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Future Flight Test Plans of an Axisymmetric Hydrogen-Fueled Scramjet Engine on the Hypersonic Flying Laboratory

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FUTURE FLIGHT TEST PLANS OF AN AXISYMMETRIC HYDROGEN-FUELED SCRAMJET ENGINE ON THE HYPERSONIC FLYING LABORATORY

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Abstract

Under a contract with NASA, a joint Central Institute of Aviation Motors (CIAM) and NASA team is preparing to conduct the fourth flight test of a dual-mode scramjet aboard the CIAM Hypersonic Flying Laboratory, "Kholod." Ground-launch, rocket boosted by a modified Russian SA-5 missile, the redesigned scramjet is to be accelerated to a new maximum velocity of Mach 6.5. This should allow for the first-time measurement of the fully supersonic combustion mode. The primary program objective is the flight-to-ground correlation of measured data with preflight analysis and wind-tunnel tests in Russia and potentially in the United States. This paper describes the development and objectives of the program as well as the technical details of the scramjet and SA-5 redesign to achieve the Mach 6.5 aim test condition. The purpose and value of a joint Russian-American program to attain overall hypersonic air-breathing technology objectives are discussed. Finally, the current project status and schedules to reach the final flight launch are discussed.

Introduction

Internationally, several countries, such as the United States, Japan, France, Germany, and Russia, continue to vigorously pursue air-breathing propulsion technology solutions to efficient, low-cost, point-to-point rapid global access and space transportation. The scramjet, its performance potential, and its design methodology validation are at the center of this quest. Programs, such as this joint Russian-American project, seek to address this last major aeronautics frontier.

To date, the Central Institute of Aviation Motors (CIAM), Moscow, Russia, has conducted three rocket-boosted flight tests of its axisymmetric dual-mode Mach 6 design scramjet (fig. 1). The first was in November 1991, and the second involved a joint project with the French in November 1992. These flights achieved approximately Mach 5.35 and Mach 5.6 respectively (ref. 1). The third attempt was also with the French. In this March 1995 attempt, the engine failed to operate because of some onboard system problems. All scramjet flights were flown captive-carry atop the SA-5 surface-to-air missile that included an experiment flight support unit known as the Hypersonic Flying Laboratory (HFL), "Kholod" (ref. 1).

In November 1994, NASA contracted with CIAM to continue exploring the scramjet operating envelope from the ram-scram, dual-mode operation below Mach 6 to the full supersonic combustion (scram) mode at Mach 6.5. To accomplish this objective, the higher heat loads required redesign of the combustor and active cooling system; meanwhile, the increase to Mach 6.5 required modifications to the SA-5 booster to improve performance. The contract specifies the building of four identical engines to accomplish all required ground and

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flight tests. The first two engines are dedicated to wind-tunnel tests up to Mach 6 simulated flight conditions. The third is designated for flight test, and the fourth will be a backup flight test engine. NASA ground testing of one of the first two engines at the NASA Langley Research Center, Hampton, Virginia, is planned after completion of the flight phase. The CIAM C-16 V/K wind tunnel (fig. 2) was upgraded to provide extended test time with a new Mach 6 facility nozzle and will thoroughly test a complete full-scale engine before flight test. Test conditions are as follows:

Hydrogen consumption, kg/sec	0.3	1.4
Air mass flow rate, kg/sec	20	30
Air temperature, °K	2000	2500
Air pressure at aerodynamic nozzle entrance, MPa	1.0–7.5	20
Air flow Mach number at nozzle exit, MPa	3.6	8
Test duration, sec	30	30

