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Overview on the National Programme to Enhance Cryogenic Upper Stage Technologies to Extend European and German Competences in Future Launcher Developments - PROCEED

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Abstract

Competitiveness in space business and cost-efficient access to space requests for state-of-the-art technologies which evidence reliability and cost savings. The dilemma of new and innovative technologies aiming for the application in Next Generation Launchers (NGLs) originates from their lower maturity and the associated lack of confidence. For this reason technology programmes such as PROCEED are established in order to close these technology maturity gaps. PROCEED aims at extending upper stage competences and combines the maturation and evaluation of 10 promising technologies and tools. The paper gives an overview on the programme and on the corresponding technologies as well as tools being matured and evaluated.

1. Introduction

Competitiveness in space business and cost-efficient access to space requests for state of the art technologies which evidence reliability and cost savings by adjusting the right balance between performance improvement and recurring / non-recurring costs. The dilemma of new and innovative technologies aiming for application in launchers originates from their lower maturity and confidence. Thus a sufficient technology readiness level (TRL) and confidence level of a specific technology has to be verified beforehand to allow launcher programmes to gain related benefits. In consequence technology programmes such as ESA's FLPP (Future Launch Preparatory Program) or national agency programmes are essential to close these technology maturity gaps.

One of these technology programs is called PROCEED which stands for "Programme to Enhance Cryogenic Upper Stage Technologies to Extend European and German Competences in Future Launcher Developments". The national PROCEED programme is co-funded by the German Space Agency (DLR) and aims at developing and extending upper stage competences for next generation launchers. It combines the evaluation and maturation of 12 promising technologies and tools which are oriented towards new developments such as ARIANE 6 and which have the potential to significantly enhance the upper stage performance or to significantly reduce costs.

The presentation will give an overview on the PROCEED programme and on the corresponding technologies and tools which are clustered according to their evolvement potential in 3 branches, i.e. System Improvements, Smart Avionics, and Equipped Insulated Tank Demonstrator. Several development areas such as launcher integration, avionics, materials and structures as well as the propellant management are comprised. Being in the first year of the PROCEED programme the presentation focuses on the development objectives and expected results.

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1.1 Project Overview

The PROCEED programme started mid-2016 and will run for a duration of approx. 3.5 years. As seen in Figure 1 the PROCEED programme contains of three major branches allocated to technologies and tools for System Improvement, Equipped Insulated Tank (EIT) Demonstration, and Smart Avionics.

