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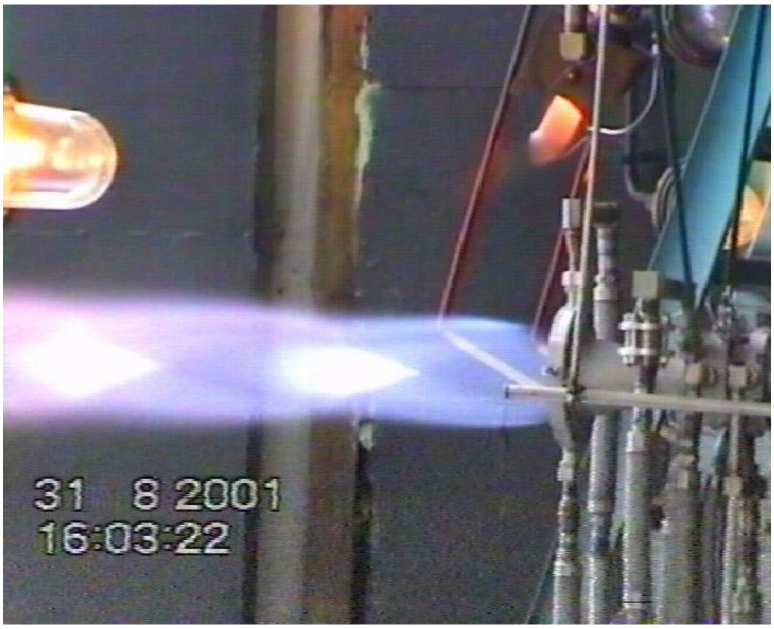

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Recent Developments For Future Launch Vehicle LOX/HC Rocket Engines

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ABSTRACT

Recent investigations into the use of non-toxic propellants for propulsion of reusable first stages for medium launchers or booster stages for TSTO launch vehicles show the potential to satisfy the market's performance and cost requirements. The main expected advantages are high propellant density, reduced handling effort, and reduced safety precautions.

System studies to identify the best non-toxic hydrocarbon propellants have been performed. The chamber cooling performance was assessed regarding limitations by propellant dissociation and coking. Advantageous propulsion system configurations were investigated.

Engines from Astrium and from CADB have been tested already with hydrocarbon fuels. Currently, several injection elements are tested in a subscale chamber with LOX-methane and LOX-kerosene in a cooperation of Astrium, DLR, CADB, and Rosaviakosmos.

ENGINE AND THRUST CHAMBER CONCEPT STUDIES

This study builds on the discussion in a previous paper [1, 2, 3]. Non-toxic propellants are of interest as substitutes for current storables like NTO, MMH or UDMH which are highly toxic and chemically aggressive. Another application would be to replace solid propellants for boosters because of their low specific impulse and pollutive combustion products.

Requirements for non-toxic propellants were formulated, among these: Performance characteristics and density equal to or higher than storable propellants, storability at ambient conditions with at most moderate cooling effort, easy and cheap handling, and material compatibility. Screening a variety of candidates identified hydrocarbon (HC) fuels as suitable non-toxic propellants.

Engine system studies were carried out in order to generate reference engine parameters for the three propellant combinations chosen, LOX-methane, LOX-propane and LOX-kerosene. Thrust chamber design and performance evaluations, in particular with respect to the cooling design, were performed.

Performance of Non-Toxic Propellants

An ODE-analysis of the theoretical specific impulse of several LOX-HC and H_2O_2-HC combinations revealed methane (CH_4), propane (C_3H_8) and kerosene as best performing. The results are plotted in Figure 1.

Methane and propane require a moderate cryo-cooling effort for liquid ground storage. Kerosene can be stored and handled at ambient conditions. It is the densest of all three fuels and can enable compact launcher design. HC fuels will potentially reduce the propellant costs [4].

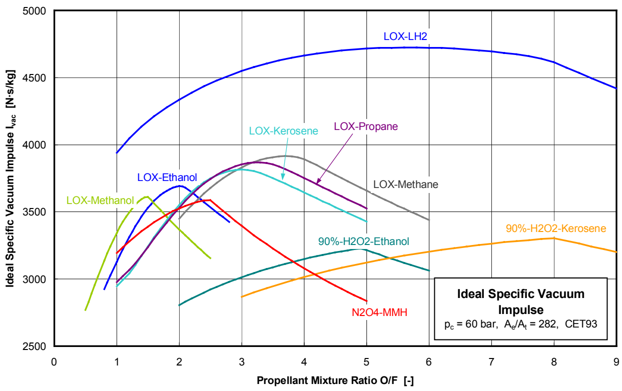

Figure 1: Theoretical mass-specific vacuum impulse of various non-toxic propellants

Main Chamber Size Consideration

Possible future applications like liquid boosters require a total thrust of 4000 kN and more [9]. The chosen engine design parameters of 2000 kN thrust at a chamber pressure of 150 bar reflect a typical future booster stage engine. Figure 2 shows the thrust chamber throat diameter for a LOX-HC liquid booster. The thrust chamber size for the chosen design parameters seems to be similar to Vulcain 2. Thus, the thrust chamber manufacturing facilities available in Europe pose no constraint on the envisaged size of the chamber while a 4000 kN-chamber would result in a 40% larger chamber dimensions.

