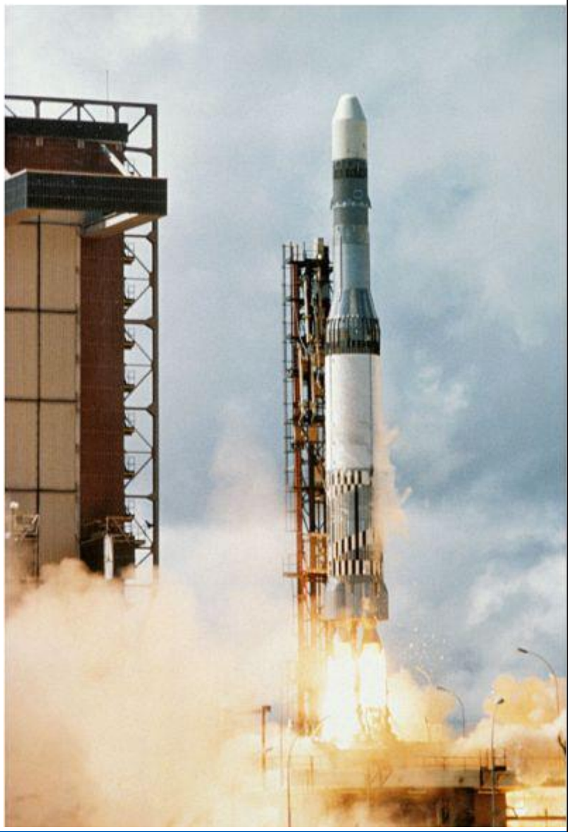
- Early Beginnings
  - ELDO and Europe
  - Technology Developments
- Things That Went Wrong, ARIANE 1 – 4, ARIANE 5
  - Failures and Description
  - Lessons Learned
- The Present
  - ARIANE 5 ECA, ARIANE 5ES
  - Soyuz in Courou
  - Vega
- Where does Europe go?
  - ARIANE 5ME
  - ARIANE 6
- The Future of LRE Modeling

Early Beginnings

European Launcher Development Organisation (ELDO)

- Great Brittain 1. Stage Blue Streak LOX/Kerosene RZ-2 (2 x 667 kN),
- France, 2. Stage Coralie NTO/UDMH Vexin-A (4 x 66 kN),
- Germany 3. Stage Astris NTO/AZ50 (23,3 kN)

- Launch Pad in Woomera / Australia
- No successful mission > 10 attempts
- Program abandoned 1972



The ELDO Times

Europe / Stage 1: Blue Streak

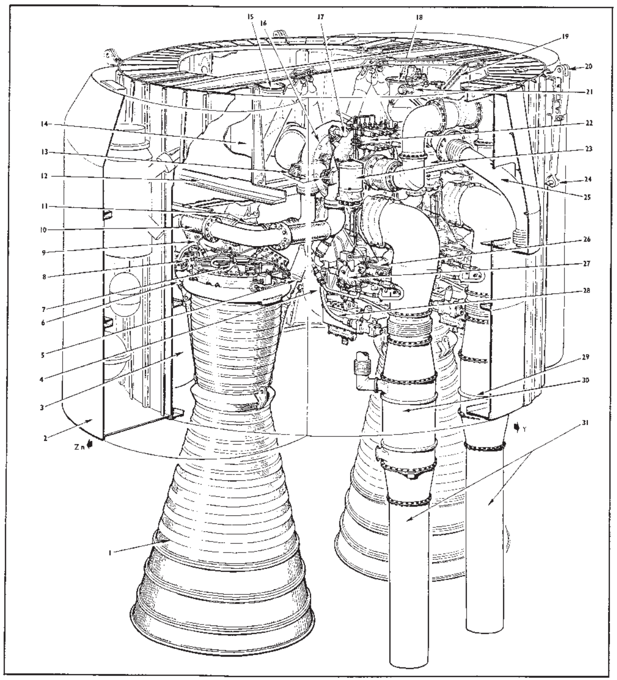
Engine RZ-2

Developed at Rolls-Royce, based on American S-3 Engine (Rocketdyne)

•Thrust:	667 kN
•Propellants:	LOX / Kerosene
•Cycle:	GG

Prior to first flight of Europe 1:

Tests:	30
Total Test Time	842 s



KEY

1. Tubular wall thrust chamber.
2. Equipment fairing.
3. Engine oil tank.
4. Liquid nitrogen bottle.
5. Pitch control ram.
6. Yaw control ram.
7. Igniter fuel valve.
8. Main fuel valve.
9. Main lox valve.
10. Propellant flexible.
11. Gimbal mounting.
12. Main motor beam.
13. Pump mounting.
14. Thrust bracket.
15. Lox inlet to pumps.
16. Lox pump.
17. Reference pressure loader.
18. Fuel inlet to pumps.
19. Turbopump vee frame.
20. Attachment to tank bay.
21. Fuel tank valve.
22. Pneumatic manifold.
23. Engine relay boxes.
24. Launcher bracket.
25. Main fuel probe.
26. Gas generator.
27. Lox regulator.
28. Instrumentation box.
29. Heat exchanger (nitrogen).
30. Heat exchanger (gox).
31. Turbine exhaust.

Reference: JBIS May 1991

Europe / Stage 2: Coralie

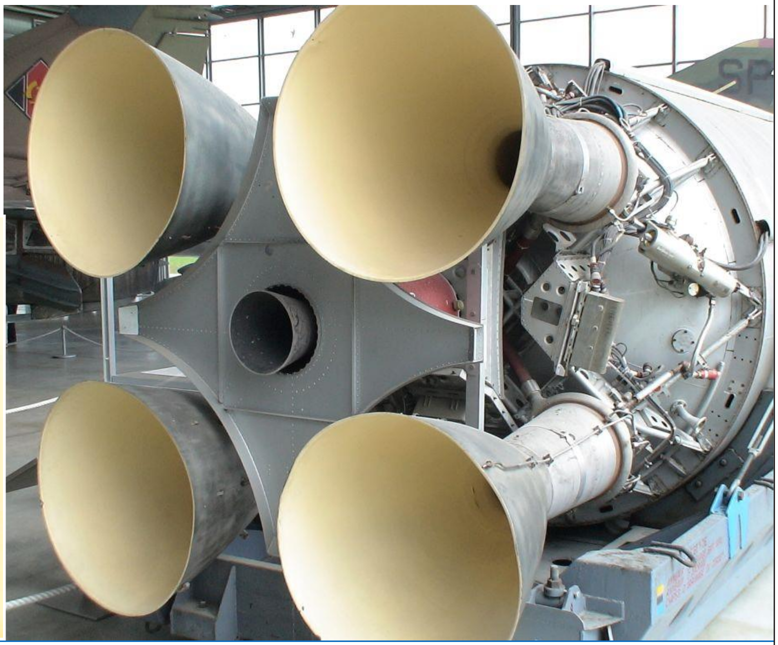
Engine Vexine-A

Reference: Haeseler,
Deutsches Museum
Schleissheim

Developed at Snecma (H. Bringer)

First flight: Europe 1 F6 (1967)

- Thrust: 265 kN
- Propellants: N2O4/UDMH
- Cycle: GG



Europe / Stage 3: Astris

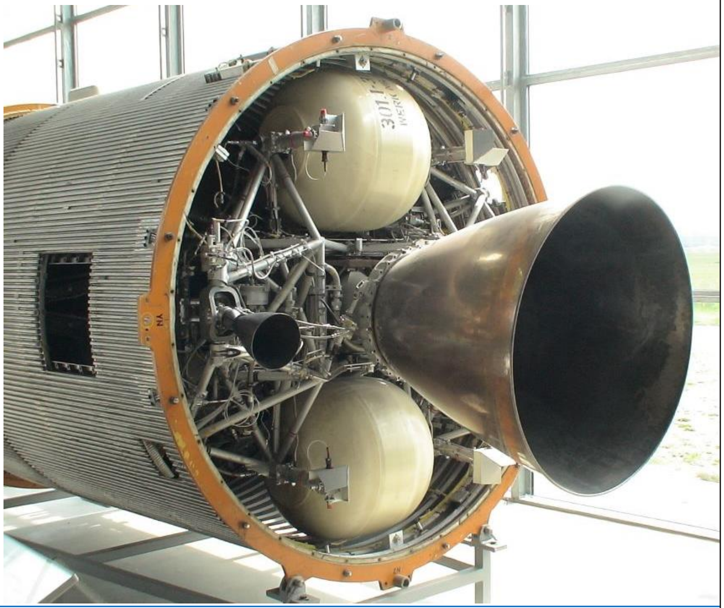
Engine RZ-2

Reference: Haeseler,
Deutsches Museum
Schleissheim

Developed at MBB / ERNO

First flight: Europe 1 F7 (1968)

- Thrust: 22,5 kN
- Propellants: N2O4 / AZ50
- Cycle: pressure-fed

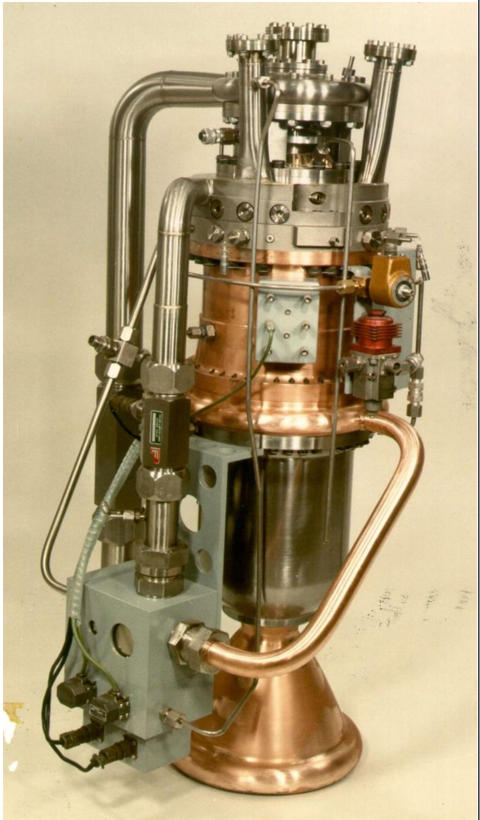


Interesting Developments

P-111 Engine

- LOX / Kerosene Staged Combustion Engine with oxygen-rich Pre-burner
- Developed at Bölkow / MBB (1956 – 1967)
- Single shaft turbo-pump, axially integrated with pre-burner and main chamber
- Main chamber regenerativ cooled with LOX
- Copper liner, machined cooling channels and galvanic closed with Cu and Ni outer liner

• Thrust:	49 kN (5 – 49 kN)
• Spec. impulse	306 s
• Mixture ratio:	2,7 (2.1 - 4)
• Chamber pressure:	85 bar
• Pre-burner pressure:	116 bar
• Pre-burner temperature:	920 K



Interesting Developments

BORD 1: Demonstration of Regen. Cooling for High Pressure Rocket Engines

Main Design Data:

•Propellants	LOX/LH2	-
•Mixture Ratio O / F	6	-
•Chamber Pressure	205	bar
•Nozzle Area Ratio	10.1	-
•Sea Level Thrust	13	kN

Main Test Results:

•Successfully tested operational range of

•Chamber Pressure	38-285	bar *
•Mixture Ratio	4-8	-
•Coolant Inlet Temperature	30-210	K
•Coolant Mass Flow	40-215	% **
•Max. Test Time (one single chamber)	360	s

*** Limited by test stand capability**
**** % of regen. flow (by-pass cooling)**

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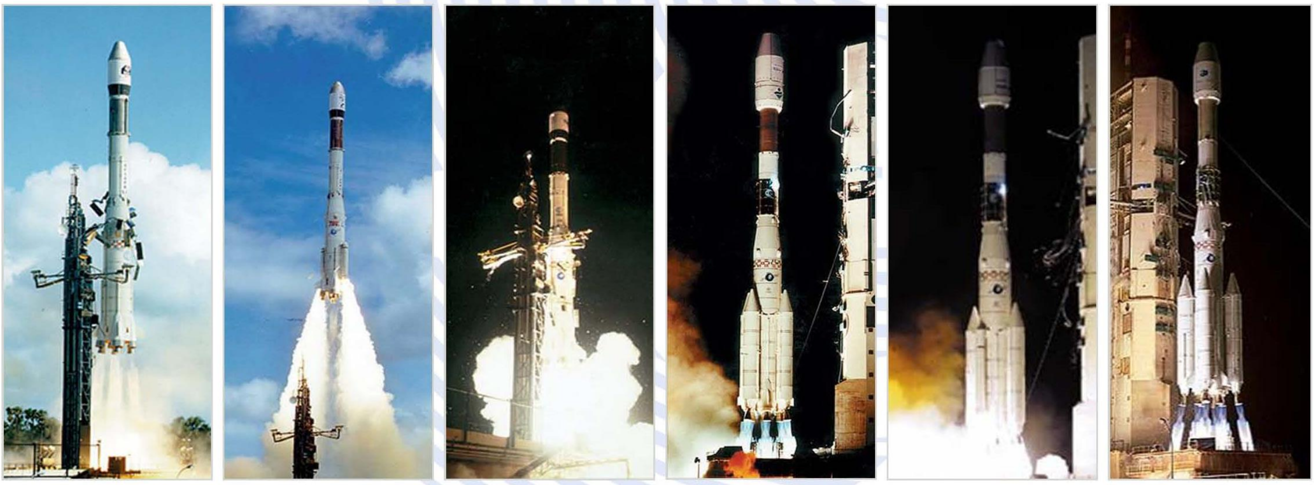
The Past

ARIANE 1 – 4:

Operational from 1979 until 2003 with a total of 144 launches and 7 failures



1st AR1 . LO1 1979 | 1st AR3 . V10 1984 | 1st AR2 . V20 1987 | 1st AR4 . V22 1988 | 100st AR4 . V134 2000 | Last AR4 . V159 2003

The Past

ARIANE 1 – 4: Failures, Reasons and Lessons Learned

Flight	ARIANE	Date	Failure
L02	AR1	23/05/80	1st stage, HF Instability on Viking engine
L05	AR1	10/09/82	3rd stage, HM7B engine gear box rupture
V 15	AR3	12/09/85	3rd stage, HM7B engine non ignition
V18	AR2	31/05/86	3rd stage, HM7B engine non ignition
V36	AR4	22/02/90	Feed line obstruction by a cloth
V63	AR4	24/01/94	3rd stage, HM7B engine failure
V70	AR4	01/12/94	3rd stage, HM7B engine failure

