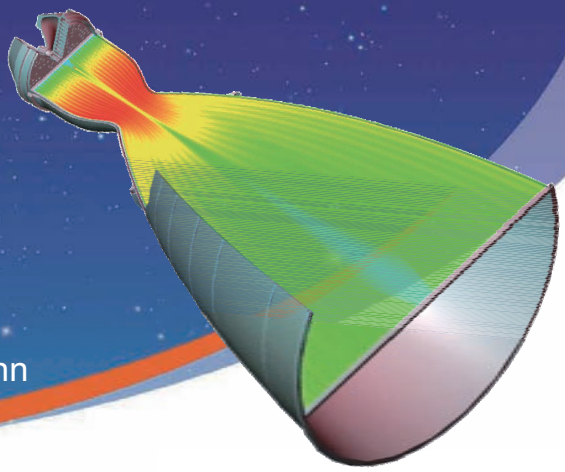
New Horizon of Rocket Engine Modeling and Simulation
September 28-29, 2010, Tokyo

# Astrium ST's Liquid Propulsion Heritage and Simulation Capabilities



**Oliver Knab**

Astrium Space Transportation
Development Launcher Propulsion
Head of System Analysis

TP24-P-157/2010

Astrium Space Transportation, Ottobrunn

All the space you need

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AN EADS COMPANY



## EADS - **The step beyond**

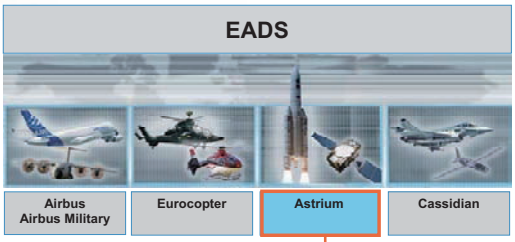
**EADS**

| Airbus<br>Airbus Military | Eurocopter | Astrium | Cassidian |
|---|---|---|---|

**E**uropean **A**eronautic **D**efence and **S**pace Company

Propulsion & Equipment

## Astrium's Liquid Propulsion Heritage & Simulation Capabilities
### Astrium's Activities within the EADS Group

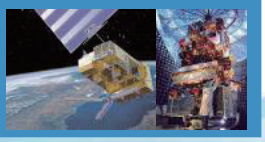



**Astrium Space Transportation**

The European prime contractor for civil and military space transportation and manned space activities

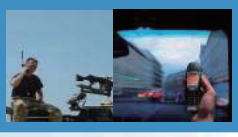
**Astrium Satellites**

A world leader in the design and manufacture of satellite systems



**Astrium Services**

At the forefront of satellite services in the secure communications, navigation and Earth observation fields



**Astrium:**

- 15000 employees in France, Germany, the Netherlands, Spain and the UK
- ranking first in Europe, third in the world
- € 4.8 bn turnover in 2009
- shareholdings in Arianespace (Ariane launcher), Starsem (Soyuz launcher) and Eurockot (Rockot launcher)





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## Astrium's Liquid Propulsion Heritage & Simulation Capabilities
### European Access to Space: Europe's Launcher Family

| **Operator:** | Arianespace | | Starsem | Eurockot | Arianespace |
|---|---|---|---|---|---|
|  |  |  |  |  |  |
| **Ariane 5 ME** (in development) | **Ariane 5 ESC-A** | **Ariane 5** (de-commissioned by 2009) | **Soyuz** | **Rockot** | **Vega** |
| **GTO capability** | | | | | |
| **12 t** | **10 t** | **6 t** | **2.4 t / 3 t** | **LEO capability** | |
| **> 20 t** 300 km - 51°6 | | | **2.5 t / 5 t** 1,400 km | **1.1 t** 700 km | **1.5 t** 700 km |

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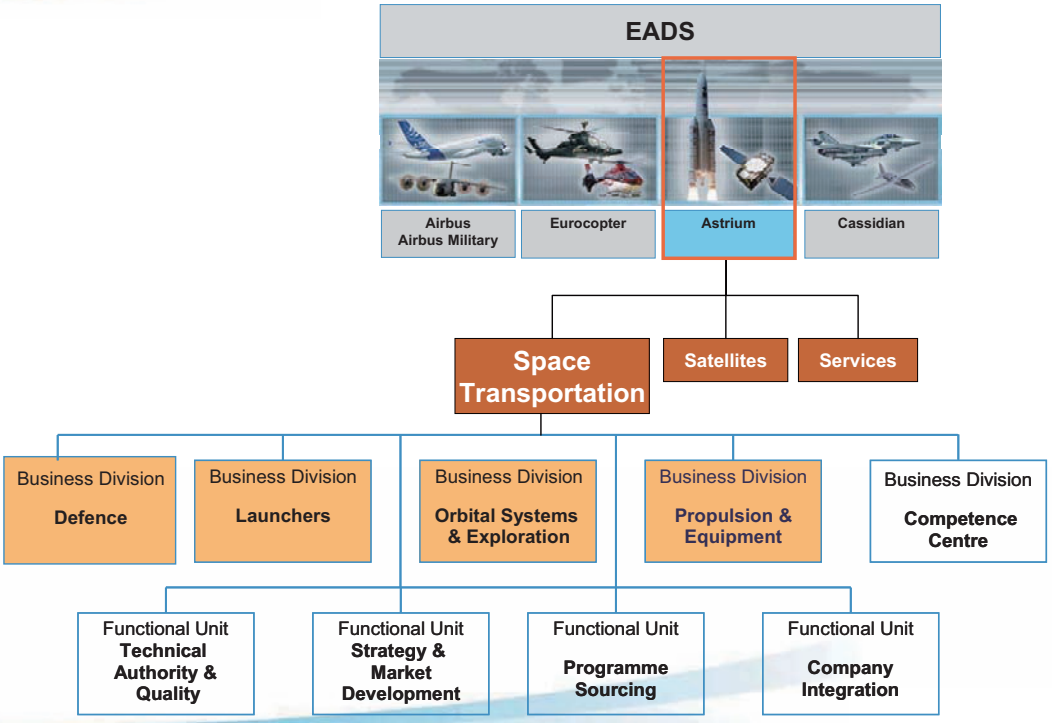
## Astrium's Liquid Propulsion Heritage & Simulation Capabilities
## **Astrium Space Transportation (Astrium ST)**





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## Astrium's Liquid Propulsion Heritage & Simulation Capabilities
## **Astrium ST's Product and Capability Portfolio**

- Ballistic missiles, missile defence
- Launchers: Ariane, Soyuz, Rockot, Vega
- Future launchers
- Orbital systems: Columbus, ATV, Operations, Atmospheric re-entry systems
- Propulsion & equipment
- System design, system integration & production





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## Astrium's Liquid Propulsion Heritage & Simulation Capabilities
## From MBB via DASA to EADS

| Year | Company | |
|---|---|---|
| 1955 | Ludwig Bölkow (helicopter & airplane development) | MBB |
| 1965 | Bölkow GmbH (also missiles and space propulsion) | |
| 1969 | Foundation of Messerschmitt-Bölkow-Blohm (MBB) | |
| 1981 | MBB-ERNO (merger with the Northern Germany space company) | |
| 1989 | Deutsche Aerospace DASA (subsidiary of Daimler-Benz) | DASA |
| 1995 | Daimler-Benz Aerospace | |
| 1998 | DaimlerChrysler Aerospace | |
| 2000 | Foundation of EADS (merger of the German DaimlerChrysler Aerospace, the French Aerospatiale-Matra and the Spanish CASA) | EADS |
| 2003 | Reorganization of space activities ➔ EADS Space Transportation | |
| 2006 | Reorganization of space activities ➔ EADS Astrium | |





