AIAA-93-5010
Systems Studies on Spaceplane Powered by Airbreathing Propulsion - Alternative Version TSTO Concept -

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AIAA/DGLR FIFTH INTERNATIONAL AEROSPACE PLANES AND HYPERSONICS TECHNOLOGIES CONFERENCE
30 NOVEMBER - 3 DECEMBER 1993 / MUNICH, GERMANY

Systems Studies on Spaceplane Powered by Airbreathing Propulsion - Alternative Version TSTO Concept -

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Abstract

In 1987, Japan's National Aerospace Laboratory of the Science and Technology Agency (NAL) initiated a research program defining a spaceplane systems concept along with the development of the required hypersonic technological base to support this concept. This initiative was based upon the Space Activities Commission's long-term space policy for future space transportation system development.

The spaceplane concept, optimally configured as a single stage to orbit (SSTO), horizontal take-off and landing system, with integrated hypersonic airbreathing propulsions, is a potentially promising option, which has been presented at the previous 1991 and 1992 conferences (Scram/LACE SSTO). In the systems studies, a two stage to orbit (TSTO) concept was also examined as a reference to the SSTO concept.

This paper will discuss a TSTO spaceplane concept with emphasis on a booster vehicle powered by a rocket based LACE (Liquid Air Cycle Engine) airbreathing propulsion system.

I. Introduction

The need for a fully reusable space transportation system has been driven by the inherently expensive operational costs of current ballistic based launch systems. To overcome the disadvantages of the current system, a reusable, safe and flexible, horizontal take-off and landing system, is required as a successor to the current systems which will be phased out around the year 2010.

Japan's future space transportation policy was deliberated by the Consultative Committee on Long Term Policy under the Space Activities Commission and the Advisory Committee on Spaceplane under the Research and Development Bureau of the Science and Technology Agency, in 1987. Based on the program plan of these committees, a technological base spread across a wide variety of engineering disciplines would be built through research and development efforts in a time-phased scenario aimed at proposing a fully developed spaceplane at the turn of the century. Key technological areas currently being addressed under this effort are as follows: aerodynamics, structure and materials, guidance and control, computational fluid dynamics, manned flight and airbreathing propulsion.

Ideally, for the case of simplicity an SSTO spaceplane is the ultimate goal of this technological drive. TSTO concepts introduce the complexity of two vehicles and operational aspects of the entire launch system become more complicated. However, whether SSTO enabling technologies will be available to fill the void foreseen by the phase out of current launch systems is still uncertain. A TSTO option is thus becoming an attractive and possibly a necessary in-between step in the development of future space transportation.

This paper examines a TSTO concept studied as an alternative reference to NAL's SSTO concept. This study was conducted to help further understand the operational features and assess the technological feasibility of the two systems.

II. Spaceplane Concept

The main objective of developing a new space transportation system is to reduce current operational costs while improving safety, reliability, and comfortability for manned vehicles. Along with this, enhanced operational flexibility with quick turn around capability is desired. In order to achieve these objectives, the following system design features have been incorporated into the design of spaceplane.

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(i) to exclude vehicle expendability (fully reusable)
(ii) to utilize aircraft-type operation ground facilities, and to exclude the complexity of vertical launch
(iii) to employ the system capabilities for horizontal take off and landing and reduce thrust loading at take off by wing lift, with multi-engine redundancies
(iv) to reduce the heavy liquid oxygen and to improve propulsion performance by integrating an advanced airbreathing propulsion system

These are illustrated in Table 1.

In order to assess the feasibility of the above concept a set of baseline mission requirements were tentatively set as follows:

- Space transportation to and from Low Earth Orbit (500 km destination orbit with inclination angles of up to 28.5 degrees) with a crew of 10 and a payload recovery capability of 2 tons
- Short term experimental laboratory in orbit for earth observation, microgravity, etc
- Servicing of platforms and satellites with resupplies, maintenance and repair, space passenger tour by orbital or sub-orbital flight (with orbital stay time of minimum five days)

NAL's SSTO spaceplane and TSTO booster-orbiter systems were both designed to meet these requirements and address the objectives of a new form of space transportation system.

III. TSTO System Concept

As was mentioned in the introduction, disadvantages to TSTO launch systems are obvious. The drawbacks, however, were accepted in the basic design philosophy for TSTO in order to avoid the current problems faced with SSTO systems, which are as follows:

- Scramjet propulsion has not yet fully matured and is still a critical technology for SSTO concepts
- Airbreathing propulsion may not be suitable for accelerators such as spaceplane because the wide ΔV regime requirement presents off-design penalties
- Development cost of advanced hypersonic airbreathing propulsion is very high and a design to test methodology has not yet been established
- Actively cooled structure technology is not yet mature

This TSTO vehicle concept was designed with, as much near-term structure technology as possible. It was designed to achieve orbiter separation in low flight dynamic pressure, and is powered by a rocket based propulsion system. In order to improve propulsive performance and reduce the quantity of oxidizer carried, an airbreathing cycle was included in the engine design. This airbreathing engine, a LACE-C (Liquid Air Cycle Engine - with Compressor), will be discussed in the following section.

