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French–Russian Partnership on Hypersonic Wide-Range Ramjets

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France and Russia have an ongoing fruitful cooperation to jointly develop a wide-range ramjet (WRR) able to accelerate a reusable launch vehicle from ~ Mach 3 to Mach 12. The WRR engine has a fully variable internal geometry, which enables a high performance level over the whole Mach-number range. Propulsion-oriented system studies have been conducted both on 30-tons-class experimental flight vehicle and on 500 tons-class single-stage-to-orbit (SSTO) reusable vehicles. In particular, the WRR airbreathing propulsion system has been integrated into a SSTO generic vehicle. Then, trajectory simulation, using mass, propulsion, and aerodynamic models, has allowed determining the payload as a function of total takeoff weight, confirming the utility of the variable geometry features of the WRR. Preliminary experimental and numerical studies have been conducted for several years to design the WRR prototype. The present contribution describes the synthesis of this engine and provides an overview of this common work. Consideration is given to various aspects of the project, including system studies, technology development, and analyses using contour control codes.

Introduction

IN a large part of the flight regime, the airbreathing mode appears to be a good solution for reusable space launchers (RSL). Dual-mode ramjets have been studied to propel such two-stage-to-orbit (TSTO) or single-stage-to-orbit (SSTO) vehicles. For example, in the French Research and Technology Program for Advanced Hypersonic Propulsion (PREPHA) program the study of a generic SSTO vehicle led to the conclusion that the best type of airbreathing engine could be the dual-mode ramjet (subsonic then supersonic combustion).[1,2]

Two main approaches are possible for this dual-mode ramjet: a fixed or a highly variable geometry. The variable geometry concepts of dual-mode ramjets have theoretically higher performance along the airbreathing trajectory. However, the technological challenge associated with very hot movable panels and the associated increase of weight (actuators, transmission, hinges, etc.) could counterbalance the increased performance.

Wide-Range Ramjet Concept

The French/Russian team have designed several concepts of dual-mode ramjets for launchers with fixed or variable geometries. In the partnership[3] the studies have led to the concept of a wide-range ramjet (WRR) with variable geometry. The air intake is variable with a fixed throat. The combustor is variable also, and the engine is dual fuelled.

The WRR concept engines are designed to be able to propel a PREPHA class vehicle or SSTO launchers (typical takeoff weight of 450–600 tons). In this case the corresponding full-scale ramjet (FSR) has typically a total width of 10 m. The height of the duct at the entrance of the combustor is about 0.66 m.

Demonstration of the performance would be performed with a Prototype-class WRR engine, able to thrust a 30-tons-class-vehicle (such as BLIK project) up to Mach 12. In this case the duct at the entrance is 257 mm high, and the width of the airbreathing engine is typically 2 m. For ground-testing demonstration the width of the Prototype is 0.212 m.

A subscale WRR (width 100 mm) has been also investigated for ground testing and flight testing under a 2-tons/5-m-class experimental vehicle (width 400 mm typically). In this case the height at the end of the air intake is typically 50 mm. Table 1 summarizes the WRR engines studied.

A sketch of the WRR engine is shown in Fig. 1. The WRR combustor has challenging characteristics: 1) operation from at least Mach 1.5 up to Mach 12; 2) use of variable panels during operation along the trajectory; 3) optimization of propulsive performance (checked with theoretical studies, CFD work, thrust measurement during reduced scale tests, etc.); 4) Modification of the contour by a control-command computer connected to sensors on the engine in order to maximize the performance all along the trajectory; 5) use of subsonic and then supersonic combustion; 6) use of kerosene and then hydrogen as fuels; 7) structural ability to reach at least Mach 12 flight conditions; 8) creation of an external chamber where the actuators are enclosed (its medium is protected from the hot gas flow either by means of pressurization or blowing into side gaps of the movable walls); and 9) possible extension to the higher speeds by the use of oblique detonation wave engine (ODWE) mode, see, for example, Ref. 4.

System Studies

Methodology and Tools

The increase of payload of a future SSTO reusable launcher must be quantifiable from the expected performance potential of the dual-mode ramjets in case of variable or fixed geometry. Thus, advanced studies have been carried out to assess the potential interest of the variable geometry. Simple parametric calculations have been made on trajectories and weight breakdowns of a "rubber" generic SSTO vehicle computed.

The studies have been realized thanks to a computer code called PROSIT. This code allows simulating trajectories at an advanced study level (three degrees of freedom, simple aerodynamic laws). A mass model has been set up, which allows taking into account the scale factors effect (notion of rubber vehicle). Aerodynamic characteristics and mass breakdown depend in particular on the volume of fuel consumed.