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Manufacturing installations as well as test benches in Europe are designed for today's thrust levels of up to approximately 2500 kN. A larger chamber and engine size would require costly modifications.

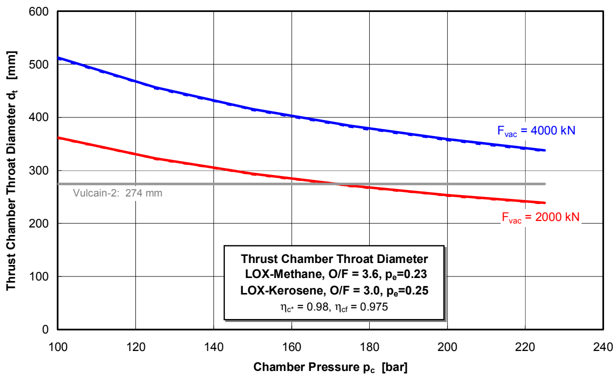

Figure 2: Main combustion chamber throat diameter as a function of chamber pressure and thrust

Main Chamber Cooling

The regenerative cooling capability of the main chamber is limited by the available fuel flow rate and by the coking temperature limit. Above a fluid-specific temperature threshold, which may occur inside the cooling channels of a regeneratively cooled combustion chamber or nozzle extension, hydrocarbons tend to decompose leading to the formation of a carbon layer at the cooling channel wall (coking). This layer has an insulating effect reducing the heat transfer from the cooled chamber wall into the coolant.

In existing LOX-kerosene engines soot deposition from imperfect combustion is observed on the hot-gas side of the thrust chamber. The formation characteristics and the insulating effect of a soot layer are important for the design of thrust chambers. Experience shows that LOX-ethanol does not produce significant soot, while LOX-propane and LOX-kerosene exhibited a heat flux reduction due to soot on the chamber wall [5, 4].

Laboratory experiments performed with liquid methane and propane flowing through copper tubes showed that even trace amounts of sulfur-containing impurities result in corrosion of copper-alloys used nowadays for chamber liners [7]. Electro-deposited gold and platinum coatings greatly reduced the corrosion. However, reliable application of such coatings will increase costs for manufacturing and quality assurance. Other authors reported that no coking was detected in methane-cooled stainless-steel and copper tubes [8].

The extent of coking and sooting depends on the operational conditions like chamber pressure, mixture ratio, coolant pressure and temperature. The upper wall temperature limit is given by the material properties and the required lifetime. For the study the hot-gas wall temperature was limited to 800 K. The possible effect of soot and coking could not be considered for lack of reliable data.

The coolant-side wall temperature is limited to the coking limit of the coolant. Cooling analyses for large thrust chambers were performed for methane, propane and kerosene. Figure 3 shows the coolant and the wall temperature for a predicted chamber cooling with kerosene. A ZrO_2 thermal barrier coating has been assumed for this prediction to achieve coolant-side wall temperatures below the coking limit for kerosene.

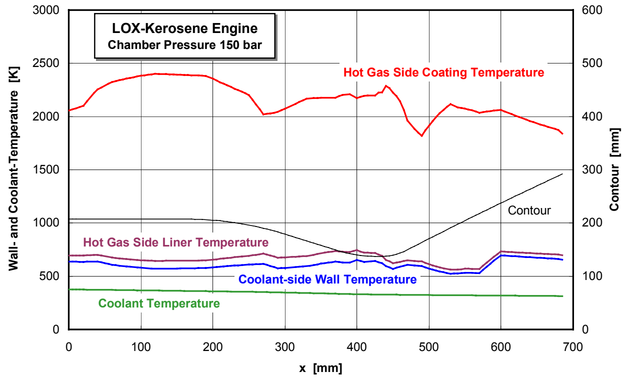

Figure 3: Coolant analysis for LOX-kerosene

The predicted coolant bulk temperature and the margin to the coking temperature limit are compared in Figure 4 for the three propellants pairs with the usual chamber liner material temperature limit.

For the Astrium thrust chamber design with a copper liner, methane as coolant creates the lowest pressure loss and the largest margin towards the coking temperature limit. Propane can be employed, too, without a basic design concept change. The maximum occurring coolant-side wall temperature of around 700–730 K for copper liners is below the coking limit of methane and very near the coking limit of propane. Thus, the coking temperature is no cooling limitation for methane and almost none for propane.