KEY REQUIREMENTS IN ACHIEVING Space Plane OBJECT

OBJECT :
- Enhance Operational Flexibility, Safety / Reliability
- Reduce Operational Cost

REQUIREMENTS :
- Totally Reusable
- Horizontal Take-Off and Landing
- Ability to Abort Safely at All Times following an Initial Failure
- Quick Turn Around
- Acceleration by Advanced Hypersonic Airbreathing Propulsion System

Table 1

A slush-hydrogen mixture of 50% solid/liquid fuel (SLH_2) is used to increase the energy density of the vehicle's fuel and to simultaneously increase the amount of coolant available for liquifying air with LACE. These two features are the critical enabling technologies for this TSTO concept and are the current focus of research at NAL.

The main characteristics of both the booster and orbiter have been outlined in Table 2, and an illustration of the booster-orbiter combination is shown in Figure 1.

IV. Vehicle Specifics

As in most space vehicle concepts, the propulsion system design predominates and determines many of the physical aspects of the vehicle. It also dictates the flight path and other parameters for the system. The predicted performance of the LACE-rocket system proposed for this TSTO concept has likewise been used extensively in its design.

A schematic diagram of a single LACE-C system is shown in Figure 2, and the specifications are listed in Table 3. The proposed booster for this TSTO system is equipped with five of these LACE-rocket engines. Each

Total Length	77.8 m
Wing Span	27.8 m
Height	9.7 m
Body Length	75.8 m
Body Width	6.4 m
Body Height	7.4 m
Wing Delta Angle	60.0 deg
Wing Aspect Ratio	1.416
Wing Area	470.0 m^2
Take-off Wing Loading	957.4 kg/m^2
Landing Wing Loading	186.2 kg/m^2
Dry Weight	87.5 ton
Crew	10 persons
Propellants	
(i) SLH2	122.6 ton
(ii) LOX	85.4 ton
(iii) Jet Fuel	18.2 ton
Vehicle Gross Weight	450.0 ton
Landing Weight	91.8 ton
(i) Body	*22.8*
(ii) Wing (Main & Tail)	*15.8*
(iii) Thermal Structure	*0.3*
(iv) Engine Thrust Structure	*1.3*
(v) Propulsion System	*39.9*
LACE	*(16.7)*
SLH_2 TANK	*(13.8)*
LOX TANK	*(2.3)*
JET FUEL TANK	*(0.9)*
Supply System	*(3.6)*
(vi) Sub Systems	*6.5*
Main Engines	
(i) LACE (100ton thrust at S.L.S.,5 engines)	5 set
(ii) Jet Engine (12ton S.L.S,)	2set

Table 2 TSTO Vehicle Characteristics (Booster)

Total Length	38.7 m
Wing Span	16.7 m
Height	10.0 m
Body Length	35.7 m
Body Width	4.4 m
Body Height	5.0 m
Wing Forward Swept Angle	70 deg
Wing Aspect Ratio	1.18
Wing Area	222.4 m^2
Landing Wing Loading	155.2 kg/m^2
Dry Weight	33.7 ton
Crew	10 persons
Propellants	
(i) SLH2	13.4 ton
(ii) LOX	80.6 ton
(iii) RCS & OME	4.1 ton
Vehicle Gross Weight	132.6 ton
Landing Weight	34.5 ton
(i) Body	*6.0*
(ii) Wing (Main & Tail)	*4.8*
(iii) Thermal Structure	*4.6*
(iv) Engine Thrust Structure	*0.3*
(v) Propulsion System	*6.75*
ROCKET	*(1.8)*
SLH_2 TANK	*(1.38)*
LOX TANK	*(1.36)*
RCS & OME SYSTEM	*(1.75)*
Supply System	*(0.45)*
(vi) Sub Systems	*11*
Main Engines	
(i)ROCKET (100ton thrust at S.L.S,)	1 set

TSTO Vehicle Characteristics (Orbiter)