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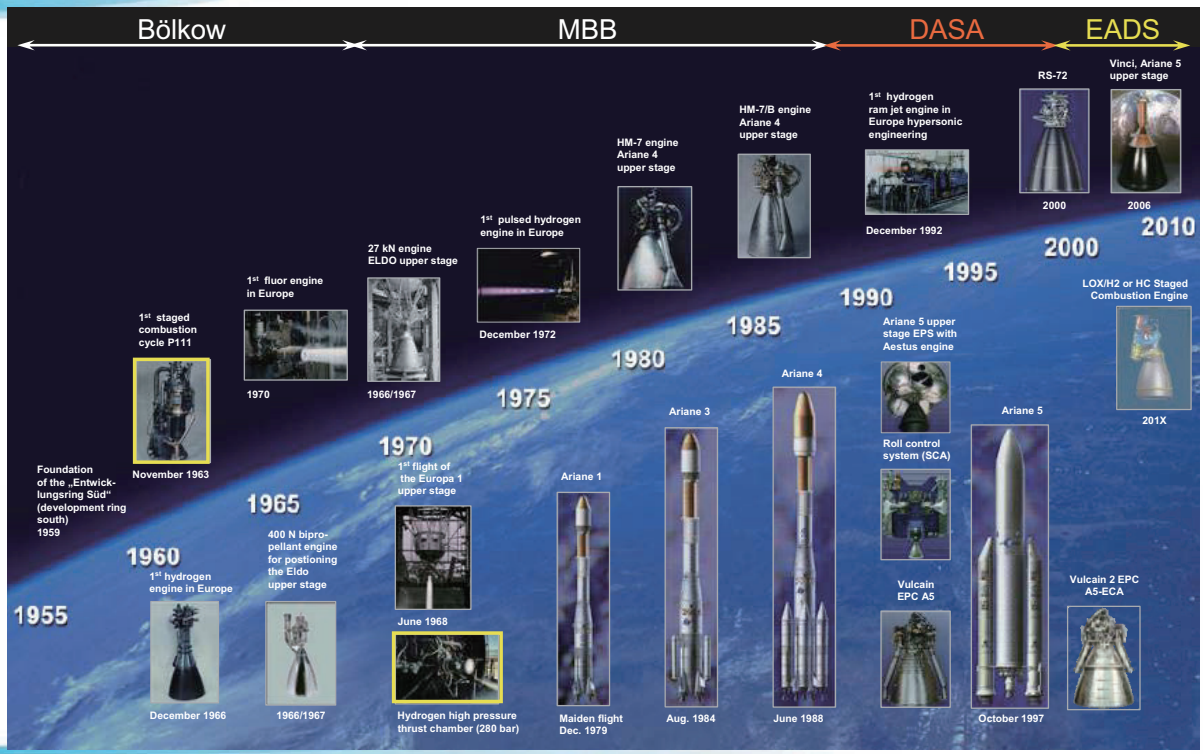
## Astrium's Liquid Propulsion Heritage & Simulation Capabilities
## Astrium's Propulsion Heritage and Business





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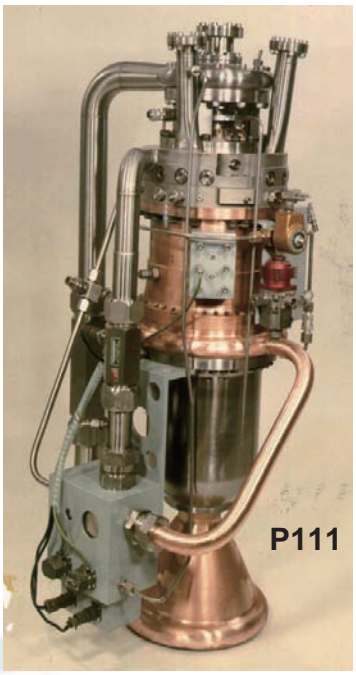
## Astrium's Liquid Propulsion Heritage & Simulation Capabilities
## LOX/Kerosene Heritage: The P111 Engine

- Development 1956 – 1967 by former Bölkow GmbH.
- Feasibility demonstration of a LOX/Kerosene, staged combustion cycle, ox.-rich preburner.
- Single shaft turbopump, axially integrated with preburner and main chamber (for interceptor aircraft integration )
- LOX-regenerative cooled main chamber.
- Copper liner with milled cooling channels, electro-deposited copper and nickel close-out for high pressure applications.
- Main performance data:

$F_{sea}$ = 49 kN　　$\varepsilon_{NE}$ = 10.6

$p_c$ = 85 bar　　$O/F_{MCC}$ = 2.7

$p_{PB}$ = 116 bar　　$T_{PB}$ = 920 K





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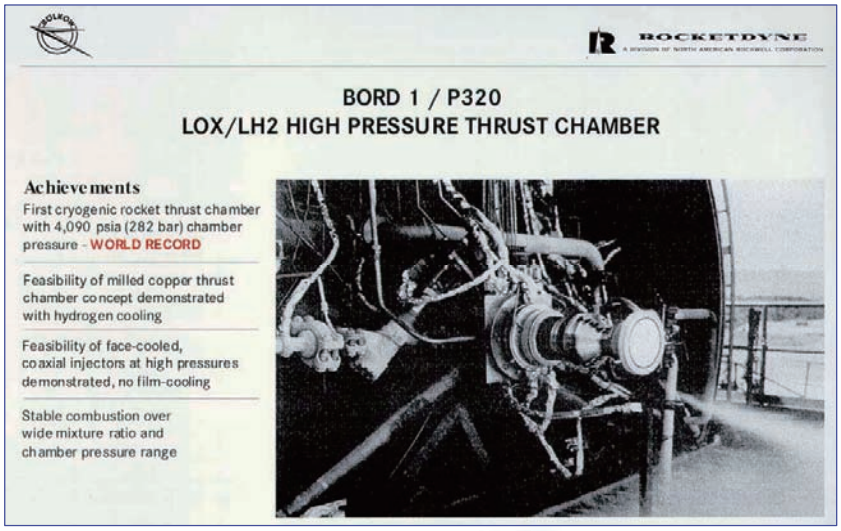
## Astrium's Liquid Propulsion Heritage & Simulation Capabilities
## LOX/$H_2$ Heritage: The Bord 1 Thrust Chamber

- Began in early 60s
- Data Exchange Agreement in 1962
- Modified Master Data Exchange Agreement in 1967
- Success of 1968 testing was a key factor in NASA decision to award SSME to Rocketdyne
- Also a key factor in Germany's propulsion industry becoming a European leader in thrust chamber design and production

BORD 1 – **BO**elkow/**R**ocket**D**yne




$F_{sea}$ = 130 kN, $p_c$ = 283 bar, $O/F_{MCC}$ = 6.0





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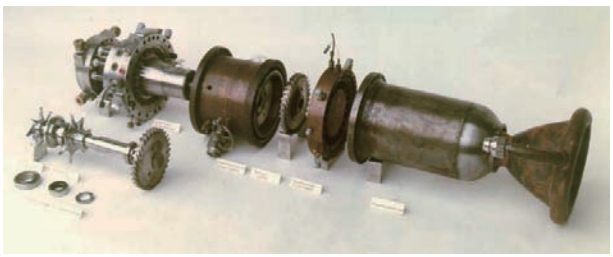
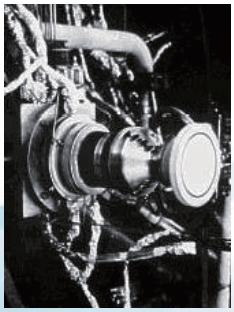
## Astrium's Liquid Propulsion Heritage & Simulation Capabilities
**MBB / DASA Ottobrunn Thrust Chamber Background**

- Invention and Patent for Regenerative Cooled Copper Combustion Chamber Liner

- Successful LOX Rich Preburner Staged Combustion Engine Demonstration – P111



- J-2 Engine Coax Injector Technology acquired through Cooperation with Rocketdyne in BORD-1 Program







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## Astrium's Liquid Propulsion Heritage & Simulation Capabilities
**Astrium's Current Rocket Propulsion Portfolio**

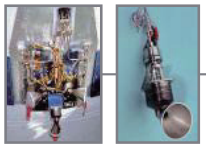
0.5N 1N 2N 5N 20N 400N

Monopropellant Hydrazine Thrusters

4N 10N 200N 400N/500N

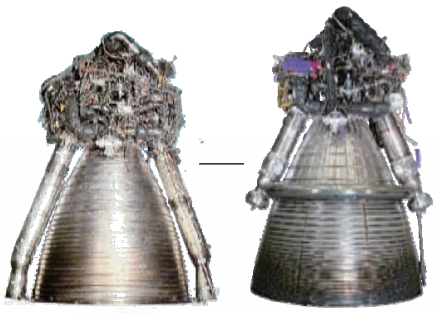
Bipropellant MON/MMH Thrusters

Attitude Control System SCA Main Stage



HM-7B Thrust Chamber for Upper Stage ESC-A

Aestus Engine Upper Stage EPS



Vulcain 1 / 2 Thrust Chamber for Main Stage





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## Astrium's Liquid Propulsion Heritage & Simulation Capabilities
## **Upper Stage Propulsion Pre- and Development Activities**




| Status | Pre-development | Pre-development | Pre-Development | Development |
|---|---|---|---|---|
| Engine | 3 – 8 kN Storable Pressure Fed Engine | Aestus II / RS-72 Storable Turbo-pump-Fed Engine | ROMEO LOX/$CH_4$ Gas Generator Cycle | Vinci Engine Ariane 5 ME Upper Stage |
| Astrium ST participation | Includes foreseen development, test and production of the engine | Includes foreseen development, test and production of the engine | Includes foreseen development, test and production of the engine | Development, test and production<br>- thrust chamber<br>- LOX/$LH_2$-valves |
| Thrust | 4 – 8 kN | 35 - 65 kN | 420 kN | 180 kN |
| Propellants | NTO/MMH | NTO/MMH | LOX/$CH_4$ | LOX/$LH_2$ |
| Performance | > 320 sec | > 338 sec | > 345 sec | 464 sec |