Summarized in Fig. 2, the iterative process is based on the PROSIT computer code using a rubber SSTO vehicle. This method was validated in particular with more detailed studies performed in

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Table 1 WRR engines family overview

Name	FSR	Prototype	Prototype	Subscale	Subscale
Purpose	Operational	Flight test	Concept demonstration by ground testing	Ground testing	Flight test
Vehicle type	SSTO	BLIK	——	——	5/6 m long
Vehicle weight	500 tons	30 tons	——	——	2 tons
Width	10 m	2 m	0.212 m	0.100 m	0.4 m
Combustor entrance	660 mm	257 mm	257 mm	50 mm	50 mm
Operating domain	Mach 1.5–12	Mach 1.5–12	Mach 3–6.5	Mach 6	Mach 1.5/4–8/12
Years of operation	2030	2020	2000/2001	1995–1997	2010
Movable geometry	Yes	Yes	Yes	No	If necessary

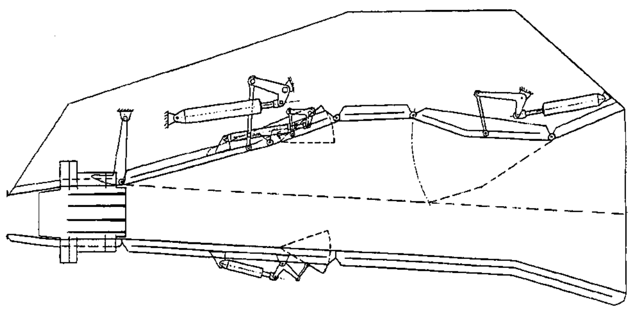

Fig. 1 Common WRR scheme.

the PREPHA program.[5] The orbit target is 80 × 500 km , 28.5 deg for the PREPHA-type SSTO generic vehicle.

To obtain the propulsion assumptions, several tools were available to simulate the operation of an airframe-integrated dual-mode ramjet. Most assume that the combustor flowfield is one-dimensional (direct and inverse methods, with several semi-empirical laws are used). Computational fluid dynamics (CFD) and semi-empirical tools are also used by both partners to compute the flowfield around the forebody, air intake, and nozzle. These tools have been used both for system studies and for test preparation and analysis. CFD analysis of the combustor flowfield is currently used, in particular with the ONERA MSD code.

A number of computer codes were used to design the Prototype configuration, simulate flowfields, and estimate the structure thermal state and propulsive performance. Numerical simulations have been carried out for the flight Mach range from 2.5 to 12 and 15.

Optimization and performance estimation of the air intake have been made using one-dimensional, two-dimensional, and three-dimensional codes accounting for real gas and viscous effects. The combustion chamber has been designed and its operation simulated mainly with one-dimensional codes including equilibrium gas models, semi-empirical boundary-layer model, and empirical approximations for the combustion efficiency and pressure losses.[6] The nozzle has been designed and simulated with two-dimensional codes accounting for nonequilibrium effects and boundary layer on the walls. Special attention was paid to optimizing performance for a wide range of flight conditions.

The thermal analysis has been performed by both partners using semi-empirical tools. These tools allow taking into account the component testing of heat protecting elements and to extrapolate to the different engines under investigation (effect of size, of mass flows, of flight conditions, of wetted area per airflow cross section, etc.).

Thirty Tons Class Vehicle

The Prototype-class WRR concept (combustor entrance of 257 mm) was first proposed by a group of Russian researchers in 1992. The WRR concept with a variable geometry dual-fuel, dual-mode combustor, and a variable geometry air intake was considered for a 36-m-long, 30–35 tons experimental hypersonic vehicle called "BLIK." The vehicle was assumed to have rocket engines for the takeoff, landing, acceleration at subsonic and low supersonic speed and maneuvering, and a WRR operating at Mach 1.5–12. The Prototype WRR concept for a BLIK-class vehicle was finally accepted by the French and Russian specialists in 1993. Experimental, computational, and technological efforts have been ongoing since 1992 to evaluate the Prototype performance, then subsequently design and manufacture the experimental combustor intended to demonstrate feasibility of the Prototype concept during the future connected-pipe tests at Bourges–Subdray Center (see Table 1).

A scheme of the Prototype WRR flowpath is shown in Fig. 3. The air intake with a two-wedge ramp and a mobile cowl is located 22 m from the vehicle leading edge. The mobile cowl provides inlet self-start at low Mach and desirable matching the shock pattern.

The combustor geometry is adjusted for flight conditions in order to obtain the maximum thrust (efficiency). Movable flameholders penetrate into the duct at low Mach numbers to ensure stable combustion. The nozzle has fixed geometry optimized for a wide range of flight Mach number. The combustor fixed wall, on the lower part of the vehicle, is set at 8 deg. It enables placing all geometry control mechanisms inside the cowl and somewhat improve the cowl stiffness and nozzle performance (decreasing the pitching moment).

