Hypersonic Turbomachinery-Based Air-Breathing Engines for the Earth-to-Orbit Vehicle

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Hypersonic air-breathing engines will make the Earth-to-orbit vehicle completely different from the present one powered by rocket engines. The space plane propelled by a certain hypersonic air-breathing propulsion system is expected to appear in the next century. The turbomachinery-based engine (turboengine) is a candidate for the space plane propulsion system and will be combined with scramjet and rocket engines. Turboengines, including turboramjet, air-turboramjet, and their modifications, may be applied as the accelerators to the space plane having a high specific impulse at a rather low supersonic Mach number. Here, a conceptual study of these turboengines with preliminary system design, performance calculations, and consideration of relative merits of the engine concepts is performed for the configuration, performance, weight, and size. An engine evaluation with mission capability of the space plane for assumed requirements is made. As a result, engine performance depends on the liquid oxygen utilization, and weight and size of the engine are important factors for application to the space plane. Thus a certain optimization of the engine system itself and of a combination of the engines would be necessary.

Introduction

JAPAN is presently discussing future space development programs, including a challenge for manned space activities.[1] Construction of a space infrastructure, which would consist of space stations, satellites, space platforms, space transportation systems, and other space systems, is anticipated for the 21st century. A safe, economic, and highly operable space transportation system carrying people to space is expected. The space plane, which is based on aeronautics and takes off and lands horizontally, may be the most favorable for this purpose because the technical achievement in aeronautics with the safety and comfortability concept could be widely applied.[2]

The space plane will be one of the most challenging subjects in the scientific and technical fields for the next 20 years. The United States, Europe, and Japan began to promote their own study programs of the single-stage-to-orbit (SSTO) vehicle or the two-stage-to-orbit (TSTO) vehicle in which the hypersonic air-breathing engines will be installed.[3-5] Each of them includes extremely challenging programs in its technology research and development.

The National Aerospace Laboratory (NAL) of Japan is now very active in research on high-speed vehicles, including the space plane, and its propulsion systems. For the propulsion system of the space plane, turboengines (turbomachinery-based engines), ramjet, scramjet, liquefaction air cycle engine (LACE), and reusable rocket engine are being investigated. Liquid hydrogen is selected as the fuel because of its inherent potential as a coolant and as a thermodynamic working fluid. Some combination of propulsion concepts should be applied to the space plane because no one concept is optimum over the entire flight speed, namely $v = 0$–8 km/s.

A system study of air-breathing engines to select the optimum propulsion concept is necessary in order to visualize the space plane concept to be developed. Thus, a certain engine selection methodology should be developed. Conceptual study, presented in this paper, is a preliminary step for establishing such methodology.

This paper describes a result of the conceptual study on some promising turboengines, namely turboramjet (TRJ) and air-turboramjet (ATR) engines including the gas-generator cycle (ATR-GG), the hydrogen expander cycle (ATR-EXP), and the liquefied air cycle (ATR-LA) engines. The turboengines are combined with scramjet and rocket engines for constructing the space plane's propulsion system. Figure 1 shows a typical flight path of the space plane reaching low Earth orbit and flying back to the base on Earth.[6] In this figure, the turboengine is applied until the vehicle reaches Mach 6 (point A), and the scramjet engine is used for higher flight speed up to Mach 12 (point B) (line TE + SCRJ + R). The flight trajectory using other engines such as the LACE is assumed to be similar to that shown in this figure.

The study is based on the performance analysis and preliminary system design of the engines and flight analysis of the space plane in which a particular propulsion system is in-

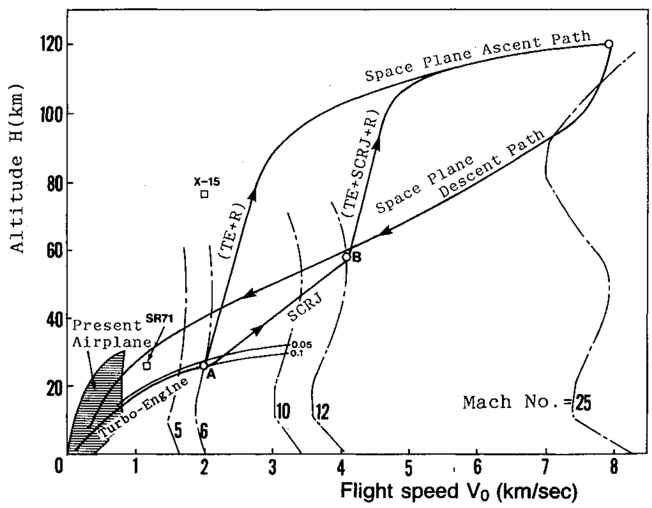

Fig. 1 Flight path of space plane.