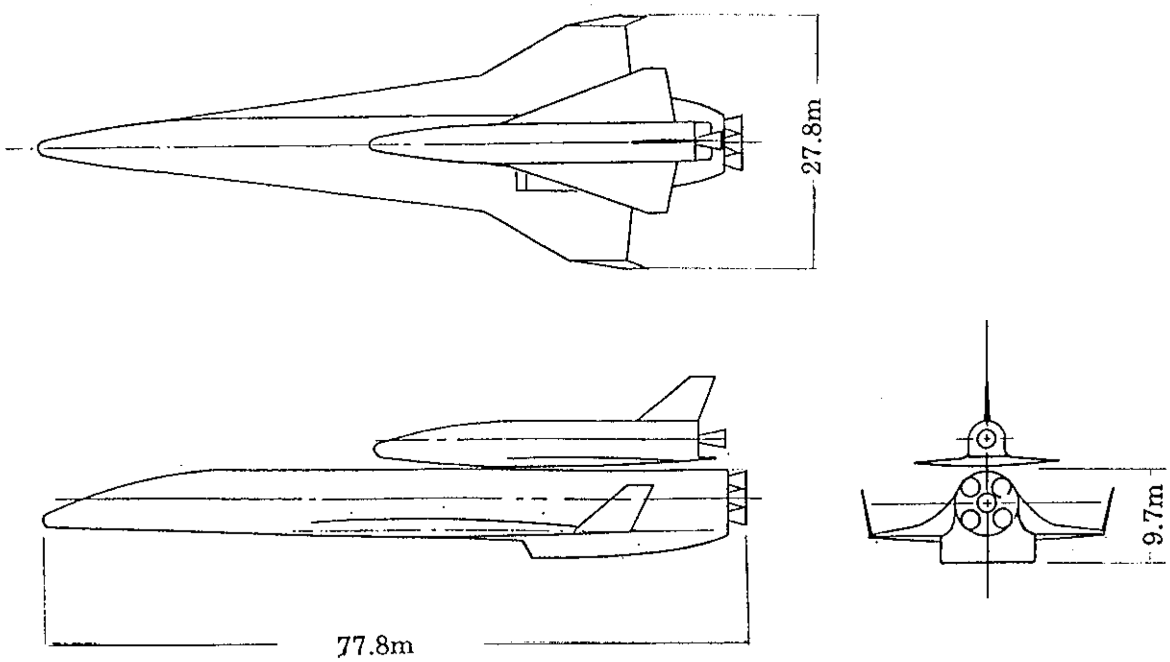


Figure 1 General View of Present TSTO Spaceplane

of these engine systems is capable of producing 100 tons S.L.S. thrust and is designed to operate in two modes, LACE and conventional rocket.

Initially, at low altitudes operating in the LACE mode, each engine ingests air through an intake. This air is cooled through a series of heat exchangers by utilizing the 125 tons of slush-hydrogen (SLH_2) on board. Along with the help of a compressor, the cooled air is driven into the liquid state. It is then used as the oxidizer in an LE-7 type rocket engine and burned with the higher enthalpy state liquid hydrogen.

The performance of this engine system has been estimated over a range of mach numbers and altitudes with some of the results shown in Figures 3 and 4. The first showing the estimated specific impulse and the second the engine thrust.

Results similar to these indicated that a larger number of separate inlet-engine systems provided a higher Isp and also that the larger the total inlet area the higher the Isp. The number of LACE systems and the air intake area were optimized, or more appropriately stated, compromised, according to these results, to achieve a maximum effective Isp over the flight path, all within permittable design constraints of the LE-7 engine. A five engine system with a total capture area of 22.5 m^2 was chosen as an optimum for the system.

At higher altitudes, when the liquification of air becomes impractical, the engines operate as a conventional rocket. The liquid air oxidizer being replaced with LOX from a tank carried on board. During this phase of operation, the thrust from the engines is essential constant and does not depend on altitude or speed as it does in LACE mode. See Figure 5 for a complete time history of the estimated thrust and drag.

The only other propulsion system installed on the booster vehicle is a set of two turbojet engines, each with 12 tons S.L.S. thrust which have been incorporated to enable a powered landing for the booster on return from its sub-orbital flight.

The orbiter's power plant is another LE-7 type rocket engine modified slightly with a higher expansion ratio nozzle. It produces 113 tons thrust at vacuum and is fueled by SLH_2 and LOX both carried internally in tanks. Figure 6 is an illustration of the modified engine and nozzle for the orbiter. This system is very typical and poses no technical challenge to the design. The orbiter is also equipped with the necessary RCS and OME sub-systems.

Using the HASA (Hypersonic Aerospace Sizing Analysis) data base, a weight estimation was made of the vehicle concept according to the mission outline. The entire system's gross take-off weight (GTOW) was estimated at a value of 450 tons due to sizing optimization.