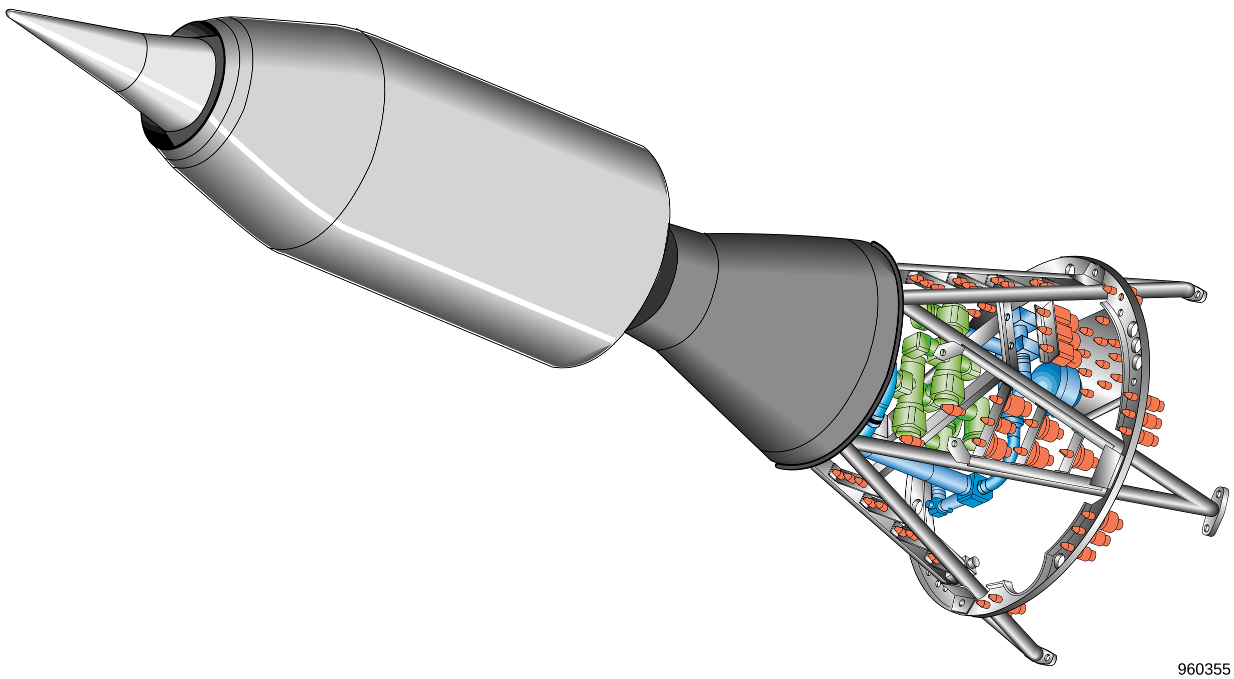

Figure 1. Scramjet external view.

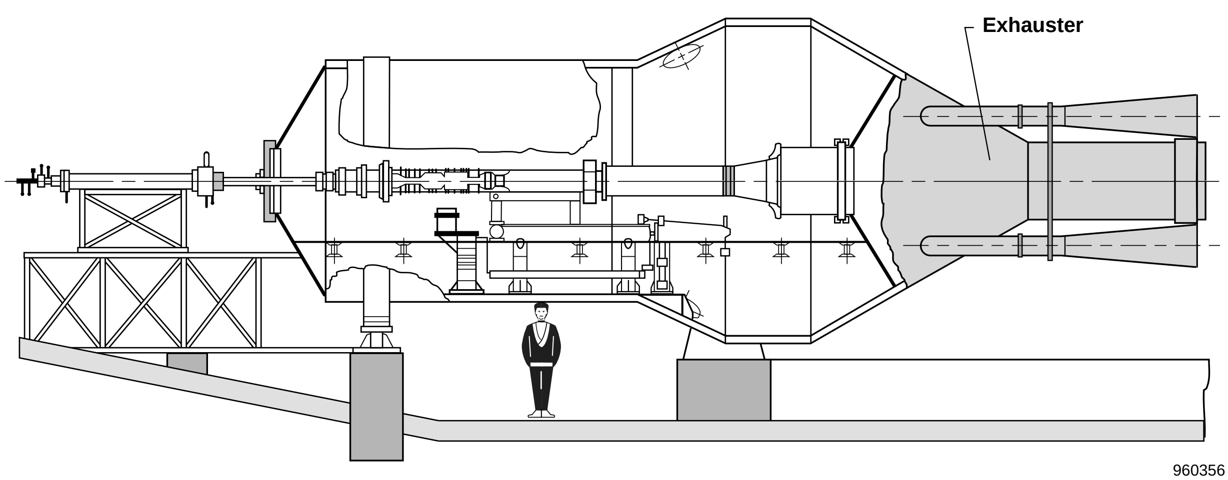

Figure 2. The C-16 V/K facility for scramjet large-scale models test.