The chosen combustion chamber contours are schematically illustrated in Fig. 4 for flight Mach numbers 3 and 5 (subsonic combustion mode), 6 and 8 (supersonic combustion mode). Estimated Prototype performance is shown in Fig. 5 as a function of the fuel specific impulse, I_{sp} (here in meters/second) vs the flight Mach number at $ER = 1$, in cases of hydrogen and kerosene fueling. Obtained values of the I_{sp} include contributions of the inlet and nozzle additive drag.

PREPHA-Class (500 Tons) Vehicle

System studies on a SSTO vehicle, performed in the framework PREPHA, have shown how airbreathing propulsion, combined with high-performance rocket propulsion, could improve the feasibility of a fully reusable SSTO space launcher. Nevertheless, performance, obtained with the provided technology level, was not sufficient to allow the use of a landing-gear system sized to comply with full mass vehicle takeoff requirements because the weight penalty mass has to be considered. Thereby, either a horizontal takeoff with a trolley (whose development and operation costs would be important) or a vertical takeoff is necessary. During these studies, tradeoff between technological complexities, mass, and performance led to considering airbreathing engine with fixed combustor geometry.

As already explained, PROSIT trajectory simulations using mass and aerodynamic models, already defined for generic vehicles, allow determining the available payload as a function of total takeoff weight for each assumption. Comparison with PREPHA-designed fixed combustor engines [called Double Col Thermique (DCT)] has been performed with the same analysis tool and the same assumptions, except for the combustor geometry.

The purpose of these studies is not to design a SSTO launcher as was done for during PREPHA program. The aim of this simplified analysis is to be able to estimate the benefit of variable geometry compared with fixed geometry. The system studies are permanently under refinement from preliminary assumptions of level 1 up to level 3 future studies, which will take into account the Prototype test results. Details can be found in Refs. 7–9.

To realize level 2 assumptions, several computations have been performed, and FSR performance has been calculated when

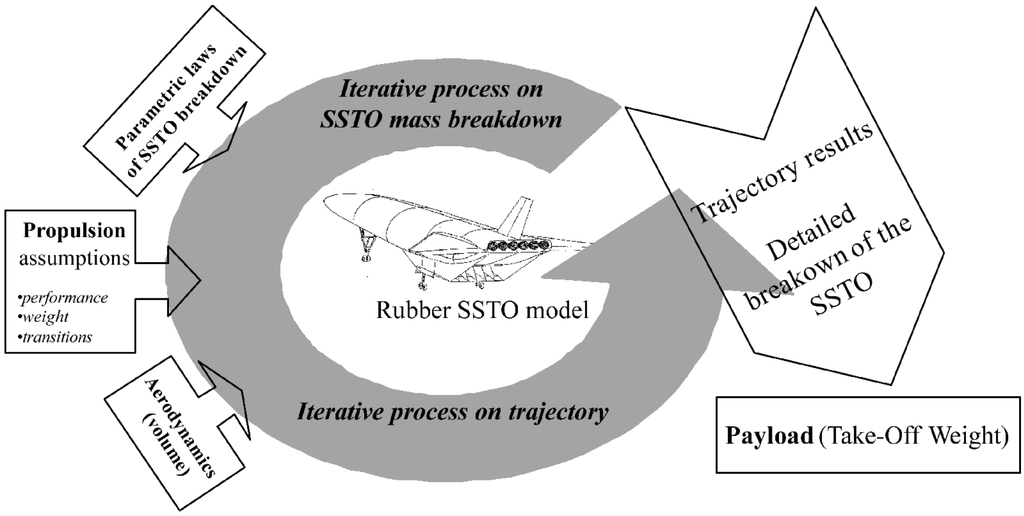

Fig. 2 Methodology for propulsion oriented analysis of SSTO payload as a function of take-off weight (TOW).

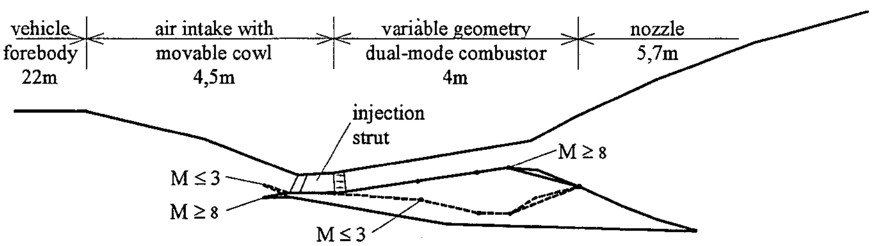

Fig. 3 Scheme of the Prototype WRR flowpath.

