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System Studies on Space Plane Powered by Scram / LACE Propulsion System

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Abstract

For the promotion of extended and diversified space activities, it is required to build immediately the technology bases capable of supporting such space activities.

Especially, the development of the low-cost space transportation system to and from lower earth orbit, as driven by the clear need for affordability and operational flexibility, would be key issue.

For such advanced systems, the spaceplane integrated by hypersonic airbreathing propulsion system, optimally configured as single stage to orbit, horizontal take-off and landing system, should be potentially promising option.

In Japan, National Aerospace Laboratory of Science and Technology Agency (NAL) has initiated to study the spaceplane concept and develop the required hypersonic technology bases since 1987.

The primary purpose of the spaceplane program is to provide technology as well as to provide a base of research and development capabilities in critical disciplines for the future development of manned space transportation system.

The present paper will discuss the current activities on SSTO spaceplane research program, with an emphasis on the vehicle system concept powered by SCRAM / LACE hypersonic airbreathing propulsion system.

Discussions will also include SSTO spaceplane configuration characteristics and its operational features.

I. Introduction

Spaceplane is the new concept for next-generation manned space tranportation system as a succesor of current STS in the 21st Century. Japan's policy for future space transportation system development was deliberated by the Consultative Committee on Long Term Policy under Space Activities Commission, and Advisory Agency in 1987 [1),2)].

Based upon these discussions , National Aerospace Laboratory of Science and Technology Agency has initiated Spaceplane Research Program to define the spaceplane system concept and to develop the related hypersonic technology bases for the future development of next-generation manned space transportation system, i.e., Spaceplane, configured as full-reusable, single stage to orbit (SSTO), horizontal take-off and landing system as Japan's leading concept, since 1987. [4)-5)]

Key technology research objectives and issues in the respective research technology field such as Aerodynamics, Structure and Materials, Guidance and Control, Conputational Fluid Dynamics, Manned Flight and Airbreathing Propulsion, which are underway at NAL, are summarized on Table 1.

The current status of the Spaceplane Research Program is in technology maturization phase, to provide technology as well as to provide bases of R&D capabilities in critical disciplines, which would also identify and develop technology to increase future spaceplane mission performance and to enable new missions.

The present paper will summarize the current activities on spaceplane research with an emphasis on SSTO Spaceplane concept characterized by Scram / LACE hypersonic airbreathing propulsion system. Discussions will also include spaceplane system configuration and its operational features.

II. SSTO Spaceplane Concept

Spaceplane is the new concept for next-generation manned space tranportation system as a succesor of current STS in the 21st Century. Spaceplane concept objectives and key design features in achieving the mission objectives are summarized in Table 2.

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The key issues for the spaceplane are the reduction of operational cost as well as the guarantee of the enhanced operational safety, reliability, comfortability for manned vehicle and operational flexibility such as quicj turn around capability.

In achieving the above cited Spaceplane objectives, the system design features include;

(i) the utilization of aircraft type operation ground facilities,

(ii) to exclude the vehicle expendability and the complexity of vertical launch,

(iii) to employ the system capabilities for the powered approach and landing and less thrust loading at take off (by wing lift) with multi-engine redundancies

(iv) the reduction of heavy liquid oxygen by integrating airbreathing propulsion system (only enough on-board oxygen to fire engines for a final acceleration into orbit, to maneuver in space, and eventually to re-enter the atmosphere).

To assess the concept feasibility and to define system configuration, the baseline mission requirement for SSTO Spaceplane is tentatively set as summarized below, i. e.,

- *Space transportation to and from Low Earth Orbit (500Km destination orbit with inclination angles of 28.5deg.) of 10 crew and payload recovery of 2 ton.*
- *Short-term experimental laboratory orbit for earth observation, microgravity etc,*
- *Servicing to platforms and satellites with resupplies, maintenance and repair, and space passenger tour by orbital or sub-orbital flight (with orbital stay time of minimum 5 days).*

Space plane system studies are underway with the specific objectives by the above mentioned SSTO space plane concept by providing the relevant data bases in NAL. 6)-9)

(In the system studies, we have also studied TSTO concept in some details to undersrtand the difference in operational features and to assess the vehicle structure technology feasibility as the reference to the SSTO concept. To our understandings, the concept is characterized dominantly, as a consequence, by the selection of hypersonic airbreathing propulsion system to be integrated. And in achieving the mission objectives cited in the previous section, the SSTO concept would have better performance capabilities than TSTO in terms of the operational aspects, granted that the scramjet engine being feasible.)

In the system concept and configuration analysis,

One of the key issues is to to evaluate the adaptability of the hypersonic airbreathing engines to SSTO spaceplane and to identify the technology needs and to obtain propulsion performance data required for spaceplane system studies.

For the feasibility of the SSTO spaceplane system, the key technology issue is to the develop the high performance and minimum weight hypersonic airbreathing propulsion system satisfying the required weight and sizing constraints and operating efficiently across the high ΔV regime. Airbreathing propulsion must have required high thrust for acceleration against trasonic drag and higher effective specific impulse at hypersonic flight regions, which is superior to those of conventional liquid rocket engines.

The airbreathing propulsion concepts were evaluated based upon the following design criteria ;

- High ΔV *capability*
- *High thrust to weight ratio*
- *High effective specific impulse*
- *Propulsion system integrability (From take off to orbital speed)*
- *Account for Japan's technology bases*

It was understood that for higher hypersonic operating range, the scramjet engine was the only promising option and the feasibility of SSTO system depended upon the maximum operation limit of scramjet engine.

Also acceleration to an orbital speed by the scramjet engine would be far beyond from our scramjet technology bases.

And if acceleration by the scramjet engine was achieved to $M = 16 \sim 18$, which would correspond to roughly half of the energy required to orbit, the resulted fuel fraction would be approximately 75%.