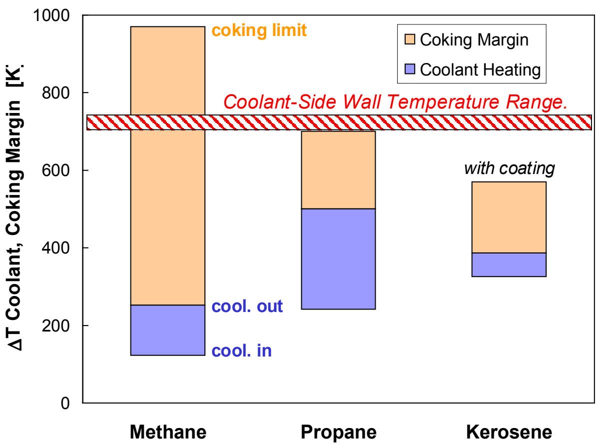

Figure 4: Coolant heating and margin to coking

In contrast, kerosene cooling may require a thermal barrier coating to keep the coolant-side wall temperature below the coking limit of around 560 K. Zirconium oxide ZrO_2 was assumed for the cooling assessment. Film cooling or mixture ratio bias near the wall (trimming) may be also necessary. Both film cooling and trimming can cause additional thrust chamber performance losses.

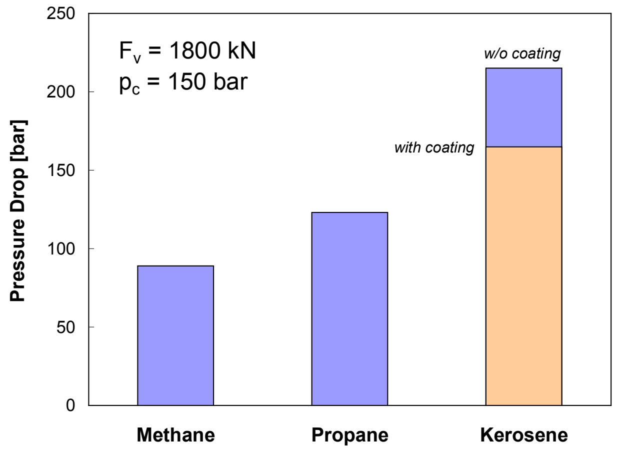

Figure 5: Main chamber coolant pressure loss

Engine Cycle Selection

For all three propellants, the main properties of gas generator (GG) cycles and staged combustion (SC) cycles were compared, each cycle in turn with fuel-rich, and oxidizer-rich preburners. Examples of these cycles are depicted in Figure 6.

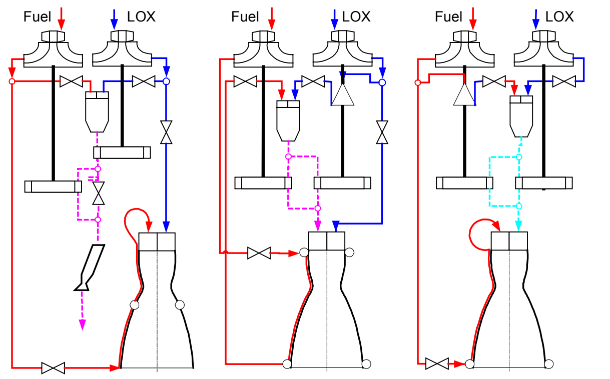

Figure 6: Studied engine cycles: Gas generator (left), fuel-rich staged combustion (center), oxidizer-rich staged combustion (right)

The gas generator cycles were rated by the engine performance they produced. A fuel-rich gas generator mixture ratio produces better engine specific impulse than an oxidizer-rich mixture ratio due to higher specific heat capacity of the turbine gas, see Figure 7. The difference in specific vacuum impulse is about 14 s for all three fuels studied.

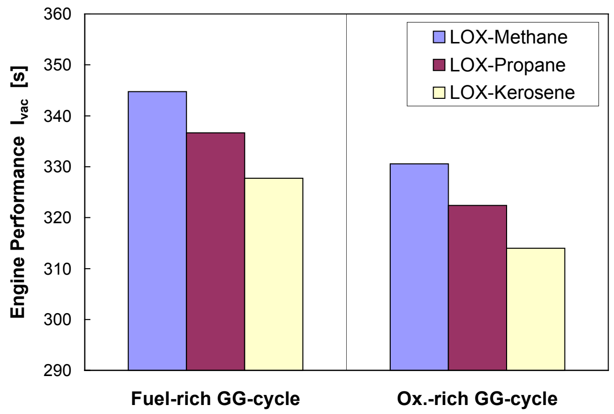

Figure 7: Performance for gas generator engines

For staged combustion cycles, the pressure cascades resulting from thrust chamber cooling and turbopump power requirements are compared in Figure 8 taking LOX-methane as example. The pumping requirements are lower for the cycle using a oxidizer-rich preburner, because no fuel is rerouted to the preburner after passing through the thrust chamber cooling channels. The small amount of fuel required for the preburner is delivered by a low-powered kick stage.

The fuel-rich cycle results in higher fuel-pump requirements and requires an additional LOX-kick-stage, while the ox.-rich cycle results in similar lower pump requirements without a kick-stage. The preburner pressure is also lower in the ox.-rich cycle. However, the oxygen-rich environment of the preburner gas may cause additional complexity for the turbines as well as for hot-gas lines and valves.