The Past

ARIANE 5:

Operational since 1996 in different versions (AR5 G, AR5 G+, AR5 ES, AR5 ECA) with a total of 71 launches* and 3 failures

Flight	ARIANE	Date	Failure
V501	AR5	04/06/96	System design error
V510	AR5	12/07/01	3rd stage, AESTUS engine HF instability
V517	AR 5ECA	11/12/02	Cryogenic stage, Vulcain 2 engine failure

***flight 71: 29.08.2013**

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Failures and Lessons Learned

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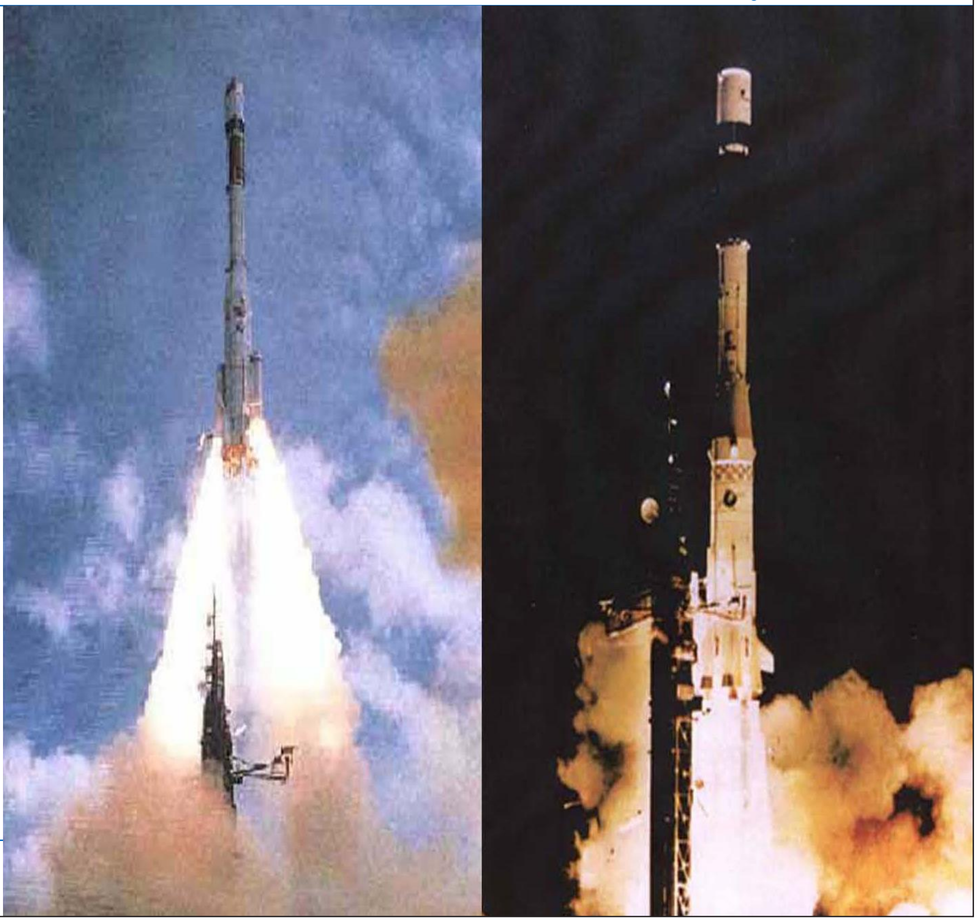
ARIANE 2, ARIANE 4:

V15, V18 FAILURE EVENTS

3rd Stage,
HM7B engine
no ignition



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Failures and Lessons Learned

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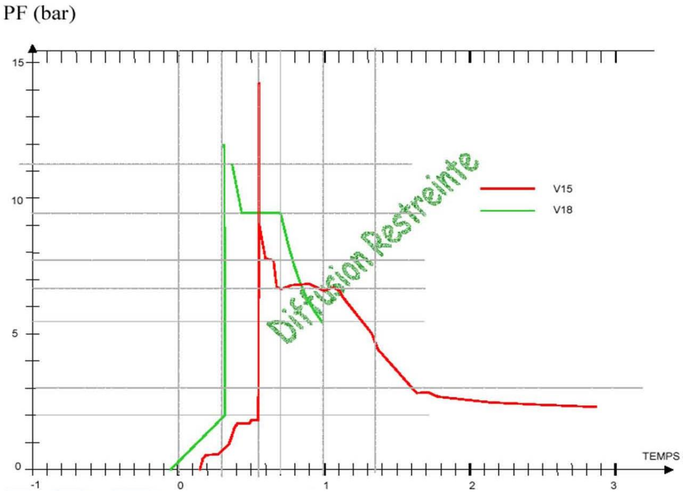
V15, V18 FAILURE EVENTS

- At H2+8.26s The starter is initiated and the turbo pump rotation starts
- Some hundred milliseconds later the LOX injection valve is opened
- At H2+8.85s for V15 and H2+8.608 s for V18, The solid propellant igniter is ignited, under a chamber pressure of 2 bars, leading to:
    - Significant overshoot in chamber pressure and the TPH pressure
    - Pressure wave propagation in LH2 line
    - LH2 vaporization
    - Hydrogen pump stall
    - Impossibility for the gas generator to start correctly
    - HM7B extinction



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Failures and Lessons Learned

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V15, V18 Inquiry Results

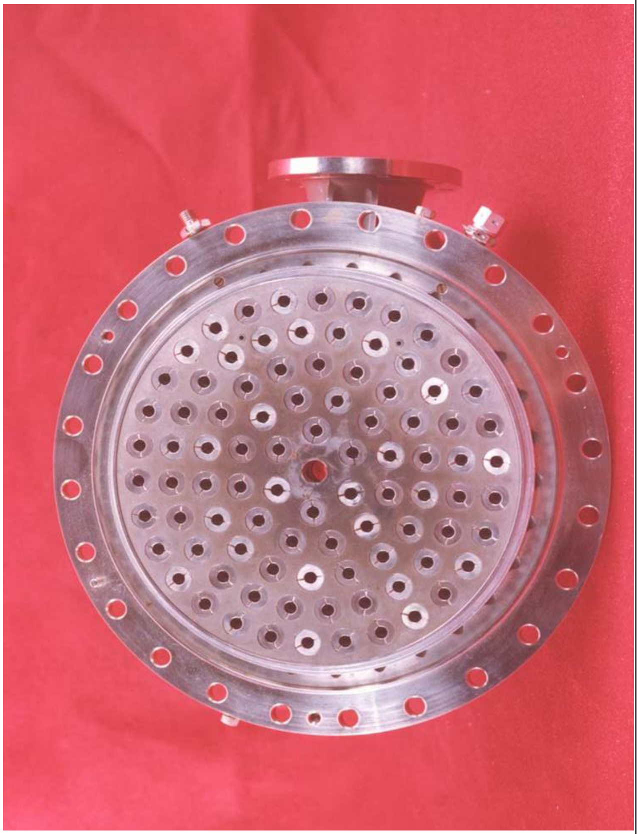
V15 and V18 failures have common reasons: Considerably cold engines

- V15, leakage of main LH2 valve
- V18, cooling down of igniter gas by the LH2 venting

Deviation of mixture ratio (H2 in excess) which led to:

  - Ignition pressure overshoot
  - Ignition delay

The main failure reasons were a weak igniter design and a lack of knowledge of the ignition process and in particular the margins of the hardware.



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Failures and Lessons Learned

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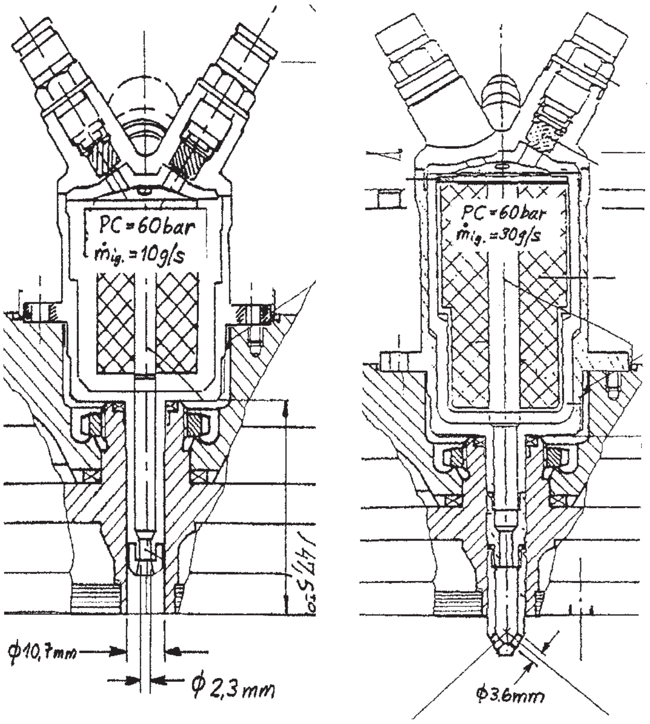
V15 and V18 Correcting Measures and Consequences

- Technological improvement of the injection valves to prevent any leakage with subsequent cold startup conditions and LH2 excess
- Improvement of igniter design and power
  - Increase of solid propellant charge
  - 2 outlets of hot gases oriented towards injectors
- Hot fire acceptance test under vacuum conditions instead of an atmospheric test



Before V19 **After V19**

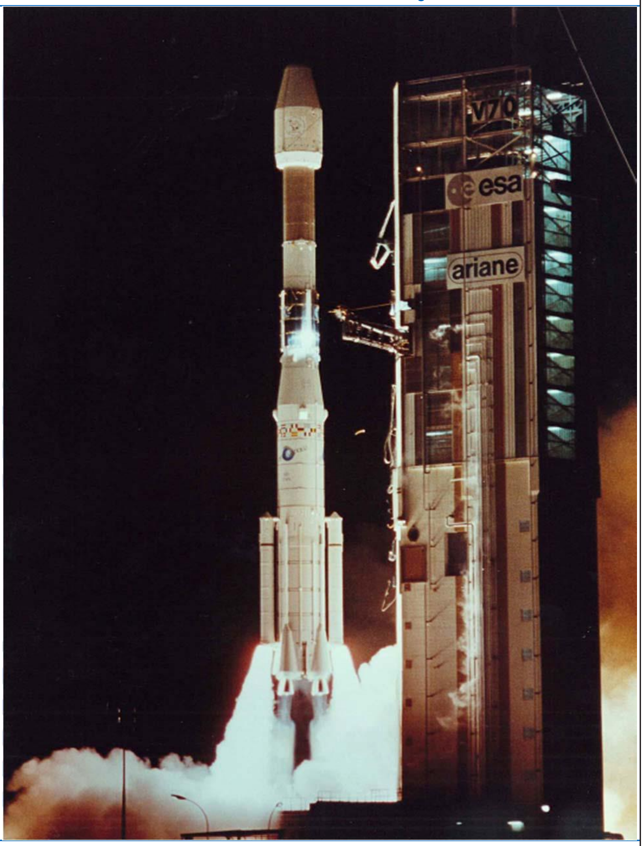
V15 and V18 Correcting Measures and Consequences

V15 and V18 are the only ARIANE successive failures which are similar in nature

- The LH2 valve leakage before ignition, during V15, had hidden the lack of margins in the ignition process (after 13 successful ignitions in flight).
- The ARIANE launches were grounded for 16 months.
- It became clear that it absolutely necessary to determine the margins of each component in order to raise the robustness of the entire system.

ARIANE 4:
V 70 FAILURE EVENT

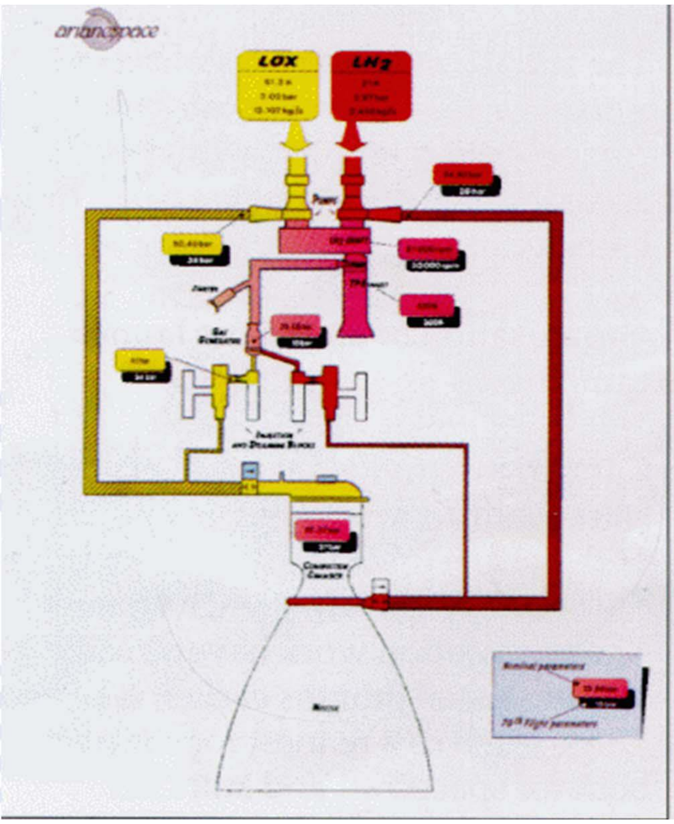
- First and second stages operated nominal.
- At HM7B engine ignition, all engine parameters were outside their tolerance bands from the moment on when the gas generator was fuelled by cryogenic propellants.