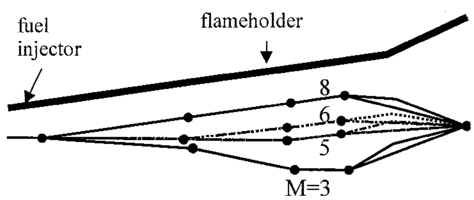

Fig. 4 Combustor variable contour configurations.

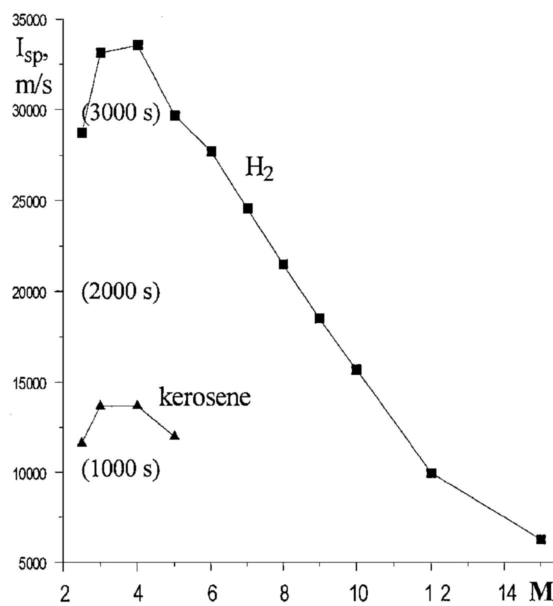

Fig. 5 Estimated Prototype performance at *ER* = 1.

adapting this engine to a PREPHA-type vehicle, using the available technology results. The air intake and the nozzle of the FSR have been assumed to be identical to the DCT integrated to the generic vehicle for the last study of PREPHA.[10] The evolution of the injected equivalence ratio with the flight Mach number has been kept constant.

The computed hydrogen-fueledFSR performance is presented in detail in Ref. 9 and illustrated on Fig. 6. The computed thrust is higher with the FSR than with the DCT, especially in ramjet mode (20–40%). The assumed value for combustion efficiency is 0.94 for the FSR performance evaluation at Mach 6, corresponding to the available experimantal results. The FSR performance has been computed as a reference curve and with a decrease or an increase of 10% along the whole trajectory. These performances have to be completed with engine weight as a function of capture area. The main technological assumptions for the FSR engine are presented in detail in Ref. 7 and summarized on Table 2.

Even with a fixed geometry combustor, it seems difficult to obtain an airbreathing engine weight of less than 1000 kg/m^2 of capture area. These performance have been used for the SSTO studies. Moreover, the methodology of such an propulsion-oriented SSTO analysis has been enhanced from the PREPHA program studies, by taking into account for each engine and for each takeoff weight: 1) optimization of the capture area, 2) optimization of the body height, and 3) appropriate wing area (and associated weight and drag) to limit the angle of attack for takeoff and landing.

The increase in computed performance could be used to avoid a trolley assistance for takeoff. The effect of uncertainties of assumptions on the computed payload has been investigated to check in particular that the relative placing of the propulsion settings of the variable geometry is not modified. The payload as a function of takeoff weight functions calculated for the FSR and DCT, with several landing/takeoff gears assumptions, is shown in Fig. 7.

The generic vehicle of the PREPHA program is not intended to be a reusable space launcher but a "generic vehicle." No payload was assumed as a target: it is close to zero with the DCT engine chosen for the PREPHA program. This approach is reasonable for the present propulsion-oriented advanced studies, using a hydrogen-fueled engine.

The FSR should enable designing a generic vehicle of PREPHA class, but using a takeoff gear with a takeoff weight of 450 tons:

Table 2 Assumptions for FSR mass estimation

Type of element	Technology	Weight
Heat protection elements	Convection cooling	12 kg/m^2
Structural plates	TiAl-alloy	21 kg/m^2
Fuel injection struts	Refractory steel	25 kg/m^2
Acuators (e.g., 120 tons)	Available technology	320 kg

Table 3 Mass budget comparison of the DCT and FSR propelled PREPHA-type generic vehicle

Propulsion concept, element (in metric tons)	DCT (fixed)	FSR (variable)
Payload mass	0	0
Airbreathing engine	21.7	20.2
Rocket engine weight	8.3	8.6
Mass LH2	112	108.5
Mass LOX	228.5	248
Landing gear	2.4 (landing)	11.7 (takeoff)
Others (airframe, tanks, avionics...)	52.1	53
Takeoff weight	425	450