For the SSTO spaceplane fueling with slush hydrogen, the design of cryogenic fuel tank of 75% fuel weight fraction is extremely difficult because of high volumetric tank being required to design within the limited vehicle volumes.

Considering these design constraints, acceleration by the scramjet engine had to be achieved to the region between $M = 16$ as the optimized compromization.

Second problem is the low speed propulsion concept which accelerates the vehicle to scramjet operating region.

Hence the final acceleration to orbital speed needed to be achieved by the liquid rocket engine, the low speed propulsion of rocket based

Technology Area	Objectives	Key Technology Issues
Aerodynamics	· Optimum cross range, acceleration, hypersonic stability and control, low-speed horizontal take of and landing capabilities. · High propulsive efficiency (vs aerothermodynamic heating). · Optimum Propulsion / Airframe integrated vehicle design.	· High Lift / Drag ratio (minimum drag), reentry capability, required wing planform area, sweep angle, profile. · Airbreathing / propulsion system integration design issues; stability and control, control effectiveness, interaction between Reaction Control System, forebody / inlet integration, nozzle afterbody design for hypersonic region, off-design performance, base drag reduction for transonic region ground effect for take off and landing. · Forebody (minimum drag, inlet performance longitudinal stability) / Inlet (compression efficiency, thrust induced moments, pitch / yaw sensitivity, flow capture / spillage / Afterbody-Nozzle (base drag, thrust-dependent moment).
Structures & Materials	· Weight reduction by structure design and advanced material selections for very low structural weight fraction vehicle. · High volumetric structural efficiency (Fuselage / Cryogenic Tank structure) design for high fuel weight fraction requirement. · Design for severe aerothermal loads. · Active cooling structure for wing / fuselage and propulsion (heat recovery).	· Advanced materials : Titanium - Aluminide intermetallics (Ti3Al-base (α-2), TiAl-Base (γ)) , metal-matrix composites such as Titanium-Aluminide composites , Carbon-Carbon composites, Ceramic-Matrix composites for light weight hot structure. · Coatings (thermal control, protection against environment) designed to have high emissivity, noncatalytic to the recombination of dissociated gases, oxidation resistance, hydrogen-compatibility. · Integral / nonintegral, pressurized structure for light weight and high volumetric Tank / Fuselage structure. · Slush Hydrogen (50% solid weight fraction) compatibility (fuel state, material) · Loads evaluation, criteria selection, thermal control system, trajectory tailoring. · Active cooling structure by high-conductivity materials including SiC coated Niobium metal, copper-matrix composites (Cu/Gr) and beryllium-alloys (Cu / Be), , for small radius nosecone and leading edge structure.
Guidance & Control	· Vehicle performance optimization · Highly reliable and redundant guidance, control and stability for all flight phases (Takeoff, Ascent, Orbit Insertion, Deorbit Targeting, Rnadev / Docking and Deorbit Burn, Entry, Terminal Area Operations Approach and Landing, Abort Targeting and Abort) · Ability to abort safety at all times following an initial failure, to increase operational flexibility and reduce costs.	· Optimized trajectory, minimization of weight or size for the desired mission performance. · Design criteria for aerospace – worthiness. self-contained onboard autonomous vehicle guidance and control designs with fault tolerant, self-check system, AI based human / machine interface. · Optimized control and insertion to orbit, hypersonic stability and control. · Optimization of and /or interaction between aero control and reaction gas control. Control surface sizing issues ; engine out control / unstart for stability angmentation and good handling qualities throughout high q and high temperature environment and actuators (freqency requirement, hinge moment method), RCS augmentation at low q. Minimize propulsive thrust induced moments, pitch / yaw sensitivity.
Computational Fluid Dynamics	· Numerical Simulation of flight environment to compensate for the limiting capability of existing ground-based experimental facilities. · Rational vehicle design approach	· Numerical Simulation of full 3 dimensional, chemical-reacting flow fields both external to airframe, and internal to propulsion system (from vehicle nose to tail) especially for real-gas chemical reacting environment. (Propulsion / Airframe integration — Nose bluntness effect , forebody aerothermal loads, inlet flow field and performance, Nozzle flow field and performance —) · Effective for detailed design analysis for vehicle design, and test design, result interpretation.
Manned Flight	· To enhance safety and *reliability* for manned flight, task and performance management.	· Optimum Design of *Human / Machine interface.* (Visibility, instrumentation and interactive display / control) Abort recovery system, Development of manned flight criteria by flight simulations and / or flight experiments, Development of ECLSS to satisfy the required weight and high ambient stagnation temperature environment constraint. Participation of pilots on Spaceplane R&D in the earlier stages is key issue.
Propulsion	· Development of high perofrmance propulsion system to satisfy the *required weight and sizing constraint, operating efficiently across the* speed regime from takeoff to orbital speed. · Establish man – rated criteria for airbreather, rocket and/or combined propulsion system. · Propulsion is the most key enabling technology to define SSTO Space plane configuration, along with materials and structures.	· High performance minimum weight airbreathing propulsion, Propulsion (Inlet / Combustors / Nozzles) / Airframe (Noise / *Forebody / Afterbody) integration (wider ΔV capability, higher effective specific thrust* Is.p. *and higher thrust to weight ratio,* required high thrust for acceleration against transonic drag). For high speed propulsion, scramjet engine would be the only promising concept, where heat recovery cycle by injection of excess hydrogen (both regenerative cooling and recovery of internal losses) to extend SCRAM's operating limit ($M \geq 15 \sim 20^{+}$) is essential. For low speed propulsion, accelerating to SCRAM's operating limit ($M \geq 4 \sim 6$) Liquid , Rocket based LACE (Liquid Air Cycle Engine) is potentially one of promising option. · System integration of the propulsion cycles are essential.