The overall program objective is to explore and measure the full supersonic combustion mode and correlate this flight data with ground tests and with analysis techniques. This objective includes the opportunity to validate design and analysis methods and to compare NASA and CIAM ground test facility test techniques and results. This comparison will be conducted with a common set of instrumentation sensors and measurement locations to facilitate data correlation activities with predictive analysis results.

Another key objective in the joint nature of the program was to involve NASA engineering in as much of the research, analysis, and testing as possible. Besides the comparison of results, methodologies, and test techniques between the two organizations, this program gave NASA a direct opportunity to learn about Russian facilities and test techniques. An additional advantage is that NASA has provided an independent assessment of the engine design, instrumentation, and ground facility operation to CIAM (ref. 2).

Hypersonic Flying Laboratory, "Kholod"

The HFL, "Kholod," comprises the entire experimental system including the scramjet engine and the propellant, engine control, engine cooling, instrumentation, and telemetry systems. This laboratory was designed to essentially replace the size and mass of the original SA-5 payload.

Figure 3 shows a schematic of the complete HFL. The HFL consists of three main support compartments: N1, N2, and N3A/B aft of the engine. The conical N1 compartment comprises a transition section from the engine to the cylindrical booster and is covered by a thermal protective skin to shield it from the engine exhaust. This compartment contains the engine control, fuel regulator, and instrumentation systems. Compartment N2 contains the double-walled, insulated liquid hydrogen propellant tank, followed by the N3A compartment containing the pressurized helium bottle used to pump the fuel to the engine. The N3A compartment also contains the high-pressure nitrogen bottle used for the pneumatic actuators. The final N3B compartment contains the telemetry system, system batteries, and SA-5 missile control system.

Onboard HFL instrumentation includes 83 pressure transducers, 58 thermocouples, and 46 other system operation sensors. The majority of these data are telemetered at a digital 50 samples/sec except for the frequency modulation analog temperature measurements transmitted at 1.5 Hz. NASA has contributed additional instrumentation to compare with or enhance the Russian measurement system. This instrumentation included a body-mounted, three-axis, orthogonal accelerometer package and additional flowpath pressure transducers.

Axisymmetric Scramjet Description and Redesign

The hydrogen-fueled axisymmetric scramjet (fig. 4) is basically a CIAM Mach 6 design with modifications to the combustor and cooling system to allow testing at Mach 6.5. The fixed-geometry spike inlet consists of three conical section compression ramps set at 10°, 15°, and 20° ramp half angles. This geometry generates a

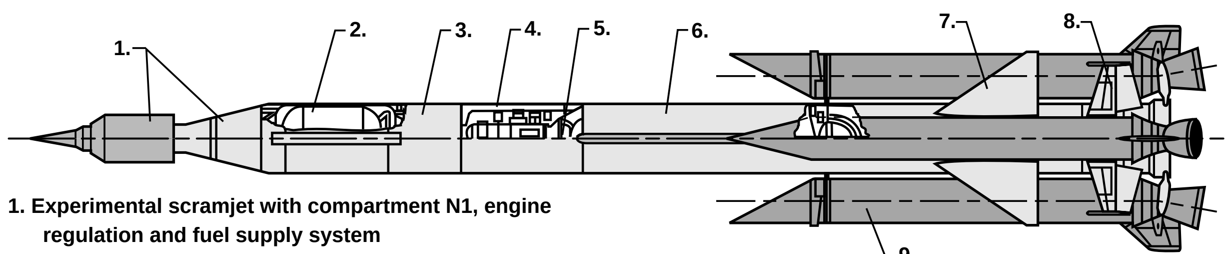

Figure 3. The Hypersonic Flying Laboratory.