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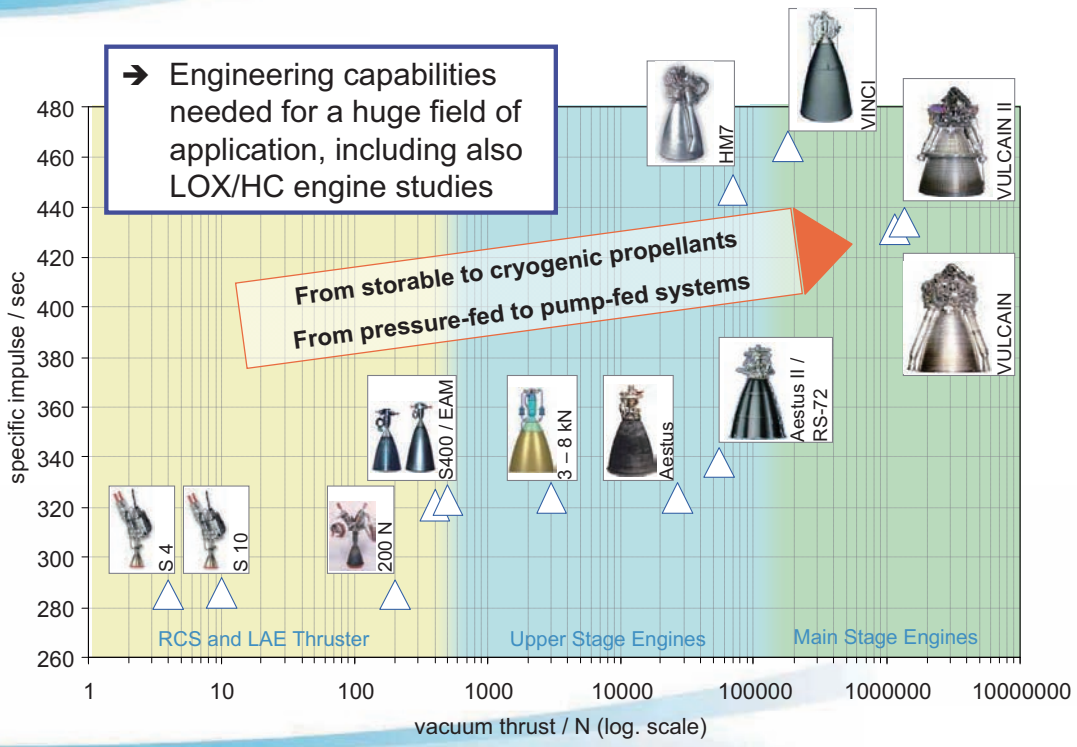
## Astrium's Liquid Propulsion Heritage & Simulation Capabilities
## **Engineering Competences for a Huge Field of Application**





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## Astrium's Liquid Propulsion Heritage & Simulation Capabilities
### TP2 – Programmes & Functional Responsibility Matrix

**TP2**
Launcher Propulsion Development
**G. Langel**

**Programmes**

| | TP21 Systems Technology & R&D Programmes — D. Preclik | TP22 Booster Propulsion Programmes — R. Nicolay | TP23 Upper Stage & In Orbit Propulsion Prog. — G. Hagemann |
|---|---|---|---|
| **Functional** | | | |
| TP21 Systems Technology & R&D Programmes — D. Preclik | | | |
| TP24 System Analysis — O. Knab | | | |
| TP25 Engineering Analysis — M. Terhardt | | | |
| TP26 Engineering Design — G. Taubenberger | | | |





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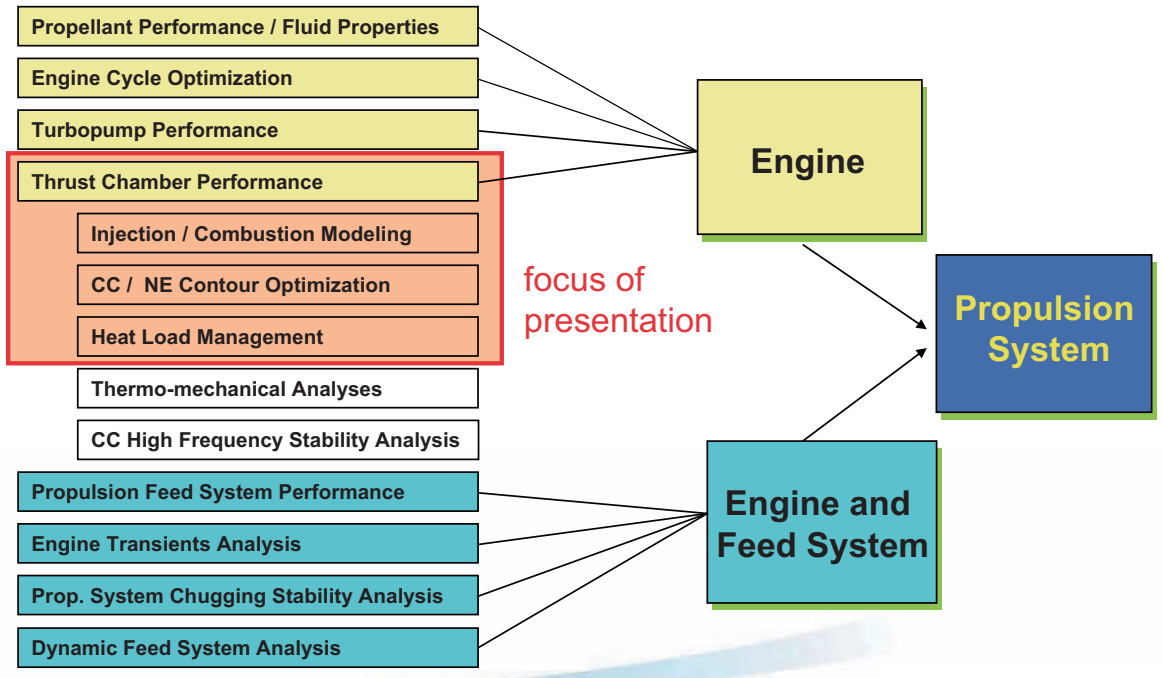
## Astrium's Liquid Propulsion Heritage & Simulation Capabilities
### Propulsion Engineering Analytical Efforts





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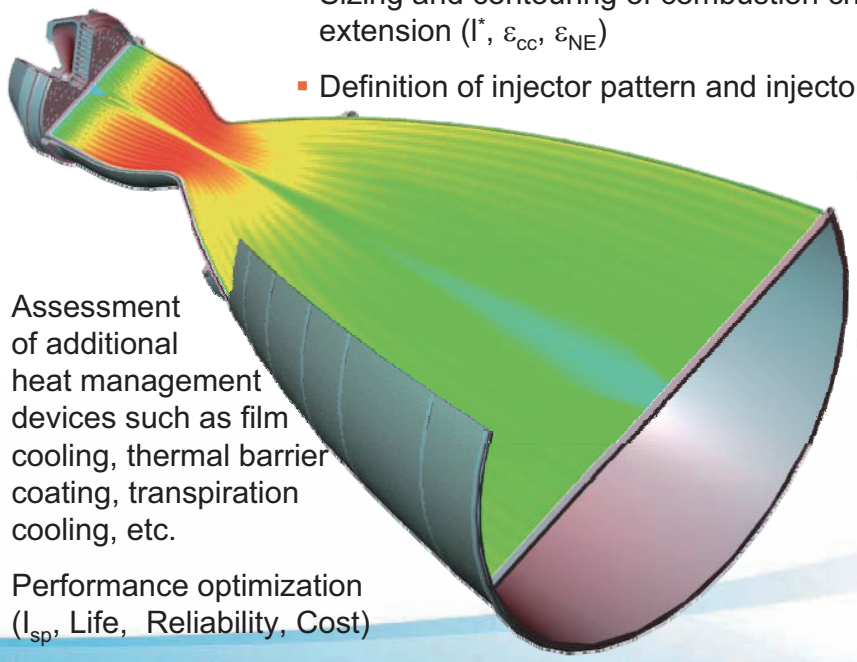
## Astrium's Liquid Propulsion Heritage & Simulation Capabilities
## **Engineering Tasks of a Rocket TCA Responsible**

Among others, main engineering tasks during a TC trade or development phase are:

- Sizing and contouring of combustion chamber and nozzle extension ($l^*$, $\varepsilon_{cc}$, $\varepsilon_{NE}$)
- Definition of injector pattern and injector element configuration



- Evaluation of heat transfer into CC & NE cooling circuit and injector face plate
- Tailoring of cooling channels and wall thickness distribution to fulfill pressure budget and life requirements
- Assessment of additional heat management devices such as film cooling, thermal barrier coating, transpiration cooling, etc.
- Performance optimization ($I_{sp}$, Life, Reliability, Cost)





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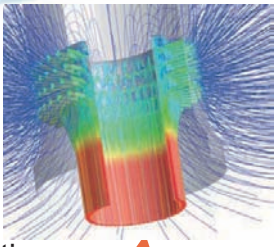
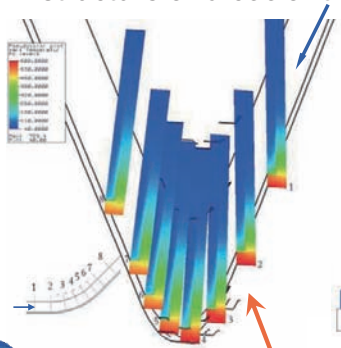
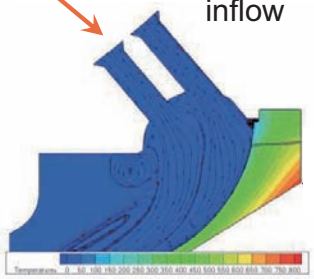
## Astrium's Liquid Propulsion Heritage & Simulation Capabilities
## **Astrium ST's Thrust Chamber Simulation Practices**



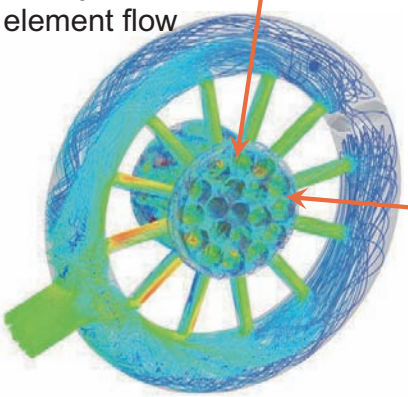
3D heat transfer into structure and coolant

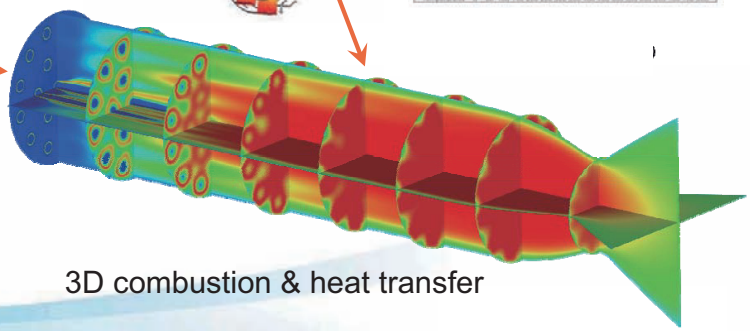


3D channel inflow



3D injection element flow





3D injector head flow distribution & heat transfer

3D combustion & heat transfer





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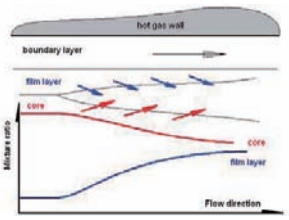
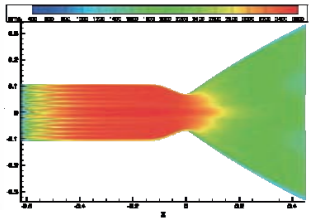
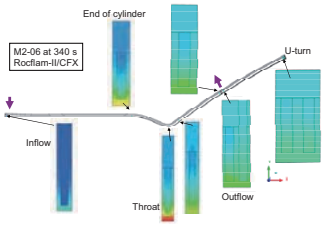
## Astrium's Liquid Propulsion Heritage & Simulation Capabilities
## **Astrium's Combustion & Heat Transfer Simulation Tools**






| | RCFS-II | Rocflam-II | CFX |
|---|---|---|---|
| Hot-gas side heat transfer | Advanced boundary layer approach, equilibrium $LOX/H_2$, LOX/HC, MMH/NTO chemistry, 2D flow expansion | 2D/axisym., multi-phase Navier-Stokes code, propellant disintegration and evaporation, turbulent $LOX/H_2$, LOX/HC, MMH/NTO combustion | 3D Navier-Stokes code, dense gas turbulent $LOX/H_2$ combustion |
| Coolant- side heat transfer | Nusselt-type correlations coupled with 1D/2D structural heat conduction computation, analytical pressure drop modeling | Restricted to heat conduction through walls and radiation cooling to environment | 3D Navier-Stokes code, fluid/structure coupling, $H_2$, $CH_4$, $N_2$, $H_2O$ real gas fluid properties |





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## Astrium's Liquid Propulsion Heritage & Simulation Capabilities
## **The Rocflam-II Spray Combustion Tool Features**

- compressible, sub- and supersonic flows
- k - ε turbulence model
  - 2-layer model or logarithmic wall function
  - compressibility effects
- chemical reaction models
  - multi-step global reaction schemes (turbulence & kinetically controlled)
    - Hydrazine/NTO, MMH/NTO, $LOX/H_2$
  - Presumed PDF with tabulated equilibrium chemistry
    - $LOX/H_2$, LOX/HC
    - $Air/H_2$, Air/Kerosene
    - Air/HTPB, LOX/HTPB
- real gas data
  - down to the injection temperature
  - for temperatures below the boiling/melting temperature: treatment of liquid water and ice as dense gases (quasi-condensation)
- Lagrangian partical tracking (Stochastic Separated Flow model)
  - multi-class, bi-propellant, discrete particle injection and sequential tracking approach
- supercritical LOX & Methane gasification model

- annular liquid film cooling model
- advanced droplet-to-wall / film interaction model
- secondary droplet break-up
- viscous heating, species diffusion
- heat conduction in solid walls & radiation
- porous walls and crack simulation
- standard Jannaf property data base
- coupling with Astrium's RCFS-II code (**R**egenerative **C**oolant **F**low **S**imulation)
- 3D conjugate heat transfer analyses by coupling with commercial CFX CFD software package

- 2-D, axisymmetric, finite volume
- Favre-averaged Navier-Stokes
- SIMPLE algorithm (pressure correction)
- implicit Stone solver

- structured,
- non-orthogonal
- curvilinear meshes
- multi-block





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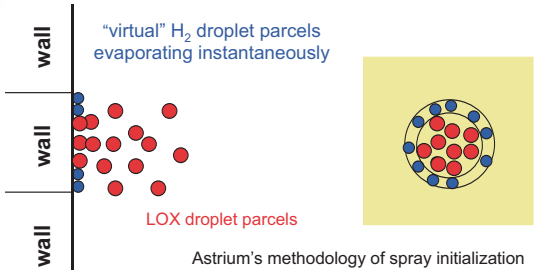
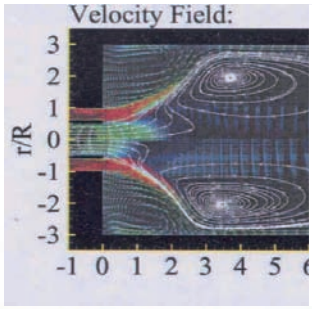
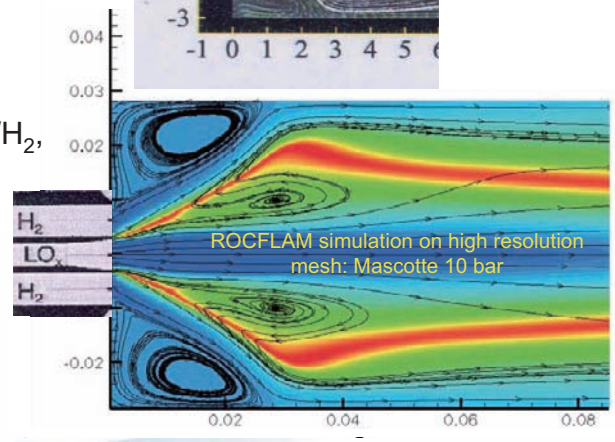
## Astrium's Liquid Propulsion Heritage & Simulation Capabilities
**Key Issue: Droplet/Spray Initialization**




Astrium's methodology of spray initialization

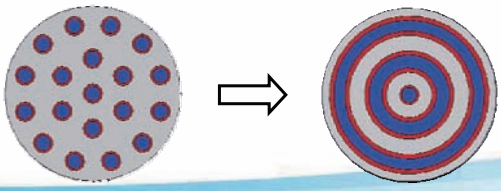



LES simulation (J. Oefelein): Sommerfeld experiment




➔ Method is suited for liquid, transcritical and gaseous propellant injection ($LOX/H_2$, MMH/NTO, $LOX/CH_4$ and LOX/Kero)