Failures and Lessons Learned

V70 Inquiry Results

- HM7B engine thrust limitation due to gas generator power deficiency
- Turbo-pump rotating speed was measured to 50000 rpm instead of 60000 rpm
- The most probable reasons for this power deficiency were:
    - pollution in a “venturi” nozzle
    - pollution in the injectors of the gas generator



Failures and Lessons Learned

V70 Correcting Measures and Consequences

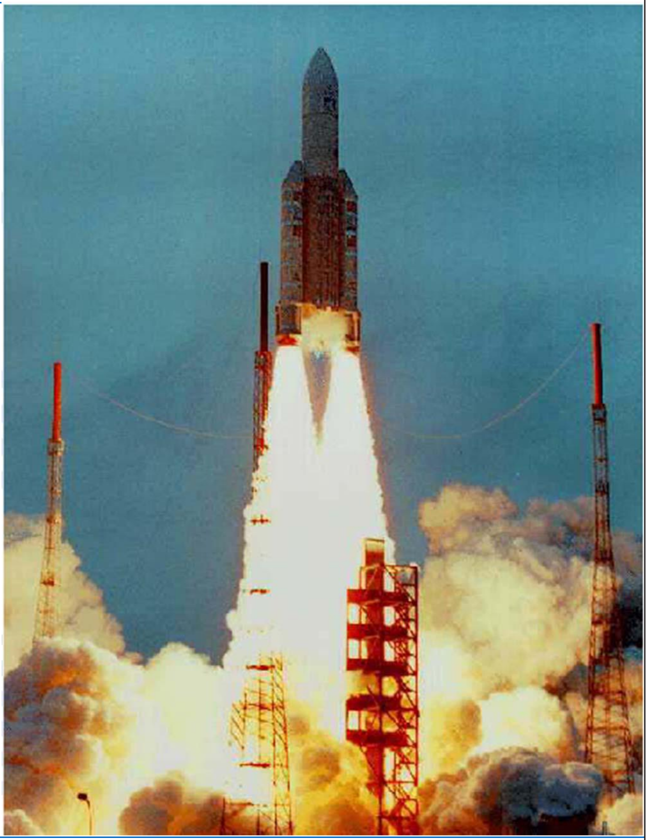
- Integration of a filter (400 µm) into the LOX injection line.
- Improvement of stage integration and flight preparation procedures at the launch site in order to prevent from any pollution which could lead to a line obstruction.

- Launcher was grounded for 4 months
- This is the only time for ARIANE that 2 failures occurred at the same year
    - V70 was the last failure of an ARIANE 4
    - Pollution of propellant lines have been later met during flight 510 and resulted in a launch abort

Failures and Lessons Learned

ARIANE 5:
501 FAILURE EVENT

- Normal ignition and lift off and nominal operation up to 36s
- At H0 + 36s, EAP and EPC thrust vector control went into maximum deviation
- Aerodynamic forces yielded breakup of launcher
- Automatic destruction of all stages



Failures and Lessons Learned

501 Inquiry Results

- At H0+36s, the redundant and nominal inertial platforms were declared to be in failure mode.
- The software of the inertial platform software which has been developed for ARIANE 4, was not fully consistent with the capabilities of the ARIANE 5 launcher.
- This inconsistency could only have been detected through end to end simulation of the ARIANE 5 flight, which was not considered necessary during the development.

Failures and Lessons Learned

501 Correcting Measures and Consequences

- Adaptation of the inertial platform software to ARIANE 5 capabilities
- Improvement of hardware and software simulation means and procedures
- Improvement of the telemetry restitutions
- Improvement of the flight program software

- ARIANE 5 Launcher grounded for 16 months

Failures and Lessons Learned

ARIANE 5:

510 FAILURE EVENT

- EAP and EPC operation nominal
- Aestus engine ignition occurred with an overshoot of the chamber pressure
- HF phenomena were triggered, yielding an overheat of the combustion chamber and a burn through of a cooling channel
- Aestus continued to operate but with deviated mixture ratio with a N_2O_4 depletion and an impulse deficit of around 20%

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Failures and Lessons Learned

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510 Inquiry Results

- At ignition, a higher than usual amount of MMH (during 400ms), resulted in an « Hard Start » because of unusual mixture ratio.
- An HF instability at 3100Hz (tangential mode) occurred since the acoustic cavities aren't operating at ignition (cold propellants instead of hot gases in the cavities).
- Overheat in the combustion chamber led to an increase of MMH temperature and thus to a decrease of the MMH flow rate.

- The most probable reason for the hard start is a combination of two events:
  - A quality problem of remaining water in the MMH feeding line, leading to ignition delay and therefore higher quantity of MMH at ignition
  - Remaining water in the N_2O_4 feeding line, leading to nitric acid, increasing the quantity of energy at ignition
- A large number of other possible reasons for the failure have been analyzed, but none of them were considered sufficient.

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Failures and Lessons Learned

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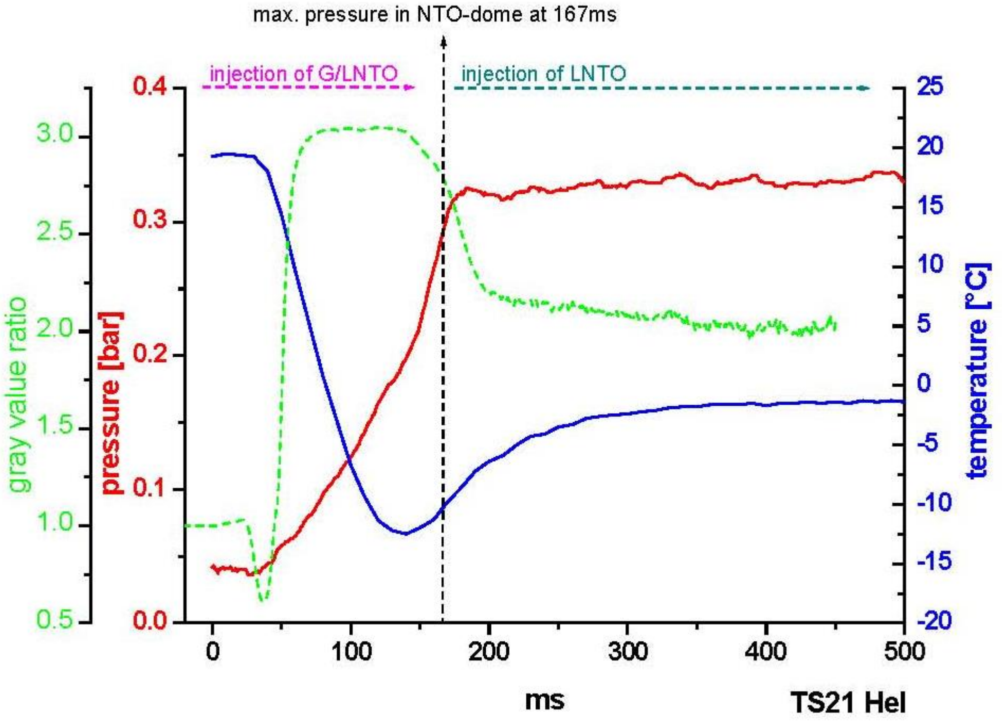
510 Inquiry Results

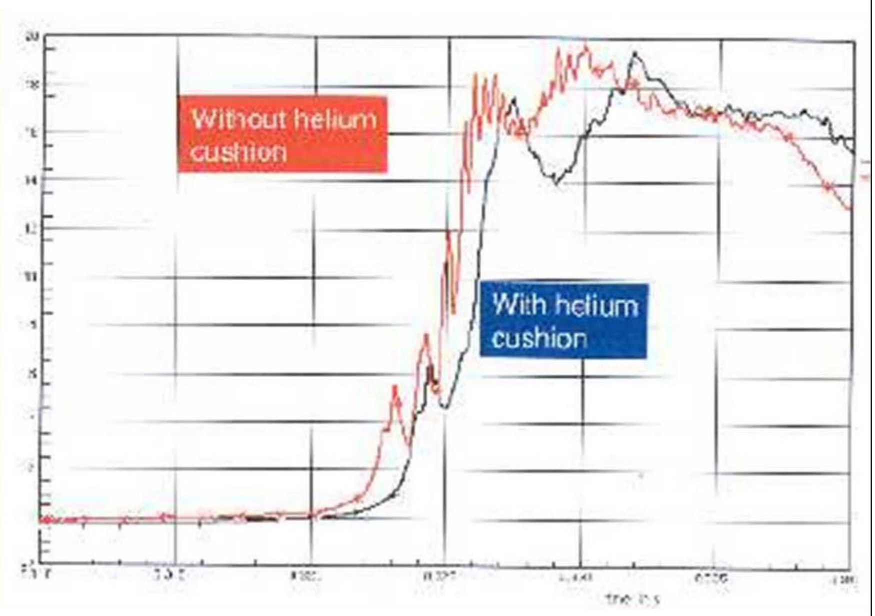


Failures and Lessons Learned

510 Correcting Measures and Consequences

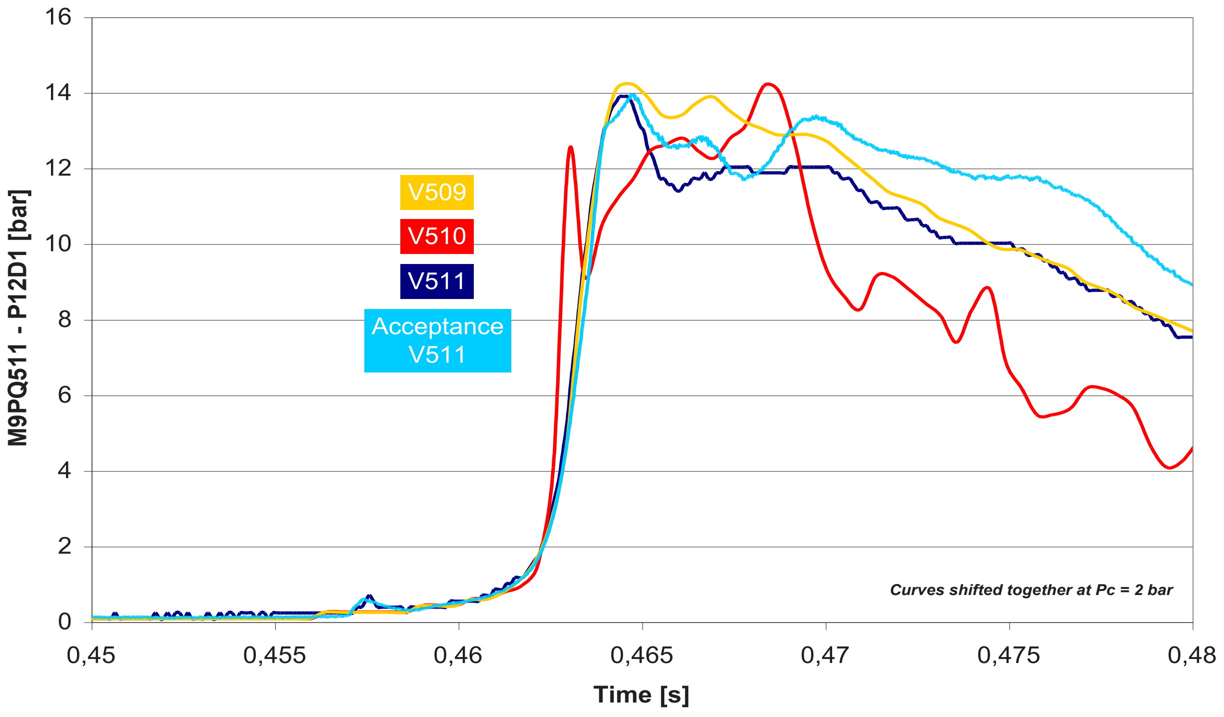
Modification of ignition sequence:

- Introduction of Helium in the MMH feed line before MMH valve opening
- Delayed MMH valve opening to avoid ignition in injection system



Failures and Lessons Learned

510 Inquiry Results



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Failures and Lessons Learned

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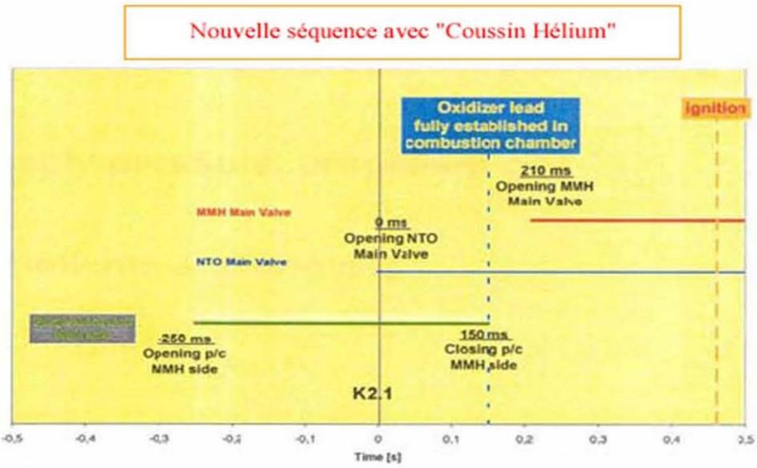
510 Correcting Measures and Consequences

Modification of production:

- additional checks
- acceptance test of each flight engine at P4.1
- new processes and checking measures (drying valves)

Modification of launch pad procedures:

- checks for water and propellant pollution
- feeding lines temperature control up to lift off
- possible temperature control during flight


Nouvelle séquence avec "Coussin Hélium"

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Failures and Lessons Learned

Lehrstuhl für Flugantriebe

510 Correcting Measures and Consequences

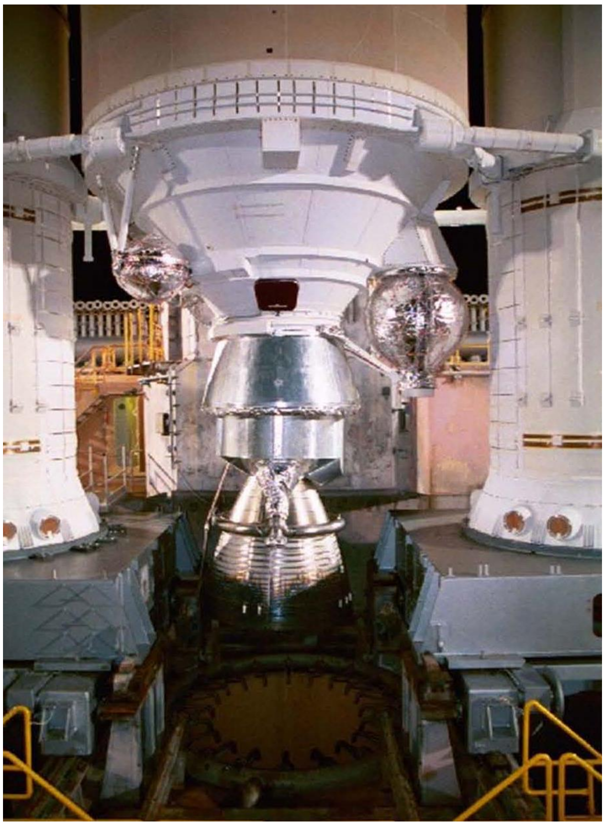
- Launcher grounded for 7 months
- No further HF phenomenon encountered during following ARIANE 5 flights
- Even for the delayed ignition case (Rosetta ignition delayed for 2 hours due to a special trajectory with a ballistic phase)
- None of the successive ignitions of Aestus for ATV for injection into ISS orbit showed any HF phenomenon

Failures and Lessons Learned

ARIANE 5:

517 FAILURE EVENT

- H0+5s: Temperature increase detected under the Vulcain 2 engine thermal protection (PTM)
- H0+138s: solid boosters separation and a further temperature increase under PTM
- H0+140s: unusual roll after booster separation
- H0+172s: pressure drop in the Vulcain 2 engine dump cooling
- H0+178s: vibrations and shocks
- H0+184.5s: turbine outlet rupture
- H0+186s: inlet pressures and nozzle pressure drop to zero



Failures and Lessons Learned

517 Inquiry Results

The most probable root cause of the flight V157 anomaly is the combination of several aggravating factors:

- Insufficient definition of the dimensioning load cases, relative to the combination of the various loads applied in flight,
- A degraded thermal condition of the nozzle, caused by cracks in the dump cooling tubes, leading to the leaks observed.