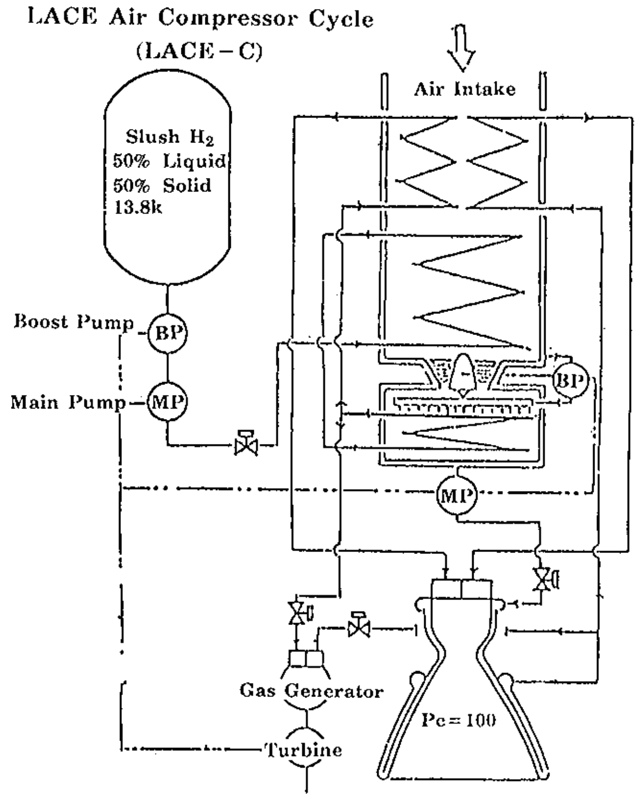


Figure 2 Schematic of LACE-C

(LACE mode)

Engine Cycle	air liquefied with compressor
Thrust(S.L.S)	100ton
Combustion Chamber Pressure	100Kgf cm^2
Specifie Impulse	1280seconds
Turbine Drive	gas generator
Compressor	axial and centrifugal max. com. ratio 12.5
Fuel	50% slush hydrogen
Combustion Chamber	radiation cooled (columbium alloy)
Nozzle Skirt	2 stage extension radiation cooled (carbon / carbon)

(Rocket mode)

Engine Cycle	gas generator cycle
Thrust (vacuum)	125ton
Combustion Chamber Pressure	100Kgf/cm^2
Specific Impulse (vacuum)	450seconds
Mixure Ratio	6:1
Propellants	LOX / LH_2