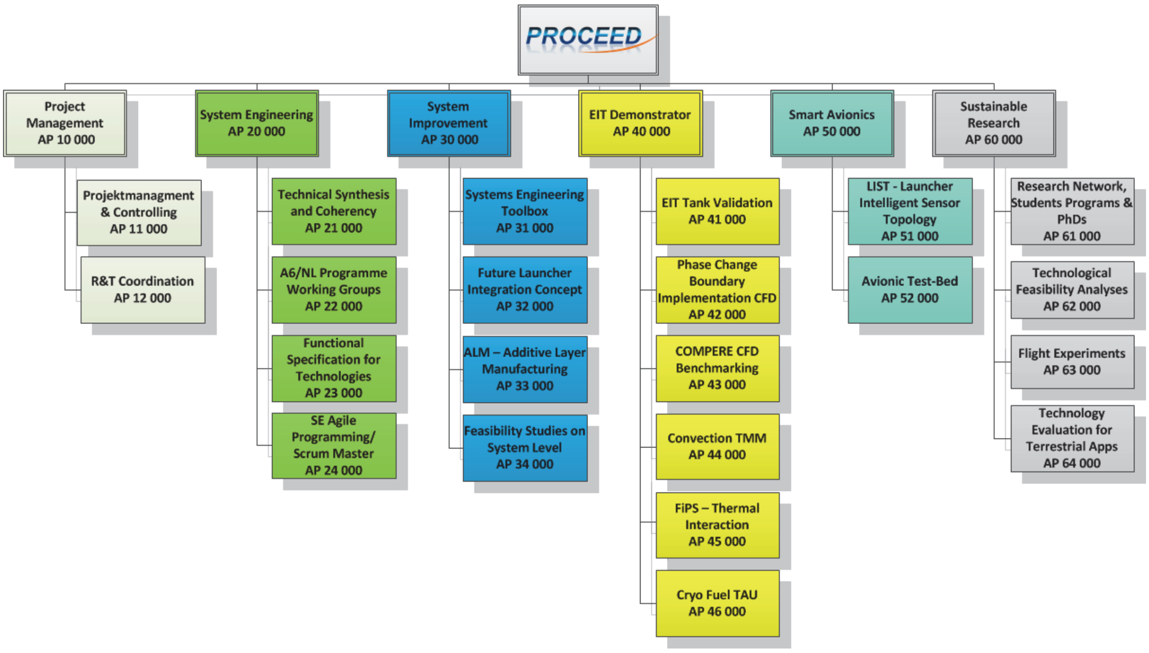

Figure 1: Work breakdown structure of the PROCEED programme

The objectives of PROCEED comprise the development and extension of upper stage competences for A6, Ariane NEXT, and or Micro-Launcher. The selected technologies and tools shall be evaluated and matured to enhance Upper Stage performance & to reduce recurring cost significantly. In particular their economic benefit must be evaluated thoroughly in order to contribute efficiently to the competitiveness of Upper Stages or Launchers respectively.

PROCEED is the successor of the DLR co-funded Technology Maturation Programme PREPARE - "Programme to Enhance Upper Stage Performance and Reliability for Future Expandable Launchers" [1].

2. Technologies and Tools for System Improvements

The PROCEED technologies & tools for System Improvements are presented in the following sections together with their objectives, main benefits as well as recent results. They comprise one tool for designing launcher upper stages in early phases (→ System Engineering Toolbox) and two technologies allocated to the domain of Assembly, Integration, Test (AIT, → Future Launcher Integration Concept) and Materials & Structures (→ Additive Layer Manufacturing). Moreover Feasibility Studies are conducted in the technical domains of Materials & Structures as well as Avionics. The present publication focuses on the principle work packages, therefore these feasibility studies are not addressed further.

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2.1 System Engineering Toolbox

Today, a system analysis loop for a launcher design concept phases 0-A generally takes several weeks, mainly due to the missing interaction or connection between the corresponding tools of the different technical disciplines. Moreover a significant effort has to be spent for the interface (I/F) coordination between the different system aspects.

For future launchers and their upper stages and in early project phases quick analysis / engineering loops are needed for instance for early design trade-offs. Also various system aspects (concurrent engineering) need to be taken into account due to complexity and the dependency of the analysed system.

Depending on the development phase these needs in simulation response (rapid analysis loops), design flexibility and accuracy of the analysis loop changes considerably, as seen in Figure 2. As also highlighted in the below figure the System Engineering Toolbox only focuses on early development/design phases and consequently on corresponding pre-definition and configurations tools.

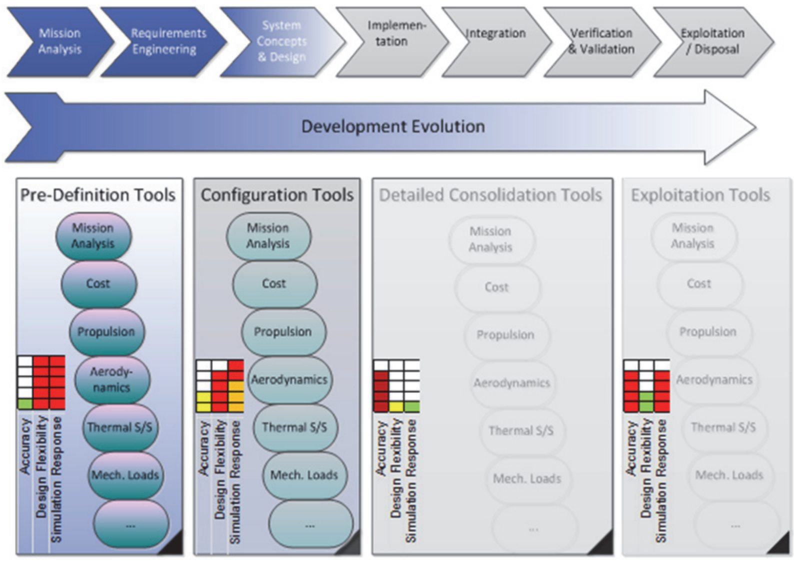

Figure 2: System Engineering Toolbox: Development evolution and phase dependent needs

The objective of these activities within PROCEED is to develop various Launcher/Upper Stage System Domain Tools and their interaction within a dedicated connecting environment to quickly generate and validate launcher concept & component designs (incl. cost estimation) during early development phase. This kit of tools for the different system aspects such as Propulsion, Thermal, GNC, Cost, Avionic, Mechanic, Design, etc. shall be connected together via Inputs/Outputs files, allowing a quick Launcher / Upper Stage configuration analysis. Figure 3 shows the rough schematic of the System Engineering Toolbox workflow.