➔ Method is suited to initialize droplets on injection rows for 2D simulations







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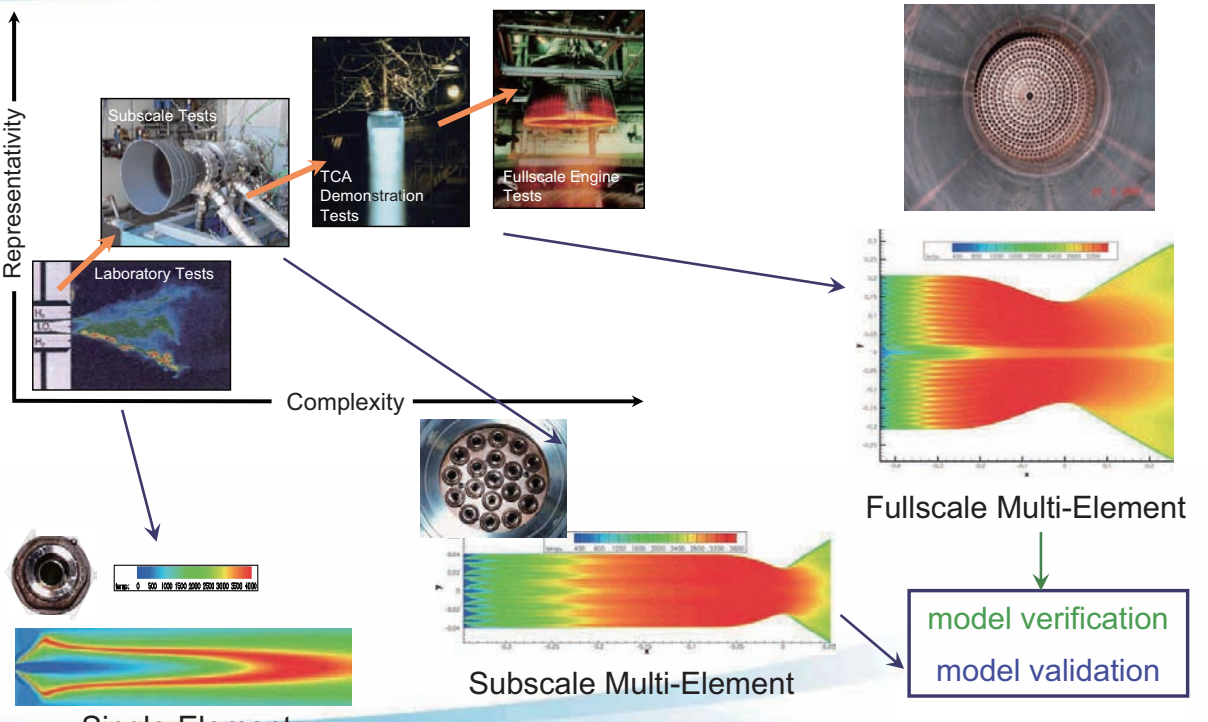
## Astrium's Liquid Propulsion Heritage & Simulation Capabilities
**Development Philosophy for Hardware & Tools**





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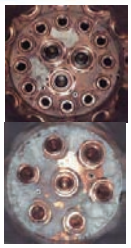
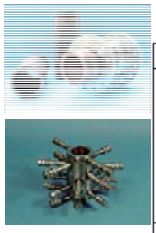
## Astrium's Liquid Propulsion Heritage & Simulation Capabilities
## **Astrium ST's Subscale Thrust Chamber Hardware Portfolio**

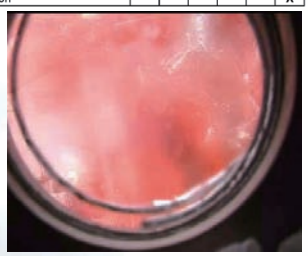


| Objective | Injector Hardware: Integral Open Cycle | Integral Expander Cycle | Modular Open Cycle | Integral Staged Combustion | Cooled Faceplate and Igniter Ring | Film Cooling Injector |
|---|---|---|---|---|---|---|
| Performance, C* | X | X | X | X | | X |
| Wall Heat Flux | X | X | X | X | X | X |
| Injection Element Type | | | X | | | X |
| Effect of Film Cooling | X | | X | | | X |
| Injector Pattern | | | X | X | | |
| Number of Injection Elements | | | X | X | | |
| Faceplate Heat Load | | | X | X | X | X |
| Type of Faceplate / Cooling | | | | | X | |
| Fuel Temperature | | X | X | X | | |
| Baffle Elements | | | X | | | |
| Injector Thermal Behaviour | | | X | X | X | X |
| H2 / CH4 Injector Behaviour | | | X | X | X | |
| Low Frequency Oscillations | X | | | X | | |
| Injection Velocity Ratio | X | X | X | X | | |
| Recess Length | X | X | X | X | | |
| Element-Wall-Distance | X | | X | | | |
| Margin Testing | | | X | X | | |



| Objective / Parameter | MCC Hardware: Capacitive | Calorimeter | Integral | Segmented [8] | Modular Liner Monoblocks | Elastic Liner |
|---|---|---|---|---|---|---|
| Performance, C* | | X | X | | X | |
| Axial Wall Heat Flux Evolution | | X | | X | | |
| Global Heat Flux | | X | X | | X | X |
| Effect of Film Cooling | | X | X | | | |
| Margin Testing | X | | | | | |
| New Start Up Sequences | X | | | | | |
| Risk Mitigation | X | | | | | |
| H2O cooling | | X | X | X | X | X |
| LH2 cooling | | | X | X | X | X |
| L* variation by hardware combination | | X | X | X | X | X |
| Liner Life Investigation | | | | | | X |
| Hot gas wall contour variation | | X | | | X | |
| PLD, APS, VPS thermal barrier coating [8] | | | | X | | |

| Objective / Parameter | NE Hardware: Tube Wall † | C/SiC Composit | Ablative Composit | Calorimeter | NE Skirt † | Cu Monoblock Cone |
|---|---|---|---|---|---|---|
| Flow Separation Characterisation | | X | | X | X | |
| Material Characterisation | X | X | X | | | |
| Axial Wall Heat Flux Evolution | | X | | X | X | |
| Global Heat Flux | X | | | X | | X |
| Effect of Film Cooling | X | | | X | X | |
| Side loads | | | | | X | |
| Phenomenology, Data Base Generation | | | X | | | X |
| LH2 cooled | X | | | | | X |
| GH2 cooled | | | | X | X | |
| H2O cooled | | | | X | | |
| Ablative cooled | | | X | | | |
| Radiation Cooled | | X | | | X | |
| Film cooled | X | | | X | | |
| Water Condensation | | | | | | X |



➔ a huge data base for model and tool validation is available





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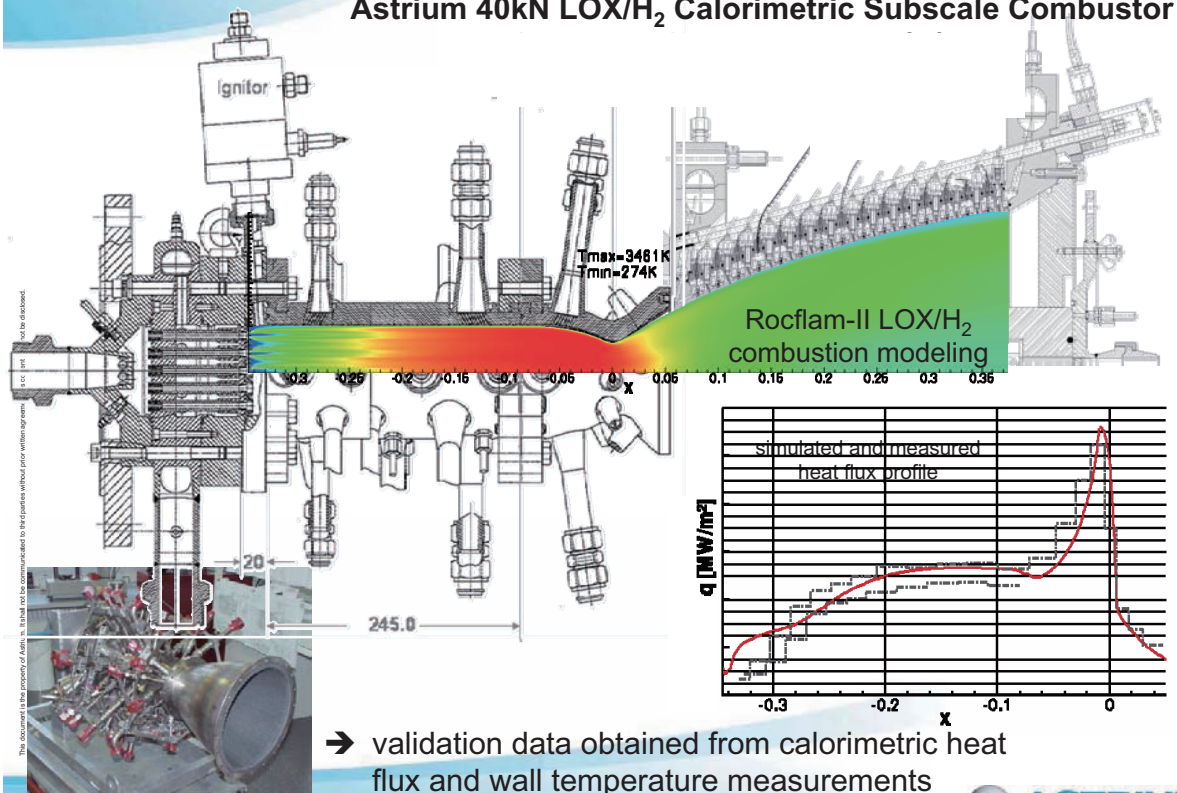
## Astrium's Liquid Propulsion Heritage & Simulation Capabilities
## **Astrium 40kN LOX/$H_2$ Calorimetric Subscale Combustor**