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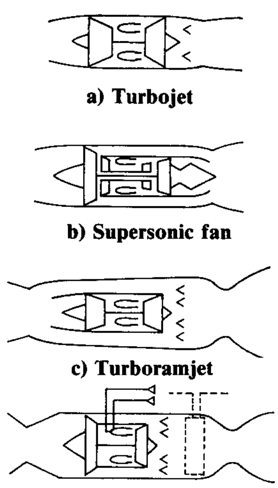
stalled. The space-plane flight analysis done here is spatially two-dimensional and made for evaluation of the engine capability to identify those that best achieve the minimum fuel burn to get to space.

The relative merits of these engine systems are described from several viewpoints. System configurations and engine performance such as thrust and specific impulse are considered to evaluate the system characteristics. Analyses of influences of fan or compressor pressure ratio and equivalence ratio to the engine are made. Engine weight and size obtained from the preliminary system design are also considered. As a conclusive analysis, mission capability of a space plane defined as the remaining weight of the vehicle in low Earth orbit, which is the rest subtracted by the fuel burned from the vehicle gross weight, is considered for an assumed mission requirement.

Engine Concepts and Cycle Descriptions

Many turboengine concepts have been investigated as candidates for the propulsion system of the space plane or hypersonic transport (HST).[6-8] From experience in development of turbojet engines for supersonic aircraft and basic research therein, it can be said that the turboengines that have turbocomponents compressing the air with compressors or fans and expanding the exhaust gas with turbines have great potential for a high-speed propulsion system even to the space plane. Turbojet, supersonic fan, turboramjet, and air-turboramjet are the typical concepts to be considered for that.[7] Their concepts are shown in Fig. 2.

Taking the operable range over Mach 3 into account, TRJ and ATR are much more feasible than the other turboengines because they have advantages of adoption of the ram technology. The TRJ (Fig. 2c) is a combined system of supersonic turbojet and ramjet. The maximum Mach number of the supersonic turbojet installed in the system would be around 3 because of the limitation of the turbine inlet gas temperature. In order to achieve a higher flight Mach number, a ramjet component is necessary. Its target maximum Mach number is set at 6.



a) Turbojet

b) Supersonic fan

c) Turboramjet

d) Air-turboramjet

Fig. 2 Turboengine systems.

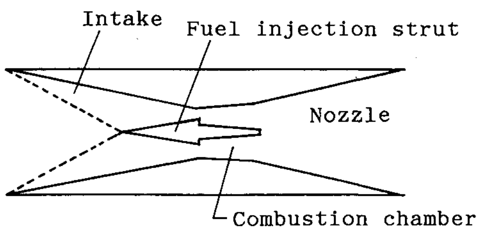


Fig. 3 Scramjet engine concept.

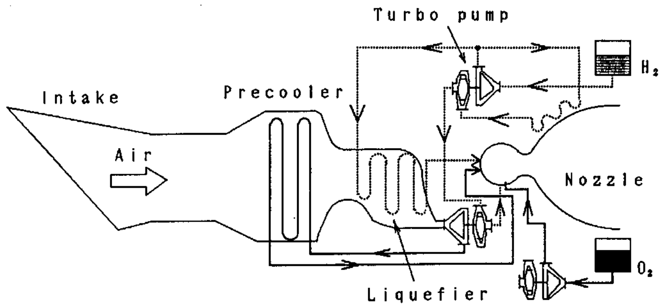


Fig. 4 Basic LACE concept.

The ATR (Fig. 2d) is a high bypass ratio turbofan engine but has a special turbine driving the fan. Its target maximum Mach number is also set at 6. Technologies of the system are based on turbofan and rocket engines. Fuel-rich combustion gas (gas-generator cycle: ATR-GG) or heated hydrogen fuel gas (expander cycle: ATR-EXP) is used as the working fluid in the fan-driver turbine. A heat resistant fan is one of the key technical problems for the engine realization. Similar to the gas-generator cycle, the ATR-LA can be considered, in which a part of the air being utilized as the oxidizer in the gas generator combustor is liquefied by cryogenic hydrogen fuel. So, a hydrogen-cooled heat exchanger will be equipped.

Figure 3 shows a concept of the fixed geometry scramjet engine, which was originally investigated at the NASA Langley Research Center.[9] A main air/gas path consists of an air intake, a combustion chamber, and a nozzle. In the space-plane performance study, scramjet engine performance carried out in our lab[10] was used.

Figure 4 shows a concept of the basic LACE system. The system is based on the rocket engine, but liquefied air is utilized as the oxidizer in the rocket engine combustion chamber instead of installed liquid oxygen. The air breathed in through the intake is cooled and liquefied by a multistage hydrogen-cooled heat exchanger installed in the diffuser.

Figures 5–7 show enthalpy i-entropy s diagrams of the TRJ, ATR, and LACE engine cycles. As shown in Fig. 5, the TRJ cycle is a combination of the reheat turbojet cycle and ramjet cycle. The operational mode changes with the flight Mach number. In a medium range Mach number such as 2 to 4, the turbojet-ramjet combined mode is used.