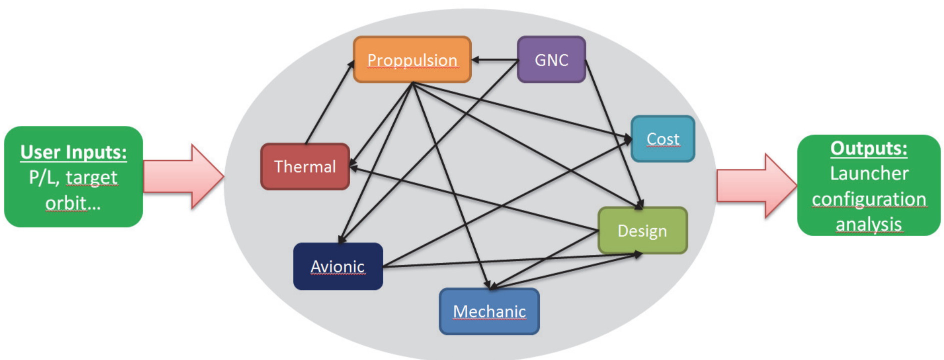

Figure 3: Rough schematic of the System Engineering Toolbox workflow

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Apart from the main activities of developing Launcher / Upper Stage System Domains software modules and their implementation into the connecting environment the coordination of these tool developments and interfaces is essential for an operational System Engineering Toolbox. Towards the end of the development activities a software validation shall be performed via a use case.

In particular through the development of the right tools (quickness & flexibility versus accuracy) and the integrated interlinking of these tools a powerful System Engineering Toolbox can be established able to perform fast (pre-) design loops including costs and able to early identify design driving parameters. The tool then also allows to analyse design optimisations and association which is attractive not only for new launcher/upper stage development (ARIANE NEXT, micro-launcher → fast concept launcher design and validation + NRC and RC) but also for specific Launcher / Upper Stage evolutions (→ RC impact).

2.2 Future Launcher Integration Concept

In this work package Future Launcher Integration Concepts for Upper Stages are developed taking into account the industrial 4.0 opportunities. This comprises the establishment of new, efficient document flows for the whole Assembly, Integration &Test (AIT) procedures, the analysis of cyber physical-system solutions and the concept study itself to establish a cyber-physical system in the AIT process for its optimisation, i.e. increasing efficiency, robustness, quality, reactivity and decreasing RC.

