Air-breathing propulsion for transatmospheric flight

Aerospace specialist Antonio Pasini reports the findings of a Rome symposium that posed a pathway for independent European development of the hypersonic airplane.

The symposium on "Air-breathing Propulsion Advances for Transatmospheric Flight" took place Feb. 22 at the University of Rome. The author had an opportunity to discuss the papers presented with Dr. Amilcare Bosso, general manager of public relations for FIAT Aviazione.

Winged vehicles powered by air-breathing propulsion systems have a major role to play in space transportation. The technological steps toward perfecting such vehicles are analyzed here in terms of those typical of advanced military engine development programs.

Strict integration is required between vehicle and propulsion systems, and the whole must be suited to cruise and ascent trajectory requirements. The key inducement to the development of such systems is cost reduction, in the face of expanded space transport needs. The goal is a drastic reduction of operating costs—as much as 90%. One major advantage of the new designs is that they would permit planes to take off from normal runways—for Europeans a decided plus. Like the Space Shuttle, these vehicles will be recoverable and reusable.

The lift trajectory of winged launchers in the atmosphere entails high aerodynamic drag losses, requiring high specific-impulse (high net thrust/propellant flow) propulsion systems for this phase of the mission. On the other hand, air-breathing engines exploiting the oxygen of the atmosphere as an oxidant achieve a higher payload capability if compared with expendable launching systems, provided that such propulsion systems have good thrust-to-weight ratios. The availability, therefore, of proper propulsion systems for the air-breathing phase of the space transportation mission is fundamental for winged launchers.

Several studies were carried out in 1950s and 1960s showing the merit of such systems, which highlighted certain very severe technology limitations. Yet, over the past two decades, developments in cryogenics, materials, aerodynamics, and systems—together with a greater readiness of European industry to apply advances to high-speed propulsion—have changed the picture, making feasible the winged launcher with air-breathing propulsion.

Air-breathing propulsion requirements

The European Space Agency (ESA) has recently promoted studies of this technology by favoring collaborative activities of major European aerospace industries. FIAT Aviazione participated in the first study in 1987, in collaboration with SNECMA/SEP, one of the largest French engine producers, and SNIA BPD, the Italian chemical and aerospace conglomerate, and it is now working on a second-phase study with Britain's Rolls Royce and MTU, the largest German aerospace engine producer. This is a subcontract, with overall contract responsibility vested in the West German firm Messerschmitt-Bolkow-Blöhm (MBB).

This second-phase study includes two launcher concepts: single stage to orbit (SSTO) and two stages to orbit (TSTO). The criteria for comparison relate to the optimization of propulsion system and vehicle integration, combined with ascent trajectory dynamics.

The ascent of a launch rocket, which needs no aerodynamic lift in atmospheric ascent, occurs at relatively low dynamic pressure, while in the case of winged launchers, flight at high dynamic pressure (0.4-0.7 bar) is necessary to have adequate lifting characteristics. The extreme importance of system optimization with respect to mission requirements and ascent trajectory is connected with the close relationship of useful payload capability to transition velocity and maximum dynamic pressure.

The transition velocity has to be considered as the stage separation velocity for the TSTO—this is the same point in the SSTO at which first stage reentry, or engine mode change occurs. From this point, a transfer into orbit trajectory is adopted. With reference to the dynamic pressure band and to the heat flux band, it appears that for subsonic combustion air-breathing engines, the limit of the transition velocity is mainly dictated by the engine itself, while a supersonic combustion ramjet could allow a higher transition velocity. In any case, the technology challenge related to supersonic combustion seems to indicate the scramjet as a long-term solution.

It follows from these considerations that the propulsion system requirements for these winged launcher systems can be summarized as follows:

- operational capability through a wide range of Mach numbers;
- high specific impulse;
- high thrust-to-weight ratio;
- high thrust-to-cross-section ratio for optimum aerodynamic integration with the vehicle—in fact, in this type of launcher, the air-intake cross-section represents a considerable portion of the overall vehicle cross-section;
- high degree of throttle control.