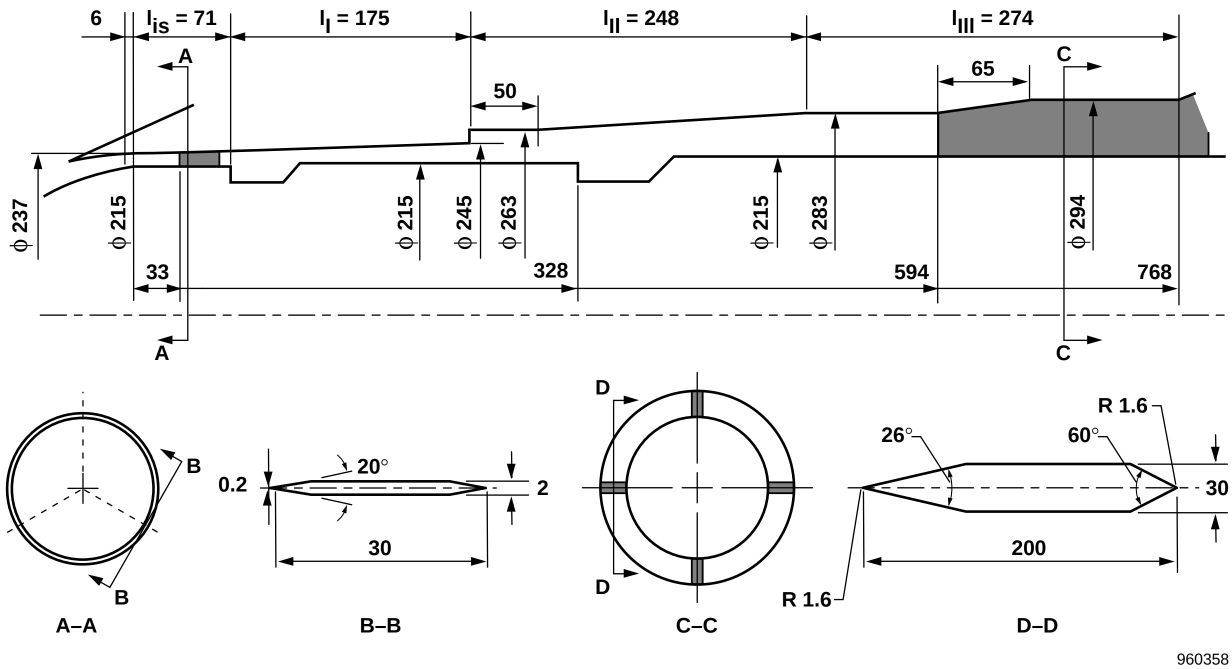

Figure 4. The dual-mode scramjet combustor.

single shock-on-lip condition at Mach 6 on the inlet leading edge or cowl lip, allowing for a slightly oversped flow condition at Mach 6.5. This inlet design was deemed to yield satisfactory engine performance without having to redesign and retest the entire inlet.

The inlet spike and inlet leading edge were uncooled, but the EP-666 stainless steel alloy material was replaced on the leading edge with a new steel-chromium-aluminum alloy called “Fekral.” This new material was necessary because analysis revealed excessive temperatures would be obtained for the leading-edge material at Mach 6.5 compared to past flights. Such temperatures exceed the capability of the EP-666 steel. The new Fekral material has approximately the same low thermal conductivity as the EP-666 steel. However, its much higher heat capacity allows Fekral to survive longer at the elevated temperatures to complete the aim test conditions of a 5-sec test time at Mach 6.5. The external cowl is coated with a chromium-nickel spray near the front to increase heat emissivity to 0.90.

In the combustor area, the isolator between the inlet throat and the first fuel injector station was lengthened 33 mm. The combustor section between the first and second fuel injector stations was lengthened by 45 mm. A final third row of fuel injectors completes that section before entering a truncated internal nozzle section. Each injector station is followed by a flame holder cavity containing electronic spark igniters that operate continuously. The flame holder cavity at the second injector station was modified to a simple aft-facing step.

Liquid hydrogen direct from the propellant tank circulates through the engine as regenerative coolant before being injected into the engine for combustion. The combustor area cooling system was modified to provide more efficient cooling before injection of the gaseous hydrogen fuel. The engine cowl-side of the flowpath is cooled by an all-steel liner; whereas, the (hot side) central body of the flowpath has a new modified copper alloy liner containing chemically milled 2- by 2-mm longitudinal cooling channels. The cold internal or back side of the center body copper cooling liner is an all-steel skin silver soldered to the hot side copper. For practical manufacturing and component integration purposes, small sections of the hot side cooling liner were left as stainless steel for instrumentation sensor installation and in the front section of the flame holders for fuel injector installation. The internal nozzle section aft of the last support pylon was also left as an all-steel cooling liner. The entire engine, including internally routed sensors, lines, and valves, was then welded together in a single unitized construction. All lines and instrumentation wiring were then run out the aft end of the engine center body to the rest of the HFL.