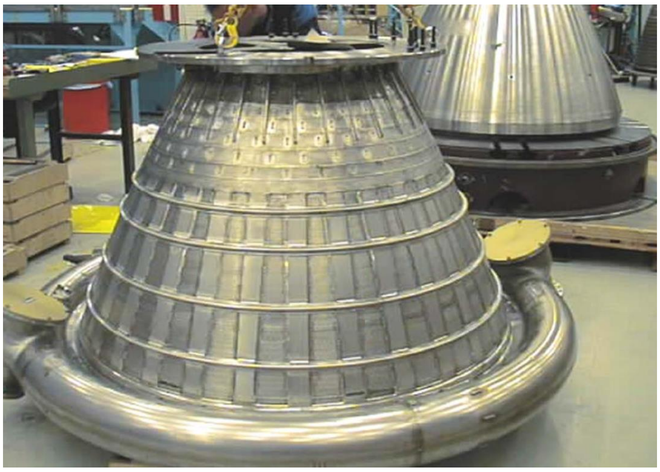
This led to the :

- "progressive degradation of the nozzle inner wall leading to the collapse of the upper section due to axial buckling in the vicinity of the first stiffener, followed by a rupture of the nozzle"

Failures and Lessons Learned

517 Correcting Measures and Consequences

- Increase of the LH2 dump cooling mass flow rate
- Thermal barrier coating in the nozzle
- Reinforced mechanical design



- ARIANE 5 ECA launches stopped for 18 months
- Restart of ARIANE 5G production (Vulcain 1)
- Re-inforced Vulcain 2 back in to flight and is successful since 2003 on both ARIANE 5 ECA and ARIANE 5 ES versions which are the two versions in operations today.

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The Present: Vega

Small Launcher:

•GLOW = ~ 136 to, H = 30 m, D = 3 m

Four stages:

•P 80 (solid), Z23 (solid), Z 9(solid), AVUM (UDMH/NTO)

Reference performance:

•1.5 to at 700 km circular polar orbit and a very flexible mission range

- Equatorial, polar & SSO orbit (5.2° to -102°)
- 300 kg to 2 500 kg payload mass towards 300 km to 1 500 km altitude

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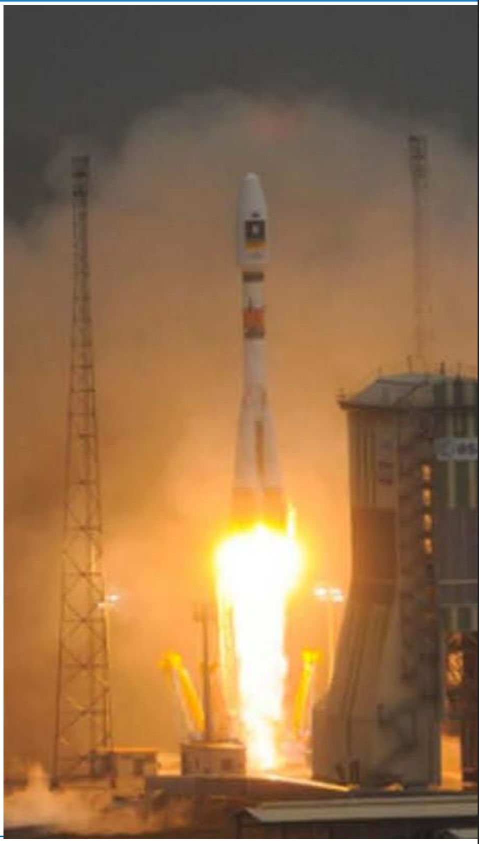
The Present: Soyuz



Medium Size Launcher:

- GLOW = ~ 310 to, H = 46.3 m, D = 10.3m

Four stages (all liquid):

- 1st, 2nd and 3rd LOX/kerosene,
- Fregat Upper Stage

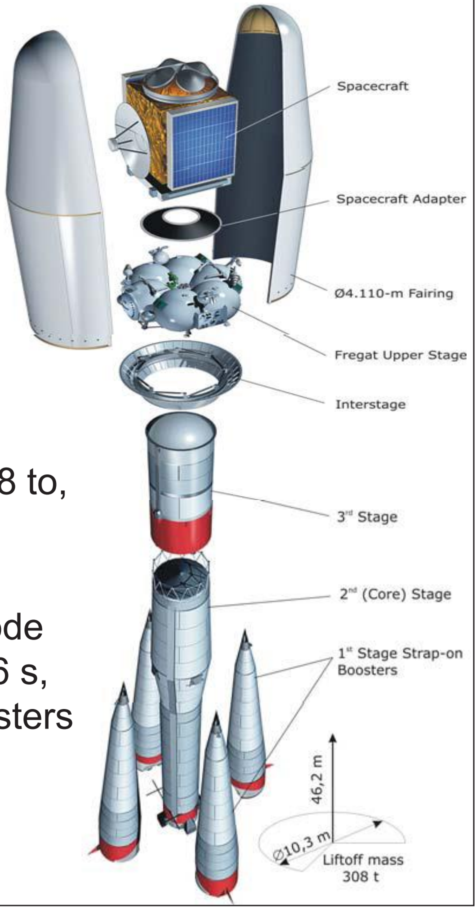
Performance:

- GTO: 3060 kg
- MEO (24000 km / 56°) 1590 kg
- SSO (660 km / 98°) 4900 kg

The Present: Soyuz

Soyuz in Courou

- 1st Stage: 4 Boosters, RD 107A, LOX/Kerosene, T(sl, v) = 84 to, 102 to, I_{sp}(sl, v) = 265s, 319s, p_c = 58 bar, pump fed driven by H_2O_2, (Glushko)
- Core Stage: RD 108A, LOX/Kerosene, T(sl, v) = 79 to, 99 to, I_{sp}(sl, v) = 255s, 319s, p_c=51 bar, pump fed driven by H_2O_2, (Glushko)
- 3rd Stage: RD-0124, Lox/Kerosene, T(v) = 29.8 to, I_{sp}(v) = 359 s, p_c=157 bar, staged combustion cycle, kN Vernier thrusters, (CADB)
- 4th Stage: RD Fregat, S5.92 (storable), two mode thrust capability T = 1.98 to / 1.4 to, I_{sp}(v) = 316 s, p_c=97 bar, GG cycle, 12 x 50 N hydrazine thrusters for attitude control, (Isayev)



The Present: ARIANE 5

Heavy Launch Vehicle:

- 750 to GLOW, H = 46.3 m, D = 10.3m

Three stages:

- 2 solid boosters, Core and upper stage: LOX/LH_2

Performance:

•SSO, polar orbits: > 10 to for 800 km (0° north)

•ISS (ATV with AR5 ES: 19 – 21 to, mission dependent for an altitude range 200 - 400 km, inclination = 51.6°

•Elliptical orbit missions:

- For L2: 6.6 to for an apogee: 1,300,000 km; perigee: 320 km, Inclination: 14°, argument of perigee: 208°
- Moon: 7 to for apogee: 385,600 km; perigee: 300 km, inclination 12°

•Escape: 4.1 to, v_∞ = 3475 m/s, declination = 3.8°

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The Present: ARIANE 5

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ARIANE 5 Launch seen from ISS

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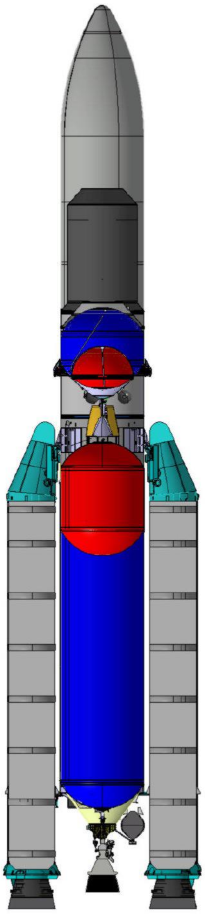
The Future: ARIANE 5ME

AR5 ME bases on AR5 ECA with an upgrade of both, Upper Stage and Upper Part:

- AR5 E Lower Composite as it is (no changes on EPC, EAP and Vulcain-2)
- Upgraded Electrical systems for versatile missions (outside Van Allen, more than 7 h mission duration)
- New Upper Stage “H28 B5 configuration”, 5.4 m diameter, 28 t propellant loading, common bulkhead
- Vinci engine: T = 180 kN, I_{sp} = 464 s
- Increased payload volume adapted to larger and heavier payloads

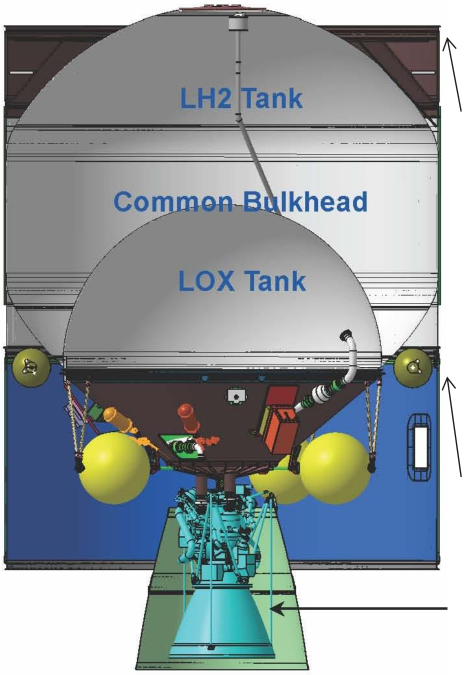
New Elements:

- Vinci engine thrust frame and functional propulsion system
- LOX / LH2 tank and equipment bay structure
- Thermal protection systems
- Attitude control and propellant settlement system



What is ARIANE 5ME ?

Upper Stage



New Elements

- Vinci Engine and Functional Propulsion System
- Engine Thrust Frame
- LOX / LH2 Tank
- Equipment Bay Structure
- Thermal Protection Systems
- Attitude control and propellant settlement system

Elements adapted from current ESC-A stage:

- Inter-Stage Skirt ESC/IPC including separation system
- Helium High Pressure Spheres (re-used from EPC)
- Propellant Filling Couplings
- Neutralization System

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What is ARIANE 5ME ?

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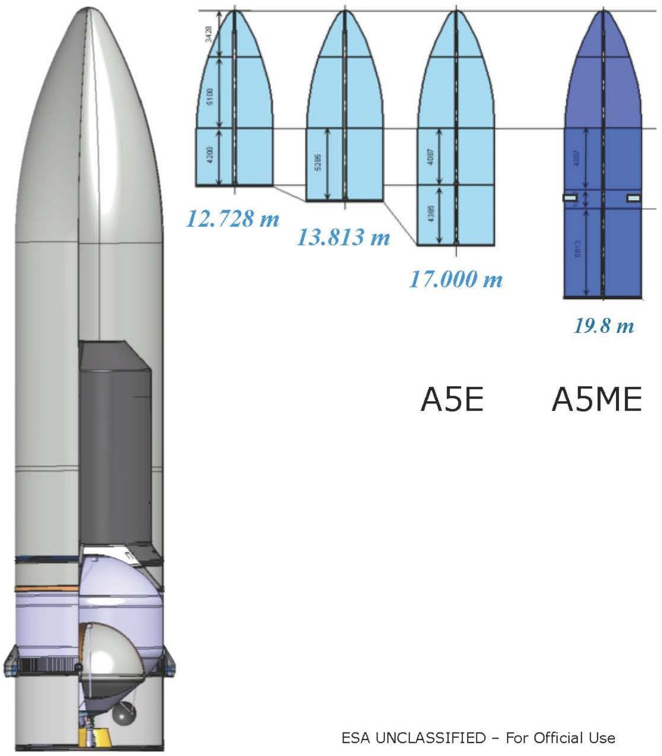
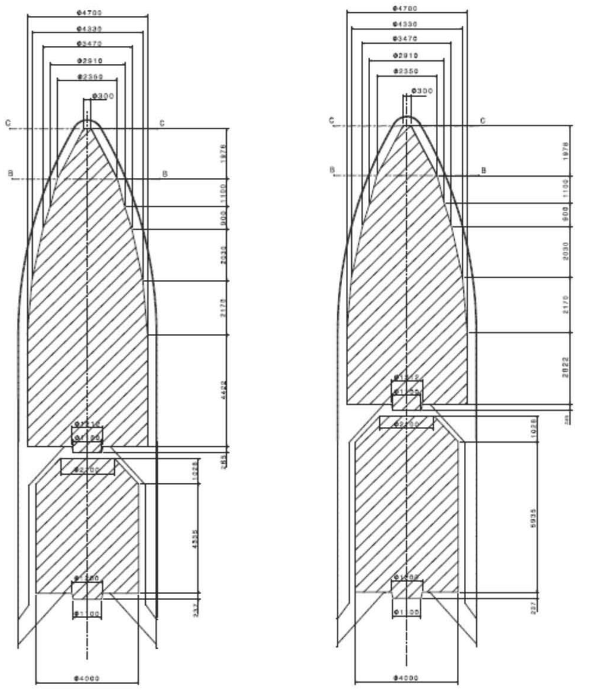
Upper Stage / Payload





European Space Agency

ESA UNCLASSIFIED – For Official Use

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What is ARIANE 5ME ?