These requirements are very demanding, and partly conflicting, if referred to any of the typical engine families like turbojets, ramjets, and rockets. But good compromises can be obtained with advanced composite engines. The two extremes can be identified: turbojets or turbofans capable of very high specific impulse, but with modest specific thrust (thrust/weight); and rocket engines with low specific impulse and very high specific thrust. Intermediate values are associated with ramjets and scramjets, depending also on Mach number.

Furthermore, very different values for specific impulse result by considering hydrogen fuel or hydrocarbon fuel. This aspect also has to be analyzed within overall system optimization, because of differences in fuel density related to tank dimensions, and storage temperature in relation to cooling capability.

A large number of composite engine concepts are available, even apart from the LACE concepts (Liquefied Air Cycle Engine), where the oxidant, liquid oxygen, is obtained by liquefying air during the air-breathing phase, reducing the mass of oxidant to be transported. This approach is still problematic and must be regarded as a longer-term development.

The turboramjet

The turboramjet concept is based on a combination of the turbojet with a ramjet. Turbojet operating range is up to Mach 3.0, at which velocity the core engine is closed off by an inlet vane structure and bypassed by primary airflow in order to allow operation in a ramjet mode. During the ramjet mode, the core has to be properly cooled to avoid heat rejection from both the hot-air environment and combustion. This can be obtained by feeding cooled air bled from the diffuser.

The core engine can be derived directly from a conventional aero-engine with advanced materials applications. Typical features of this engine materials cycle are a pressure ratio at takeoff of about 10-15, with a maximum compressor exit temperature of 900-1,000° K and turbine inlet temperature in the range of 1,800-2,000° K. (1,000° K is 1,340° F; 2,000° K is 3,140° F.) The reheat operation is expected to be stoichiometric with temperatures in the range of 2,800-3,100° K. A full variable geometry is required for air intake and the exhaust nozzle to guarantee proper matching through the wide operating range.

A variant of the turboramjet concept is the precooled turbojet where the limits imposed by stagnation temperatures in the core are overcome by cooling the air inlet flow with liquid hydrogen, by building a heat exchanger into the air intake. This could allow the core engine to operate through the whole air-exchange phase with limited changes in component operating conditions.

The turborocket

The turborocket concept results from a combination of a turbojet and a rocket. In the turbojet, the turbine and compressor flows are decoupled and the turbine is driven by a mixture of liquid hydrogen and liquid oxygen pre-burned in a gas generator. The purpose of this concept is to allow an increase in Mach number without incurring the limit of turbine inlet temperature. Since the air flow passes through the compressor in the entire operating range, the limit of this concept is represented by the temperature tolerance of the compressor blades. Composite materials, suitably protected from oxidation, must be developed for this purpose.

Typical features of this cycle are a moderate pressure ratio, about 2.5 : 1, and a turbine entry temperature of about 1,400° K. The reheat combustion is obtained downstream from the turbine, at stoichiometric conditions. During the ramjet mode of operation, starting at Mach 2.5-3.0, the compressor is windmilling and the resulting losses can be reduced by use of variable inlet guide vanes.

A variant of the above concept is the hydrogen expansion turborocket where the turbine is driven by hot hydrogen, obtained by heating the liquid hydrogen in the reheat by means of a heat exchanger. Such a concept allows improvement of the specific impulse, but extends the technology challenge to heat exchangers required to operate in a very difficult environment.

The ramrocket

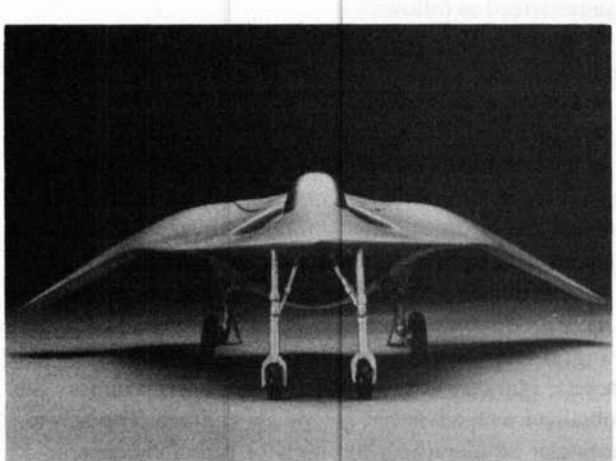
The ramrocket concept results from the combination of a ramjet and a rocket. The operating modes are:

- **Ejector mode** during takeoff phase up to Mach 1-1.5, in which rocket performance is improved by mixing rocket exhaust gases with air that participate in the combustion process (air/rocket gas flow = 1:1.3, oxygen : hydrogen = 6:1);
- **Ramjet mode** up to transition velocity, in which combustion is stoichiometric, and because of the wide range of Mach numbers, very wide nozzle geometry variation (10 : 1) is required;
- **Rocket mode** with closed air intake, in the transfer into orbit trajectory.

Performance comparison of the three basic concepts, considered in terms of specific impulse and specific thrust, suggests turboramjets are to be preferred for those winged launcher concepts where a high specific impulse is more important than specific thrust, as in the case of TSTO vehicles, with cruise capability requirements. In contrast, a ram-rocket solution is more interesting for applications in SSTO vehicles where the thrust/weight ratio is of greater importance. Turborockets offer intermediate performance characteristics and could be a good compromise, depending on the selected mission.

The technological effort on the propulsion system must be oriented according to which composite engine concept is chosen. This remains true even though the challenge can be generalized as an increased temperature capability inclusive of the installation features. In fact, high dynamic pressure and Mach number in the air-breathing phase lead to high internal pressures (about 10 bar at Mach 7, but varying with the intake geometry selected) and high stagnation temperatures (2,100° K at Mach 2) resulting in severe thermal and structural loads on engine components, especially air intakes and turbomachinery.

A fully reusable space plane


The Capuani design for a reusable scramjet.

The goal of reusable space plane programs is to develop new propulsion systems, systems that will go from Earth's surface into space and back again.

In the 1930s, German aeronautical scientist Eugen Sänger designed the first horizontally launched spacecraft, which could take off from an airport-type runway. The Sänger project, led since the 1960s by German aerospace giant Messerschmitt-Bolkow-Blöhm (MBB), has been an effort to investigate novel ways of propelling a plane from the Earth's surface into supersonic and hypersonic regimes, all the way to the Mach 25 needed to go into orbit.

Sänger's key concept was to use the oxygen in the atmosphere to burn hydrogen fuel, rather than carrying along liquid oxygen, which has been done since the German V-2 of the 1940s. The MBB Sänger project envisions a turboramjet first stage which, carrying the second-stage orbiter, reaches a speed of Mach 7 at an altitude of about 110,000 feet.

At this point, the rocket engine on the orbiter is ignited and the second stage separates, carrying its payload into orbit, while the first stage lands horizontally. According to MBB, one advantage of this two-stage design is that the first stage produces, as a by-product, a hypersonic (Mach 7) airliner, similar to the U.S. concept for an "Orient Express."

Although most of the effort internationally in the various aerospace plane projects has necessarily been in the area of challenging and risky new propulsion systems, Dr. Alfredo Capuani in Italy has been testing new aerodynamic designs to minimize the drag and maximize the efficiency of the overall spaceplane design. Capuani's work takes its lead from the research in supersonic aerodynamics of Adolf Busemann, who solved the problem theoretically of destabilizing shock waves that form around aircraft as they approach the speed of sound.

The unusual geometry of the Capuani spaceplane is derived from the formation of a "Busemann biplane" configuration, where the shock waves formed from the air flow around the wing of the plane are canceled by the use of two wings. In the Capuani design, it is the relationship between the wings on the spaceplane and on the carrier/first-stage vehicle that produce the Busemann biplane effect. The Capuani design also includes a high-powered lift design, which can make use of short airport runways.

Furthermore, to optimize engine performance during the air-breathing phase, a good compromise for combustion in respect to thrust and specific impulse is to design for stoichiometric combustion, which in turn means to operate at reheat temperatures on the order of 3,000° K, with resulting severe thermal loads, especially in exhaust nozzles.