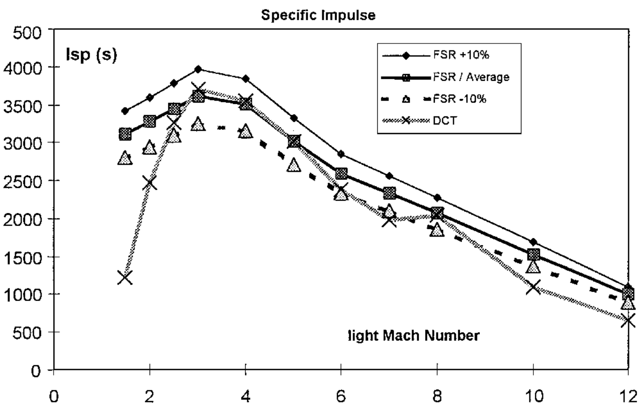

Fig. 6 Computed fuel specific impulse for FSR (including uncertainties) and DCT.

this point was estimated as impossible for every other fixed engine model. Computed mass budget is available for each PROSIT computation after iterations for given assumption of propulsion and for TOW. The computed generic vehicle mass breakdown for the cases of the FSR with landing gear and the DCT with takeoff gear are shown in Table 3.

Examination of Table 3 is educational: in particular, with these assumptions the WRR is less heavy than the fixed DCT, in particular because its better performance allows the use of a smaller capture area (20 m^2 vs 24 m^2). Refining the vehicle should lead to a positive payload with the FSR and takeoff sized landing gear, but designing such a launcher is beyond the scope of the present effort. Other system studies have been performed and presented in details in Ref. 9: comparison with a rocket-based combined cycle-type engine, use of ODWE mode, cryogenic hydrocarbons, etc.

Conclusion on System Studies

The system studies under the scope of the French/Russian partnership (details in Ref. 9) have taken into account progressively more and more accurate features, particularly optimization of the capture area for each takeoff weight. The main results are 1) general assumptions of the present method are close to current literature, in particular Ref. 11; 2) big interest of the variable WRR concept; 3) potential interest of ODWE mode; and 4) no major interest, with these assumptions, for using cryogenic hydrocarbons instead of hydrogen, or for integrating the rocket in the main airbreathing propulsion system. The present parametric system study gives interesting guidelines for the use of a variable geometry propulsion system for future airbreathing launchers (SSTO or TSTO).

Further system studies should be investigated: 1) the use of WRR of FSR type for other type of reusable airbreathing launch vehicles (for example TSTO as evaluated in Ref. 12) and experimental vehicles; 2) computational estimation of the FSR performance after ground test of the Prototype; 3) dual-fuel concept optimization; 4) liquid endothermic hydrocarbons applied to the WRR; 5) coupled optimization of the FSR operation along the trajectory, taking into account WRR control code capability and regenerative cooling with associated optimised fueling strategy; 6) more detailed analysis of the system effect of gas injection for the sealing of movable walls; and 7) new vehicle concept encompassing the benefits of dual-mode ramjets.

Component Testing

Subscale Combustor Tests

Testing of a reduced-scale combustor (entry cross section 50×100 mm^2) has been carried out. The injection system and the contour of the shape are the same as the Prototype, but at a reduced scale. Test has been conducted up to Mach 6 conditions. The static pressure distribution is presented in Fig. 8 for several equivalence ratios (0, 0.5, 1). The precision of wall pressure measurement in the combustion chamber provided by pressure transducers is normally within 1.5%. These results correspond to injection of hydrogen. Supersonic combustion has been achieved without thermal blockage up to stoichiometric conditions. From integral estimations the combustion efficiency is 0.9 ± 0.1 at equivalence ratio ~ 1. This assessment is consistent with other test data obtained with different fuels and duct geometries.[13,14]

Thermal Protection Technology

Several concepts of thermal structures (HPE: Heat Protection Elements) have been developed and tested to evaluate the capability of the Prototype to withstand thermal loads: porous leading edge cooled by injection (transpiration); panels protected by thermal barrier coatings and convectively cooled (HPE.C); panels cooled both convectively and by injection (transpiration) (HPE.C.I); use of air-cooled panels (HPE-A) for cost and risk reduction, for the first tests of the Prototype; and hinges cooled by air or hydrogen films.

More than 40 variants of designs for actively and passively cooled elements of leading edges and heat protective wall panels have been tested since 1994. Details can be found in Refs. 15 and 16.

In close association with analytical studies (see, for example, Fig. 9), different tests have been performed, such as tests in plasmatron; tests at the exit of the heater; tests at the exit of a supersonic combustion chamber model (with a shock generator to increase the heat load); and tests with one HPE panel alone, with two panels in series, with four cooled walls.