Lehrstuhl für Flugantriebe

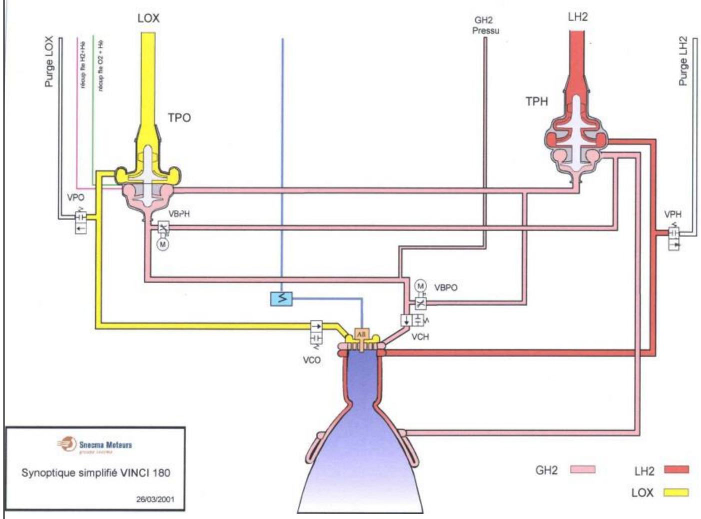
VINCI

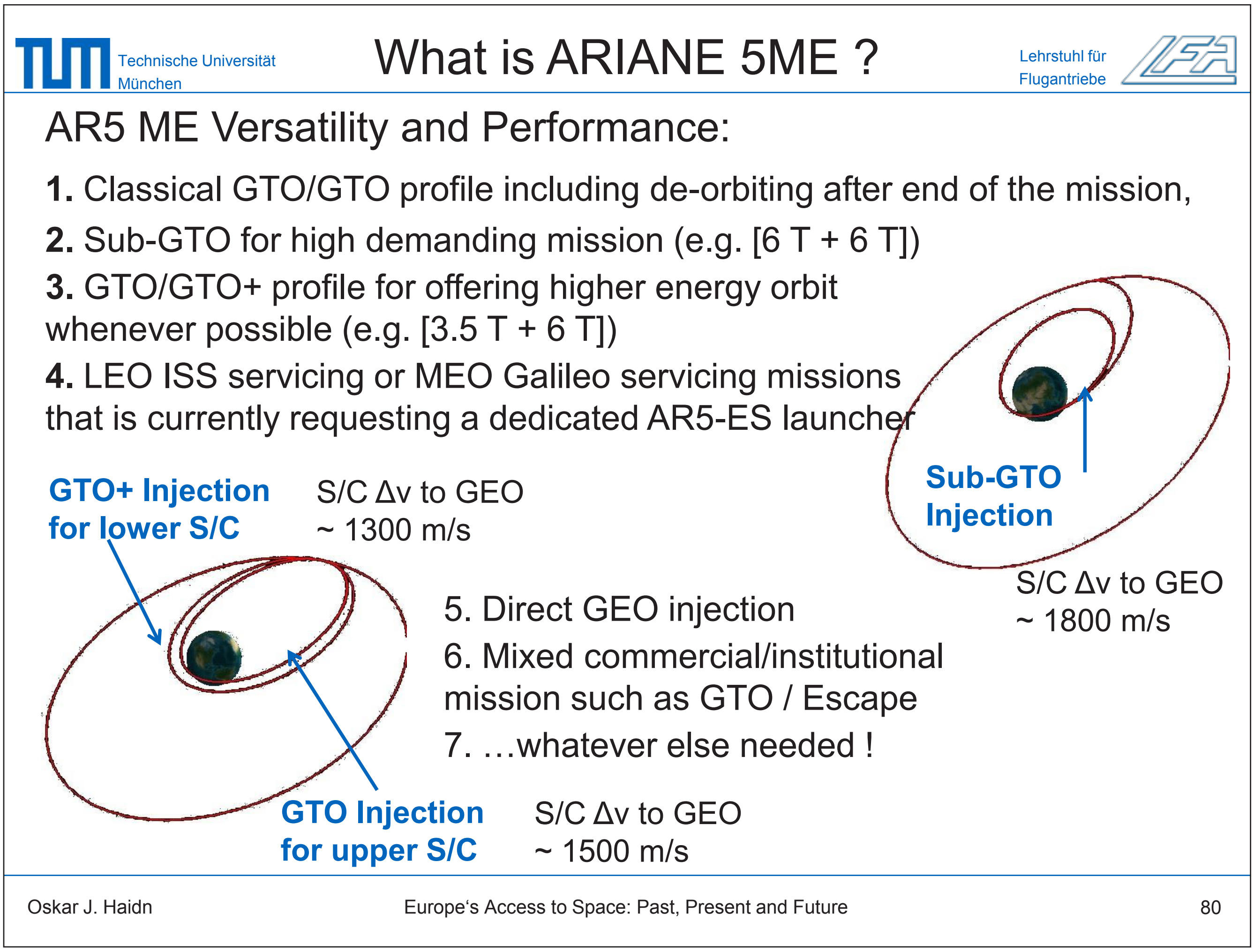
LOX/LH2 Expander Cycle Engine

T (v) = 180 kN
I_{sp} (v) = 464 s
R_{of} = 5,8
p_c = 61 bar

LOX = 33,69 kg/s
TPO = 18015 rpm
TPO p_d = 81 bar

LH2 = 5,81 kg/s
TPH = 90127 rpm
LH2 p_d = 224 bar





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What is ARIANE 5ME ?

Lehrstuhl für Flugantriebe

AR5 ME Versatility and Performance:

1. Classical GTO/GTO profile including de-orbiting after end of the mission,

2. Sub-GTO for high demanding mission (e.g. [6 T + 6 T])

3. GTO/GTO+ profile for offering higher energy orbit whenever possible (e.g. [3.5 T + 6 T])

4. LEO ISS servicing or MEO Galileo servicing missions that is currently requesting a dedicated AR5-ES launcher

Sub-GTO Injection

S/C Δv to GEO
~ 1800 m/s

GTO+ Injection for lower S/C

S/C Δv to GEO
~ 1300 m/s

5. Direct GEO injection

6. Mixed commercial/institutional mission such as GTO / Escape

7. …whatever else needed !

GTO Injection for upper S/C

S/C Δv to GEO
~ 1500 m/s

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Why ARIANE 5ME ?

Lehrstuhl für Flugantriebe

Five good Reasons

1. Implement environmental protection (upper stage de-orbiting)
2. Improve launch service competitiveness
3. Meet market needs more closely and better respond to changing customer needs
4. Implement versatility to serve multiple orbits
5. Keep the ARIANE family alive beyond 2030

ARIANE 5ME

Current Status

The project is actively progressing throughout phase C in 2013

- Concept review ending phase A has been completed mid of 2011, triggering phase B that was run between 2011 and 2012,
- Launch System PDR was positively concluded in May 2012, freezing the launcher and ground segment architecture trades. Lower level PDR have since all been completed,
- Investments on the new upper stage tank manufacturing facility in Bremen and on the Cryogenic System Hot Firing Test Stand (in Lampoldshausen, a unique facility in Europe) have been launched,
- Testing pace is high, with the 5th Vinci engine test campaign (out of 9) taking place this year : the engine has accumulated so far more than 15500 s / 60 ignitions for a standard use in flight of 900 s / 2 ignitions.

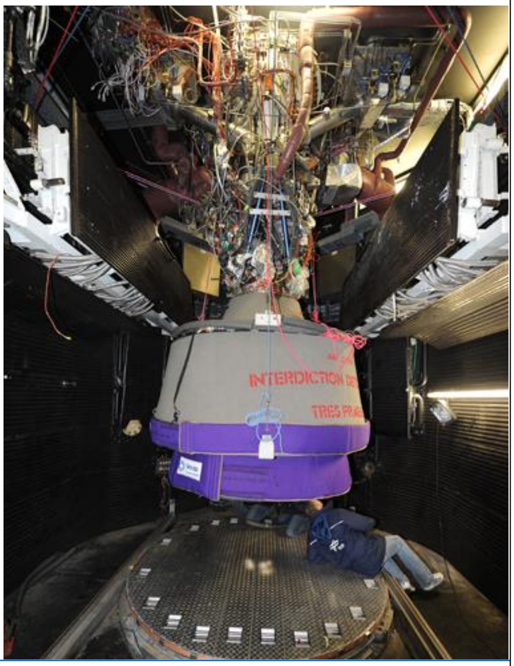
ARIANE 5ME

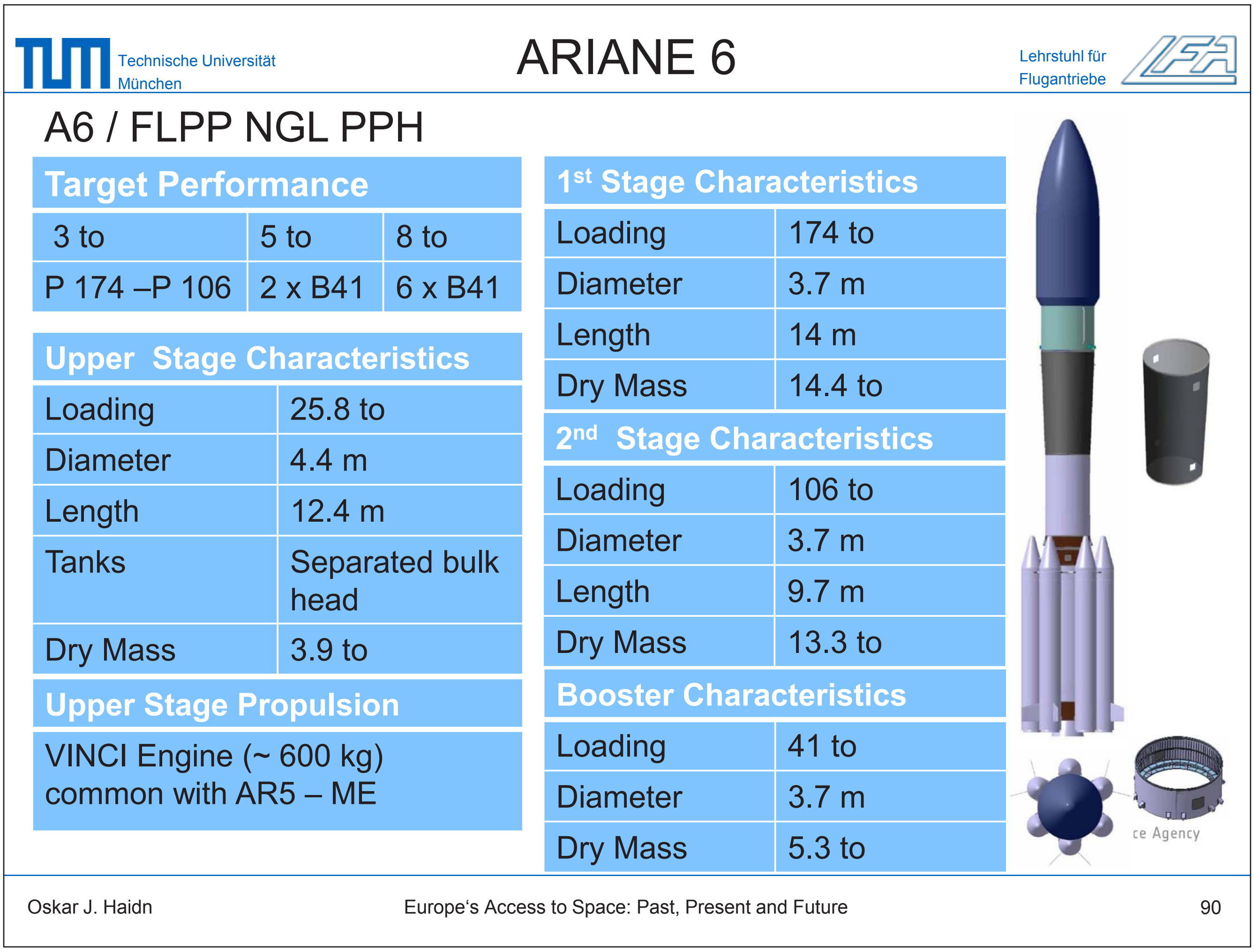
Current Status

VINCI M3 engine has seen 11 firing tests with a cumulated duration of 6286s (record for a single Vinci engine, corresponding to a total of 9 flights).