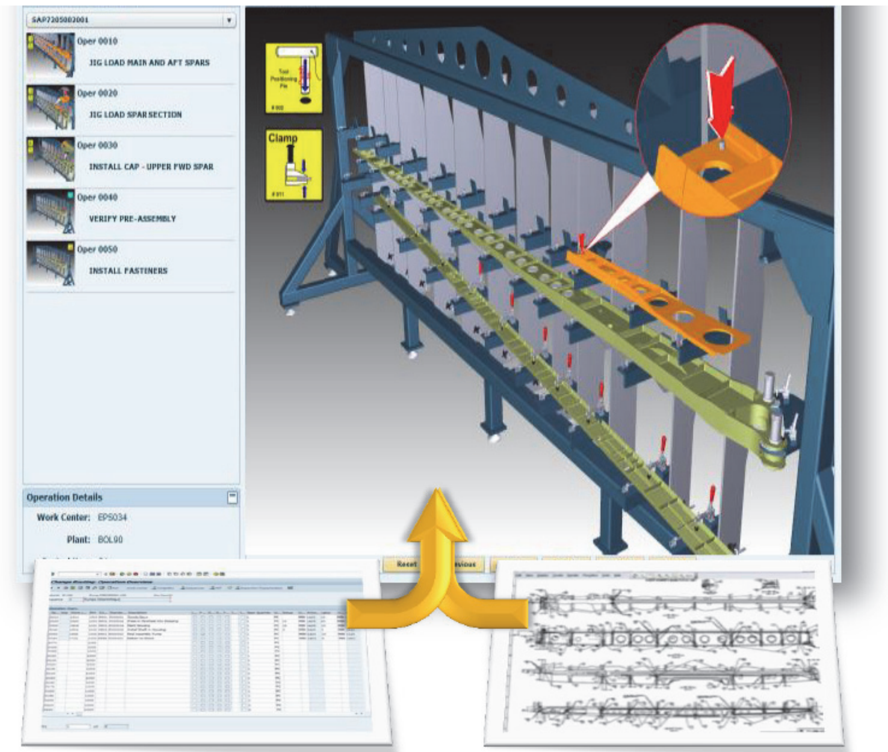

Figure 4: Illustration of efficient document flows for the assembly

The current production and information process is still dominated by paper procedures and paper lists as well as technical drawing which the integrator manually uses to perform his AIT work. As illustrated in Figure 4 these intricate procedures shall be harmonised /optimised in a dedicated data management system as well as by the use of appropriate cyber physical-system solutions. The latter can be new electronic devices such as tablets or head mounted displays for integration instructions. Through a dedicated data management system a real time data processing of the production process (and progress) as well as interactive planning to detect and reduce delays becomes feasible which will significantly optimise the AIT process and decrease RC.

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2.3 Additive Layer Manufacturing

Additive Layer Management has become an enabling technology over the recent years due to its benefits such as mass savings up to 30%, lead time reduction, and the possibility to "easily" manufacture complex structures. Benefiting from the in-house experiences from projects such as PREPARE [1, 2] and ALM ISCAR [3] the ALM activities within PROCEED shall consolidate and finalise the complete ALM industrialisation processes and philosophy for printable aluminium alloys. This includes the development of design rules (incl. design interpretation), the definition of manufacturing processes requirements as well as the establishment of an applicable quality assurance plan. Emphasis is put on the designing and sizing process which accounts for topology optimisation as well as for guidelines for dimensioning aerospace parts.

The topology design steps are illustrated in Figure 4 by the design evolution from 1. local shape generation for I/F via 2./3. global shape generation and shape combination to 4. conversion into a solid.

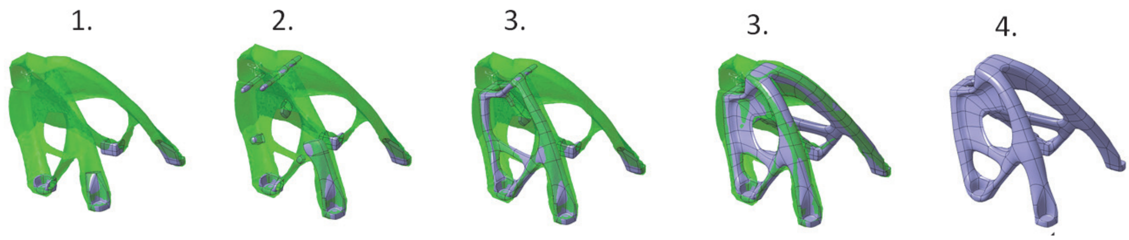

Figure 5: Illustration of topology design optimisation/evolution steps

One of the main challenges in the topology design process is the design interpretation of topology optimised part which is driven by the industrial needs such as low cost, low mass, short manufacturing time, compliance to sizing rules, and consideration of fracture control measures.

This work package shall significantly contribute to the final goal that Additive Layer Manufacturing is implemented as a conventional industrial manufacturing process for secondary structures in launch vehicles.

3. Tools for Equipped and Insulated Tank Demonstrator

The PROCEED activities in the branch Equipped Insulated Tank (EIT) Demonstrator comprises the development of new tools and features (such as →Convection Thermal Mathematical Model), the further development of already existing tools (→Phase Change Boundary Implementation CFD, →FiPS® Thermal Interaction, and → Cryo Fuel TAU-Code), as well as their demonstration and validation (→EIT Tank Validation, →COMPERE CFD Benchmark).

3.1 EIT Tank Validation

Within the EIT Tank Validation a new equipped and insulated tank is developed and manufactured for demonstration and testing with LH2. This includes the complete design and justification process of the tank in accordance with A6 concept requirements and with the German Technical Supervisory Association (TÜV) regulations in order to be able to operate the tank with LH2 within the DLR RY facility (Institute of Space Systems).