Table 3 Specifications of LACE-C

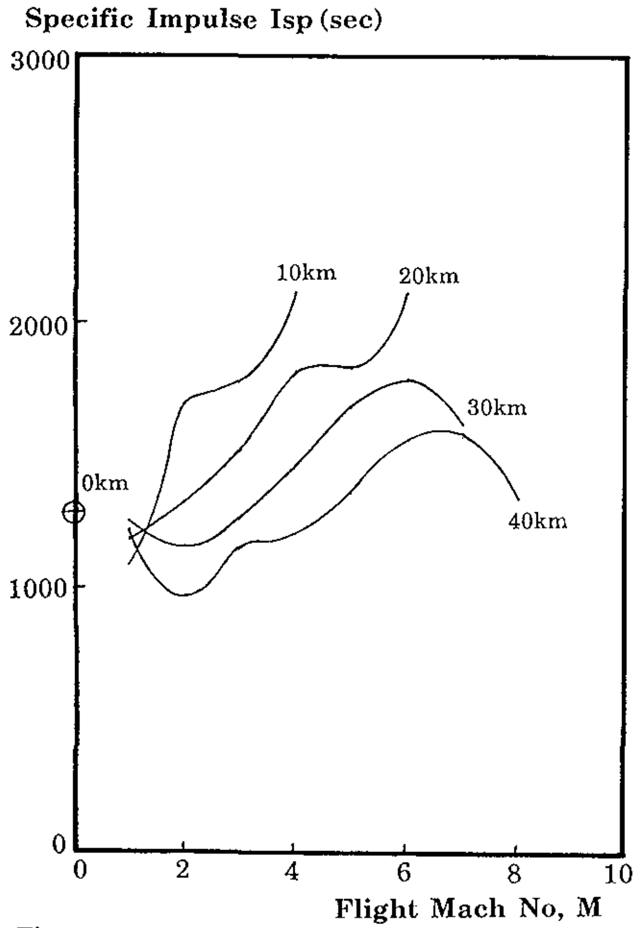


Figure 3

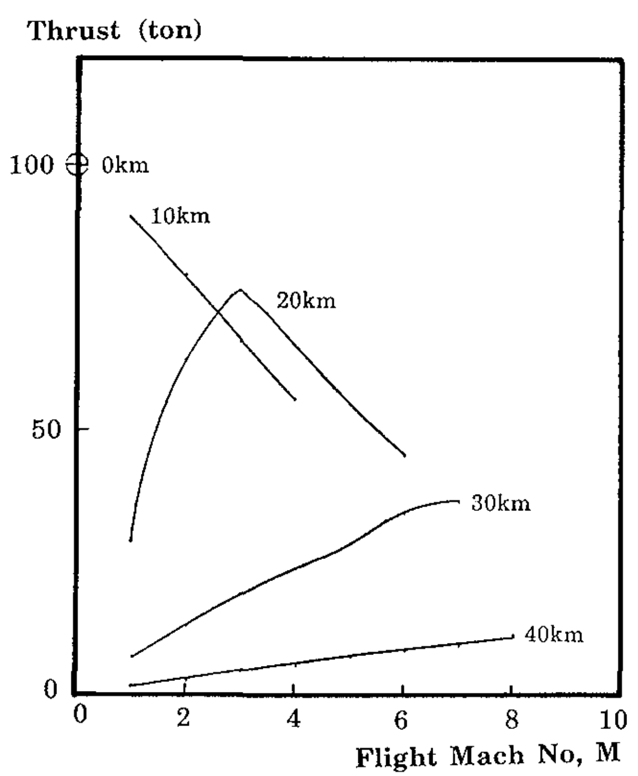


Figure 4

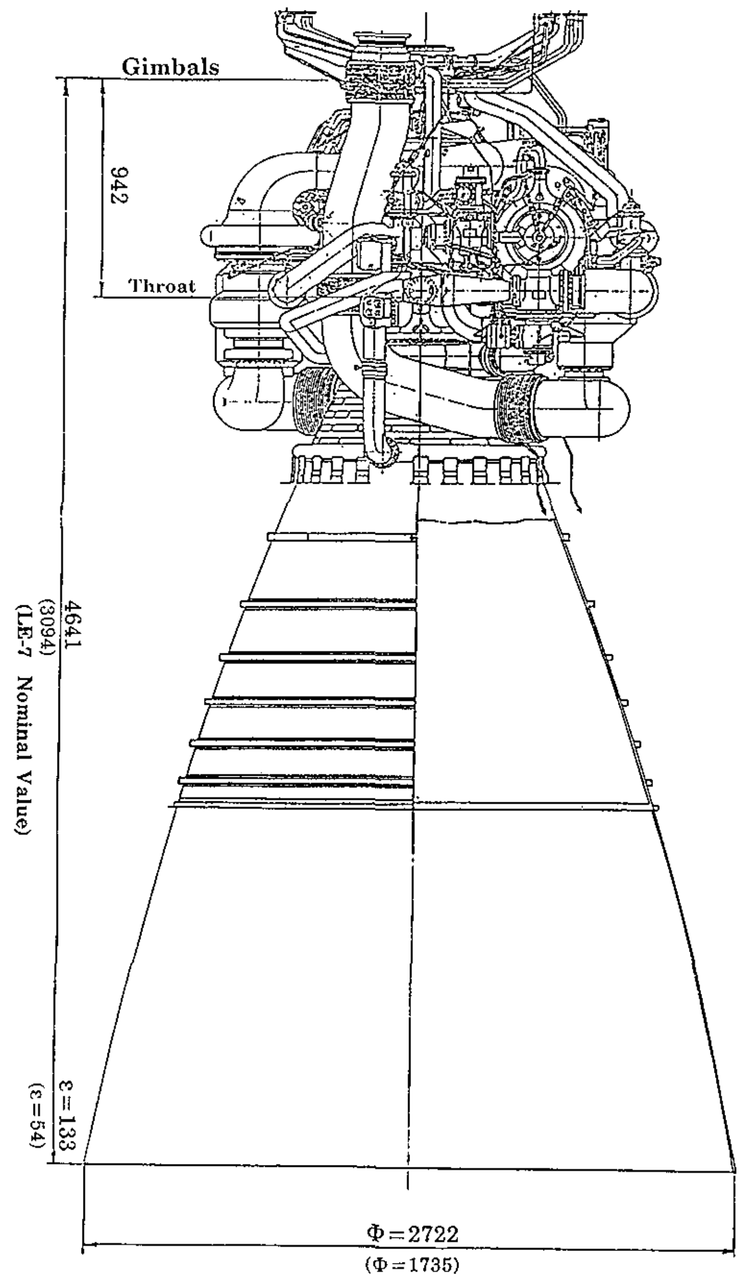


Figure 6 Modified LE-7 Rocket

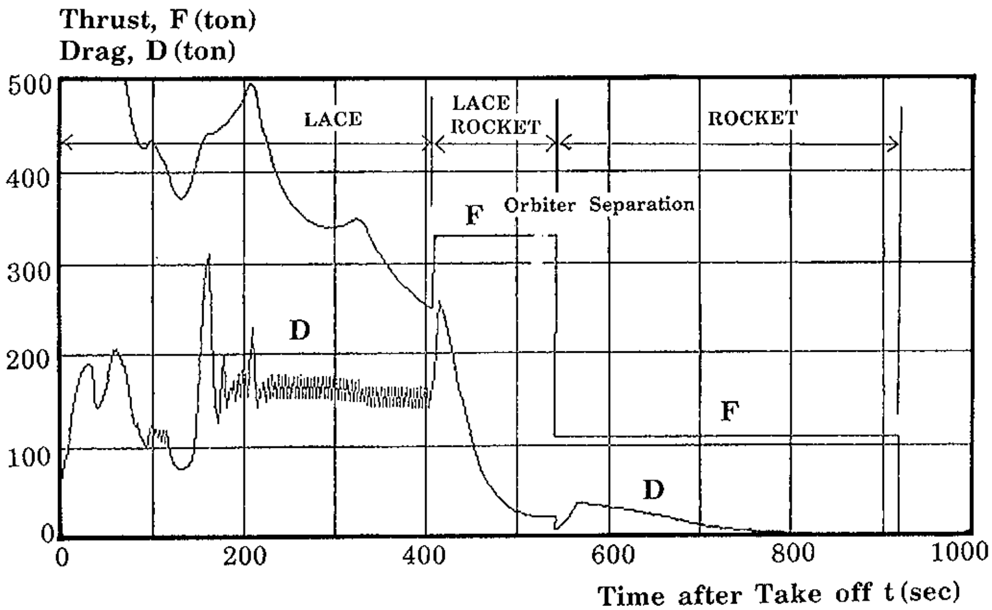


Figure 5 Estimated Thrust and Drag

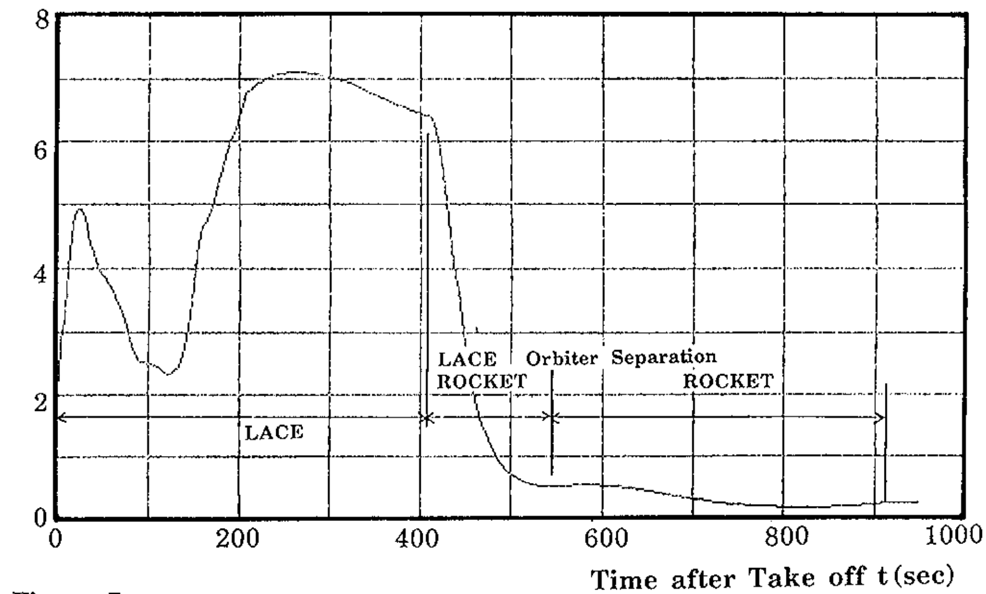


Figure 7

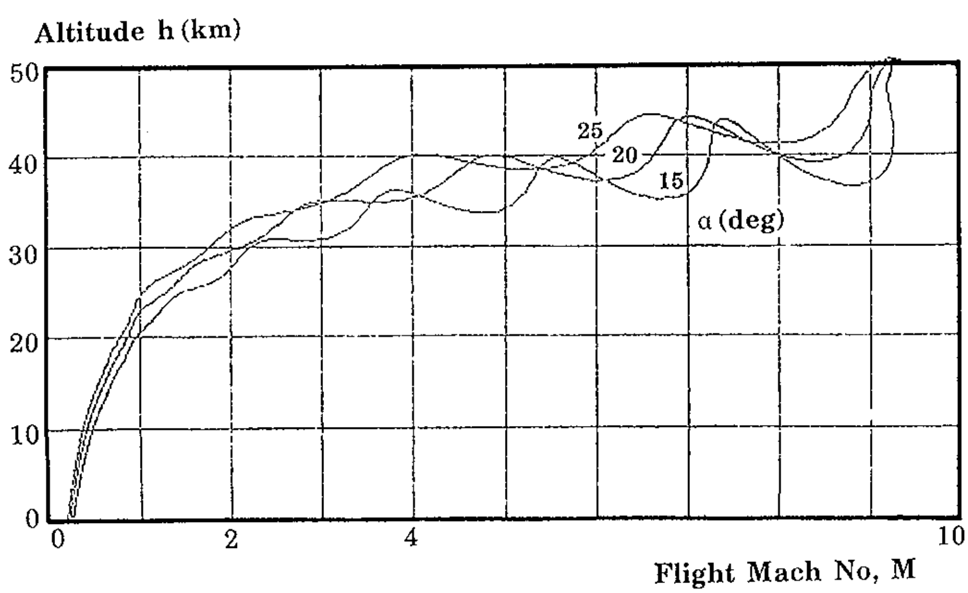


Figure 8 Unpowered Gliding Reentry (Booster)

V. Flight Trajectory

According to the predicted performance of the chosen propulsion systems, the following flight trajectory was selected as an optimum.

The booster and orbiter take-off from an airport type facility under the power of the five LACE engines which burn hydrogen with "newly" liquified air. In order to reduce the aerodynamic drag associated