To increase the safety margin caused by the use of metallic alloys, the thermal efficiency has to be maximized, in particular for the fuel-cooled panel. Maximizing this thermal efficiency leads to use of high-temperature alloys for the hot walls; use of three-dimensional configurations, in particular multilayers architectures, such as the "double deck" (Fig. 10); and enhancement of the heat exchange of the coolant.

Because of the Prototype definition, the most important parameter of HPE (after demonstration of its capacity to withstand the heat flux with the available fuel mass flow) is the weight per unit area. The goal is a metallic HPE specific weight lower than 12 kg/m^2 (assumption of the system studies).

Tests of leading-edge samples (with radius of bluntness of 1.5 mm) have been conducted under strong shock/shock interaction conditions. Their results permit to be confident in the capability of the optimized porous leading edge to work up to Mach 12 conditions.

Technology Demonstration: The Prototype

Prototype Characteristics

The system studies estimation has to be verified from the point of view of technology and engine operation. The main aim is to check the WRR expected performance with cooled structures and

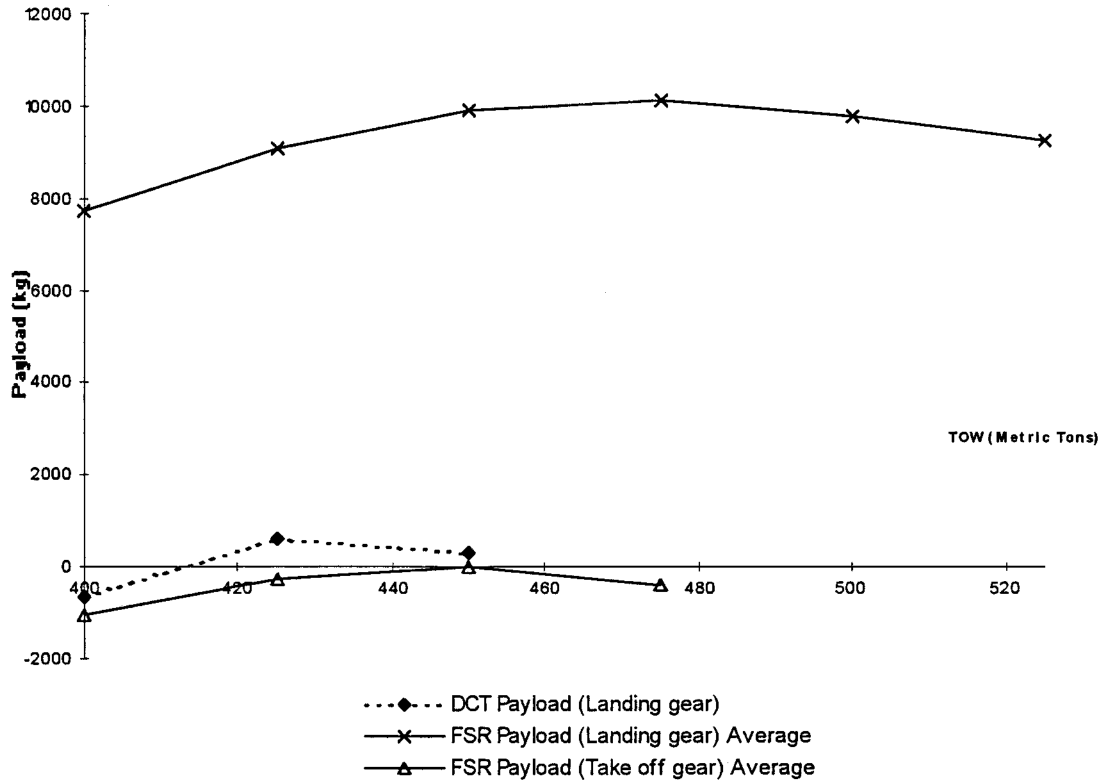

Fig. 7 Computed payload as a function of TOW for FSR and DCT with several assumptions for the landing gear.

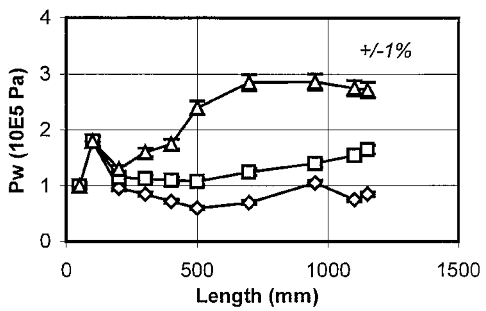

Fig. 8 Static pressure distribution for several ER for Mach 6 tests; ◇, *ER* = 0; □, *ER* = 0, 5; and △, *ER* = 1.