Modification of the SA-5 Missile Booster

Figure 5 shows the SA-5 booster with the HFL. This 1960's operational missile was selected by CIAM because of its performance and trajectory compatibility with the experiment requirements of the axisymmetric scramjet. The SA-5 has four strap-on solid boosters in addition to the main liquid fuel rocket engine and is launched from a railroad car. The HFL size and weight, basically replacing the original payload, allowed the SA-5 to attain its operational maximum speed of Mach 6. Modifications to the missile pushed it to Mach 6.5 at a dynamic pressure of approximately 1200 lb/ft^2 for this flight experiment. These modifications included several weight reduction measures onboard the HFL and the missile, such as reducing the size of the control fins along with control system changes, increasing the liquid propellant load, and improving performance of the solid-booster propellant. The launch angle was also increased from the original 48° to 52°. Figure 6 shows the trajectory for the upcoming flight.

Program Plans, Status, and Schedule

Figure 7 shows the program schedule. Technical design and engine manufacturing issues, along with extensive upgrades and checkout of the CIAM C-16 V/K wind tunnel have caused some program slippage in the original fall 1996 flight date. The present flight date is scheduled for spring 1997 and could be as early as January, depending on weather conditions. A fourth engine, intended as a second backup flight engine, is available for retest or additional follow-on test objectives.

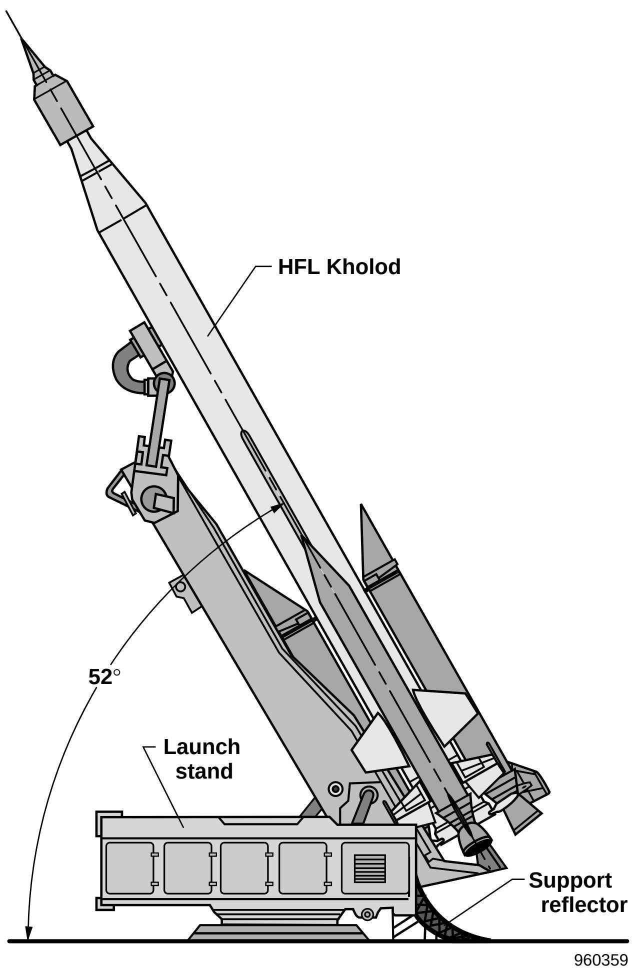

Figure 5. Modified launch stand for HFL "Kholod" for Mach 6.5.