The ATR cycle diagram (see Fig. 6) is characterized by heat addition processes in its gas generator (ATR-GG) or heat exchanger (ATR-EXP) and turbine expansion process as shown in the figure. This is also a combined cycle, which consists of a turbine cycle and a fan-ram burning cycle. The enthalpy drop in the turbine process is larger than the fan compression enthalpy change because the flow rates of the working fluids in the turbine process are much less than that of the fan process.

Figure 7 shows a cycle diagram of basic LACE. Ram compression and subsequent air liquefaction processes are indicated. The pumping work of the air is comparatively small because the air is liquefied. The turbopump processes of the propellants are not shown in the figure.

Engine System Arrangement of Turboengines

System studies from preliminary engine design of the turboengines were carried out by the authors in Ref. 11, which gives engine configurations, sizes, and weights. Figure 8 shows a conceptual illustration of the turbojet subsystem and ram combustor of the TRJ engine. This is called integrated or laparound TRJ because a turbojet subsystem is installed inside the ramjet system. A rather low pressure ratio of the engine is suitable because of the presence of considerable ram compression at high Mach number flight.

The overall system configuration with intake and thrust nozzle being installed on the space-plane fuselage is shown in Fig. 9. The engine has three operation modes—turbojet, com-

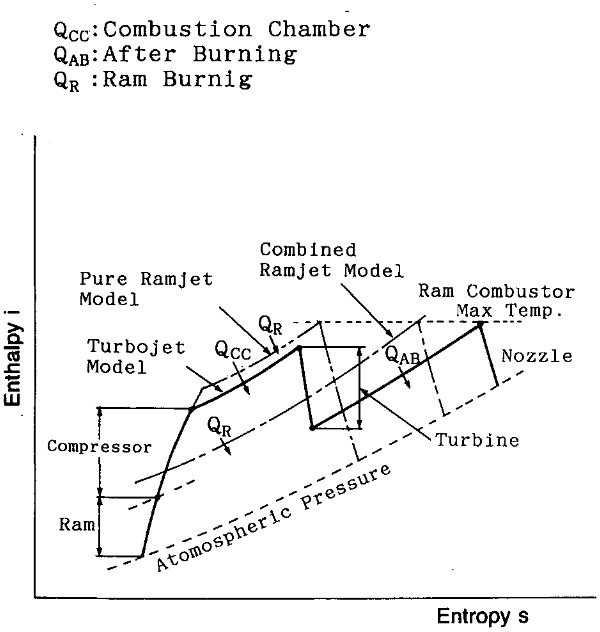


Fig. 5 Enthalpy-entropy diagram of TRJ cycle.

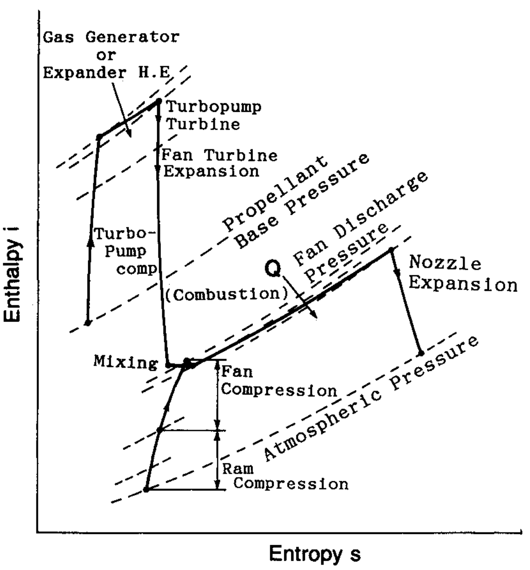


Fig. 6 Enthalpy-entropy diagram of ATR cycle.

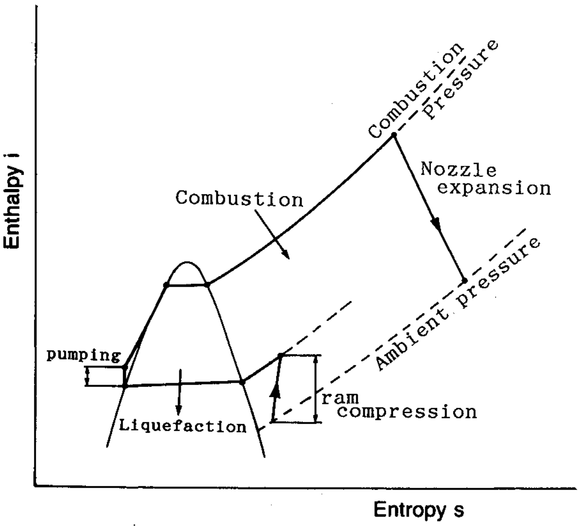


Fig. 7 Enthalpy-entropy diagram of basic LACE cycle.

bined turboram, and ramjet mode—which change with the flight Mach number. In the ramjet mode operation, a pair of the shutter doors closes in order to protect the turbojet section from the hot air coming. The air intake is also variable to optimize its operation.