➔ validation data obtained from calorimetric heat flux and wall temperature measurements





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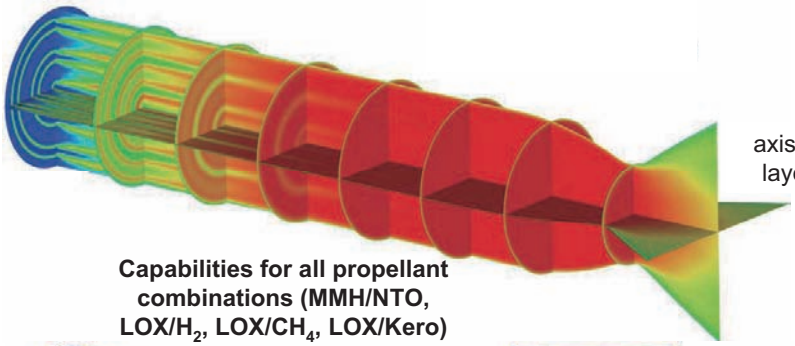
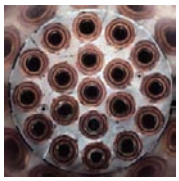
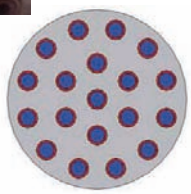
## Astrium's Liquid Propulsion Heritage & Simulation Capabilities
## 2D versus 3D Flow Field Resolution

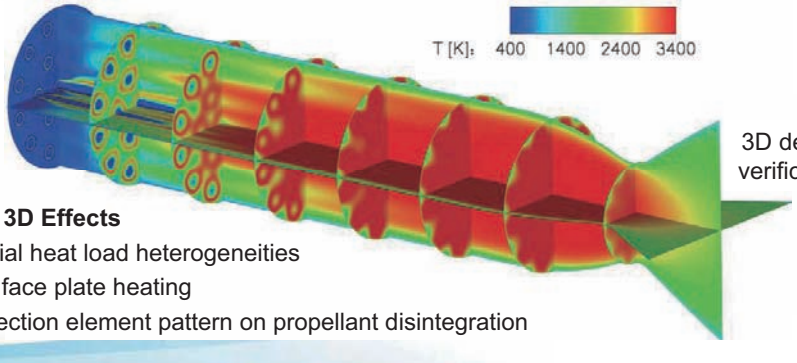


axisym. layout



**Capabilities for all propellant combinations (MMH/NTO, LOX/$H_2$, LOX/$CH_4$, LOX/Kero)**






3D design verification

**Resolution of 3D Effects**

- circumferential heat load heterogeneities
- non-uniform face plate heating
- impact of injection element pattern on propellant disintegration





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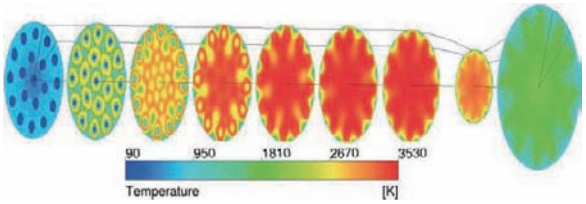
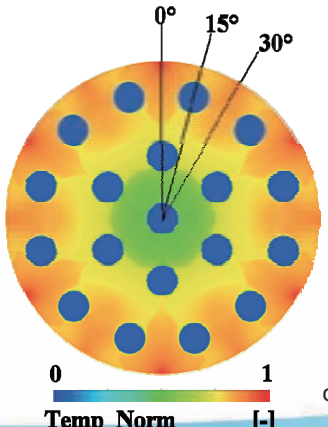
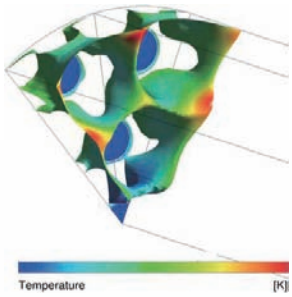
## Astrium's Liquid Propulsion Heritage & Simulation Capabilities
## 3D $H_2/O_2$ Combustion & Heat Transfer Modeling with CFX

- Dense gas approach (single phase) ➔ restricted to transcritical $H_2/O_2$
- Real gas properties down to cryogenic temperatures
- Flamelet combustion approach
- PPDF turbulent combustion

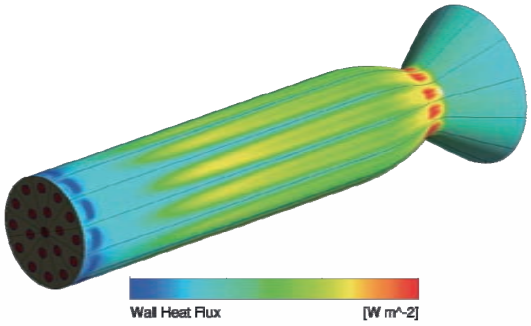



Resolution of injector pattern on propellant disintegration




Resolution of 3D effects close to the injector head




Resolution of heat load heterogeneities





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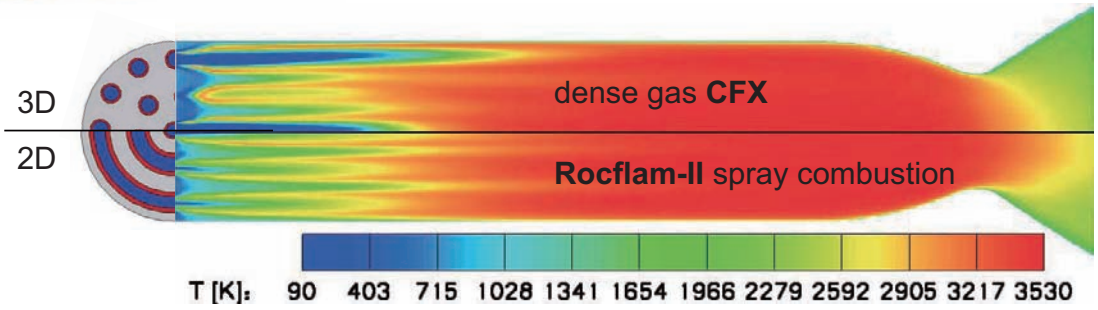
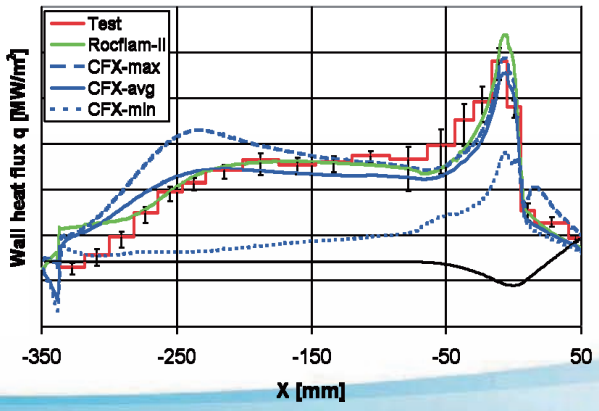
## Astrium's Liquid Propulsion Heritage & Simulation Capabilities
## 3D $H_2/O_2$ Combustion & Heat Transfer Modeling with CFX




| | $\eta_{C^*}$ | Qint,rel |
|---|---|---|
| | [%] | [%] |
| Rocflam-II | 98.80 | 102.00 |
| CFX | 96.63 | 95.86 |
| Test | 98.50 | 100.00 |