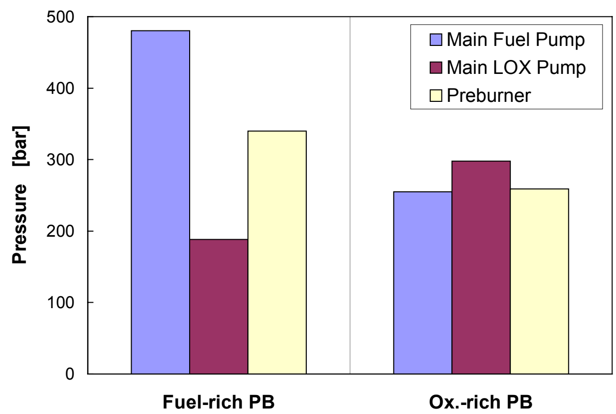

Figure 8: Pressures in LOX-methane staged combustion engine

Non-toxic Propellant Comparison

Based on above results the fuel-rich gas generator cycle and the staged combustion cycle with oxidizer-rich preburner were chosen for comparing the three non-toxic propellant pairs. Figure 9 gives the obtained engine performance in terms of vacuum specific impulse.

Clearly, LOX-methane yields the best performance, LOX-propane is inferior by 5-9 s, while LOX-kerosene is even more inferior by 10-17 s.

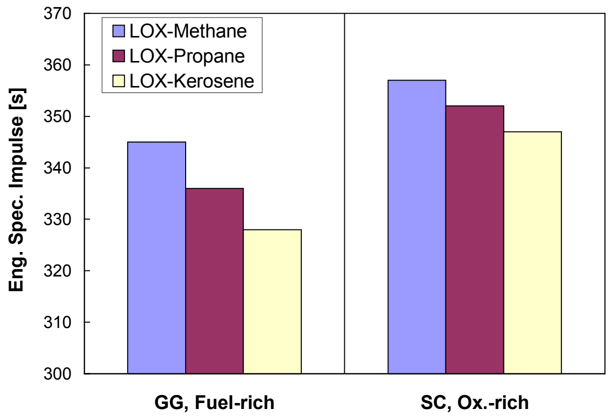

Figure 9: Engine performance for hydrocarbon fuels

In the light of the above considerations, the three propellant alternatives were rated as follows:

- Methane appears to be the first choice for an engine with Astrium thrust chamber design operating on non-toxic propellants due to its good performance, cooling capabilities and low soot production.
- Kerosene has the advantages of ambient storability, high density, and a vast amount of practical expertise available for rocket engine design. However, its cooling capabilities are inferior to methane for conventional thrust chamber design. A countermeasure is to reduce the heat flux by applying a thermal barrier coating (TBC) to the liner hot-gas side. Coatings are currently under development at Astrium.
- Propane has less performance and cooling capability than methane. Unlike kerosene it has to be cooled for liquid storage and has lower density. Propane does not seem to yield a significant advantage and was therefore eliminated as an alternative for the purpose of further studies.

Propellant Cost Considerations

For today's launch vehicles the costs for the tanked propellants are of secondary importance compared to the costs of preparing the launch vehicle structure and systems for launch and launch operations. In case drastic reduction of the latter costs become available either for low-cost expendable vehicles or reusable vehicles, the influence of the propellant costs will increase. Some propellant costs are given in [4]. Hydrogen is approximately 15 times more expensive than 98% H_2O_2, while aviation kerosene costs only one quarter of H_2O_2. Liquid oxygen is even cheaper.

Kerosene will get expensive when the world-wide oil resources will cease, current estimations give a time period of approx. 30-40 years. However, methane as liquefied natural gas is said to be available for another 100-120 years. The costs for methane are said to be three times less than kerosene [10].

LOX-HC ENGINE CONCEPTS

Several engine concepts were defined based on the results of engine system trades as given above for the propellants LOX-methane and LOX-kerosene.

The gas generator cycle engine as illustrated in Figure 10 uses fuel-rich gas for the turbine drive. Boost pumps are used to obtain better turbopump efficiencies, and hence a better engine performance.

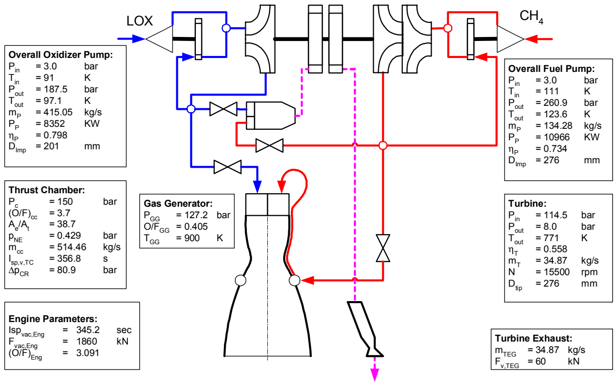

Figure 10: LOX-methane fuel-rich gas generator cycle engine concept.

