System engineering presentation of the European staged combustion demonstrator SCORE-D

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ABSTRACT

The intent of this publication is to provide an overview of the system engineering of the European staged combustion demonstrator SCORE-D. The SCORE-D is a staged combustion cycle engine demonstrator of 140 tons nominal vacuum thrust . It is a cryogenic hydrogen-oxygen engine as a baseline, compatible with existing European test
stands. SCORE-D is designed and will be tested in the frame of the ESA Future Launchers Preparatory Programme (FLPP).
The engine preliminary concept was defined at an Architecture Key Point held in April 2010. Its basic features are a serial staged combustion cycle architecture, a single pre-burner, turbines in parallel, a control strategy based on the use of the pre-burner oxygen valve and a hot gas valve downstream of the pre-burner for throttling and mixture ratio trimming.
This publication is focused on the presentation of the engineering activities which took place at system level up to the System Requirement Review held at the beginning of 2011 before the start of the engine preliminary design phase. It also presents the concept choices and preliminary design of the major sub-systems.

SCORE-D is designed as a demonstrator which has the primary goal of mastering a staged combustion engine system. In addition to testing a staged combustion demonstrator, a strong focus is placed on improving the maturity level of technologies which will become increasingly important for space propulsion such as health monitoring and the all-electric engine control. Throughout the design and testing of SCORE-D, introducing new technologies and monitoring the progress of their maturity is a prime objective of the demonstration.
The SCORE-D program is an essential element in the preparation of the development of a high thrust first stage engine for a New Generation Launcher and it provides potential technology spin-offs for the evolutions of existing launcher first stage propulsion or liquid booster application.

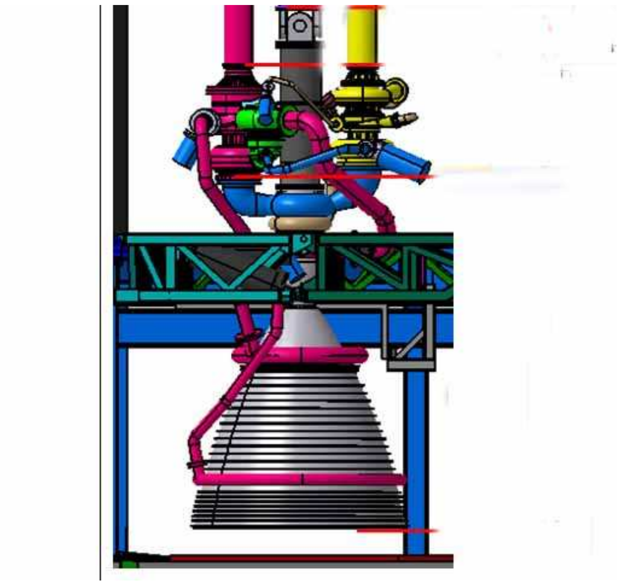

Figure 1 : Representation of the SCORE-D demonstrator at the test bench.

Introduction

In parallel with the development of an improved Ariane 5 version with the Vinci expander engine associated to a new cryogenic upper stage, the preparation of a future new generation launcher was initiated with the technological demonstration of a high thrust staged combustion engine designated as SCORE-D. This program capitalizes on the results of research and technology programs and previous demonstration programs such as the VULCAIN X (TPX,GGPX,NEX nozzle and valves) funded by CNES in France, SNSB the Swedish space agency and Belgium. Since 2005 activities involving Snecma and its partners Astrium GmbH and Avio Spa are also going on under the ESA Future Launchers Preparatory Program (FLPP) focusing on the preparation of the 2020-2025 generation of high thrust engines.

The Future Launcher Preparatory Program (FLPP) with its dedicated Main Stage Propulsion program started in 2005. It was focused on the preparation of the enabling tools and technologies, along with the system and sub-system architectural choices, that will be used to design and develop the main stage propulsion system of a new generation launcher which is foreseen to enter into service in the years. 2020-25.

The SCORE-D demonstration is in line with the FLPP general approach of integrated demonstrators prior to developments. Its purpose is to integrate technologies into a mid-scale Staged Combustion Engine demonstrator and raise their maturity level in view of their use in a future development.

The ESA FLPP program aims at achieving a demonstration at engine level in the decade 2010-2020 which would open the path for the development of an operational engine with a thrust around 200 tons and over. The system studies performed in partnership with ASTRIUM GmbH and AVIO in the frame of FLPP 2.1.1 have confirmed the “mid-scale approach” as the best compromise between cost and risk reduction for the demonstration. The “mid-scale approach” consists in using the available test benches at their limits which leads to a 140 tons thrust engine.