with higher velocities, the booster climbs quickly to 20 km before accelerating to higher mach numbers. It then accelerates to mach 7 at 27.8 km at which point, due to the reduced efficiency of the LACE cycle, the conventional rocket mode begins and zoom climbs the booster-orbiter to an altitude of 49.8 km at mach 9.4 using only three of the booster's rocket engines. At this point, the orbiter's single rocket ignites and it separates from the booster. The dynamic pressure at separation is extremely low (0.5 tons/m^2 - see Figure 7) relieving the separation design of any aerodynamic complexities. The booster then skip glides as it reenters the more dense segment of the atmosphere (see Figure 8) and under jet power returns to an appropriate launch site. The orbiter accomplishes the final stage of the flight with two separate rocket burns. The first immediately after separation and the second at an apogee altitude of 500 km. Figures 9, 10, and 11 illustrate the flight path up to the end of the first orbiter rocket burn in terms of mach number, time and down range distance.

At any point in the climb, the ability to abort is available fulfilling the safety requirement of the system.

1-1. **Initial Gross Weight** 450 ton

1-2. **LACE Cutoff**

- (i) Altitude 27.2 km
- (ii) Relative Velocity 2098.8 m/sec
- (iii) Mach Number 7.0
- (iv) Flight Path Angle 0.6 deg
- (v) Vehicle Weight 342.3 ton

1-3. **Rocket-mode LACE Cutoff**

- (i) Altitude 49.8 km
- (ii) Relative Velocity 3095.7 m/sec
- (iii) Mach Number 9.4
- (iv) Flight Path Angle 1.1 deg
- (v) Vehicle Weight 242.6 ton