The staged combustion cycle as illustrated in Figure 11 uses oxygen-rich turbine gas from the preburner in order to obtain lower and more balanced pump and turbine pressures. It is assumed that the hot oxygen-rich environment can be handled without large risk. Boost pumps are used to allow for higher main pump speeds, which is important for the chosen single-shaft configuration.

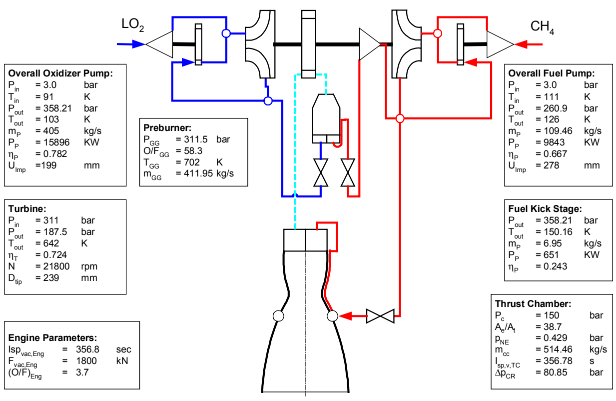

Figure 11: LOX-methane oxygen-rich staged combustion cycle engine concept.

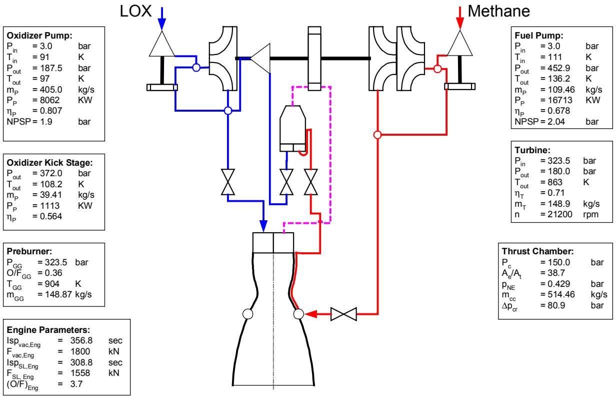

Figure 12: LOX-methane fuel-rich staged combustion cycle engine concept.

The staged combustion cycle with fuel-rich preburner is also feasible for LOX-methane as shown in Figure 12. The decision for the type of preburner depends on the criticality of the hot ox.-rich environment for feedlines and turbines created by a oxidizer-rich preburner.

Such and other engine concepts have been proposed also by other authors [9, 10, 11].

TESTS OF LOX-HC THRUST CHAMBERS AND ENGINES

Aestus Tests with LOX-Ethanol and LOX-Methanol

The Ariane 5 upper stage engine "Aestus" was developed by Astrium for the storable propellant pair NTO-MMH. Tests were carried out with LOX-Methanol and LOX-Ethanol, which showed good thrust chamber operational behavior and performance, see Figure 13. Only minor engine modifications were necessary like implementation of an igniter and adaptation of some seal materials. The successful ignition and stable operation was demonstrated in a cooperation of Astrium and Boeing Propulsion & Power towards a non-toxic orbital maneuvering engine OME for the Space Shuttle [1].

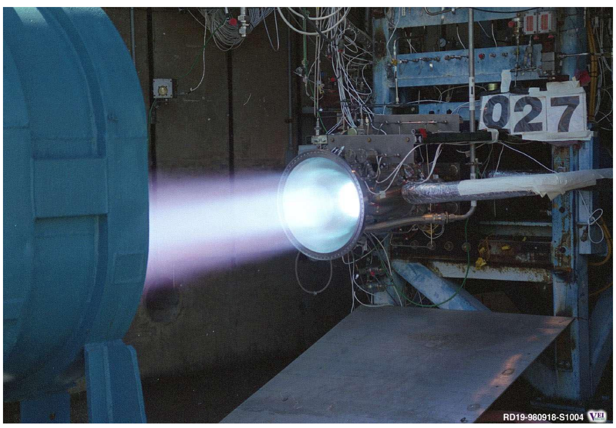

Figure 13: Aestus engine test with LOX-ethanol by Astrium and Boeing Propulsion & Power

Conversion LOX-Kerosene to LOX-Methane

In 1998 CADB carried out two hot tests of the experimental demonstrator engine RD-0110MD. The basic engine RD-0110 is currently used in the third stage of the Russian Soyuz Launcher using LOX-kerosene [12]. The engine RD-0110MD run during the demonstrator test with LOX-LNG (liquefied natural gas) at chamber pressure 54 bar and GG pressure of 48 bar, see Figure 14.