When initiated in 2009 - 2010, the guidelines of the SCORE-D demonstration were:

- Maximum integration of the enabling technologies considered as necessary for the future target engine, technologies previously prepared in the FLPP and in national programs,
- Best compromise between size and cost which means to be as much as possible representative of the challenges of a full scale (200 tons thrust and over) staged combustion engine in a limited cost environment,
- Minimization of bench tests adaptation,
- Simplification of manufacturing, inspection and assembly operations,
- Modularity of the design for rapid and flexible adaptation to various test configurations and testing rate optimization.

A Preliminary Requirement Review was held in December 2009 establishing the above guidelines and the System Requirement Review was held in March 2011 confirming the corresponding design choices.

<u>The SCORE-D specification</u>

At a Scale Key Point held in April 2009, the thrust level was set at the equivalent of a 140T vacuum thrust . SCORE-D is a ‘mid’ scale ground demonstrator, which means its thrust scale is maximized while staying compatible with the limitations of the current European test benches (P5, PF50, PF52, P3.2) in term of mass flow. The thrust of the future flight application is assumed to be in the class of a 200 tons vacuum thrust.

The SCORE-D architecture was chosen at an Architecture Key Point in June 2010 and its specification approved after a System Requirement Review held in march 2011.

The flight mission of the future target engine is assumed to be similar to Vulcain 2 with respect to number of cycles and duration of operation.

The design of SCORE-D is based on the following requirements and criteria:

- To prepare a high performance first stage engine and, in order to fulfil this goal, to be capable of a chamber pressure higher or equal to 150 bar at the nominal demonstration point
- To be representative of a future engine for which reliability, robustness and low recurring cost will be essential requirements
- To allow throttling and mixture ratio variation over a large range
- To incorporate all the technologies considered as critical for a future first stage engine

Engine architecture and system engineering

The SCORE-D is a LOX/LH2 staged combustion cycle engine demonstrator, which delivers a thrust of approx. 140 tons in vacuum.

Its reference thermodynamic cycle (see figure 1) is based on a serial scheme with a single fuel-rich pre-burner. In the serial cycle, the full hydrogen flow discharged by the fuel pump is used for cooling the combustion chamber through regenerative cooling channels before feeding the pre-burner where its combustion with a small fraction of the oxygen flow produces fuel-rich hot gases for the turbines.

The turbines are fed in parallel. The two hot gas streams which are expanded through the turbines are routed to the main injector, mixed together and subsequently burnt in the main combustion chamber with the remaining oxygen flow.

The oxygen pump is composed of a main pump for the feeding of the main combustion chamber and of a split pump (or pre-burner pump) fed in series for the feeding of the pre-burner. A significant part of the oxygen is tapped-off at the outlet of the split pump and routed to the combustion chamber inlet creating a by-pass of the split pump in order to increase its mass flow and obtain a split pump specific speed which ensure its feasibility .