Figure 6 shows the final design of the tank demonstrator (left image) which is designed to be mounted on the hexapod at DLR RY facility for testing.

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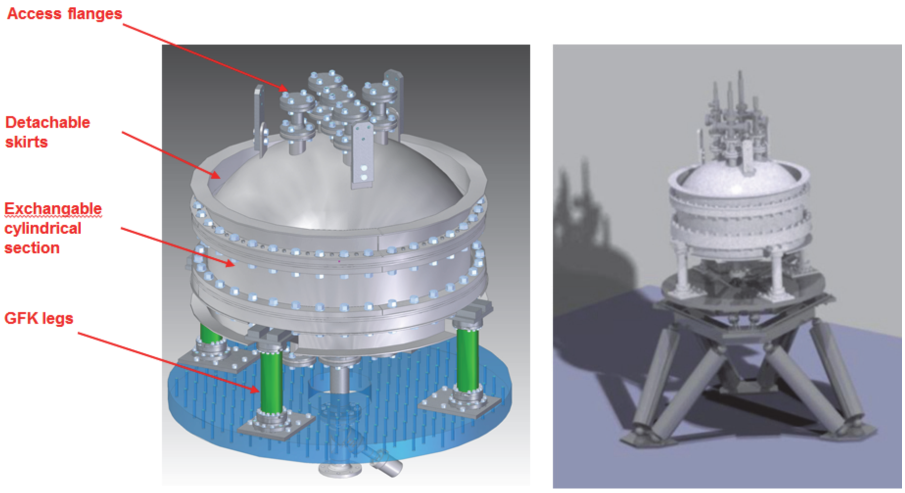

Figure 6: ASL Equipped and Insulated Tank demonstrator design (left), mounted on the hexapod (right)

The work package emphasis lays on the validation of the new tank materials (AlMgSc), new developed external tank insulations, and the analysis of the thermal tank characteristics.

The tank is currently in manufacturing evidencing the expected feasibility and characteristics of the manufacturing process for AlMgSc. For detailed information on the status of maturation of the AlMgSc alloy 5028 please refer to a dedicated publication provided in [4].

Besides the insulation the tank will also be equipped with instrumentations such as thermocouples, temperature diodes, pressure sensors and flow meters allowing to determining the insulation performance and the heat transfer characteristic of the tank or insulation respectively. In addition the tank and its instrumentation will be used for the validation of CFD solvers as well as for determining the characteristics during chill down and drain processes.

Through the validation results it is expected to improve the applied engineering tools and thus to reduce safety factors which again will lead to reduced RC.

3.2 Phase Change Boundary Implementation CFD

Within the former programme PREPARE [1] the CFD solver was validated by the test cases SOURCE-2, Saturn AS203 (see Figure 7) which showed the need for new boundary conditions for phase change computation. Although custom phase change models haven been implemented showing a good validation status, these phase change models are not applicable for A6 due to coarse grids and inherent deficiency in commercial flow solvers due to the volume of fluid model [5]. Thus the present activities comprise the implementation and validation of new boundary conditions for vaporisation and condensation in commercial flow solvers to large tanks.

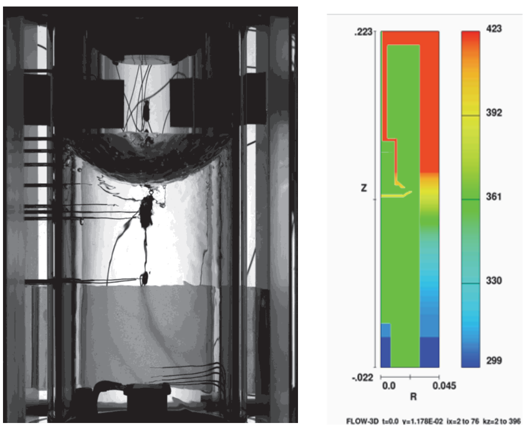

Figure 7: SOURCE-2 experiment (left) and computation example (right)

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With the new boundary conditions for vaporisation and condensation existing cryogenic sloshing data of conducted experiments will be analysed and validated.

It is expected that this activity will enable the improved prediction of internal tank pressure evolution by increased precision and stability of CFD solver. The increased precision and stability capability enables to further reduce margins (leading to mass savings and reduced RC) as well as validation testing efforts in the future (fewer design iteration leading to a reduction of NRC).