2. **Orbit Flight Trajectory** 450 ton

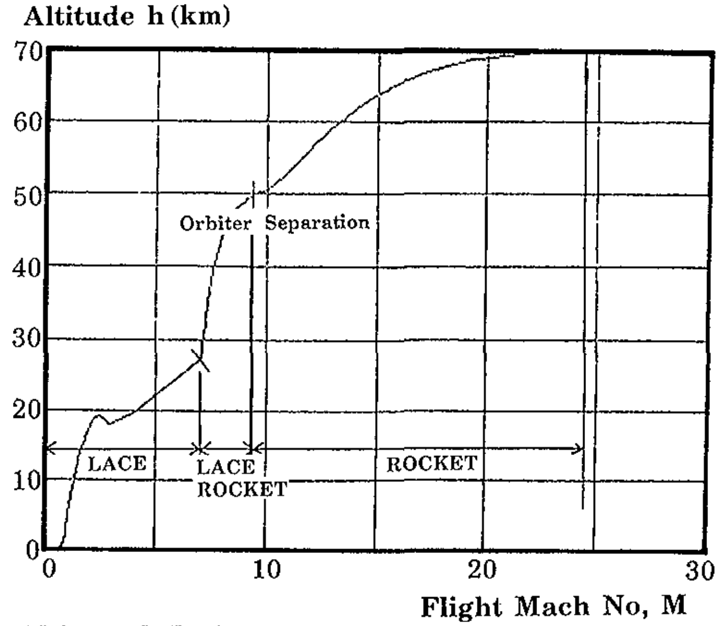
2-1. **Initial Gross Weight** 132.6 ton

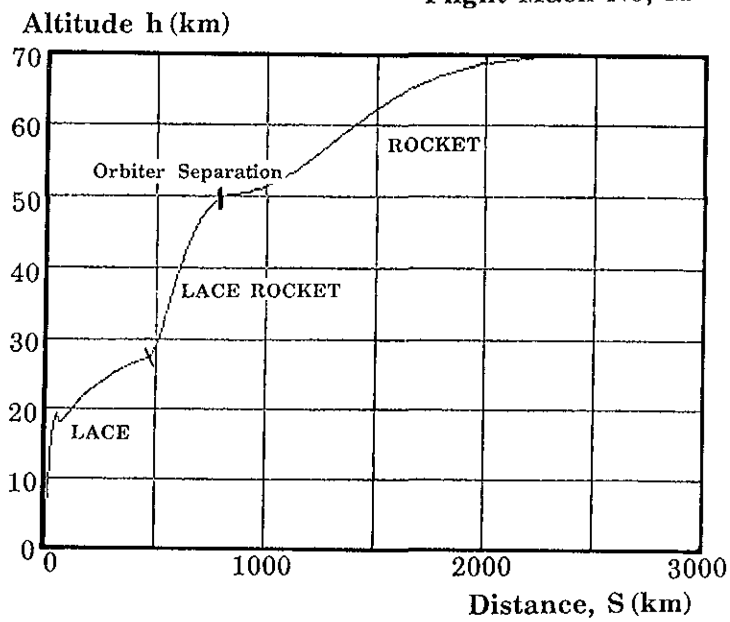
2-2. **Rocket Cutoff (1st)**

- (i) Altitude 70.0 km
- (ii) Inertial Velocity 7987.6 m/sec
- (iii) Apogee Altitude 500.0 km
- (iv) Perigee Altitude 70.0 km
- (v) Vehicle Weight 39.6 ton

2-3. **Rocket Cutoff (2nd)**

- (i) Altitude 500 km
- (ii) Relative Velocity 7612.6 m/sec
- (iii) Apogee Altitude 500.0 km
- (iv) Perigee Altitude 500.0 km
- (v) Vehicle Weight 38.5 ton





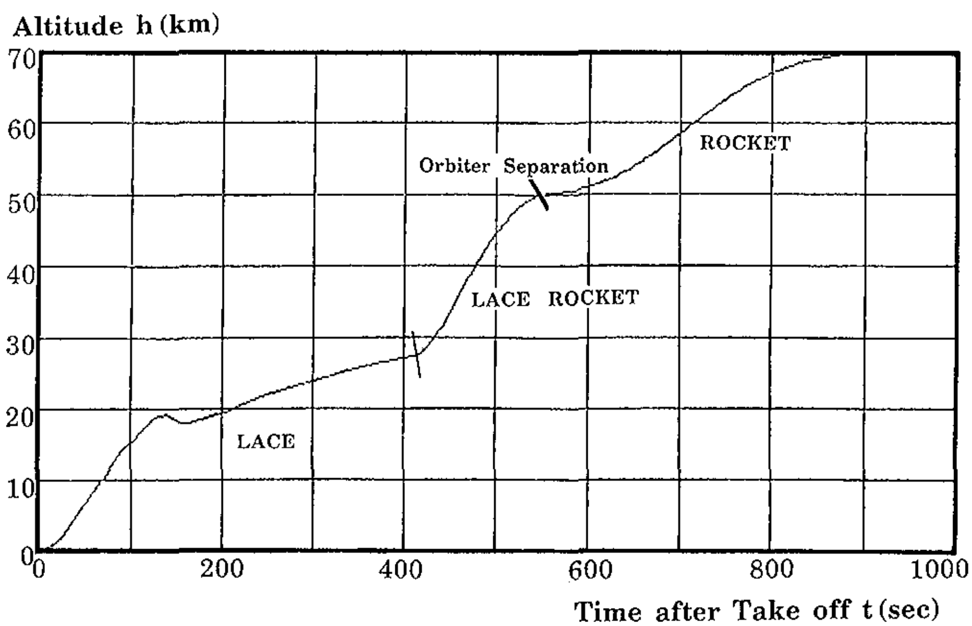


Figure 9, 10, 11 Ascent Flight Trajectory

VI. Concluding Remarks

A TSTO concept, primarily initiated by the National Aerospace Laboratory of Japan, has been presented here. In order to meet the objectives of a safe, inexpensive, reliable, and efficient future space transportation system, the concept that was studied was based on a booster vehicle powered by a rocket based LACE engine.

This spaceplane's concept feasibility primarily depends upon the performance of the LACE system. A LACE ground system test is expected after the first successful launch of NASDA's H-II rocket, scheduled for February 1994.

The present TSTO concept is hence to be refined and updated using these on-going disciplinary research results.

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