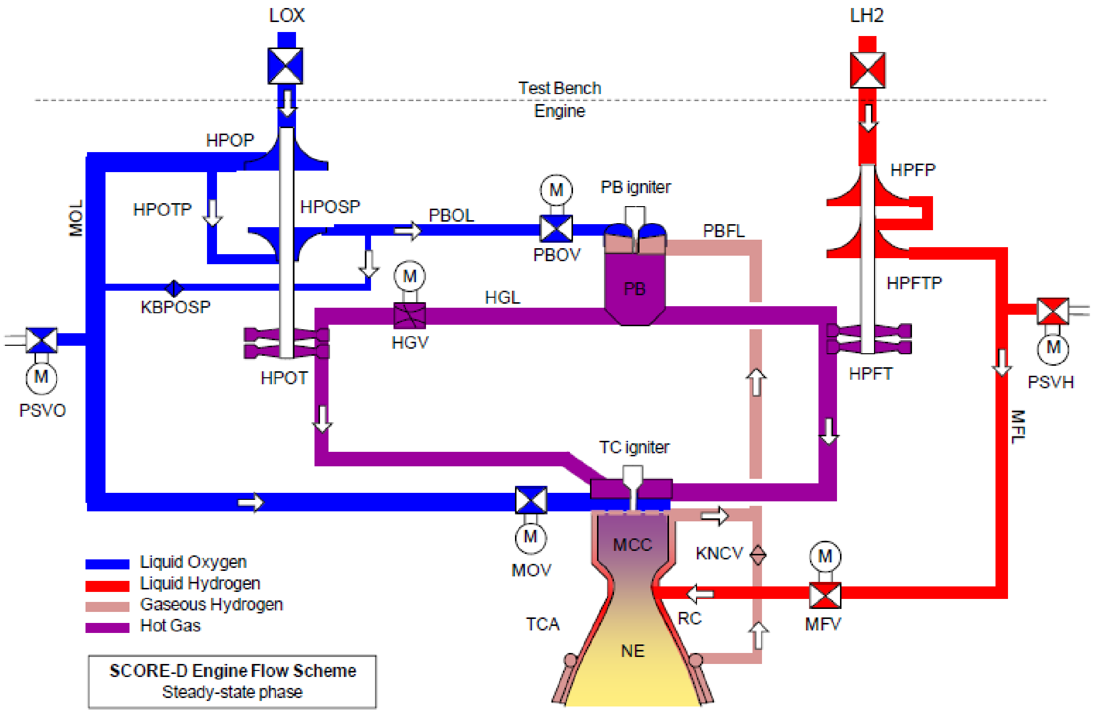

Figure 2 : SCORE-D flow schematic

The following main valves are located upstream of both combustion devices, pre-burner and main combustion chamber, and provide a shut-off function:

- The MFV (Main Fuel Valve**)** opens the hydrogen flow towards the thrust chamber regenerative circuit and then to the pre-burner, isolating both of them during chill-down. The MFV is located at the hydrogen pump outlet just upstream of the regenerative circuit.
- The MOV (Main Oxidizer Valve) opens the oxygen flow towards the main combustion chamber and isolate it during chill-down. The MOV is located just upstream of the chamber oxygen injection. This position close to the chamber ensures chill-down of the complete oxygen piping before engine start-up.
- The PBOV (Pre-Burner Oxidizer Valve) opens the oxygen flow towards the pre-burner and isolate it during chill-down. The PBOV is located just upstream of the pre-burner oxygen injection, also close to the pre-burner inlet to ensure chill-down of oxygen pipes before engine start-up.

The steady-state control function is based on the use of two regulation valves which control the thrust and the mixture ratio. These two valves, the Pre-Burner Oxidizer Valve (PBOV) and the Hot Gas Valve (HGV), ensure throttling and mixture ratio trimming.

- in addition to its shut-off function, the PBOV enables to control the pre-burner feeding in liquid oxygen through a variable pressure drop.
- the HGV is located on the hot gas circuit downstream of the pre-burner and just upstream of the oxygen turbine. The HGV enables to control the distribution of the hot gas flow rate between the two turbines by adjusting the pressure drop of the hot gas flow. No upstream-downstream sealing function is required for this valve.

All the valves can be actuated in a variable position during start-up and transient phases with the sole exception of the HGV.

Finally, two discharge (or power shedding) valves are considered in the cycle: the PSVH on the Hydrogen side and the PSVO on the Oxygen side enable to discharge a part of the propellant flow rate to adapt pump operation in transients, primarily the emergency shut-down transient.

The following command strategy is assumed on the SCORE-D:

- For transients, the open loop mode is the reference
- For Steady-state operation, the reference is the closed loop regulation based on the chamber pressure and engine mixture ratio parameters (using PBOV and HGV).

All these valves are assumed to be electrically-actuated. The valves electric actuation is part of a global demonstration objective towards an all-electric engine control.

Two major functional models of the engine are used in order to perform the numerical simulations which are necessary to establish the engine technical specification and the sub-system requirement specifications:

- the engine functional steady state model
- the engine functional transient model

The quality of the simulation, i.e. the physical representativeness and degree of accuracy, is essential to provide a good understanding of engine behaviour and master the staged combustion system which is the core of the demonstration. This includes the capability to represent high bandwidth phenomena such as rapid mixture ratio variation or pressure oscillations when closing valves. Additionally, reliable simulations decrease the risk of modifying specifications of sub-systems and especially valve specifications as the design evolves and enter into more detailed phases.

The functional steady state model is used to derive the demonstration operating envelop and issue sub-system performance requirements. The transient model is an essential tool to establish valve and control device requirements.

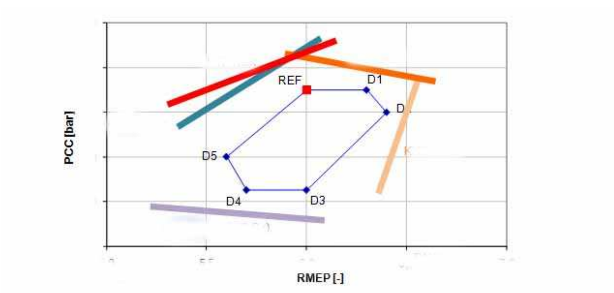

Figure 3 : **Construction of an operation domain: PPC (chamber pressure vs RMEP mixture ratio at pump inlet)**. The operating domain is extended toward low thrust and high mixture ratio in order to anticipate the future need of a first stage engine. The domain takes into account limitations of sub-systems (as lines theoretically placed around the domain) or contributes to specify their position as part of an interactive process beween engine system and sub-system designer.