Figure 10 shows a system arrangement of the expander cycle ATR-EXP engine. A fan, a small diameter turbine, a ram combustor with fuel injector/flameholder system, a regenerative heat exchanger, and a variable thrust nozzle are shown. A two-stage fan is driven by a five-stage turbine connected with a high loading reduction gear. The fan pressure ratio, whose sea level value is between 1.7 to 3.5, is programmed to vary as a function of the flight Mach numbers because ram pressure increases for higher flight Mach numbers. The regenerative heat exchanger heats the hydrogen fuel up to about 1000°C and is installed at the ram combustor or nozzle to obtain necessary heat from the combustion gas. Existence of the heat exchanger causes pressure drop of the gas flow and engine weight penalty.

The system arrangement of the gas-generator cycle engine is similar to that shown in Fig. 10 except for the existence of a gas generator instead of a heat exchanger. Oxygen for gas-generator combustion is necessary and supplied from an installed oxygen tank.

The ATR with the air liquefaction system (ATR-LA) is shown in Fig. 11. Liquefied air to be supplied to combustion in the gas generator is made in a hydrogen-cooled liquefier installed downstream from the air intake.

Table 1 shows weight and size of the 15 ton (147 kN) thrust engines determined from the preliminary system design study of TRJ, ATR-GG, ATR-EXP, and ATR-LA. ATR-GG is the lightest of all. In Table 1, advanced materials means that advanced materials such as ceramics and advanced carbon-carbon composites are adopted, and conventional material means conventional material is being used in the engine. Use of advanced materials may make the engines lighter by more than 30%.

Engine Performance

Thrust F_N and specific impulse *Isp* were calculated for the engine performances of the TRJ, ATR-GG, ATR-EXP, and ATR-LA. The component parameters such as adiabatic efficiencies of the turbomachinery, combustion efficiency, pressure loss coefficients of the flow paths, and mechanical losses are assumed according to current technology. Variable intake and nozzle are adopted, but geometric limitation of the intake, which means a maximum inlet opening area, is considered. The air intake is geometrically fixed for a Mach number higher than 4.

Thrust and specific impulse of the TRJ are shown in Figs. 12 and 13. The thrust, which is indicated by the thrust density defined as the thrust divided by the fan frontal area, increases with flight Mach number very rapidly for every altitude condition at a flight Mach number lower than about 4. The specific impulse is 3000–4000 s, as shown in Fig. 13. It is a considerably high value compared to the present chemical rocket engines whose *Isp* is on the order of 450 s.

Thrust and specific impulse of the ATR-GG as functions of Mach number and altitude are shown in Figs. 14 and 15. Simi-

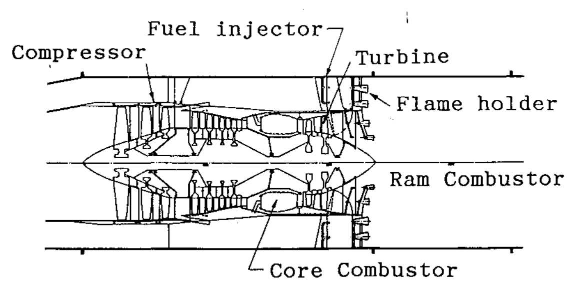


Fig. 8 Turboramjet engine system (core section).

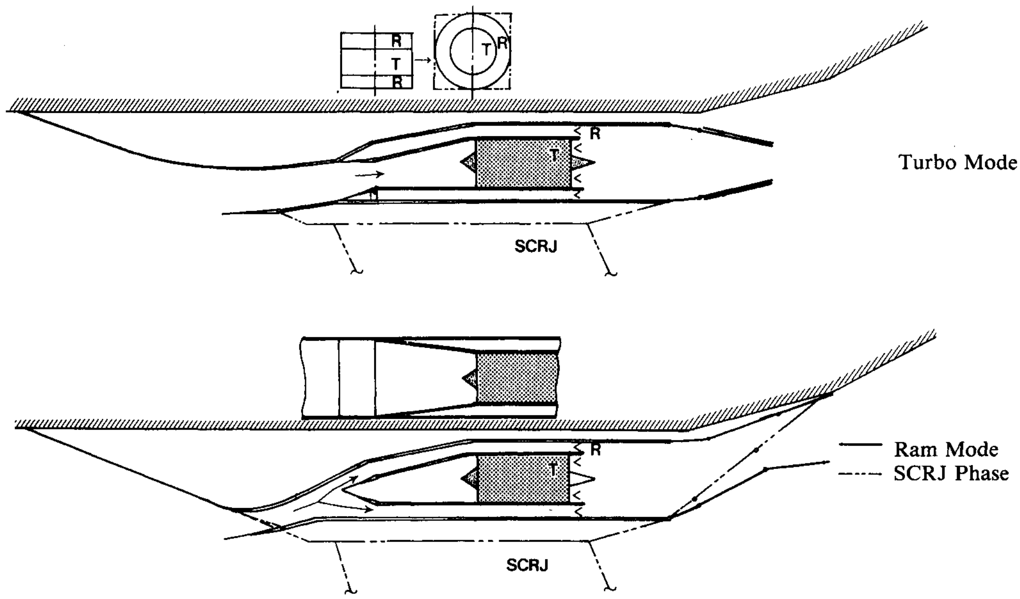


Fig. 9 System arrangement of TRJ installation.