Table 1
Key Technology Research Objectives and Isuues

KEY REQUIREMENTS IN ACHIEVING
Space Plane OBJECT

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

REQUIREMENTS :
- Totally Reusable
- Single Stage To Orbit (SSTO)
- Horizontal Take-Off and Landing
- Ability to Abort Safely at All Times following an Initial Failure
- Manned Operation (Largely Autonomous)
- Acceleration by Hypersonic Propulsion System

Table 2

concept had an advantage in the system integrability view point.

In the present SSTO concept studies, we have selected LACE (Liquid Air Cycle Engine) for low speed propulsion concept, accounting for performance capability and Japan's technology bases.

(We have liquid engine technology through the development of LE-5 and LE-7 rocket engines and LACE technology research is underway by MHI/ NASDA in Japan.[10])

Based upon the previous concept analysis, the concept characteristics of the SSTO Spaceplane are summarized as follows;

- *Integrating the Scram / LACE hypersonic airbreathing propulsion system with an acceleration of the scramjet engine to Mach number up to 20 (at least 16)*
- *Fueling with slush hydrogen with fuel weight fraction less than 70%*
- *Total gross weight of 350ton with the structural weight reduction by approximately 20% vs current technology potential [11]*

III. SCRAM/LACE Propulsion System

— Extension of hypersonic operating range —

The scramjet engine would to be most feasible propulsion concept at hypersonic flight of Mach number over 5. The fraction of the scramjet propulsive energy achieved by converting hydrogen fuel combustion became less as the hypersonic flight Mach number increases.

For the higher hypersonic flight regimes beyond $M \simeq 12$ where energy losses due to internal drag and or skin frictions and severe heat problems, heat recovery operation would be effective for *the extension of the scramjet engine operation* limit and improving its performance.

By using excess hydrogen fuel compared with the stoichiometric equivalence ratio of fuel to the air, active cooling can recover the heats generated by not only in the scramjet engine but also aerothermodynamic heating on the outer surfaces of airframe. The recovered heats by hydrogen would play a positive role, if they are optimally injected parallel to the engine internal flow, on producing thrust. If this mechanism is well designed, we could except the effective operation of the scramjet engine to about Mach number around 20.

Based upon the heat recovery concept, the scramjet engine performance was estimated [8),13)] using the thermodynamic energy theories as defined by Czysz [14)-16)] and Builder.[17)] ,

Of the LACE cycles, as the low speed propulsion concept, accelerating to the scramjet engine operating region of $M \simeq 5$, the air compressor cycle with tank circulation LACE was selected based upon the performance analysis. A LACE utilizes an air liquefaction system by air intake and heat exchanger and a liquefied air is used as an oxidizer. A rocket mood operation for the final acceleration to orbit, after the cutoff of the scramjet engine, is achieved by changing the oxidizer from liquefied air to LOX that is contained in the LOX tank. The slush hydrogen of 50% liquid / solid weight fraction, having high cryogenic source capability for active cooling, could also be utilized as a coolant to enhance an air liquefaction efficiency, as defind by an air-to-fuel mass flow ratio, while the LACE also needs a gas generator (GG) cycle to avoid excessive raising of fuel temperature with a booster pump. A part of slush hydrogen flow returns to a fuel tank as liquid hydrogen after passing through heat exchangers. The liquid hydrogen, therfore, is burned as a fuel in both the scram and LACE modes. The heat exchanger consists of two separate liquefication sections at low pressure and high pressure. In the high pressure liquefication process, the saturated air, which can not be liquefied in the low pressure section, is fully liquefied by increasing its pressure with an air compressor, that is, by decreasing the latent heat level.

(*cf.* Figure 1 of System Layout of SSTO Spaceplane Conpect powered by Scram / LACE Airbreathing Propulsion.)