➔ A high level of representatively has already been reached with the 3D dense gas approach

➔ However, some subjects may still be improved





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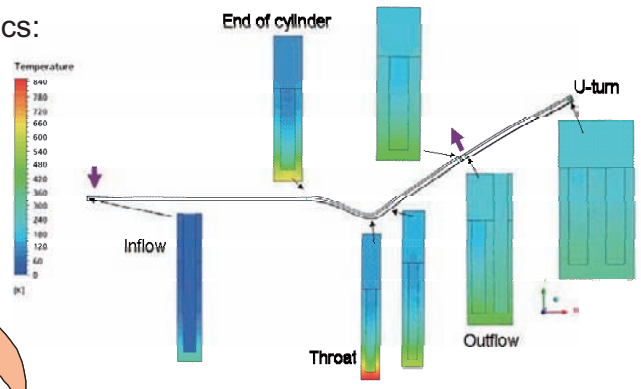
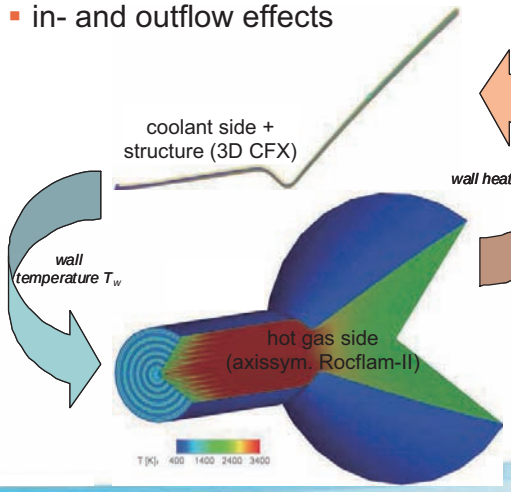
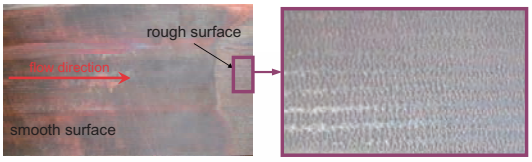
## Astrium's Liquid Propulsion Heritage & Simulation Capabilities
## Coupled Hot Gas Side / Coolant Side Heat Transfer

Resolution of channel flow characteristics:

- thermal stratification effects
- secondary flow (curvature) effects
- channel surface roughness
- in- and outflow effects




Resolution of liner surface roughening:

- temporal liner degradation
- local heat flux enhancement





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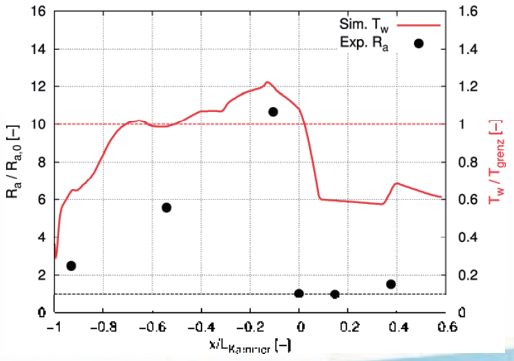
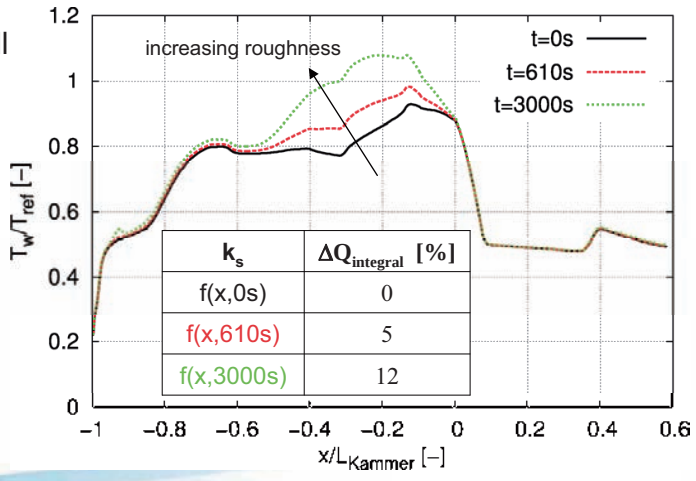
## Astrium's Liquid Propulsion Heritage & Simulation Capabilities
## **Modeling of Temporal Liner Surface Degradation**

Modeling approach:

- allowing for surface roughness in 2-layer wall turbulence model ($l_\mu = f(R_a)$)
- calibration of wall roughness value to damping factor in turbulent length scale correlation via tube flow simulations and respective experimental data
- in future: approximation of roughness evolution as a function of wall temperature level and firing time




| $k_s$ | $\Delta Q_{integral}$ [%] |
|---|---|
| f(x,0s) | 0 |
| f(x,610s) | 5 |
| f(x,3000s) | 12 |

➔ essential for accurate liner life prediction !!



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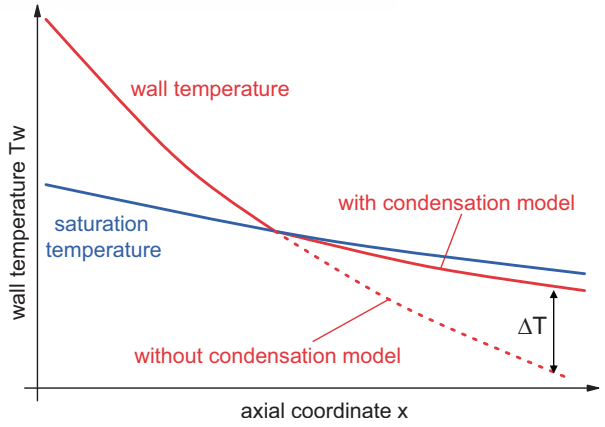
## Astrium's Liquid Propulsion Heritage & Simulation Capabilities
## **Condensation Modeling Along Subcooled Walls**




P&W CECE

Modeling approach:

- consideration of liquid water and ice species in Rocflam-II chemistry tables
- energetically correct homogeneous mixture (dense gas) model
- coupled hot gas side / coolant side conjugate heat transfer computation

➔ essential for accurate heat pick-up computations

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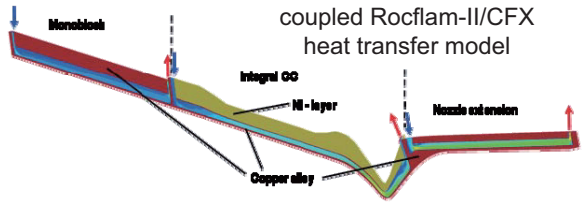
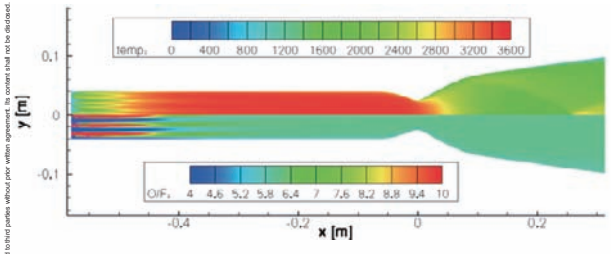
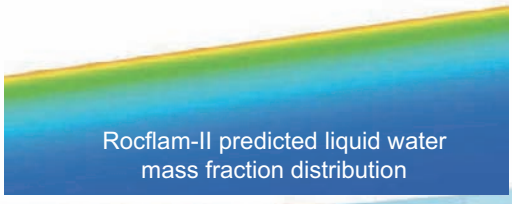
## Astrium's Liquid Propulsion Heritage & Simulation Capabilities
## **Condensation Modeling Along Subcooled Walls**