Engine transients

The engine starts using the expander effect when hydrogen starts to flow in the regenerative circuit at the MFV opening with no additional energy source being required.

Subsequently, the oxidizer valves (PBOV and MOV) are opened to let oxygen being injected in the pre-burner and combustion chamber which are then ignited.

To initiate the shut-down sequence, the oxygen valves are closed first to ensure a fuel rich environment in the combustion chamber and pre-burner. PBOV is closed first, leading to the extinction of the preburner which causes a sharp decrease of engine regime. MOV is then shut off.

MFV is closed at the latest, removing energy source from the hydrogen expansion.

The ignition systems can be a catalytic igniter which is considered as the reference for the combustion chamber or a spark torch igniter.

Engine lay-out and mechanical architecture

The engine mechanical lay-out is defined taking into account the following objectives and constraints:
- A concern for robustness including the verification of proper dynamic behaviour
- A concern for test cadence by providing easy access to instrumentation and components

The reference mechanical lay-out can be described as a power pack supported by main lines with the pump inlets upward. The short turbine exhaust lines have also a power pack supporting function. The pre-burner is located close to the fuel turbopump in order to optimize functional performance. The engine lay-out is such that high temperature and high pressure gas are short, free to expand, therefore do not induce thermal expansion loads at sub-system interfaces.

A detailed mechanical model of the complete engine is already in use to simulate the engine dynamic behaviour and provide loads at subsystem interfaces. The model is used to optimize the lay-out and shape of the major lines in order to avoid constraining loads at interfaces. The SCORE-D architecture is hyper-static and the lines are rigid lines without any gimbal joint.
The model is used to perform a dynamic analysis of the engine and compare the major frequencies of the engine (frequencies of the pendulum mode, chamber bending mode, turbo-pumps on their supports, nozzle ovalization) to their equivalent ones for VULCAIN. The use of supports incorporating a damping function is studied as part of the technological activities conducted with the SCORE-D program.