Among these tests were ones with

- the complete nozzle extension
- engine throttling down to 30 kN,
- ballistic phases followed by re-ignition
- ignition with sub-cooled Lox
- idle-mode phases (turbo-pumps inactive)





ARIANE 6

A6 / FLPP NGL PPH

Target Performance		
3 to	5 to	8 to
P 174 –P 106	2 x B41	6 x B41

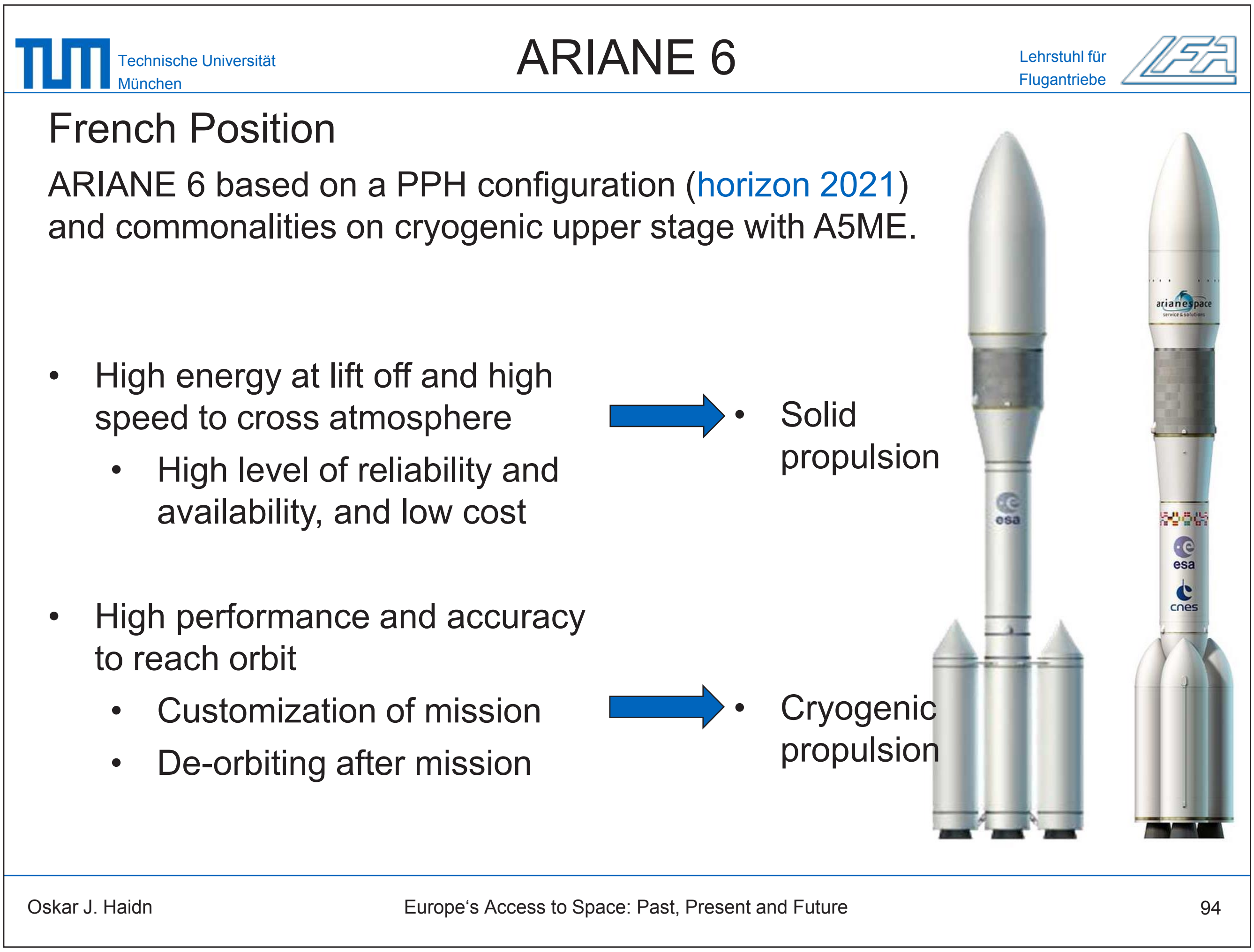
Upper Stage Characteristics	
Loading	25.8 to
Diameter	4.4 m
Length	12.4 m
Tanks	Separated bulk head
Dry Mass	3.9 to

Upper Stage Propulsion
VINCI Engine (~ 600 kg) common with AR5 – ME

1st Stage Characteristics	
Loading	174 to
Diameter	3.7 m
Length	14 m
Dry Mass	14.4 to

2nd Stage Characteristics	
Loading	106 to
Diameter	3.7 m
Length	9.7 m
Dry Mass	13.3 to

Booster Characteristics	
Loading	41 to
Diameter	3.7 m
Dry Mass	5.3 to



ARIANE 6

French Position

ARIANE 6 based on a PPH configuration (horizon 2021) and commonalities on cryogenic upper stage with A5ME.

- High energy at lift off and high speed to cross atmosphere
  - High level of reliability and availability, and low cost

→ • Solid propulsion

- High performance and accuracy to reach orbit
  - Customization of mission
  - De-orbiting after mission

→ • Cryogenic propulsion

ARIANE 6: What and When ?

German Position

- Investments in launcher programs must safeguard the balance between ESA's overall mission and ISS commitments and other infrastructure programs.
- Current ESA Member States commitments for running programs require the use of budget lines up to 2017/18 assuming constant budgets for the Member States.
- Remaining AR5 ME Development will require about 1000 M€ and will use up ESA's launcher budget corridor until 2018.
- ARIANE 6 development will require about 4000 M€.

→ Financially Speaking: ARIANE 6 Development will be challenging before 2017/18

→ We have about 3-4 years to clarify "open issues".

A "European Launcher" without European consensus will fail!

Content

- Early Beginnings
  - ELDO and Europe
  - Technology Developments
- Things That Went Wrong, ARIANE 1 – 4, ARIANE 5
  - Failures and Description
  - Lessons Learned
- The Present
  - ARIANE 5 ECA, ARIANE 5ES
  - Soyuz in Courou
  - Vega
- Where does Europe go?
  - ARIANE 5ME
  - ARIANE 6
- The Future of LRE Modeling

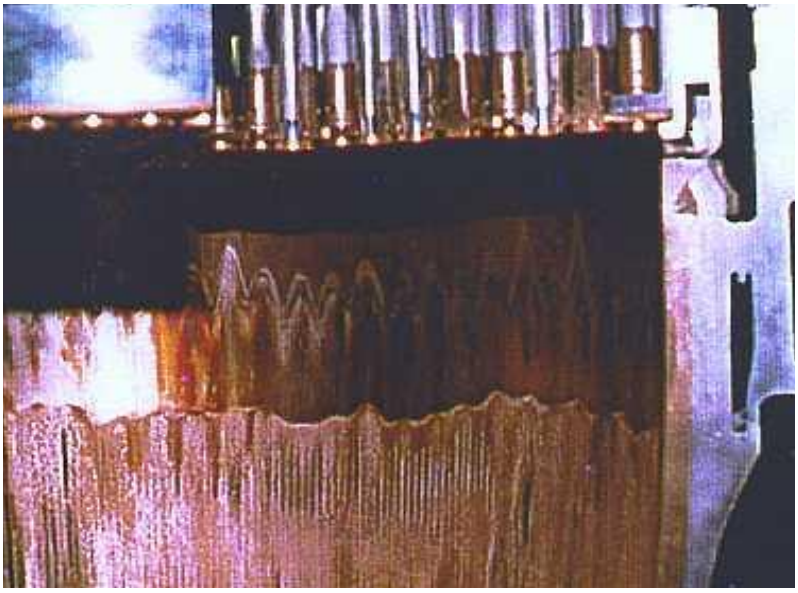
LRE Modeling

Phenomena Important for Liquid Propellant Rocket Engine Performance, Reliability and Cost

Combustion Devices / Thrust Chamber Assembly

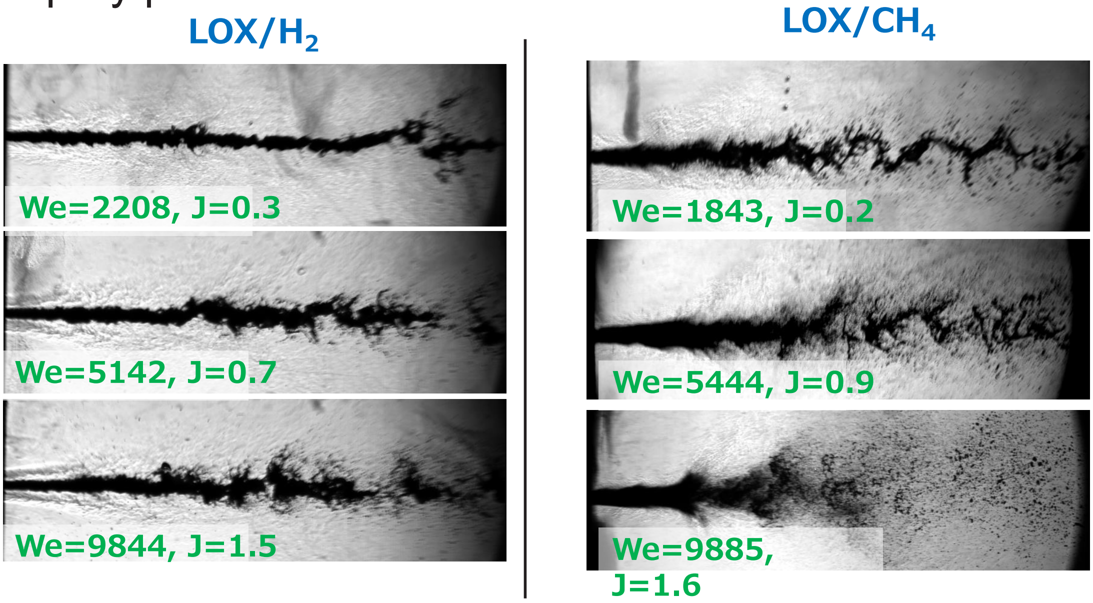
Steady State Issues

- Injection / Atomization
- Combustion
- Heat Transfer (hot gas / coolant side)
- Film Cooling
- Material Failure Issues (LCF, creep, ….)



LRE Modeling

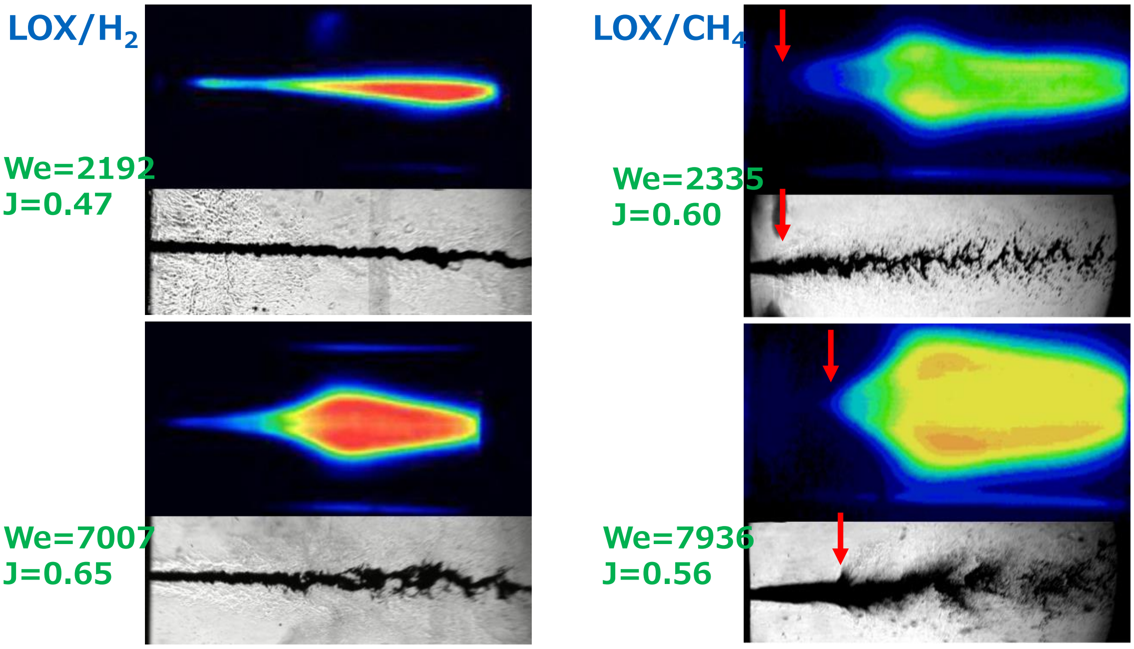
LOX-spray pattern in flames



- similar trends for variation of We and J for both propellants
- atomization significantly more efficient for CH_4
- visible break-up length much larger for H_2 than for CH_4

LRE Modeling

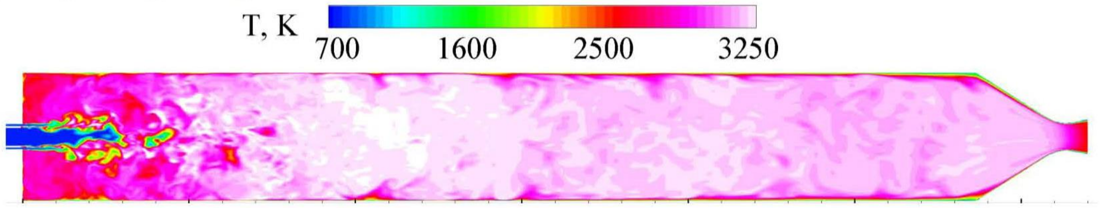
Flame holding and LOX-spray pattern



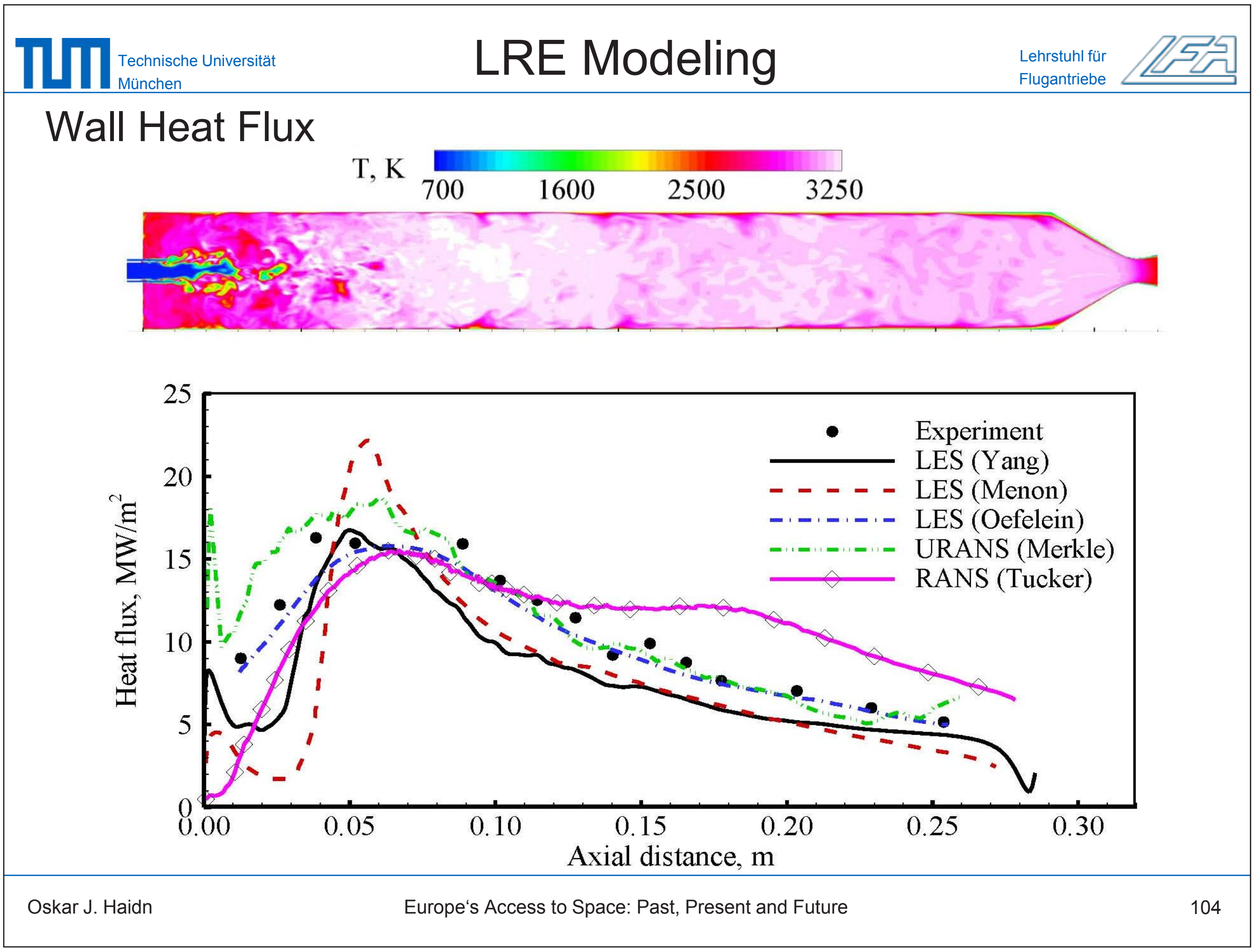
- significantly larger flame spreading angle for CH_4
- anchored flames for H_2, lifted flames for CH_4