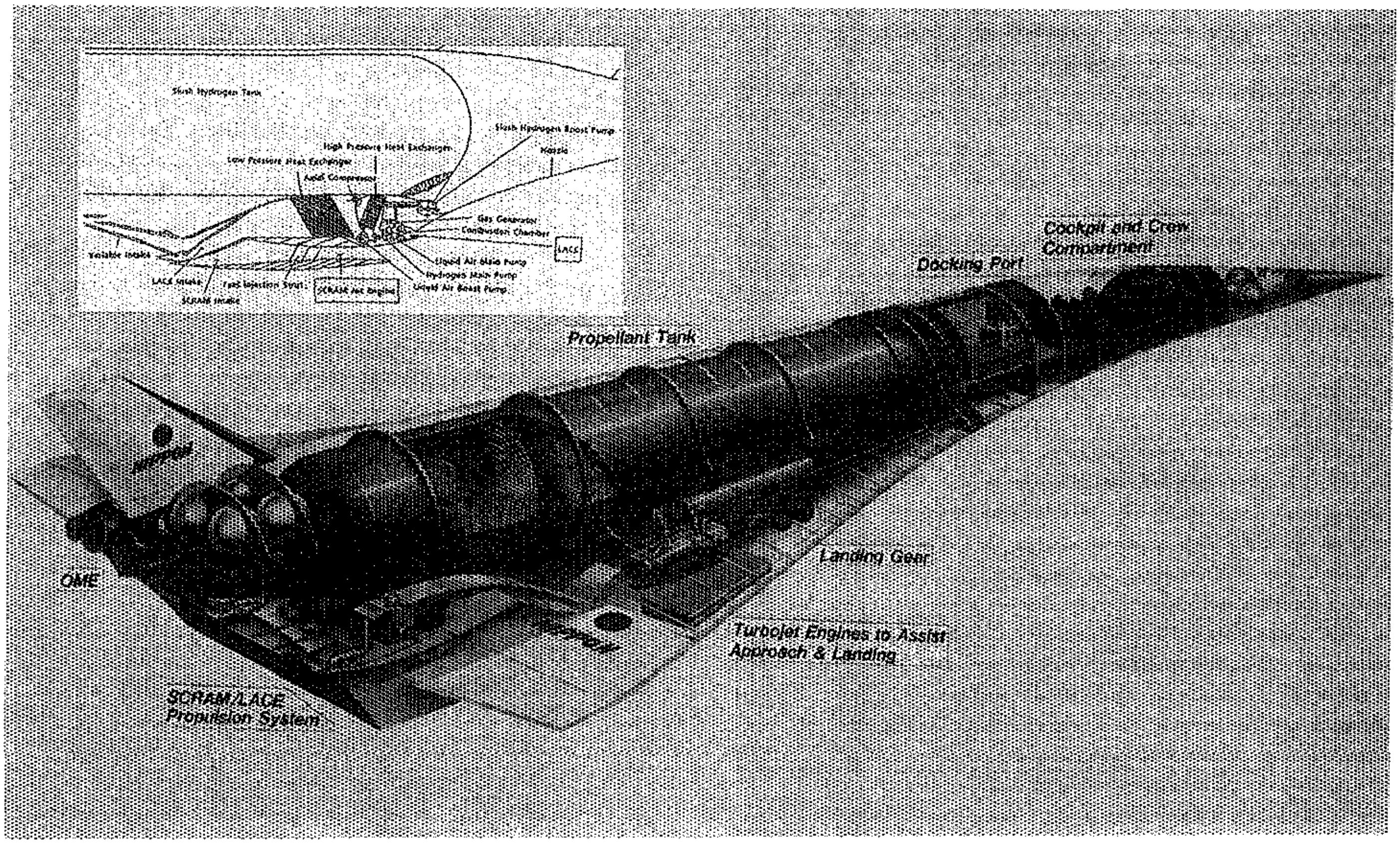


Figure 1 System Layout of the SSTO Spaceplane Powered by Scram/LACE Propulsion System

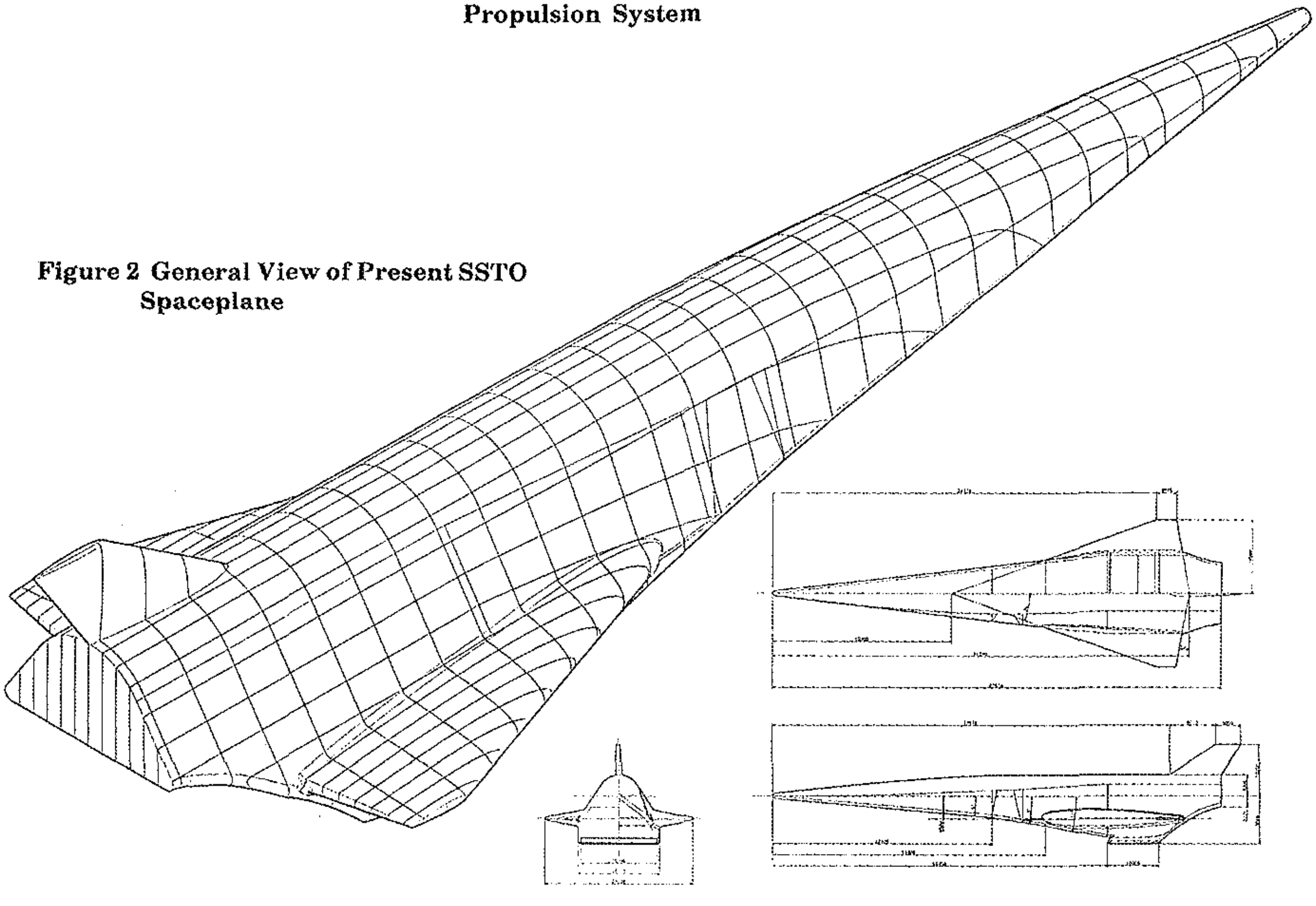


Figure 2 General View of Present SSTO Spaceplane

IV. SSTO Vehicle characteristics

SSTO Spaceplane system studies have been underway since 1987 and vehicle configurations and operational aspects were refined and up to dated using the relevant technology bases obtained by the on-going disciplinary reseacrh works.