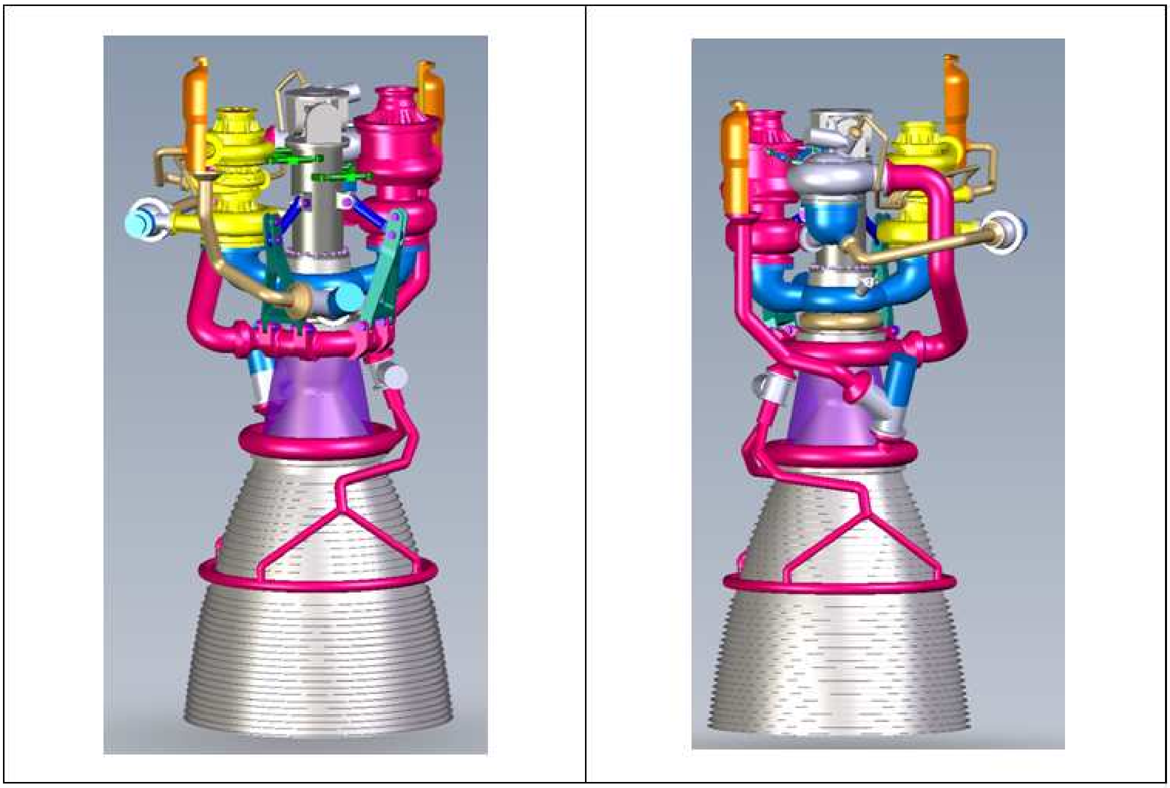

Figure 4 : SCORE-D mechanical arrangement

<u>The VULCAIN X Demonstration as source of background knowledge</u>

SCORE-D relies on the results of the VULCAIN X demonstration program. In 2009 and 2010, technologies which had previously been prepared in the frame of past Research and Technology activities were demonstrated at the Vulcain scale on a hydrogen turbopump together with a gas generator, gas generator injection valves and an electric hot gas valve. The knowledge acquired through the VULCAIN size demonstration is an essential source of background experience in preparing the SCORE-D demonstration.

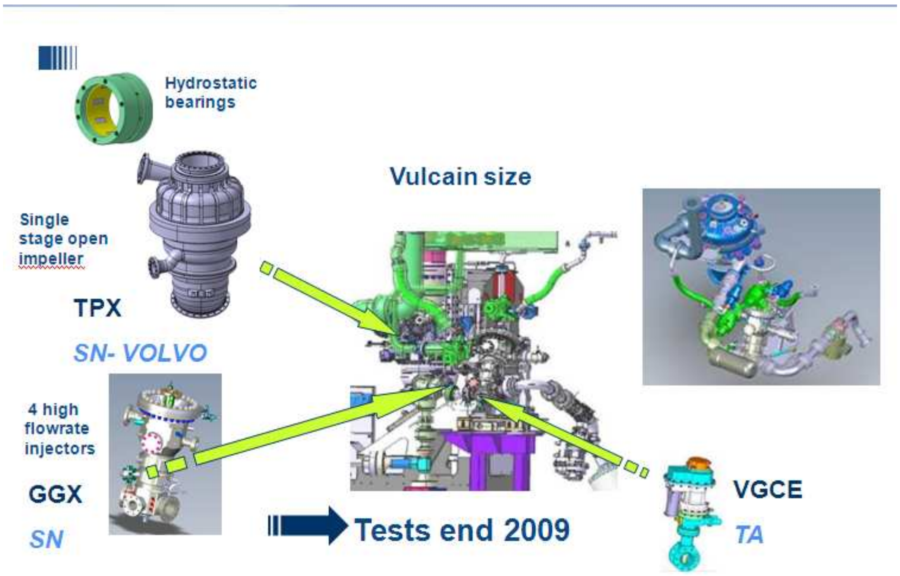

Figure 5 : The main elements of the VULCAIN X program

The SCORE-D combustion chamber and pre-burner

The architecture of the SCORE-D combustion chamber is composed of the following elements:

- An injection head with the inlet of the hot gazes coming from the turbines and their mixing in the upper part. The liquid oxygen manifold is located below the hot gaz inlet. A face plate cooling which is not foreseen as a reference could be introduced in the form of a hydrogen cooling flow.
- An ignition system for which the reference is a Catalytic Ignition Device (CID) igniter
- A chamber body with a counter-flow regenerative cooling

The optimization of the regenerative circuit with respect to pressure drop, which may deteriorate the overall system performance if too high, and wall temperature which has a direct consequence on life is an essential element of the chamber design with major consequence at system level.

The nozzle extension has a co-flow regenerative cooling circuit.

Key parameters of the Thrust Chamber Assembly are:

- A sea level thrust equal to 1144 KN (which translates into a 140 tons vacuum thrust)
- A vacuum Isp equal to 445 sec

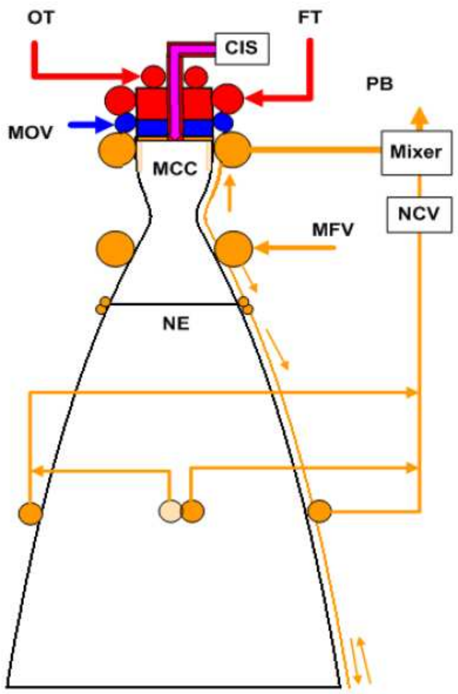

Figure 6 : Conceptual view of the combustion chamber lay-out

The pre-burner and combustion chamber benefited from a previous demonstration activity designated as the Subscale staged-combustion pathfinder. In the frame of the ESA FLPP program, the demonstration of a subscale Preburner / Main Combustion Chamber coupled system was prepared through a partnership between SNECMA and ASTRIUM GmbH. This system was successfully tested on the P8 bench at DLR (Lampoldshausen, Germany). Two distinct test campaigns were performed: one for each propellant couple (H_2/O_2 and CH_4/O_2)