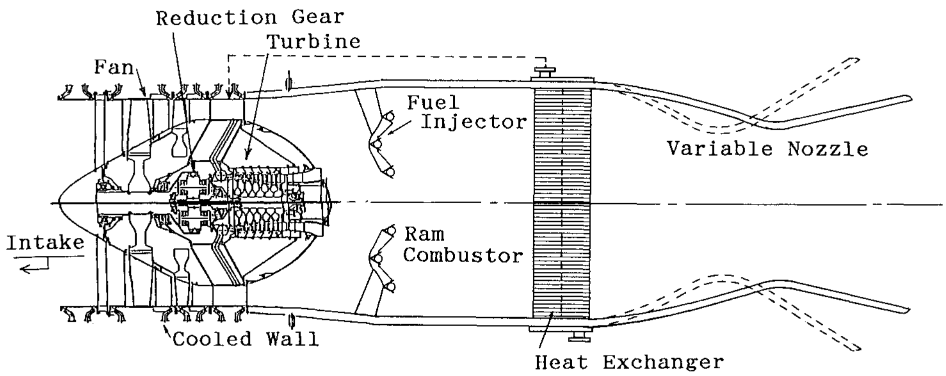


Fig. 10 Expander cycle air-turboramjet (ATR-EXP) engine system.

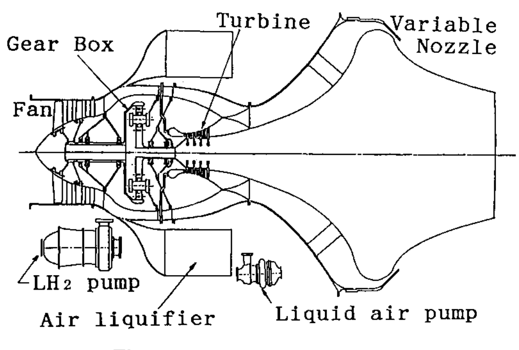


Fig. 11 ATR-LA engine system.

lar to TRJ, the thrust increases very rapidly with Mach number and decreases with altitude. ATR-GG has its *Isp* of 2000–3200 s varying with Mach number and altitude, which is also much higher than the current chemical rocket engines but lower than TRJ. The fan pressure ratio affects *Isp* in a wide range of Mach numbers but has little effect on the thrust. Performance of the ATR-EXP cycle is shown in Figs. 16–18. Thrust of the ATR-EXP is not shown because the thrust is almost the same as that of ATR-GG. The *Isp* of ATR-EXP is higher than that of the ATR-GG—especially in the low Mach number region, as shown in Fig. 16. As indicated before, lack of liquid oxygen use for turbine working fluid gives a reason for a higher *Isp* than the GG cycle, which liquid oxygen is necessary in its gas generator. Higher fan pressure ratio causes higher *Isp* at a low Mach number.

Equivalence ratio of the fuel/air mixture and the ram combustor effects on *Isp* of the ATR-EXP engine are shown in Fig. 17. The *Isp* increases with the equivalence ratio at a higher Mach number ($M = 5$). The result may be used for engine throttle consideration.

Comparison of *Isp* of the engines calculated along the flight trajectory of the vehicle is shown in Fig. 18. The *Isp* of ATR-EXP, ATR-LA, and TRJ are almost the same within their operating region, whereas the *Isp* of the ATR-GG is lower than that of the others because of liquid oxygen utilization in the gas generator.

Flight Analysis and Engine Evaluation

Flight analysis of the space plane on which air-breathing engines are installed could be a first-order evaluation of engine systems. Evaluation of the engines is made with the viewpoint of mission capability that is the remaining weight of the vehicle when it reaches at the low Earth orbit using propellant. The thrust weight ratio of the engine is also important for the evaluation. Aerodynamic parameters of the vehicle, such as lift and drag as function of the Mach number and the attack angle, were obtained from the computational fluid dynamics (CFD) and the wind-tunnel tests of the NAL vehicle configurations.[12]

Figure 19 is an example of calculated results of the total weight change of the vehicle by consuming the propellant through its flight. The results of TSTO as well as SSTO are shown in the figure. In this figure, the propulsion system consists of the air-breathing engines, which are the combination of ATR-GG or ATR-EXP, scramjet, and rocket engines. The switch velocity *Vsw* (or the switch Mach number *Msw*) means the maximum operable velocity (or Mach number) of the air-breathing engine system, and rocket engine is used beyond this vehicle speed. The cases of $Vsw = 1.8$ km/s ($M = 6$), $Vsw = 2.7$ km/s ($M = 9$), and $Vsw = 3.6$ km/s ($M = 12$) for SSTO are shown.