Main vehicle characteristics and general views of the present SSTO spaceplane configuration are presented in Table 3 and Figure 2 respectively.

Total Length	94.0 m
Wing Span	29.0 m
Height	19.2 m
Body Length	90.0 m
Body Width	16.0 m
Body Height	13.7 m
Wing Delta Angle	70 deg
Wing Aspect Ratio	1.152
Wing Area	730 m^2
Take-off Wing Loading	480 kg/m^2
Landing Wing Loading	147.2 kg/m^2
Dry Weight	106.7 ton
Crew	10 persons
Propellants	
(i) SLH2	201.61 ton
(ii) LOX	28.3 ton
(iii) RCS & OME	12.7 ton
Vehicle Gross Weight	350.0 ton
Landing Weight	107.5 ton
(i) Body	*26.4*
(ii) Wing (Main & Tail)	*14.0*
(iii) Thermal Structure	*6.5*
(iv) Engine Thrust Structure	*4.4*
(v) Propulsion System	*43.0*
LACE	*(11.4)*
SCRAM	*(9.2)*
SLH_2 TANK	*(14.3)*
LOX TANK	*(0.4)*
RCS & OME SYSTEM	*(4.6)*
Suply System	*(3.0)*
(vi) Sub Systems	
G&C System	*0.7*
Thermal Management System	*1.5*
Electronics & Communication System	*2.5*
Landing Gear	*3.9*
Actuator System	*1.2*
Life-Support System	*2.8*
Main Engines	
(i) LACE (100ton thrust at S.L.S.,4 engines)	4 set
(ii) SCRAM (Intake Area,)	*6 modules* (18 m^2)

Table 3 SSTO Vehcle Characteristics

In Figures 3 and 4, launch cost of the present SSTO spaceplane and the effect of vehicle and propulsion's life cycle flights on the launch cost as compared with the current STS (Space Shuttle at the initial design stage)[18]. Reductions of launch cost was estimated by approximately 1/10 -1/20.

Figures 5-(i), 5-(ii) and 5-(iii) show the reference ascent flight trajectories for the present SSTO Spaceplane in terms of flight Mach number, altitude and flight dynamic pressure versus time from the take off respectively.

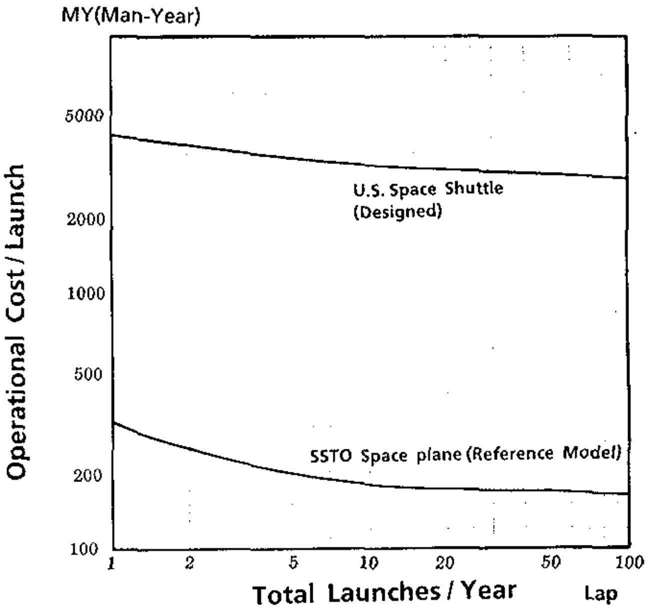


Figure 3 Launch Cost Comparison

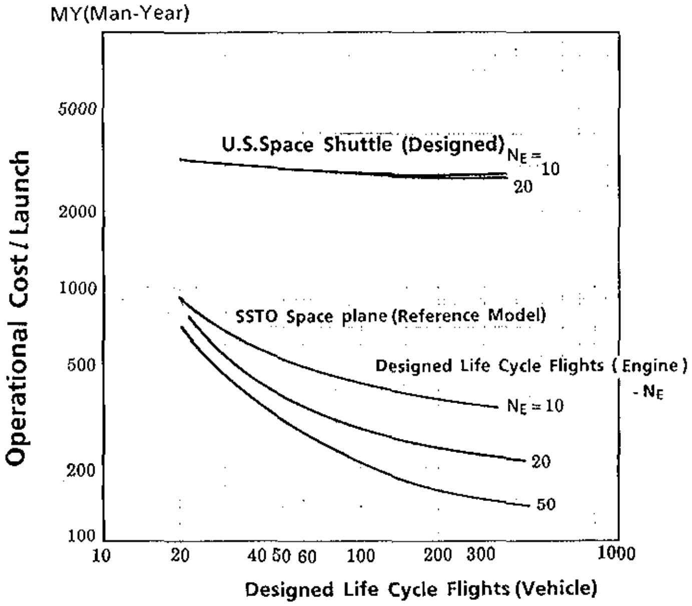
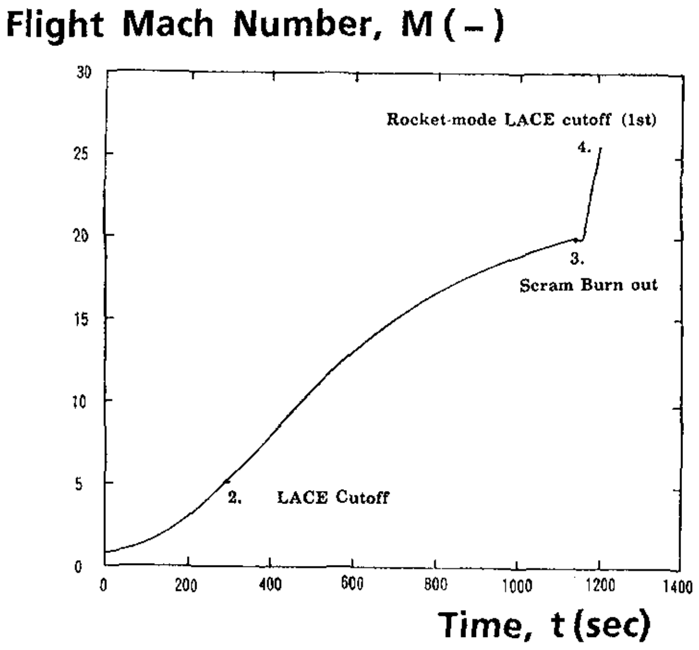