The SCORE-D nozzle extension takes advantage of the Sandwich Nozzle Extension technology developed by VOLVO Aero Corporation. A full-length dump cooled sandwich nozzle was already tested on the VULCAIN 2 engine. The nozzle is composed of an inner shell with milled channels and an outer shell, the two shells being assembled by laser welding. An external stiffening structure is added by Metal Deposition. The reduction of the number of parts and welds contributes to increase robustness and reliability.

Figure 7 : Sandwich Nozzle Extension with VOLVO Aero Corporation Courtesy

The preburner essentially comprises three functional elements: an igniter, an injection head which includes the injector and a combustion chamber body. Its architecture is characterized by an un-cooled body

The SCORE-D fuel Turbopump

The SCORE-D turbo-pump is a two stage turbo-pump with un-shrouded impellers. Un-shrouded impellers provide a higher head rise per stage since they can reach higher tip speed than shrouded impellers. The shaft lateral support is ensured by two fluid bearings. An active axial balancing system is located at the back of the second impeller. At low speed the shaft support is ensured by an axial thrust ball bearing.

The turbine is a Two-stage turbine with shrouded blades. The design of the Interface between pump and turbine results from a compromise between load carrying capability, stiffness, thermal gradient management and leak tightness.

Tie-bolts, splines between impellers, between impeller and shaft, Hirth coupling between disks ensure the torque transmission.

At the reference point, the fuel turbopump characteristics are:

- outlet pressure = 386 bar,
- hydrogen flow= 45 Kg/s ,
- rotating speed = 37500 rpm,

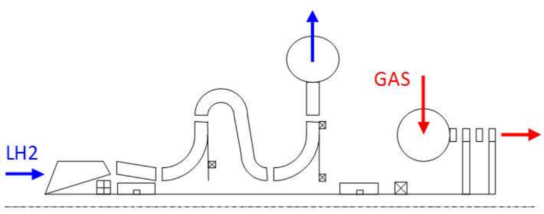

Figure 5 : Fuel turbopump conceptual design

The SCORE-D fuel turbo-pump capitalizes on the technologies acquired through the TPX demonstration. The TPX most innovative technologies are the hydrostatic bearings replacing ball bearings and an open pump impeller. TPX it-self benefited from the exploration of these technologies at a smaller scale on the TP-tech demonstrator starting in 2003. TP-tech was a small 500 kW unit with an operating speed of 110000t/mn. The TPtech program were jointly funded by CNES and Snecma. TPX was designed to have the same performance within the same interfaces as a VULCAIN 2 hydrogen turbopump. Its main objectives were cost reduction and increase in robustness. This was reached mainly through the reduction in the number of parts.

The hydrostatic bearings providing better shaft supports allow higher speeds and authorize an in board configuration for the turbine bearing compared to an outboard configuration on the Vulcain TPH. The higher open impeller performance and the research and technology activities conducted on cavitation simplify the rotating parts. From a double inducer and a two stages centrifugal impeller on Vulcain current turbo-pump, the configuration is reduced to a single inducer and a single impeller on TPX. The turbine on TPX is designed and provided by Volvo in Sweden.

The SCORE-D oxidiser turbopump

The reference HPOTP overall architecture is characterized by:

- A main pump (HPOP) that increases the pressure of the entire oxygen flow rate up to the chamber injection inlet pressure.
- A split pump (HPOSP) fed in series with the main pump that raises the pressure of a small part of the oxidizer flow up to the pre-burner inlet pressure. The single, low specific speed, shrouded impeller is placed back-to-back with the main pump. A bypass pipe is also implemented in order to increase the mass flow rate within the pump.