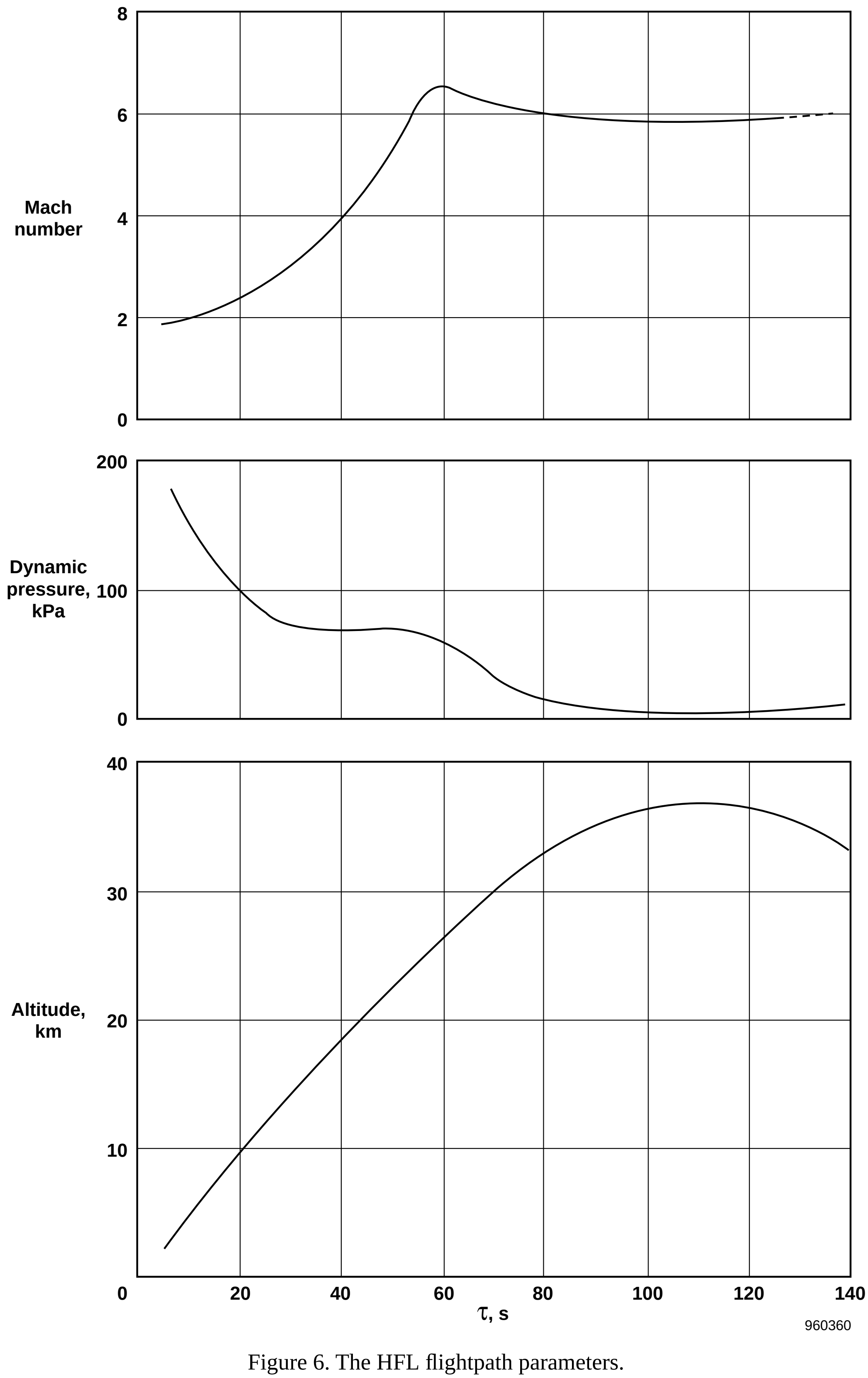

Figure 6. The HFL flightpath parameters.