Figure 4 Effect of Life Cycle Flights on Launch Cost

The LACE engines being started at ground accelerate to scramjet operating region of M=5 at the altitude of 25.5 km, followed by the scramjet engines acceleration to M=19.7.For the final acceleration to the mission orbit, LACE engines are restarted and operated under rocket mode.

Ascent flight trajectories were analyzed by estimating the scramjet engine performance with heat recovery during hypersonic flight accounting for the propulsion thrust momentum as well. (cf., Figure 6 as an example result of external nozzle design and flow field analysis)



Ascend Flight Trajectory

1.	Initial Gross Weight		350 ton
2.	LACE Cutoff		
	(i)	Altitude	25.5 Km
	(ii)	Relative Velocity	1494.0 m/s
	(iii)	Mach Number	5.0
	(iv)	Flight Path Angle	1.1 deg
	(v)	Vehicle Weight	300.0 ton
3.	Scram Burn out		
	(i)	Altitude	50.0 Km
	(ii)	Relative Velocity	6399.9 m/s
	(iii)	Mach Number	19.7
	(iv)	Flight Path Angle	3.9 deg
	(v)	Vehicle Weight	127.7 ton
4.	Rocket-mode LACE cutoff (1st)		
	(i)	Altitude	74.7 Km
	(ii)	Relative Velocity	7789.5 m/s
	(iii)	Apogee Altitude	500.0 Km
	(iv)	Perigee Altitude	-574.5 Km
	(v)	Vehicle Weight	102.0 ton
5.	Rocket-mode LACE cutoff (2nd)		
	(i)	Altitude	500 Km
	(ii)	Relative Velocity	7612 6m/s
	(iii)	Apogee Altitude	500.0 Km
	(iv)	Perigee Altitude	500.0 Km
	(v)	Vehicle Weight	94.7 ton

Figure 5-(i) Ascent Flight Trajectory
(Mach Number)

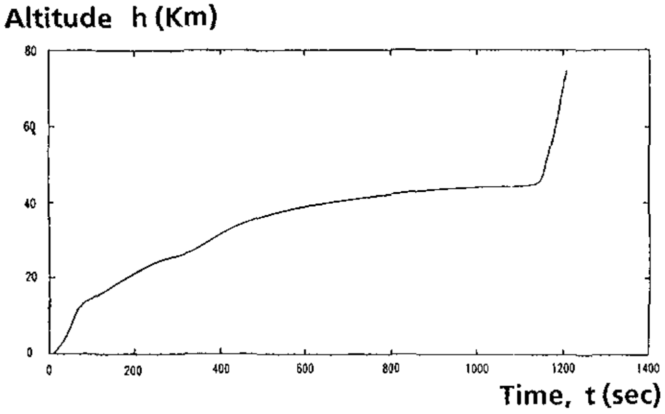


Figure 5-(ii) Ascent Flight Trajectory
(Altitude)

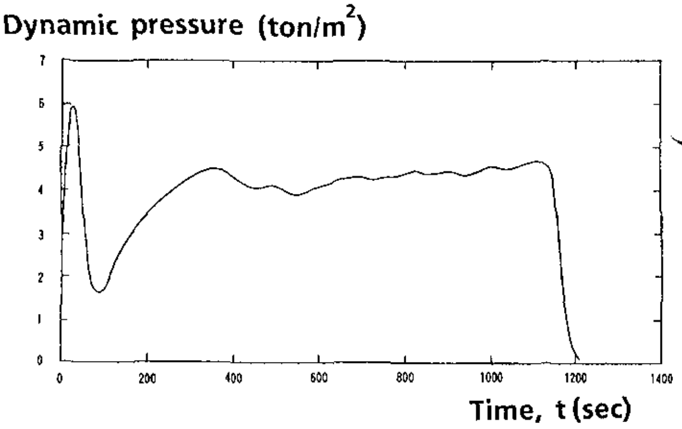


Figure 5-(iii) Ascent Flight Trajectory
(Flight Dynamic Pressure)

An active cooling concept using hydrogen fuel is applied to the whole vehicle body lower surfaces including nose cone, propulsion system and wing leading edges, intending for the surface cooling under the temperature limit of the structure and improving scramjet engine performance during hypersonic flights.

Basic vehicle structual weights were estimated based upon the HASA data base[11)] with the modifications on the cryogenic propellant tanks, airbreathing engines and electronics / avionics sub-systems and other equipments which would deviate from the HASA data base.

Advanced material potentials and trade-offs have been incorporated into the studies and minimum weight sub-system solutions have been identified to meet the objectives, and the vehicle dry weight reduction by approximately 20% was assumed.

Total vehicle weights including required propellants were estimated from flight trajectory simulations and the configuration analysis by iterations until it matched to the optimal sizing. and constraints.

The flight path and airbreathing engine's switching Mach numbers were selected to maximize the effective specific impulse during the whole flight phases.