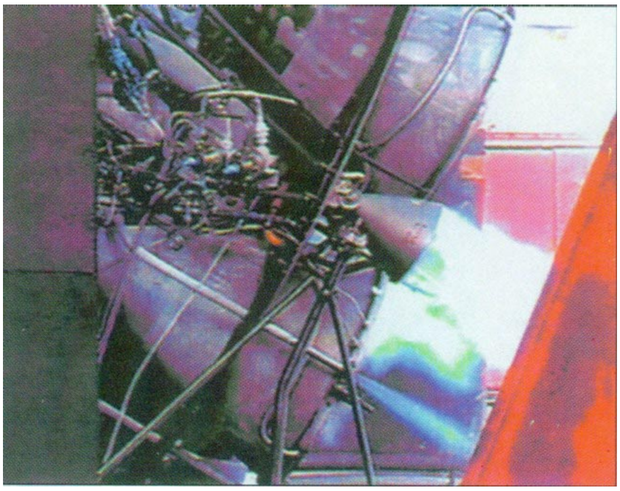

Figure 14: RD-0110MD demonstration test with LOX-LNG (liquefied natural gas) by CADB

Cooperation Astrium - CADB

In order to characterize different LOX-Hydrocarbon injection concepts, several types of injection elements are studied theoretically and experimentally in the frame of the TEHORA-2 research cooperation in cooperation with CADB in Russia.

The thrust chamber and injection technologies currently established in Europe stem from various engine developments. Chambers with storable propellants (Aestus) as well as chambers for cryogenic propellants (HM-7B, Vulcain, Vinci) were developed. A future development of a LOX-HC engine in Europe and the associated thrust chamber technology will be based primarily on the application of existing technologies to the new propellant combination with necessary modifications.

First activities focused on the injection concepts and electrical igniters. Later work needs to consider issues like compatibility of current liner materials copper and copper-alloys with the hydrocarbon fuel and its combustion products, sooting of combustion products on the hot gas side and the coking of the fuel in the cooling channel.

Today, the prediction and layout of the chamber cooling is performed with analytical tools, which are based upon the existing test data from cryogenic and storable propellant engine chambers. The application of these analytical models to hydrocarbon propellants needs to be verified and checked with experimental data.

Injection

Table 1 compares the propellant injection temperatures for the two hydrocarbon fuels to the conditions with hydrogen. In the gas generator cycle LOX is injected almost at tank temperature from the pump discharge into the main chamber (and into the gas generator), while the fuel is heated in the chamber cooling, lowering its density to gaseous ranges at supercritical state.

In the staged combustion cycles the hot oxygen-rich turbine exhaust is injected into the main chamber at high mixture ratio resembling a hot oxygen gas. The heating of the fuel in the chamber cooling is comparable to the gas generator cycle.

Full Scale Main Combustion Chamber Injection Conditions							
	Gas Generator Cycle			Staged Combustion Cycle			
	fuel-rich gas generator			*fuel-rich preburner*		*ox.-rich preburner*	
	Hydrogen	Methane	Kerosene	Hydrogen	Methane	Methane	Kerosene
LOX	95 K	95 K	95 K	95 K	95 K	—	—
Fuel	100 K	250 K	390 K	—	—	250 K	390 K
TEG	—	—	—	~650 K fuel-rich		~600 K oxygen-rich	

Table 1: Typical main chamber injection conditions

Coaxial injectors are used today in the engines HM-7B, Vulcain, Aestus. The liquid-liquid injection for LOX-kerosene gas generator engines is similar to the liquid-liquid injection of storable propellants, while the injection of gaseous methane from the chamber cooling is similar to gaseous hydrogen injection. In contrast, the gas-gas injection of oxygen-rich gas together with gaseous fuel represents new conditions, which may require an extension of the current coaxial injection element technology.

Testing injection elements for hydrocarbon fuels at subscale level requires a good simulation of the real injection conditions. Subscale tests may be performed at lower chamber pressures compared to the later application.

The main chamber injection conditions of methane are represented well if the fuel is injected not liquid but gaseous at nearly ambient temperature. It is furthermore possible to use natural gas in place of pure methane, which needs not to be liquefied by cryo-cooling.

For representing the gas generator cycle chamber, LOX is usually present at research test benches. The hot oxygen-rich turbine exhaust for the staged combustion cycle chamber can be replaced by oxygen gas at ambient temperature, which also is easily available (e.g. in pressure bottles). The industrial availability of methane-rich natural gas makes subscale tests for LOX-methane main chambers easy and attractive.

Ignition

The current European engines all use pyrotechnic ignition, while an electric spark igniter is foreseen for the Vinci engine. Test benches nowadays already use such spark igniters. The main task for a development of a reliable ignition system is the verification of the required power level, which depends also on the propellant injection.

Subscale Injector and Chamber Testing

The test specimen consists of a subscale chamber with several interchangeable injection heads. The chamber, which had already been used during a previous cooperation, consists of several water-cooled sections to allow the evaluation of the heat fluxes, see Figure 15. The chamber pressure is in the range of 35-70 bar. At 70 bar chamber pressure, the propellant mass flow rate is about 7 kg/s. Ignition is performed by an electric igniter using the same propellants.