LRE Modeling

Single Injector Staged Combustion Chamber Modeling

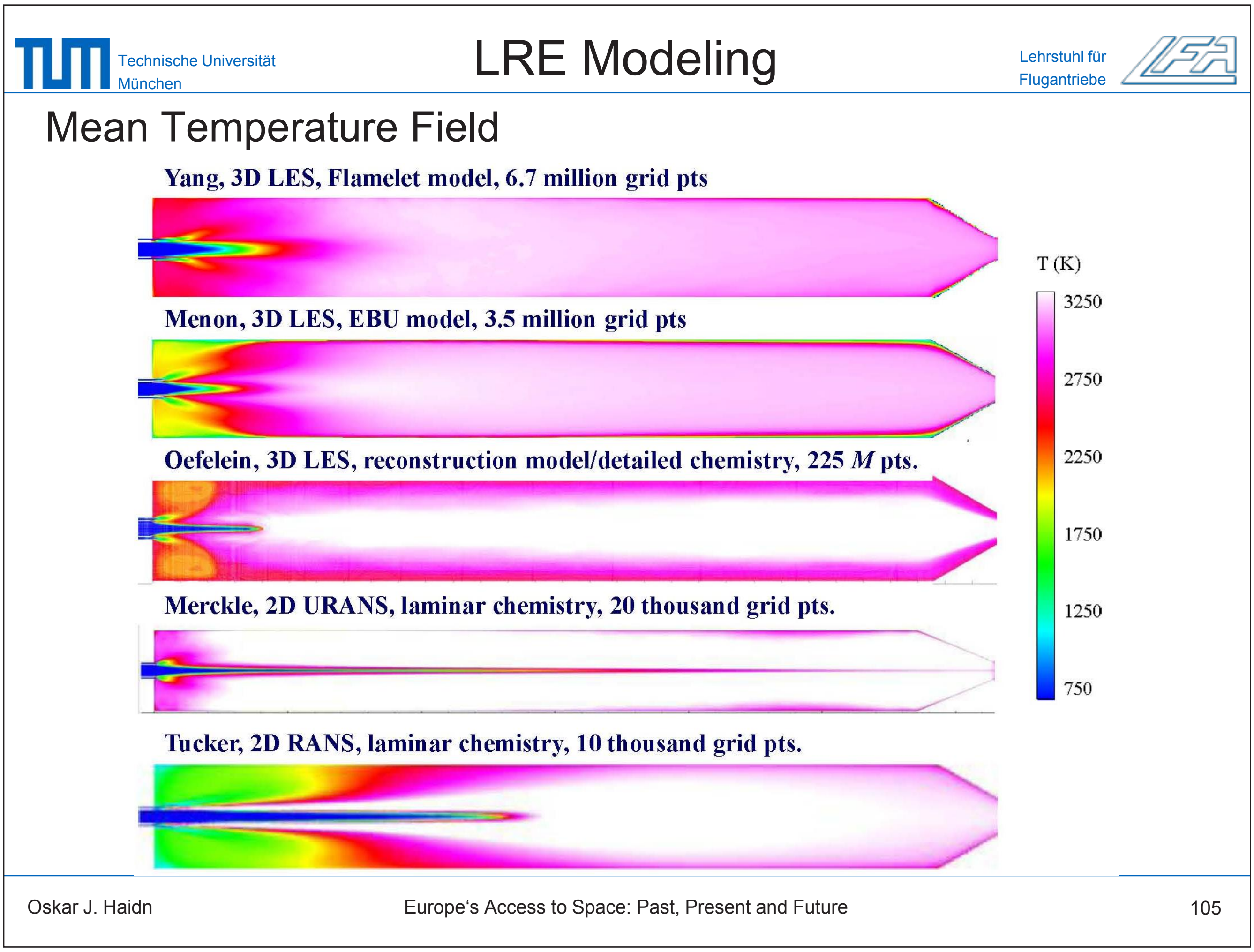


Studies	*grid distribution*	*grid number (million)*	*turbulence model*	*combustion model*
Huo & Yang (GT-1)	**440×188×60**	**6.7**	**3D LES**	**flamelet with detailed chemistry**
Menon (GT-2)	**611×87×65**	**3.5**	**3D LES**	**eddy break-up model**
Oefelein (SNL)	**1536×368×256**	**225**	**3D LES**	**direct closure with detailed chemistry**
Merckle (Purdue)	**160×120**	**0.02**	**2D URANS**	**laminar chemistry**
Tucker (MSFC)	**98×98**	**0.01**	**2D RANS**	**laminar chemistry**



LRE Modeling

Wall Heat Flux



LRE Modeling

Mean Temperature Field

Yang, 3D LES, Flamelet model, 6.7 million grid pts

Menon, 3D LES, EBU model, 3.5 million grid pts

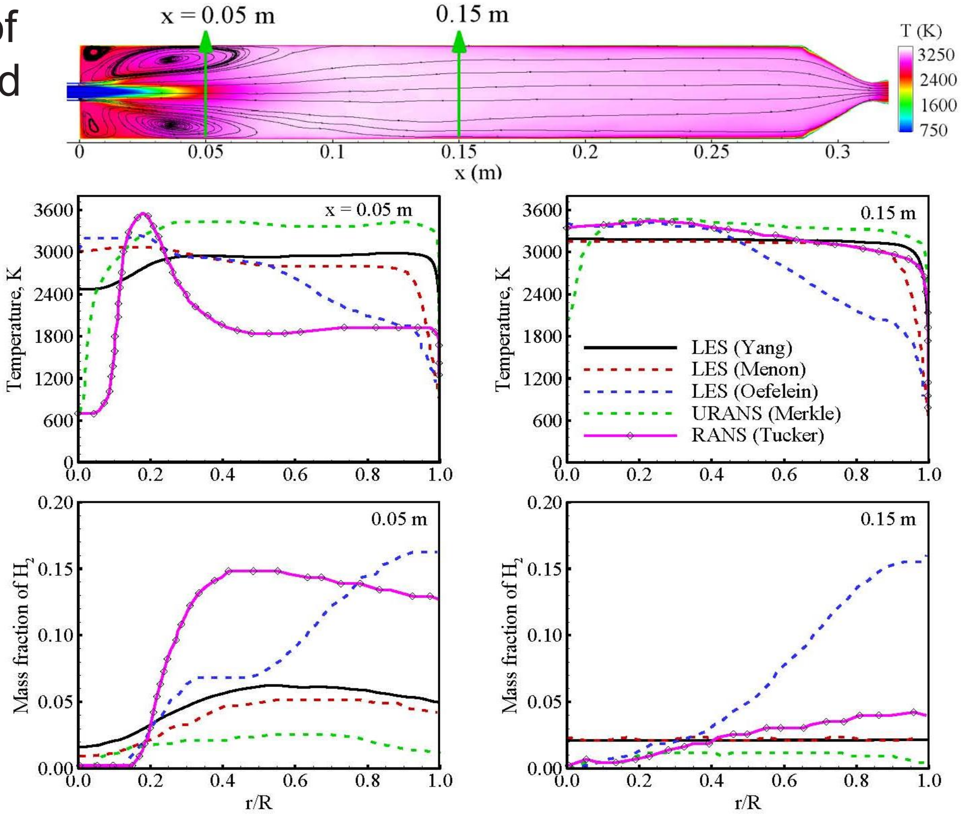
Oefelein, 3D LES, reconstruction model/detailed chemistry, 225 *M* pts.

Merckle, 2D URANS, laminar chemistry, 20 thousand grid pts.

Tucker, 2D RANS, laminar chemistry, 10 thousand grid pts.

LRE Modeling

Radial Profiles of Temperature and Hydrogen Mass Fraction



LRE Modeling

Phenomena Important for Liquid Propellant Rocket Engine Performance, Reliability and Cost

Combustion Devices / Thrust Chamber Assembly

Dynamic Issues

- Transients (start-up, shut-down)
- Launch Loads
- Combustion
- Ignition
- Dynamics
- Buffeting
- Flow Separation and Side Loads

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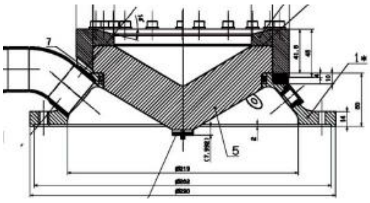
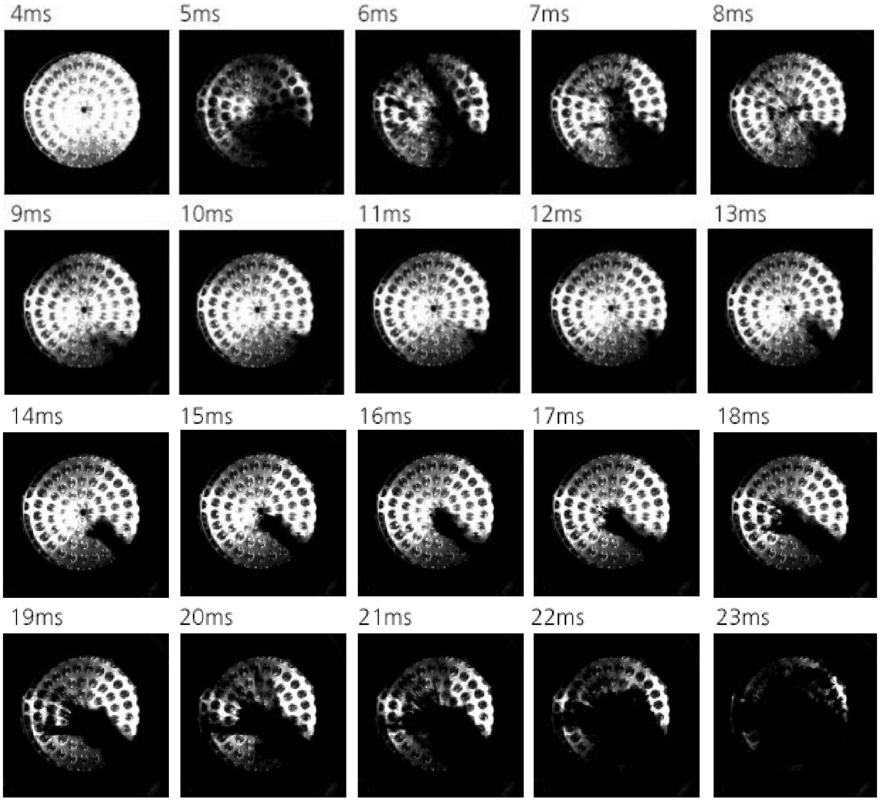
LRE Modeling

Lehrstuhl für Flugantriebe

Transient Start-up



AESTUS NTO-filling of dome



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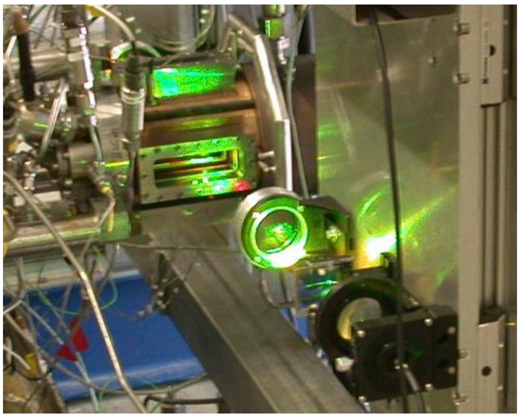
LRE Modeling