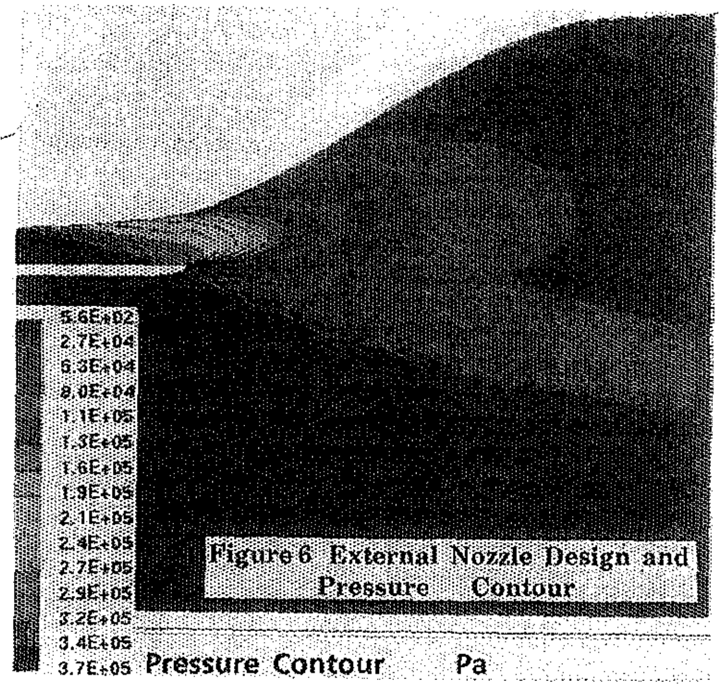


Figure 6 External Nozzle Design and Pressure Contour

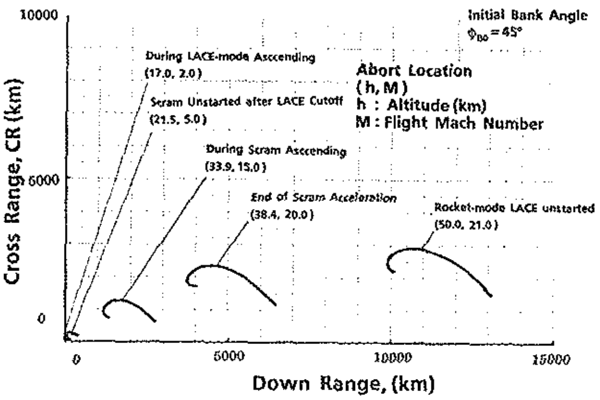
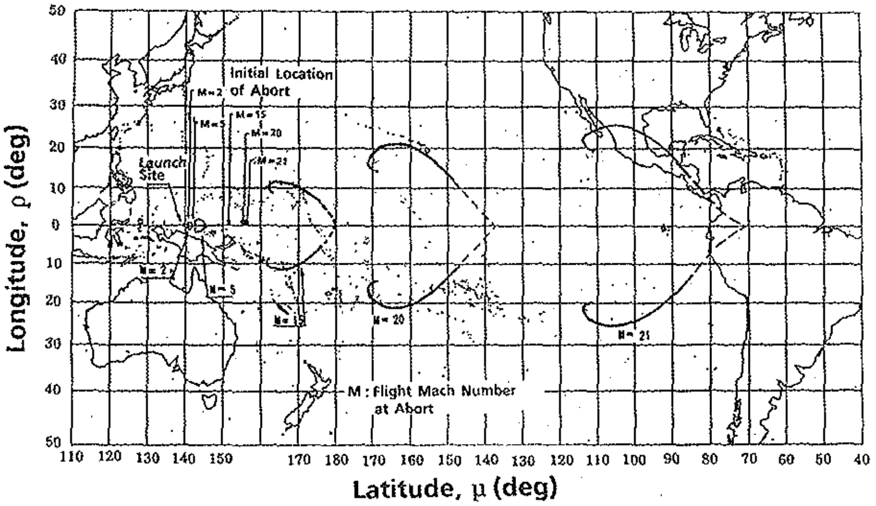


Figure 7-(i) Abort Capability during Ascent (Cross Range vs Down Range)

Figure 7-(ii) Abort Capability during Ascent (Longitude vs Latitude)