The two propellant combinations LOX-methane and LOX-kerosene were chosen for experimental investigation from the system studies. Liquid oxygen is injected around 105 K, while both methane-rich natural gas with approximately 98% methane content as well as

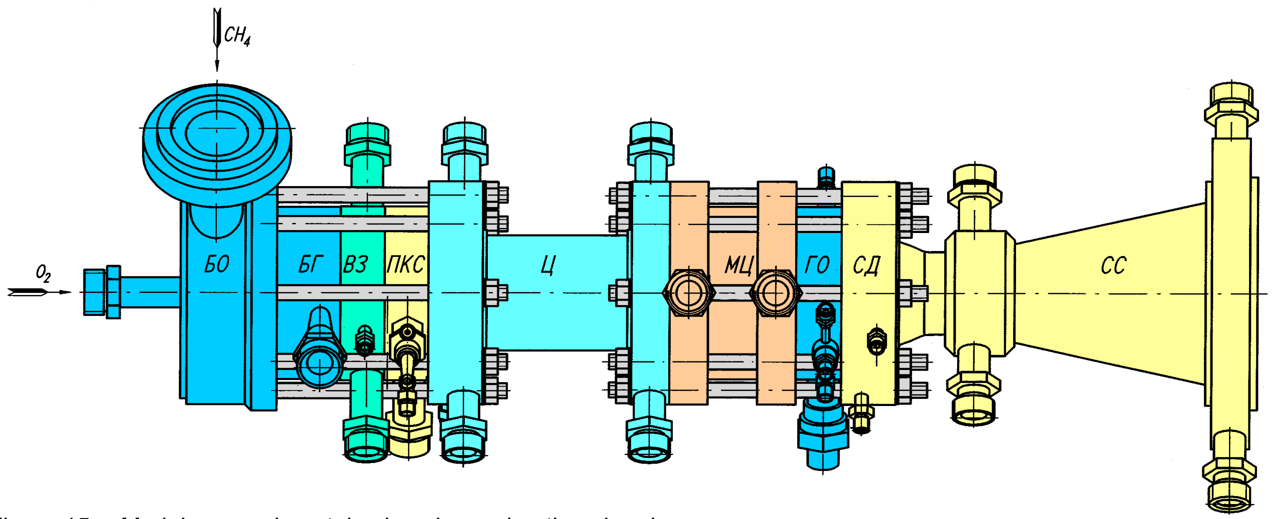

Figure 15: Modular experimental subscale combustion chamber

kerosene are injected at room temperature. The injection heads consist of body, LOX-posts, and fuel section with the faceplate, see Figure 16.

Figure 16: Subscale injection head parts

Tests with LOX-methane have been performed in August-September 2001 on CADB's test bench in Voronezh. A total of about a dozen tests were performed in the chamber pressure range 35 – 70 bar at mixture ratio in the range 3.1 – 3.8. Three different basic injection types designed by CADB and Astrium were tested. The tests demonstrated successful and reliable ignition and operation of all three injector types. Figure 17 shows a typical test with its characteristic blue flame colour, which is a pronounced contrast to usual tests with hydrogen.

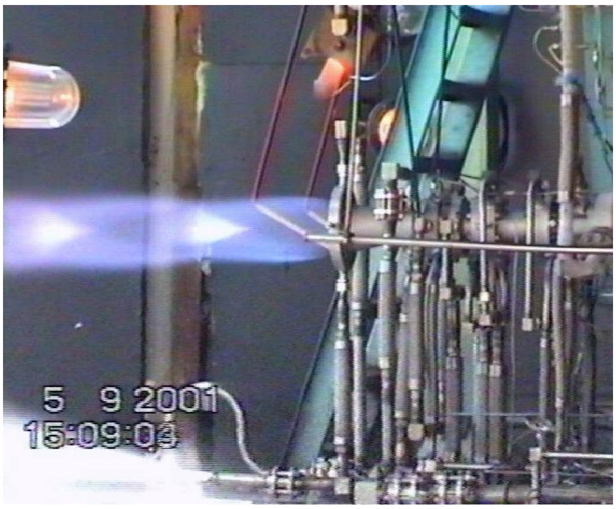

Figure 17: Subscale chamber test with LOX-methane by Astrium and CADB

All three tested injection elements were of the coaxial type building upon the similarity to the experience acquired in past LOX-H2 development programs. Impinging elements were not considered. During the test program some geometrical parameters like injection element geometry and injection velocity could be varied thanks to the modular design of the test hardware. Figure 18 shows the progress in optimization of the combustion efficiency achieved by this variation. It could be shown that combustion efficiencies comparable to the experience from LOX-H2 thrust chambers can be obtained with LOX-methane as well.

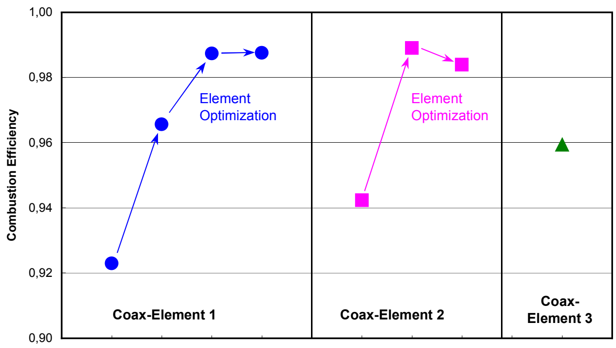

Figure 18: Results of injection element testing with LOX-methane (preliminary evaluation)

The pressure drop oscillations measured in the combustion chamber and upstream of the injection elements did not show significant higher values as those experienced in similar tests with LOX-H2. The measured coolant water heat up did coincide well with the prediction based on theoretical heat transfer relations.