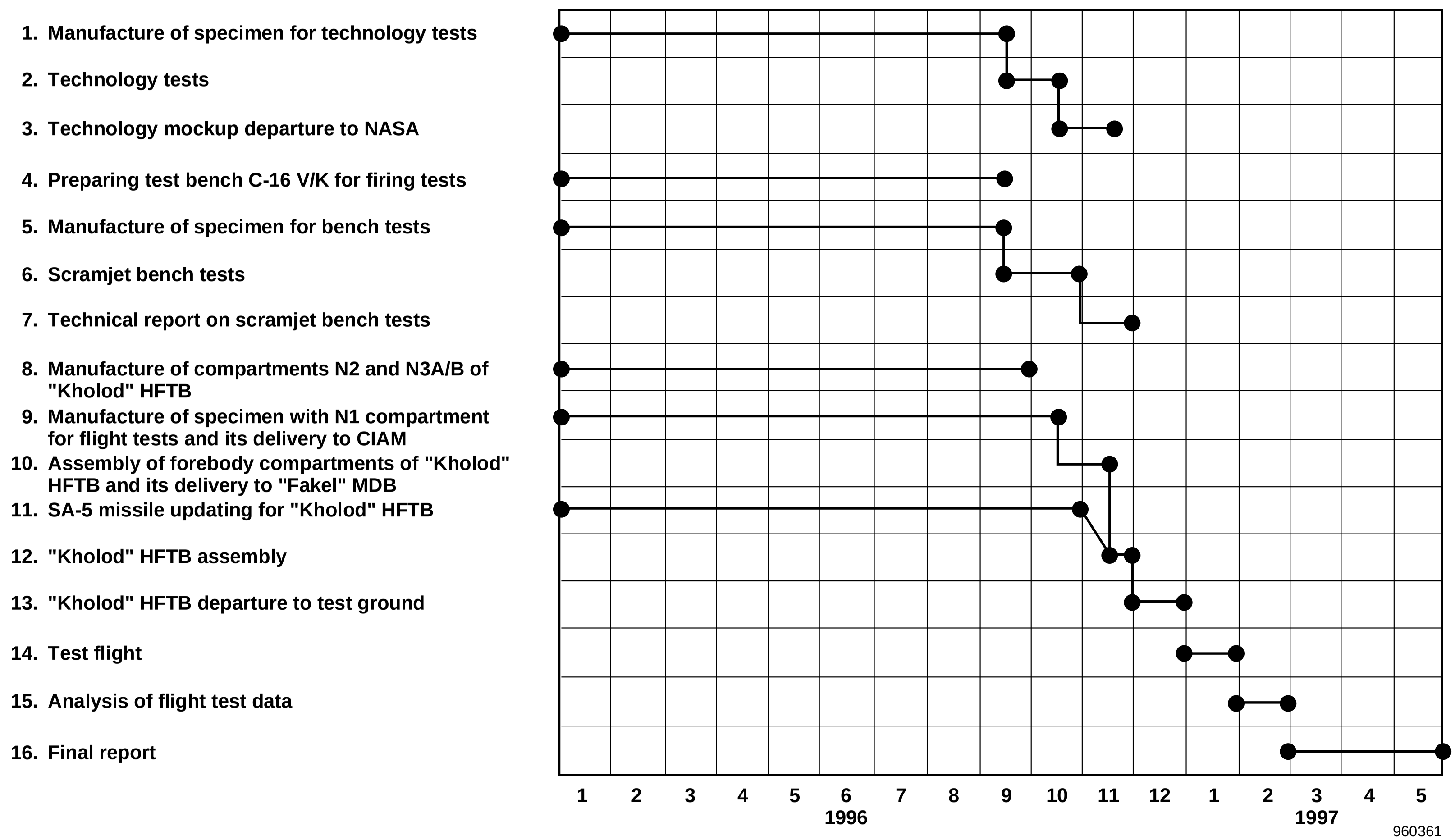

Figure 7. Program schedule.

Conclusion

This joint Russian-American scramjet flight test effort has focused on pushing the aeronautics frontier of hypersonic air-breathing flight to new levels at Mach 6.5. The current flight date is set in the spring of 1997. Significant modifications to previous flight tests with the Hypersonic Flying Laboratory and SA-5 missile were required to achieve objectives. In addition, numerous technical design and manufacturing issues had to be overcome. Nevertheless, the program has been a cost-effective way of developing hypersonic scramjet technologies. Valuable flight and ground test data with identical full-scale engines were obtained to correlate with one another and to compare with design tools and predictive analysis techniques. In addition, real synergy was achieved between CIAM and NASA in sharing design modification assessments, engineering analysis results, and other information and ideas. Valuable information was gained in comparison between ground facilities, analysis methods, sensor technology, and ground and flight test techniques.

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