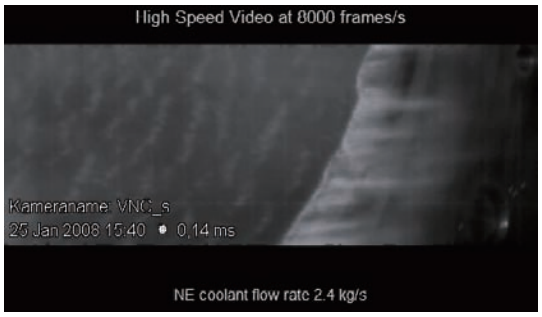


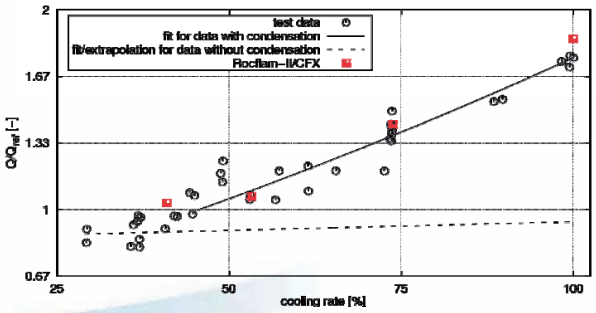

coupled Rocflam-II/CFX heat transfer model



Rocflam-II predicted liquid water mass fraction distribution




measured and calculated heat load enhancement





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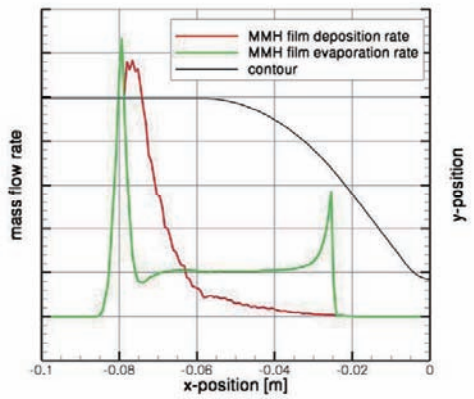
## Astrium's Liquid Propulsion Heritage & Simulation Capabilities
## **Liquid Film Cooling Modeling in MMH/NTO Thrusters**

Employed Rocflam-II models:

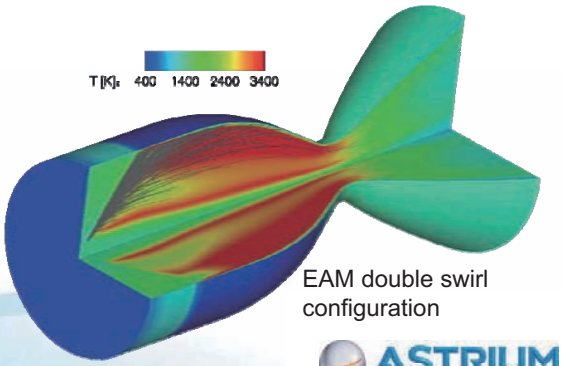
- annular liquid film cooling model
- advanced droplet-to-wall / film interaction model
- secondary droplet break-up




| S400-15 | $p_c$ [bar] | $\eta_{c^*}$ [%] |
|---|---|---|
| Test data | 10.46 | 96.5 |
| Rocflam-II | 10.74 | 97.1 |

➔ currently the 500 N EAM thruster is under development

➔ Rocflam-II analyses support configuration layout (l*, $\varepsilon_{cc}$)




EAM double swirl configuration





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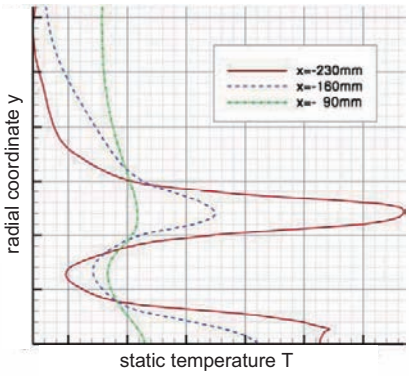
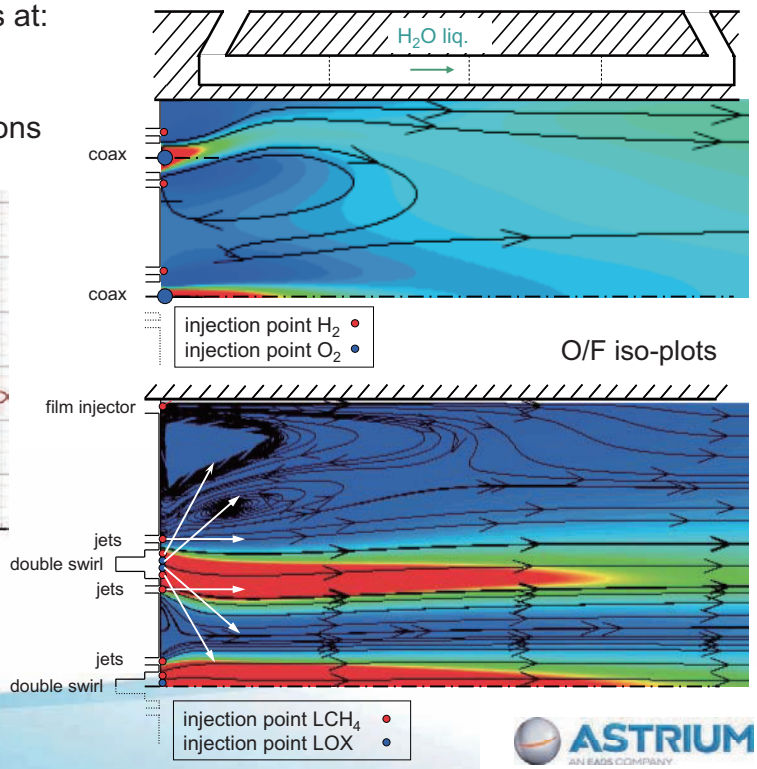
## Astrium's Liquid Propulsion Heritage & Simulation Capabilities
## **Novel Rocflam-II Modeling – Pre-burner & Gas Generator**

Spray combustion simulations at:

- low mixture ratios
- liquid/liquid injection conditions




➔ essential for thermal integrity justification and quantification of thermal stratification





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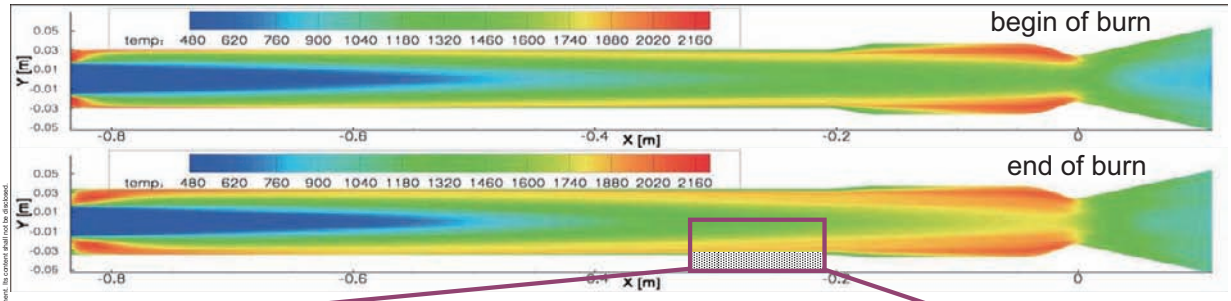
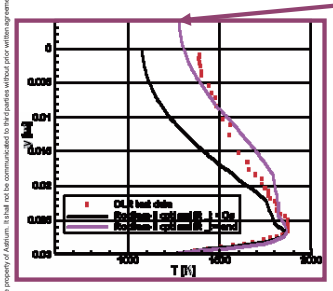
## Astrium's Liquid Propulsion Heritage & Simulation Capabilities
## **Novel Rocflam-II Modeling – Hybrid Propulsion**

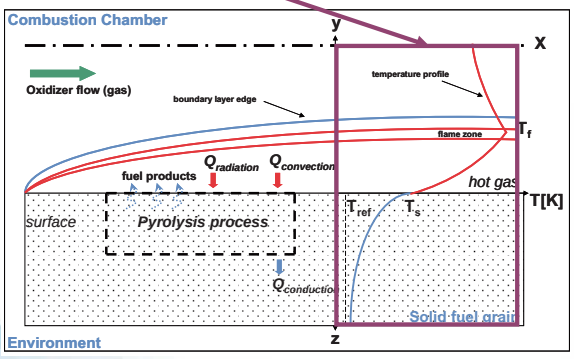
Air/HTPB combustion including a regression rate wall boundary condition $\dot{r} = f(T_s)$




Modeling approach:

- 12 species chemistry table
- heat balance pyrolysis model




| | $m_{tot}$ [kg/s] | $\eta_{c^*}$ [-] | $p_{th}$ [bar] |
|---|---|---|---|
| begin of burn | 0,9049 | **0,88** | 5,8 |
| end of burn | 0,9123 | **0,90** | 6,1 |
| DLR test | 0,9080 | **0,90** | 6,0 |

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Astrium's Liquid Propulsion Heritage & Simulation Capabilities
**Concluding Remarks**

… and at the end some thoughts on lessons learned

- understand the physics
- analyze and understand the data
- always think one level up (systems understanding)
- flight loads are not ground test loads
- it's the transients that cause the most trouble, however difficult to analyze
- value engineering judgment over analysis only
- give the talented and unexperienced a chance – they will learn quickly





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**Acknowledgement**

## Acknowledgement

The speaker gratefully acknowledges the work of his System Analysis team whose diligent efforts in further tool extension and validation valuably contribute to foster Astrium ST's leading edge rocket thrust chamber expertise.





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