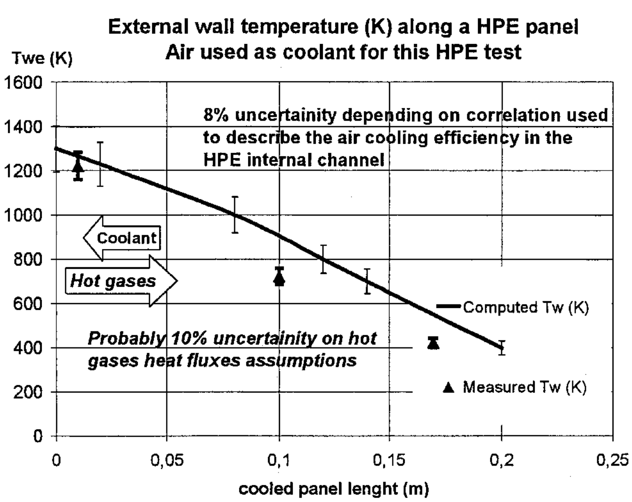

Fig. 9 Temperature along the panel (computed vs measured) for a given HPE test.

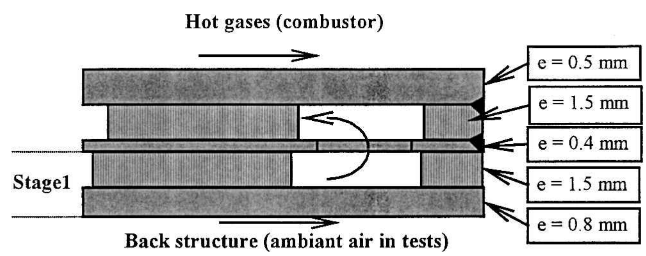

Fig. 10 Scheme of HPE-double deck (side view).

the ability to move the combustor internal contour by ground testing of a Prototype of the WRR in the Bourges–Subdray Center.

The purpose is to prove by experiments and computations the capability of the WRR to propel a SSTO launcher with a dual-fuel, dual-mode. These results should give unique information on dual-fuel, dual-mode ramjets: feasibility of technology—variable geometry (mechanical behaviour, hinge and sealing), geometry control system, cooled structures; scientific information—understanding of dual-mode ramjet process; and thrust optimization—geometry for each flight point, optimization of fuel transition.

Measurement System

The measurement system to analyze the tests performed on the hypersonic test leg in the industrial test facility of Bourges–Subdray is described in Ref. 17 and summarized in Fig. 11. This approach will be used for the Prototype. Moreover, some measurements will be used in real time for overall safety and to enhance the control procedure in order to optimize the performance along the simulated trajectory.

Manufacturing

The Prototype framework is assembled and shown in Fig. 12. Variable geometry wall panels have been connected by hinges and attached through kinematic elements to control actuators in the external chamber. The hydraulic system has been successfully tested

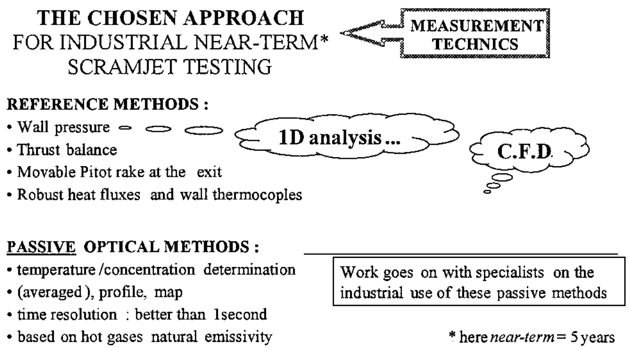

Fig. 11 Sum up of the measurement techniques for near-term industrial use.

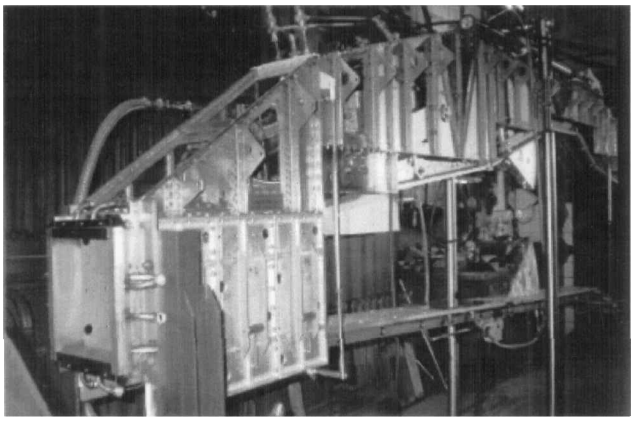

Fig. 12 View of the Prototype at Mach 3 contour without side walls and without HPE.

under working pressure up to 22 MPa. A manual control block allows realizing variable contour transformations. Manufacturing of the strut injector and flameholder framework has been completed. After solving several repeatability problems, serial manufacturing of standard $212 \times 212\ mm^2$ HPE is completed. Preparations of technological process for nonstandard HPE (particularly for flameholder) have been completed. After Prototype assembling completion, the preliminary cold test of the main systems will be done in Russia before transportation to Bourges–Subdray.