As shown here, the propellant is consumed for accelerating the vehicle, and so the total weight of the vehicle (*Wv*) decreases along its flight. The air-breathing engine consumes less propellant than the rocket engines, as indicated in the figure. The weight change of the TSTO, whose separation Mach number is 6, along its flight is also shown in Fig. 20 as a reference.

The calculated results of the mission capability *Worb*/*Wo*, which is defined as the ratio of the portion of the vehicle weight remaining on the orbit after the propellant was used to

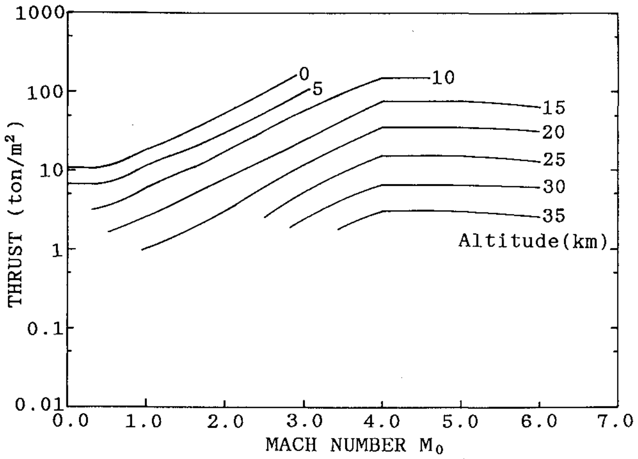


Fig. 12 Thrust of TRJ engine.

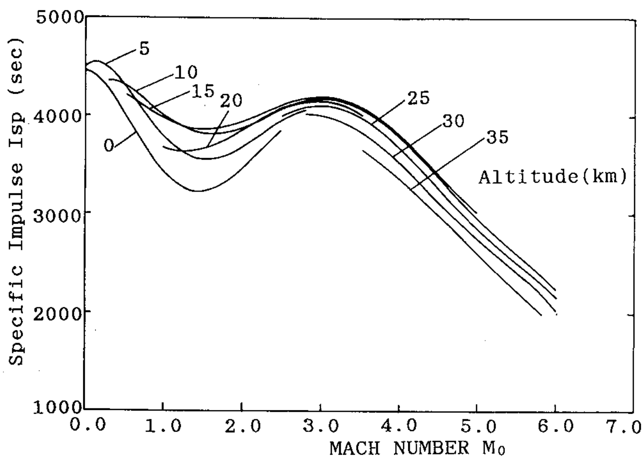


Fig. 13 Specific impulse of TRJ engine.

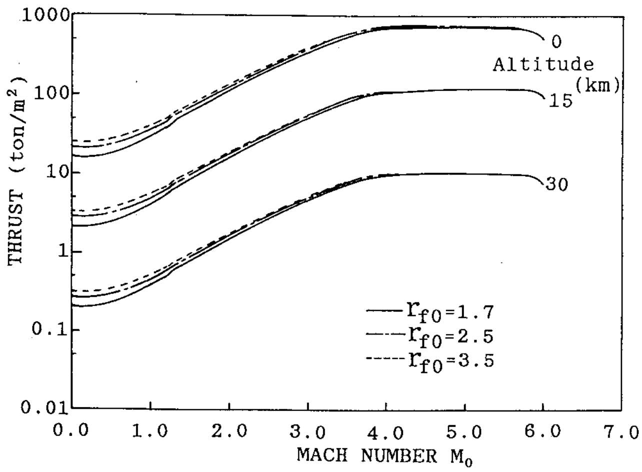


Fig. 14 Thrust of ATR-GG engine.

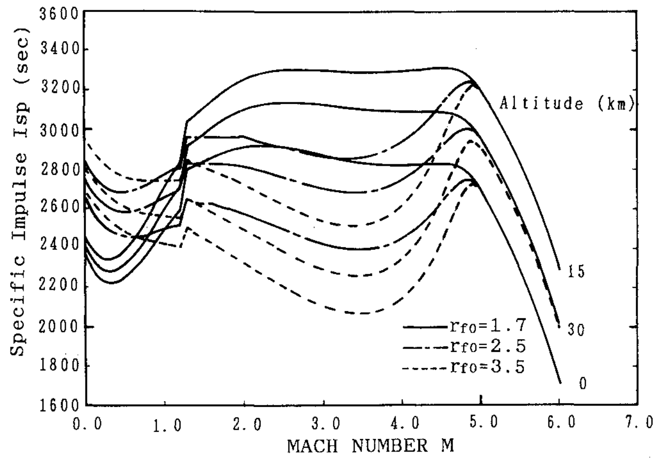


Fig. 15 Specific impulse of ATR-GG engine.