The main pump (HPOP) composed by the following components:

- A suction axial stage: inducer and deswirler
- A single centrifugal stage with a shrouded impeller and radial diffuser
- A volute with a tangential outlet

The pre-burner pump or split pump (HPOSP), which is a single centrifugal stage consisting in:

- A radial inlet
- A shrouded impeller followed by a radial diffuser
- A symmetric volute with tangential outlet

The HPOTP turbine is a two-stage turbine characterized by:

- a two stage subsonic, overhung rotor design
- a tangential inlet pipe connecting to an inlet manifold
- an outlet guide vane to minimize the pressure loss in the outlet duct

The shaft supported by two (front and rear) LOX cooled ball bearings.
An Axial Balancing System (ABS) is supporting the pump/turbine axial forces.

A Dynamic Seal Package (DSP) located between the turbine and the turbine bearing is designed with the objective of operation without or with extremely low helium consumption.

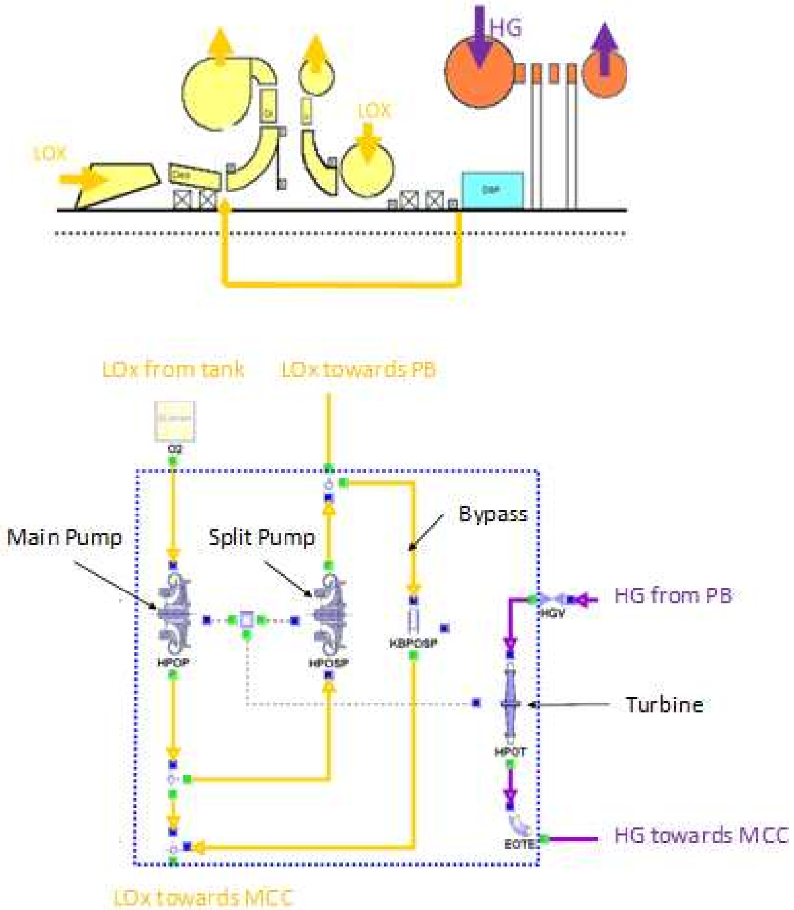

Figure 6 : Functional schematic of the HPOTP

The SCORE-D valves

The design of the SCORE-D valves is the result of a cooperation between Snecma and TechSpace Aero (Belgium).

The Pre-Burner Oxidizer Valve (PBOV) is implemented upstream the Pre-Burner on the LOX inlet flange. Its function is to regulate the LOX flow rate and it has also a shut-off function. The challenge is to obtain low actuation torque and high accuracy while ensuring the leak-tightness for the shut-off function with a high pressure dynamic seal.
Two concepts are considered:

- Valve with a cantilever supported restrictor with an architecture similar to the Vinci turbine by-pass valve.
- A “turret valve” with a hollow half ball guided by a bearing on the equator of the half ball

Component tests of the high pressure dynamic seal were already performed.
The PBOV benefits from the demonstration of a High bandwidth electrical actuation system for regulation valves designated as VRR which was test as part of the TPX-GGPX demonstration program.
The High bandwidth regulation system allows electrically actuated valves to perform steady state regulation functions, safety management functions and transient monitoring function with less actuation time scattering. Therefore it is an essential element in the trend towards ‘more electric engines’.

The Hot Gas Valve (HGV) is implemented between the pre-burner and the HPOT. Its function is to regulate the engine Mixture Ratio by modulating the head loss of the hot gases which flow into the HPOTP turbine.
The HGV is designed with the goal of minimising the actuation torque. For this reason a rotary concept is chosen as a reference with as a geometry of the flow calibrating element designated as a diapason valve.
The design of the dynamic seal which has to sustain high pressure differential and high temperature is one of the major challenge of the HGV. The dynamic seal relies on a controlled leakage technology.
The HGV benefits from the demonstration of an electrically actuated hot gas valve which was tested with the gas generator GGPX and the turbopump TPX.
Techspace Aero (Belgium) has developped an electrical brush DC actuator for the hot gas valve. This actuator is based on a high ratio gearbox concept and its technology is similar to the VINCI engine by-pass valve actuator.