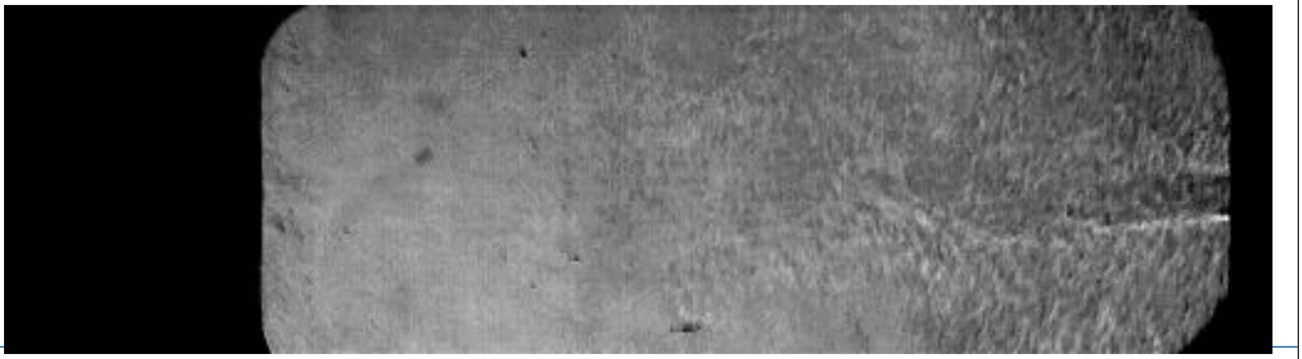
Lehrstuhl für Flugantriebe



Laser-Induced Ignition

Micro-Combustor M3

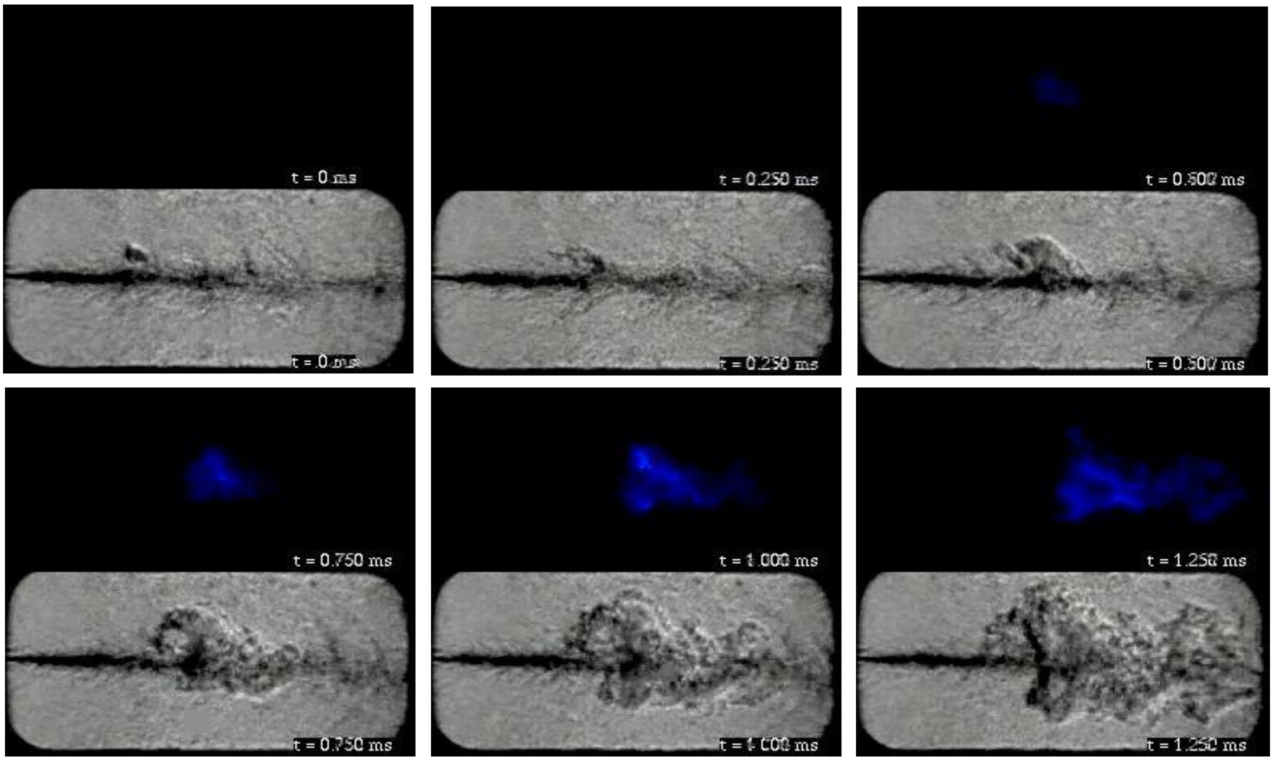
- LOX / GH2 @ ~ 80 K
- Shear coax injectors



LRE Modeling

Ignition

Failed Laser-based Ignition

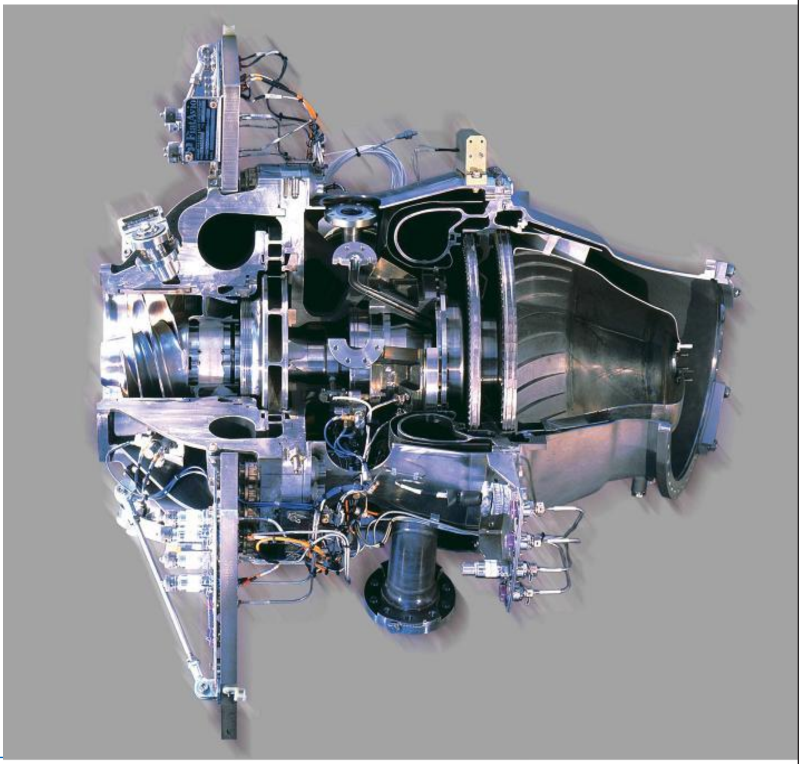


LRE Modeling

Phenomena Important for Propulsion System Performance, Reliability and Cost

Turbo Machinery

- Pump / Turbine
  - Seals
  - Bearings
  - Throttling capabilities
  - Staging
- Thermodynamics
  - Cavitation
  - Critical conditions

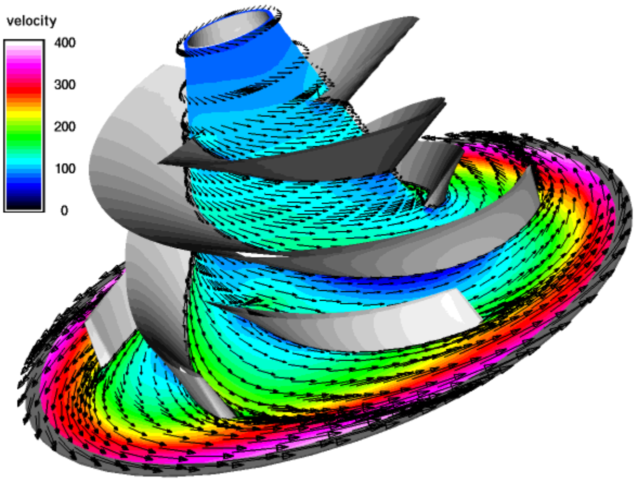


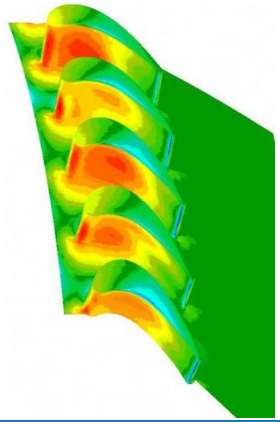
LRE Modeling

Phenomena Important for Propulsion System Performance, Reliability and Cost

Turbo Machinery

- Fluid Mechanics / Secondary Flows
- Rotor dynamics
- Mechanical Elements
- Structural
  - Stress
  - Dynamics
- Materials


Fastrac LOX Turbopump Analysis Results
Velocity contours near the hub



CFD results for unsteady pressure loads (VINCI turbine)

LRE Modeling

The Future of Modeling in Liquid Propellant Rocket Engine Development

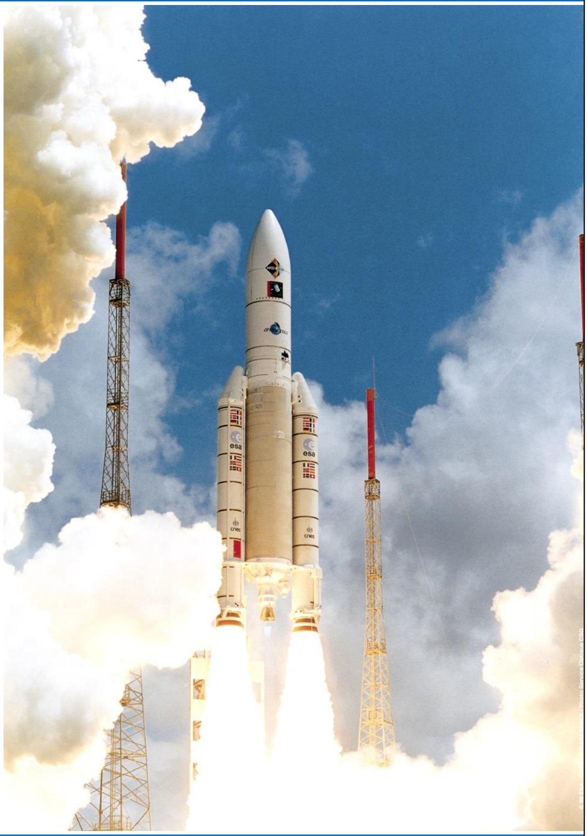
Requires a Long Term Strategic Approach with ….

- Well designed series of experiments which step by step increase the complexity of the processes studied in order to identify and understand dominating physical phenomena and to verify and validate physical models and numerical tools,
- Clear modeling logic with detailed tools with sophisticated models used to validate classical engineering tools,
- Accompanied step by step modeling effort to in order to store this knowledge in numerical tools
- Parameter studies and simulations to gain more insight into processes and help reduce cost,

……. is Bright and Promissing.

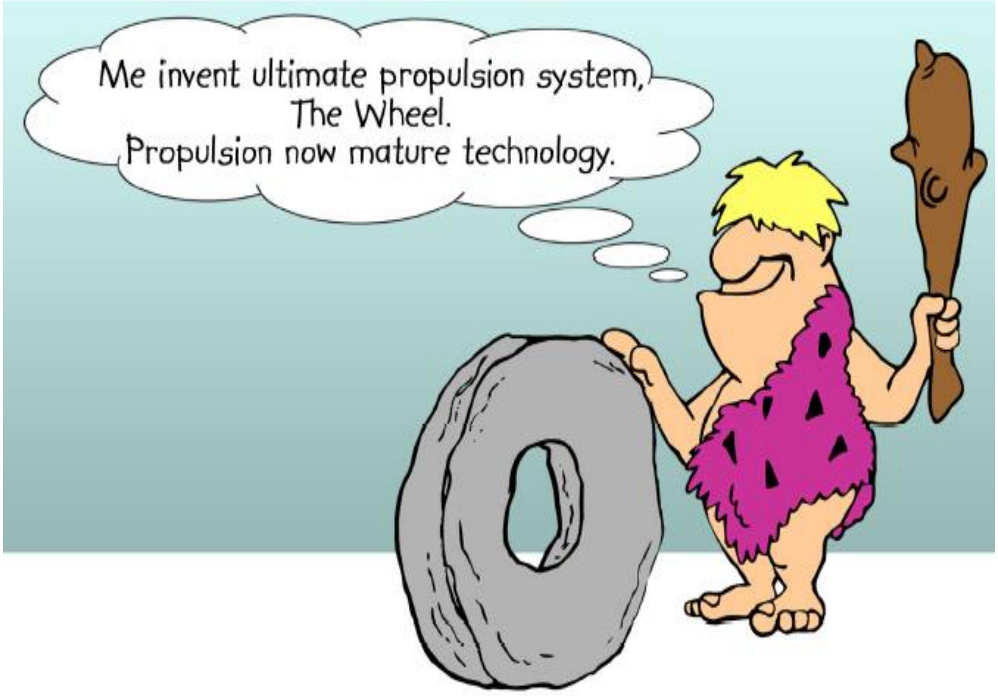
Summary

- European Early Beginnings
- Lessons Learned During the last 40+ Years
- Current European Launch Vehicles
- ARIANE 5 ME / ARIANE 6: What and When ?
- Modeling of Liquid Propellant Rocket Engines Systems and Components



Propulsion Engineers

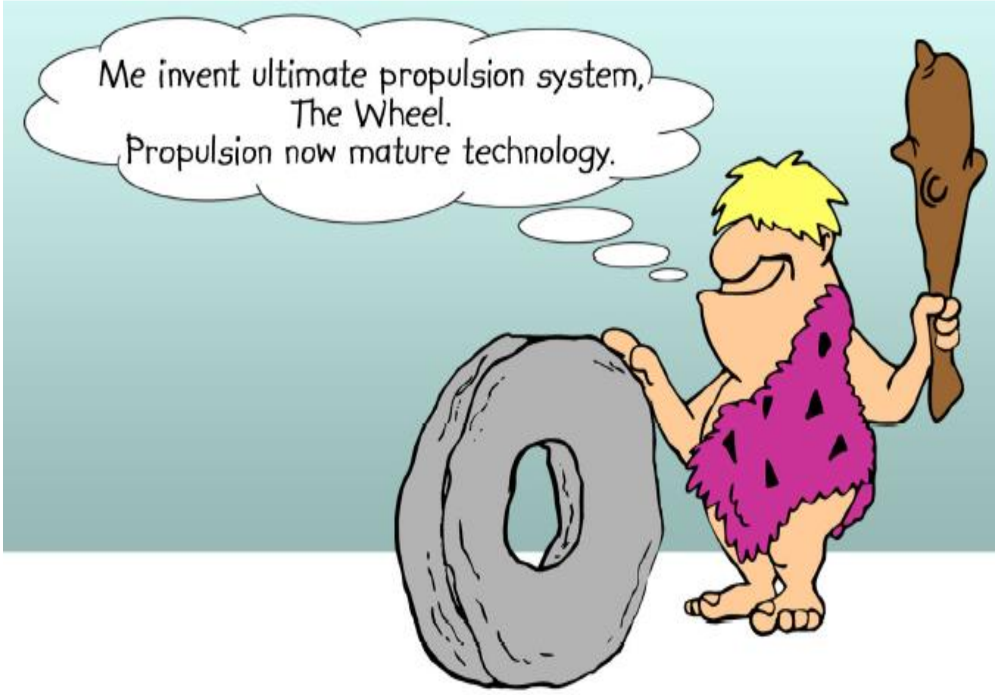
The Past



Propulsion has come a long way ……

Propulsion Engineers

The Future



… and has still ways to go.