3.3 COMPERE CFD Benchmark

This activity aims at the improvement of CFD solvers based on benchmark experiment data on propellant behaviour with increased simulation precision during ballistic and acceleration phases. The benchmark experiments are recalculated and evaluated within a R&T network cooperation called COMPERE consisting of various partners in France and Germany.

Since a dedicated publication termed “Liquid hydrogen low bond number reorientation: Experiment and numeric comparison” is available in present EUCASS proceeding further information and results from this activitiy can be found there [6].

3.4 Convection Thermal Mathematical Model (TMM)

Thermal system analysis of the launcher during its complete lifetime is performed with a Thermal Mathematical Model (TMM) in order to determine the thermal budgets, for systems layout and parametric studies or for the definition of thermal environments for partners. These thermal system analyses can become complex and time consuming and may not predict convection phenomena in cavities accurately without a dedicated CFD analysis.

This work package shall therefore develop a new convective simulation method for very fast heat budget calculations inside the launcher cryogenic upper stage (as shown in Figure 8) based on heat transfer parameters (HTPs).

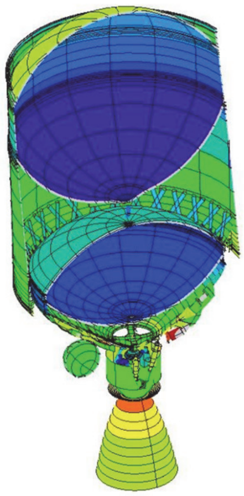

Figure 8: Illustration of Upper Stage cavities

For this new convective simulation method pre-simulation of a typical/reference cavity with CFD is performed and the heat transfer parameter for the new TMM ROM (Reduced Order Model) derived. After comparison and successful validation of the new TMM ROM with CFD simulation data a new & fast simulation tool for launcher cavities is available which shall cover turbulent and laminar flow regimes. Thereby a faster system optimisation / development process can be expected (→reduced NRC) as well as a faster response / treatment in case of for thermal convection anomalies.

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3.5 FiPS® Finale Phase Simulator - Thermal Interaction

The FiPS® tool was enhanced within the former PREPARE Programme [1]. Corresponding achievements and the capabilities of this unique FiPS® tool (overall dynamic simulation → interaction of stage rigid body dynamics & tank fluids dynamics) are described in the publication "FiPS® - Final Phase Simulator Combined Simulation of Dynamic and Thermal Fluid-Structure Interaction" [7].

The PROCCED activities shall improve the existing FiPS®-software in means of thermal interaction within the overall dynamic simulation. This includes the implementation of new features such as sloshing; internal tank pressure changes and the thermal model of entire upper stage.

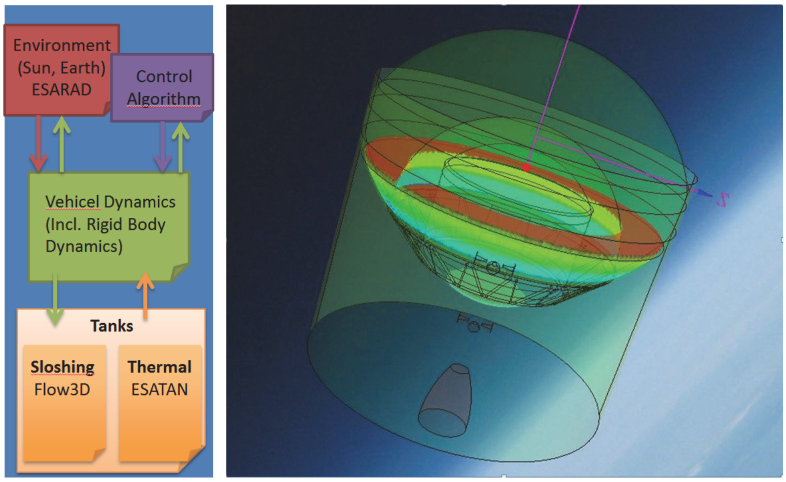

Figure 9: FiPS® process flow chart (left), illustration Upper Stage colour coded results (right)

As seen in the process flow chart (see Figure 9) the propellant characteristics in the tank, thermal and sloshing, need to be linked to the vehicle dynamics which in turn is linked with the control algorithm and the environment (sun & earth impact).