The chamber wall was in good condition after 12 tests. Some discoloration could be observed from the injector to downstream of the throat, see Figure 19. A slight soot layer was observed, which did not grow with increasing test duration and which could be cleaned easily.

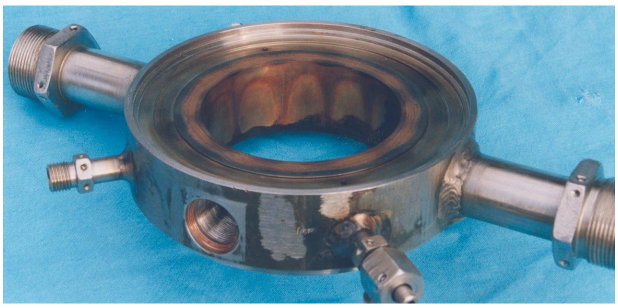

Figure 19: Chamber wall section after 12 tests showing discoloration due to heat load from injection elements

A torch igniter operating with GOX and methane was used in the tests, see Figure 20. Functional tests were performed with variation of the igniter energy. Reliable ignitions could be achieved in all tests in the subscale chamber.

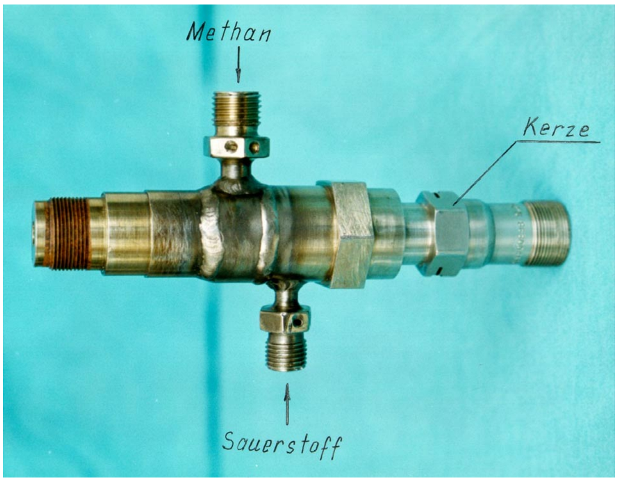

Figure 20: GOX-methane torch igniter

Similar tests with LOX-kerosene are scheduled to be performed until July 2002. Three basic injection elements designed for the injection of liquid oxygen and liquid kerosene will be tested. A continuation of this successful cooperation is in preparation with further experimental and design work.

SUMMARY AND CONCLUSIONS

Non-toxic hydrocarbon propellants have become fashionable recently aiming at more friendly environmental conditions for easier handling and thus reduced space transportation costs. Liquid methane provides the best performance and chamber cooling capability, while kerosene requires thermal protection coating or film-cooling due to the low coking temperature limit but is dense and easily storable. The danger of corrosion due to small impurities in methane was observed differently by various authors and it needs to be checked for the envisioned methane composition and liner material. It should be recommended to keep the size and thrust level of future engine developments within the range experienced today for Europe.

The engine system trade-off showed that a fuel-rich turbine gas results in higher engine performance of gas generator cycle engines. The sooting associated with fuel-rich hot gases needs to be studied in further detail. Oxidizer-rich turbine gas seems to be more attractive for staged combustion cycle engines in view of pump pressures, thus turbopump complexity. Sooting is avoided in oxidizer-rich gases. However, the oxidizer-rich environment may require specific material selection or coatings to reliably prevent hazards. A fuel-rich staged combustion cycle shows quasi the same performance and acceptable pump pressures compared to the ox.-rich cycle in case of LOX-methane, thus a fuel-rich cycle would avoid problems associated with the hot ox.-rich environment.

Further analyses of the engine configuration showed that LOX-methane is suited for single-shaft turbomachinery configuration like LOX-kerosene. For high performance and compact turbomachinery, boost pumps should be employed.

To gain experimental experience for injection, ignition, and combustion of LOX-Hydrocarbon, subscale chamber tests with different types of injection elements for LOX-methane were performed in cooperation with CADB. These tests with LOX-methane demonstrated successful ignition and operation of three injector types. The combustion efficiency could be increased by variation of injector parameters to values as high as the past experience with LOX-H2. A GOX-methane torch igniter was used successfully. These injector trade-off testing will be complemented in summer 2002 with subscale tests for the propellants LOX-kerosene using the same subscale chamber with new injection elements designed for liquid-liquid injection of LOX-kerosene.

A new phase of the cooperation is currently under discussion aiming at continuing the testing of injection elements and also including some cooling testing with methane and kerosene.

ACKNOWLEDGEMENTS

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