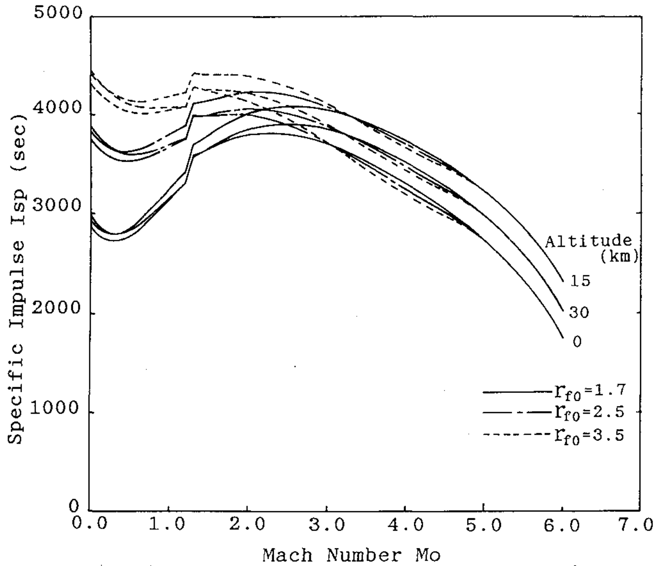


Fig. 16 Specific impulse of ATR-EXP engine.

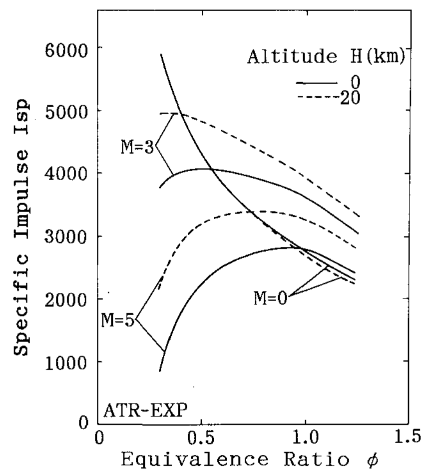


Fig. 17 Effect of equivalence ratio on specific impulse.

Table 1 Weight and size comparison

	ATR-GG, $r_{f0}=2.5$	ATR-EXP, $r_{f0}=2.5$	ATR-LA	TRJ	Reference turbojet,[a] PWA $F-100$
Thrust					
SLS, kN	147	147	147	147	106
Weight,[b] kg					
Conventional material	1570	2410	(2000)	2340	1375
Advanced material	970	1550	1330	1310	—
Thrust-to-weight ratio	15.5	9.7	11.3	11.5	—
Size, cm					
Diameter[c]	100	108	93	86/103[d]	93
Length[b]	280	380	290	300/550	486

[a]Data from *Jane's 87-88.* [b]Excluding air intake and nozzle skirt. [c]Fan diameter. [d]Engine itself, with flow separation door.

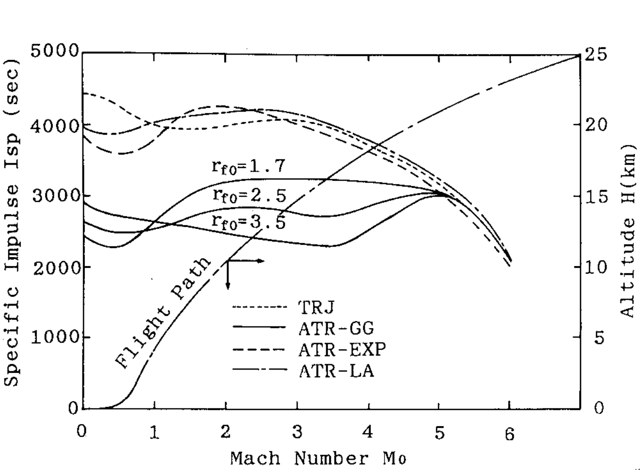


Fig. 18 Comparison of specific impulse along a flight path.

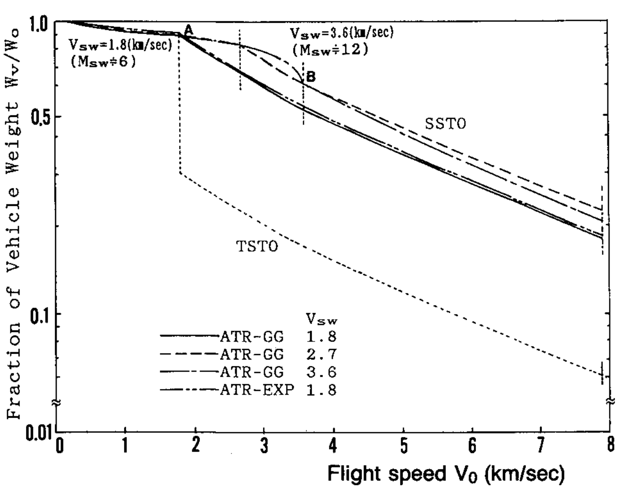


Fig. 19 Vehicle total weight change by propellant consumption through the flight.