For this a new thermal model compatible with FiPS® incl. radiation Environment (ESARAD) and thermal environment (ESATAN) is developed.

Through the new features and the thermal extension an improved performance of FiPS® is achieved by

- Consideration of environmental influence (radiation)
- Increased simulation precision of entire spacecraft
- New fast and efficient solution for thermal budget calculation
- Controller optimisation

FiPS® can be used for all types of Launcher Upper Stages and also for aircraft tanks or for satellites requesting for high pointing accuracy due to its unique overall dynamic simulation capability (interaction of stage rigid body dynamics & tank fluids dynamics).

3.6 Cryo Fuel TAU-Code

The DLR TAU Code is for about 14 years successfully in use at ASL and Airbus Defence and Space for gas dynamic external and internal flow problems involving the aero(thermo-)dynamic analysis of space vehicles (such as SHEFEX or ARV) for re-entry and landing within hypersonic, transonic, and subsonic flow ranges. An exemplary TAU-Code simulation result of an entry capsule is depicted in Figure 10 for illustration.

An extension of the TAU Code regarding simulation of cryogenic fuel behaviour of launching systems has been successfully performed within the PREPARE programme [8-10]. Nevertheless there are more highly desirable capabilities which were beyond the scope of PREPARE and thus are addressed within the successor programme.

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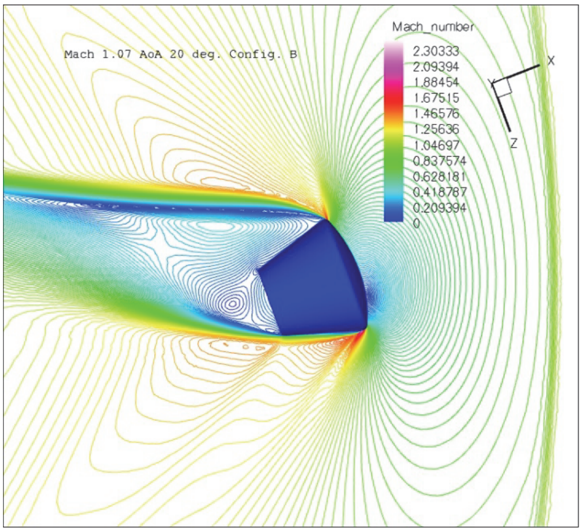

Figure 10: Exemplary TAU Code Simulation Results on an Entry Capsule

Consequently, the Cryo Fuel TAU-Code activity is a further improvement of the TAU Code software for the realistic fluid flow analysis within cryogenic fuel systems with respect to three mayor aspects:

- physics such as analysis of bubble formation and decomposition within bubble swarm,
- efficiency (faster numerics), and
- code handling (improved interfaces).

For this improvement new physical models need to be introduced into the existing TAU code software in close collaboration between DLR and ASL /Airbus DS. After implementation the TAU Code Model is validated by appropriate test case.

The expected benefits of this code development are based on expected mass savings through more accurate CFD analysis and synergies through the use of the same CFD Code-Structure for several fields of application and flow regimes in multi-disciplinary analyses.

4. Smart Avionics

The PROCEED activities in the branch Smart Avionics comprise two work packages, one related to the Launcher Intelligent Sensor Topology (LIST) and the other related to the concept study Avionic Testbed.

4.1 Launcher Intelligent Sensor Topology (LIST)

The current launcher uses a centralised avionic architecture (cf. Figure 11) including conservatism of the same technology and topology used since several decades; for instance centralized acquisition units, analogue sensors, complex distribution, and segregation of functional and telemetry measurements. Moreover analogue data acquisition and data processing is performed which implies an exhausting calibration data handling process and complex & time consuming post flight data processing.

In consequence the work package activities involve the evaluation and validation of a new avionic sensor network topology using smart & hybrid sensors/acquisition units. Some elementary work has already been performed in the predecessor PREPARE programme [11]. Moreover the work package includes an assessment of the impact through LIST on the Assembly, Integration and Test (AIT) processes.