The technological developments from the 1960s, as mentioned, have been such as to allow realistic consideration of the development of a high-speed propulsion system in the time-frame of the years 2000-2010. The technology advances achieved in commercial aero-engines and under development for future advanced military engines represent a good basis for a realistic technology readiness program.

Higher temperatures, greater strengths

The key technologies to be developed relate to increased temperature capability and advanced design methods. The advanced high-temperature metallic and non-metallic materials, composite structure, and advanced cooling techniques under study and development will be fully exploited only if—in parallel—aerodynamic design capability is improved. That means fully three-dimensional viscous-flow computer simulation codes, computational description of reacting flows, and computational structural analysis. Advances in these fields will be the basis for light-weight, high-power, air-breathing engines.

The expected advance in the aero-engine in the next 15-20 years is expected to be a transition from the advanced fully metallic engine to non-metallic engines, almost doubling the core specific power.

A very ambitious and demanding effort is therefore required in the field of materials design, so that all engine sections undergo an increase in operating temperature and strength-to-density ratio. For cold section components, an improvement of specific strength by two to three times can be expected, with a temperature tolerance increase to 920-1,250° K. Increases will occur with hot section components, which will be gradually pushed to operate up to 1,750° K with advanced cooling techniques. The aim, with advanced composite materials, will be to achieve 1,900-2,500° K without cooling. Here strength-to-density is expected to improve by three to five times.

Non-structural materials, like bearings and lubrication systems must also improve their capability to operate at higher temperatures—to around 1050° K. This will require new types of lubricants, both liquid and solid, and ceramic bearings.

Some new materials

There are already several materials and relevant processes under development which may be capable of achieving these ambitious targets in existing programs which are proceeding in parallel to the development of the advanced military engine. Obviously, the advanced non-metallic materials, even where already used for investigative tests, are not yet developed sufficiently for application in engines because of limited life. Nonetheless, the capability so far demonstrated is encouraging.

The most promising materials are:

- **High-temperature alloys.** New alloy combinations can be produced by rapid-solidification-rate, powder metallurgy applied to aluminum (up to 750° K), titanium (up to 1,250° K), and columbium (up to 1,750° K).
- **Aluminides.** These intermetallic compounds containing aluminum show great promise for increasing oxidation resistance. Again, powder metallurgy will provide considerable progress toward the future use of these materials (titanium and nickel aluminides).
- **Metal matrix composites.** These composites represent an alternative solution for high specific strength materials.
- **Ceramic matrix composites.** This class of composites has improved considerably in recent years, but intensive development is still necessary in respect to their toughness.
- **Carbon-carbon composites.** These are some of the highest-payoff, but highest-risk materials presently under development. One of the most critical problems is the anti-oxidation protection for long life, which tends at present to degrade the strength of these composites.

Technological progress in advanced aero-engines, therefore, is a fundamental basis for achieving high-speed propulsion, even if the specific requirements dictated by various composite engine concepts highlight other fields where technology development programs have to be launched. Whatever the chosen concept may be, air intakes and nozzles will require a considerable, dedicated effort, both in design and in materials development for the strong impact they have on installed engine performance (specific impulse and specific thrust), and the high degree of integration they must have with the vehicle.

Concerning the core engine, specific technological advances could be required in cryogenics, especially for feeding systems, turbines, and reheat-type hydrogen-fueled combustors. Other special areas can be added to the list depending on the concept chosen, such as highly loaded steam-type turbines and light-weight high-power gearboxes for turborockets, or advanced heat exchangers.

In addition, the integration of different engine concepts requires a solution to problems of mixing of reactive subsonic and supersonic flows.

This considerable technological effort has to be approached from the very beginning of the technology readiness program—and even more during the following development phase—with strict cooperation among major European aero-engine companies.

The technologies required for the air-breathing propulsion of the future have to be approached as a natural evolution along the technological paths already in place in advanced military programs, and have to be built on the experience already available within aero-engine industries.