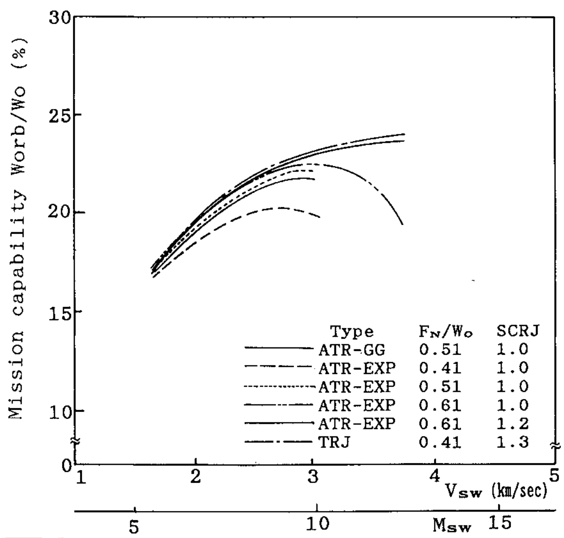


Fig. 20 Mission capability *Worb/Wo* of the vehicle vs switch velocity *Vsw*.

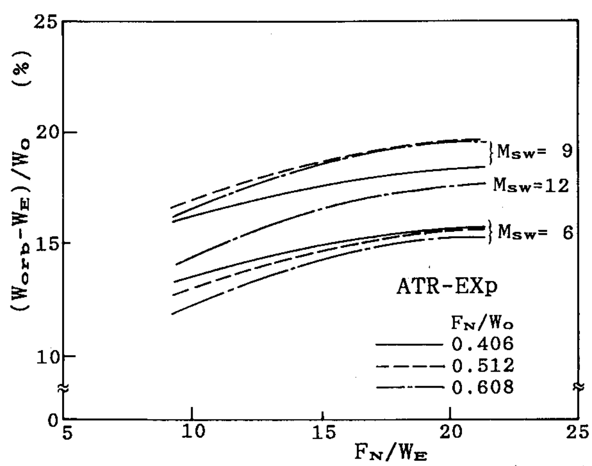


Fig. 21 Effect of engine thrust-to-weight ratio.

accelerate and elevate the vehicle to the low-Earth-orbital condition *Worb* to the gross weight *Wo*, are shown in Figs. 20 and 21.

Figure 20 shows the mission capability *Worb/Wo* vs switch velocity *Vsw* (*Msw*) using ATR-GG, ATR-EXP, and TRJ coupled with the scramjet engine for *Vsw* higher than 1.8. The turboengine thrust size compared to the vehicle weight (thrust-to-weight ratio: *Fn/Wo*) between 0.41 and 0.61 was considered. The fan pressure ratio of the ATR-GG and ATR-EXP in this study was 2.5. The scramjet sizes are expressed in figures typed under the sign of SCRJ in Fig. 21, and 1.0 means that the thrust of the scramjet engine (*Fn, s*) at the *Vsw* is the same as that of ATR (*Fn, a*) at the same speed. Similarly, 1.2 means *Fn, s* $=1.2\times$ *Fn, a* at *Vsw* and so on.

The switch velocity *Vsw* (*Msw*) is the fundamental variable affecting the mission capability. Generally, the higher *Vsw* brings the larger mission capability with the same engine size.

The differences in the turboengine performances reflect very little for the mission capability. On the contrary, the engine size affects the mission capability by every *Vsw*, that is, a larger engine with a larger thrust can elevate a larger mass to the orbit. Similarly, the mission capability is influenced by the scramjet engine size strongly for higher switch velocity. Figure 21 shows effects of the engine weight (thrust-to-weight ratio) and size on the mission capability, which is the weight on the orbit subtracted by the engine weight $(Worb - W_E)/Wo$. The variable W_E denotes the total engine weight of the turboengine installed on the vehicle. The thrust-to-weight ratio of the engine (Fn/W_E) is considered. It can be said that the lightweight engine is desirable for the space plane in principle. Although the large size scramjet is adequate for a higher switch Mach number, a rather small size turboengine is better than a large one for $Msw = 6$.

Thus the engine system, size performance, and maximum operable Mach number should be considered to obtain the desirable propulsion system by some optimization.

Concluding Remarks

A system study of air-breathing propulsion is essential to determine a concept of the space plane and its propulsion system at the early stage of research and development. A conceptual study of the turboengines including performance calculation and system evaluation was conducted.

1) System arrangements and performances of the turboengines such as TRJ, ATR-GG, ATR-EXP, and ATR-LA were presented.

2) The thrust differences between these engines are little and the *Isp* mainly depends on the liquid oxygen utilization. The *Isp* of the ATR-GG is the lowest of all, and the others are almost identical.

3) High *Isp* is favorable for the space plane performance.

4) High switch velocity from the air-breathing engines to the rocket engine is very significant in obtaining high mission capability of the space plane.

5) A high thrust-to-weight ratio that is lightweight is very important for the space plane, meaning the ATR-GG has the advantage in that even its *Isp* is rather low.

6) Engine size optimizations should be necessary for adoption to a space plane with engine combination.

For further system study, the engine-airframe integration, including air intake and an exhaust nozzle system, more detailed component data, and material to be applied, should be considered.

Acknowledgments

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