Control Codes

The control codes are designed for the ground tests of the Prototype at the Bourges–Subdray test center. However, their logic can be considered a background to create a control code for future flight tests or operational vehicles.

The Bourges–Subdray test center is using reliable computer codes for controlling main test bench systems: fluid and energy supply, air heater, fuel feeding, realtime measurement, etc. Those codes (refered here as bench computer codes) will be used for the Prototype tests. The Prototype Control Code (PCC) schematized in Fig. 13 will realize the following main functions: 1) control of hydraulic actuator driving the movable wall panels and flameholders and 2) control of shut-off valves at the input of the Prototype cooling system, fuel feeding system, ignition system, external chamber pressurization system.

The PCC will realize its functions in close connection with the existing Bench Control Code (BCC) exchanging control commands and measurement data in the frame of a global test program, thanks to a common memory zone. PCC includes algorithms for the following control routines: Prototype startup and shutdown; variable geometry transformation; variable geometry optimization to get the maximum measured thrust; analysis of Prototype state to detect emergency situations; and control actions preventing structure overheating, duct choking and overpressure, or variable contour breakage.

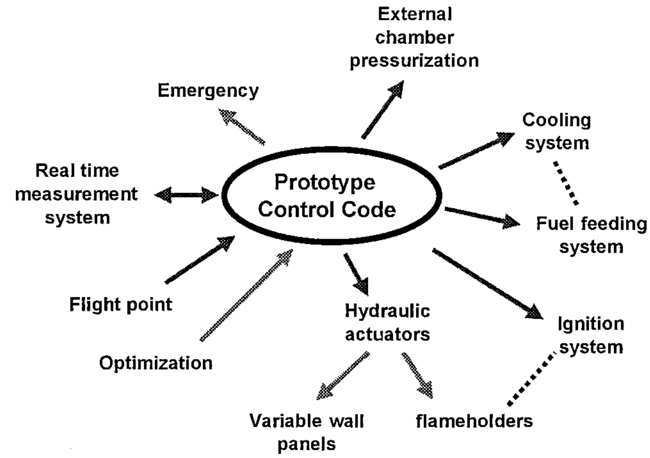

Fig. 13 Prototype control principle.

The main problem with creating the PCC is the fact that the Prototype behavior cannot be predicted in detail, and so its algorithms must be able to work in any possible situation and easily adapted to new tasks that can arise in the course of the test campaign. To develop and test the PCC's components, a special computational model of the Prototype at the test bench has been created. This specific code is referred as Integrated Computational Model (ICM). The two codes exchange data in the computer memory simulating the real-time dialogue between the PCC and BCC. The ICM code simulating the Prototype and test bench systems includes a one-dimensional time-dependent model of the gas flow from the air heater to the Prototype exit, differential models of hydraulic actuators, geometric and kinematic Prototype models, models of test bench systems, and BCC simulations of available measurements.

Actuator control algorithms have been implemented to a control computer, which will be used to test the Prototype. Geometry and actuator control algorithms have been tested on the control computer connected to the Prototype systems. The PCC will be refined during the hot tests of Prototype in connected-pipe mode.

Conclusions

Since 1993 France and Russia have undertaken a cooperative effort to develop a large-scale wide-range dual-fuel, dual-mode ramjet engine for RSL application. The concept of wide-range ramjet could be of interest for numerous airbreathing RSL projects. A variable geometry engine could also be profitable to experimental vehicles.

Initial concept studies have led to the design of a Prototype whose manufacturing will soon be completed. Preliminary tests have allowed choosing the components for WRR engines, as a basis for FSR system studies and as confident, robust, and affordable technology for the Prototype.

Beyond this technological effort, system studies are in progress and have already extensively confirmed the payoff of variable geometry for dual-mode ramjet combustor for potential airbreathing reusable space launchers.

Preparation of a scientific flight program to check the integrated aeropropulsive balance of a scramjet up to Mach 8 is under common consideration. The expected results of the French–Russian wide-range ramjet partnership will be a crucial step for the airbreathing propulsion studies for future reusable space launchers of the 21st century.

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