The MOV and MFV control the propellant flow entering the main combustion chamber (MCC). Their main function is a shut-off function and they must be able, in fully open position, to support the full propellant flow with a minimum head loss. Two possible design architectures are considered: one linear version and one rotary version.

<u>The Health Monitoring System</u>

The Health Monitoring System (HMS) is a major element of the SCORE-D demonstration. When operational, the HMS will be a significant contributor to test safety, to speed up the test analysis process and to increase the rate of testing. Under the technical coordination of SNECMA , eight different companies were involved in the development of detection algorithms at engine and sub-system level.

A software has already been implemented and successfully tested in a real-time environment into an ESA FLPP platform (DIADEM) developed by Vibrometer. This FLPP DIADEM platform is developed in the continuity of an original platform funded by CNES in the frame of a French national program. It was tested during the GGX campaign.

<u>Major demonstration milestones</u>

The SCORE-D demonstration plan consist of system, sub-system and test bench activities organized in successive phases and combined with the objective of performing a first test at mid 2018.

The system conceptual design phase was concluded by a System Requirement Review in march 2011. The sub-system feasibility review will take place over 2011 and the beginning of 2012. The subsystem preliminary and detailed design will extend from 2012 to 2014 up to manufacturing readiness reviews in the second semester of 2014. The sub-system manufacturing followed by the engine integration will proceed after the manufacturing readiness reviews. In parallel, at the beginning of 2014, a readiness review dedicated to test bench modifications will authorize their implementation. Before testing the engine demonstrator, preliminary tests will be conducted on the major subsystems.

The preparation of required adaptations of the major test benches was initiated: the P4.1 test stand at DLR in Lampoldshausen, Germany for engine system tests and the P3.2 for sub-system testing.

The SCORE-D demonstration plan also incorporates a rationale for component tests and technological tests. Typical component tests are subscale injection tests for the chamber or tests of the dynamic seals of valves. Technological tests are dedicated to enhance the maturity level of new technologies such as thick welds of high pressure components, high pressure static seal, material characterization for hydrogen embrittlement in a high pressure environment.

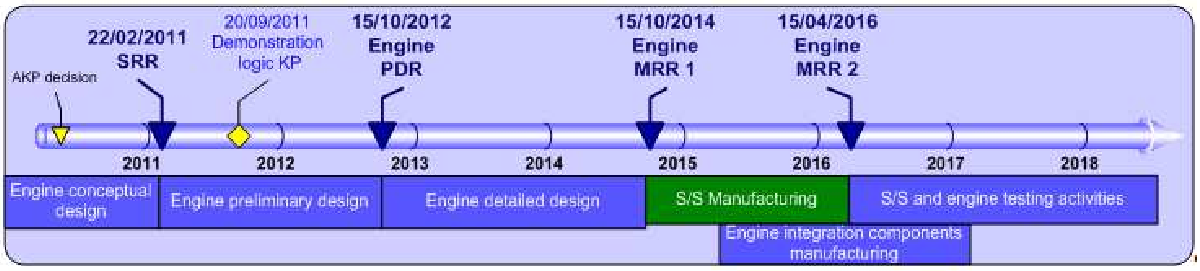

Figure 7 : SCORE-D demonstration milestones

Conclusion

The SCORE-D is a staged combustion cycle Engine demonstrator of 140 tons nominal vacuum thrust which is an essential element in the preparation of the propulsion of a New Generation Launcher.

The major achievements of the SCORE-D program over the 2010-2011 period were the following:

- The completion of the system requirement Review with an agreement on the engine specification and the objectives of the demonstration
- Steady state and transient analysis at system level which provide a solid basis for establishing the sub-system requirement specifications
- The definition of the major sub-system architecture and the initiation of the sub-system design trade-off capitalizing on the results of previous Research and development activities performed at national level.

In the conceptual phase the system engineering has benefited from advanced steady-state and transient analytical simulations which led to:

- An early and more accurate representation of the physical behaviour of the demonstrator
- Sub-system specifications which can be established with a higher degree of confidence

Some activities such as the transient analysis or the design trade-off of the engine control valves which were completed and presented at the time of the System Requirement review held at the end of the first quarter of 2011 go beyond what would normally be expected in a conceptual phase and constitute an introduction to the preliminary design phase which will extend over 2011 and 2012. Over this period, the architecture and design trade-off of all sub-systems will be finalised.

Acknowledgments

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