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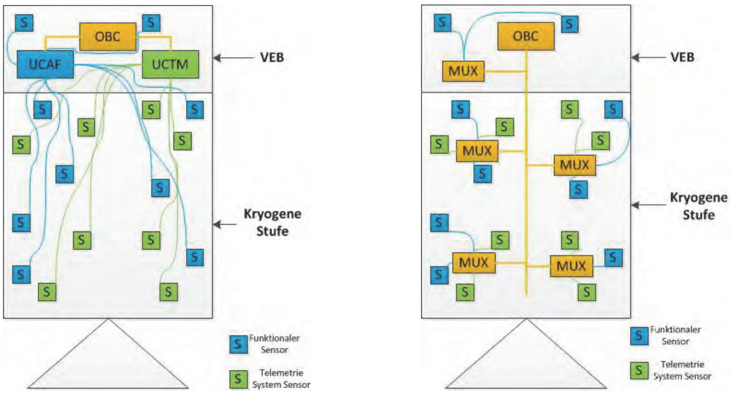

Figure 11: Schematic of a centralised avionic architectures (left) and a decentralised (right)

The results shall reveal the characteristics of an optimised avionics sensor network w.r.t. mass, availability, performance, and measuring concept. In addition the characteristics and benefits of smart sensors, hybrid sensors/acquisition units and wireless sensor communication systems shall be evaluated. Also the capability of COTS-Sensors for the application in launchers shall be evaluated.

By the above measures a significantly decreasing avionic network complexity is expected which reduces harness masses and RC due to a faster and more robust AIT process.

4.2 Avionic Test Bed

Within the Avionic Test Bed work package the concept and requirements for a future Avionic Test Bed shall be defined. This includes the conceptual definition and design of the infrastructure capable to test different avionic technology demonstrators in representative environment. The test bed shall further enable fast testing and maturation of new avionic devices.

5. Conclusion

It is of major significance to think today about the launcher technologies or tools of the future in order to remain competitive and successful in the long term. Thus the right anticipation of enabling technologies/tools is the first challenge to be mastered. Subsequently these technologies/tools need to be matured thoroughly within dedicated maturation programmes.

Thereby the proof of technology/tool gains and maturity before the launcher programme's technology selection in terms of functionality, performance, reliability, and expected cost savings must be clearly and transparently evidenced. Furthermore, the confidence in a specific technology or tool needs to be created at the stakeholder preferably through demonstrators and corresponding testing.

All the above considerations shall and will be accounted in the national "Programme to Enhance Cryogenic Upper Stage Technologies to Extend European and German Competences in Future Launcher Developments" - PROCEED through:

- the maturation and evaluation of 12 promising technologies and tools to enhance upper stage performance including demonstrators and validation tests,
- the evaluation of the economic benefit (business cases) of the investigated technologies and tools,
- the clear communication to stakeholder and partners of the technologies/tools and their benefits
- the establishment and consolidation of a network between space industry and scientific community

Based on the ambition of PROCEED to develop and extend upper stage competences for New Generation Launchers the presented technologies and tools are expected to significantly contribute to a cost efficient development, production, and operation of Upper Stages. However, the ultimate success of a new technology is accomplished when it becomes flight hardware and then contributes to the success and competiveness of the entire launcher.

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Abbreviations

A5	ARIANE 5
A6	ARIANE 6
ALM	Additive Layer Manufacturing
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
COMPERE	Comportement des Ergols dans les Reservoirs (Behaviour of Propellants in Tanks)
COTS	Commercial of the Shelf
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Space Agency)
DLR RY	DLR Institute of Space Systems
EIT	Equipped and Insulated Tank
ESC-A	Etage Superieur Cryotechnique Version A (Cryogenic Upper Stage Version A)
FiPS®	Final Phase Simulator
GNC	Guidance, Navigation & Control
HTPs	Heat Transfer Parameters
I/F	Interface
LH2	Liquid hydrogen
LIST	Launcher Intelligent Sensor Topology
LOX	Liquid oxygen
MASER 12	Material Science Experiment Rocket 12
NGL	Next Generation Launcher
NRC	Non-Recurring Costs
OBC	On-board Computer
PMD	Propellant Management Device
PREPARE	Programme to Enhance Upper Stage Performance and Reliability for Future Expandable Launchers
PROCEED	Programme to Enhance Crygenic Upper Stage Technologies to Extend European and German Competences in Future Launcher Developments
RC	Recurring Costs
ROM	Reduced Order Model
SOURCE-2	Sounding Rocket COMPERE Experiment-2
TEDS	Transducer Electronic Data Sheets
TMM	Thermal Mathematical Model
TRL	Technology Readiness Level

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