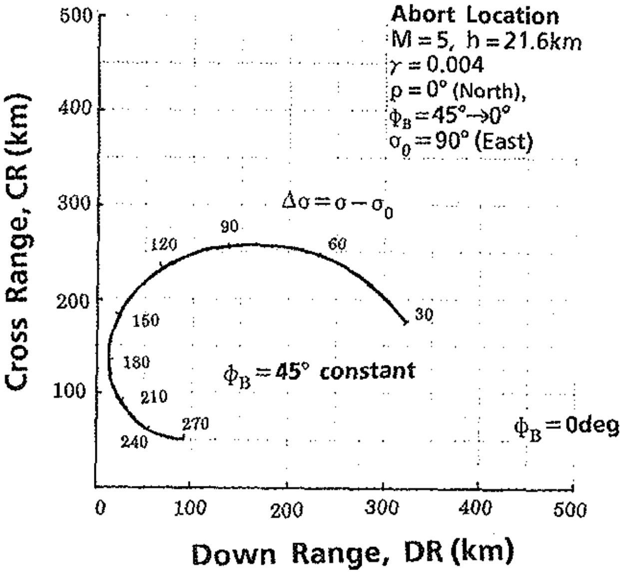


Figure 8 Azimuthal Directivity of Abort Flight

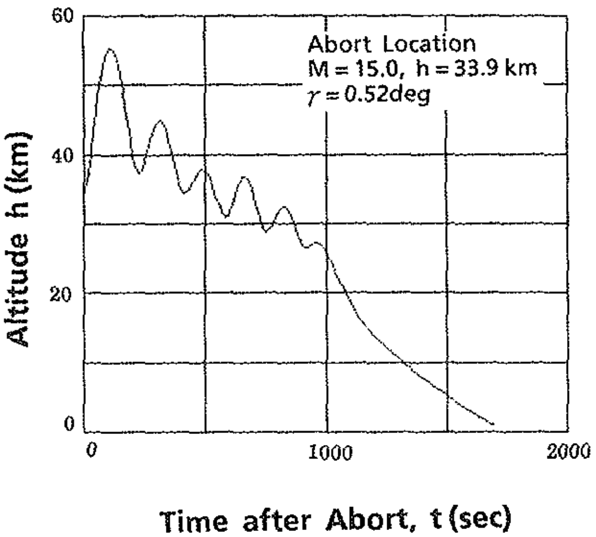
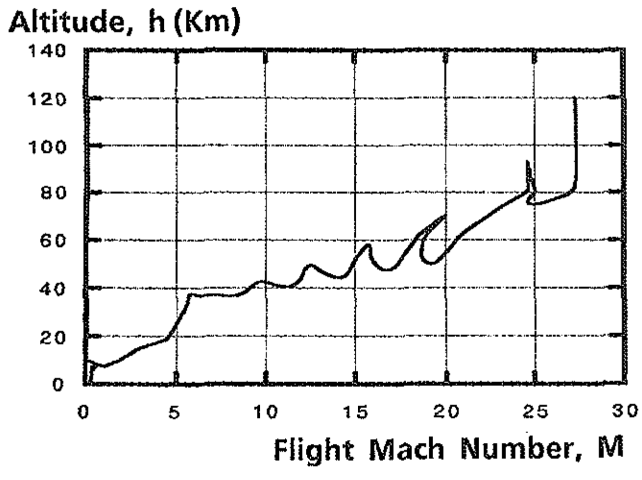


Figure 9 Time History of Altitude during Abort



Reentry Flight Trajectory

Figure 10 Reentry Flight Trajectory

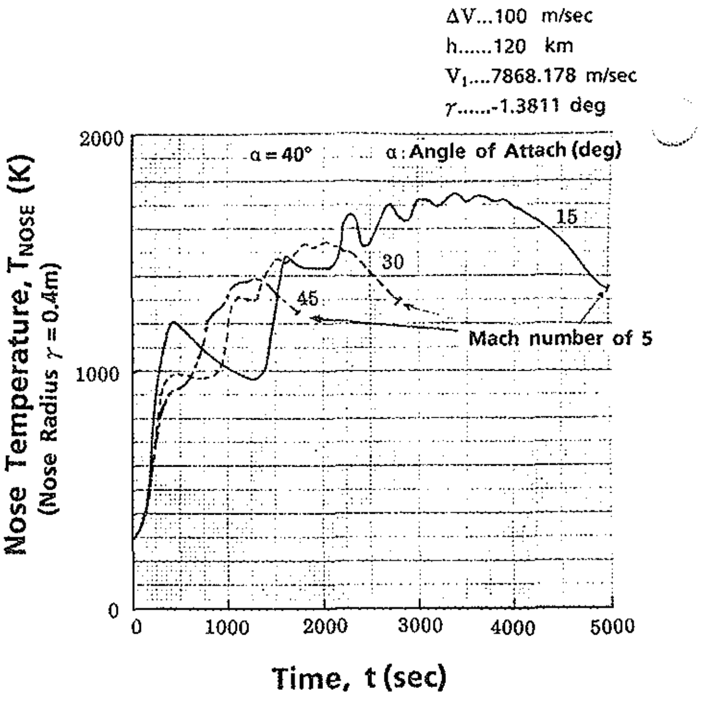


Figure 14 Nose Temperature during Descent
(No Cryogenic Source)

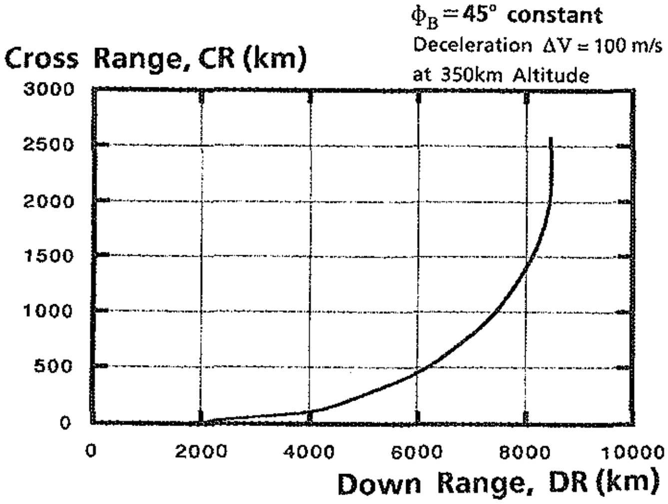


Figure 11 Cross Range Capability

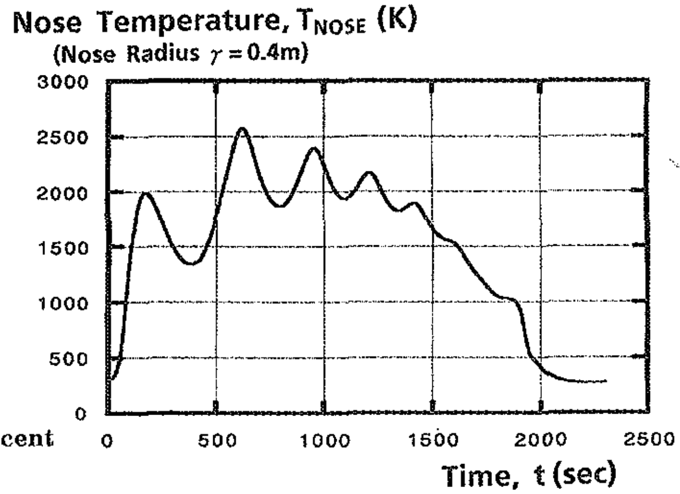


Figure 12 Nose Temperature during Descent

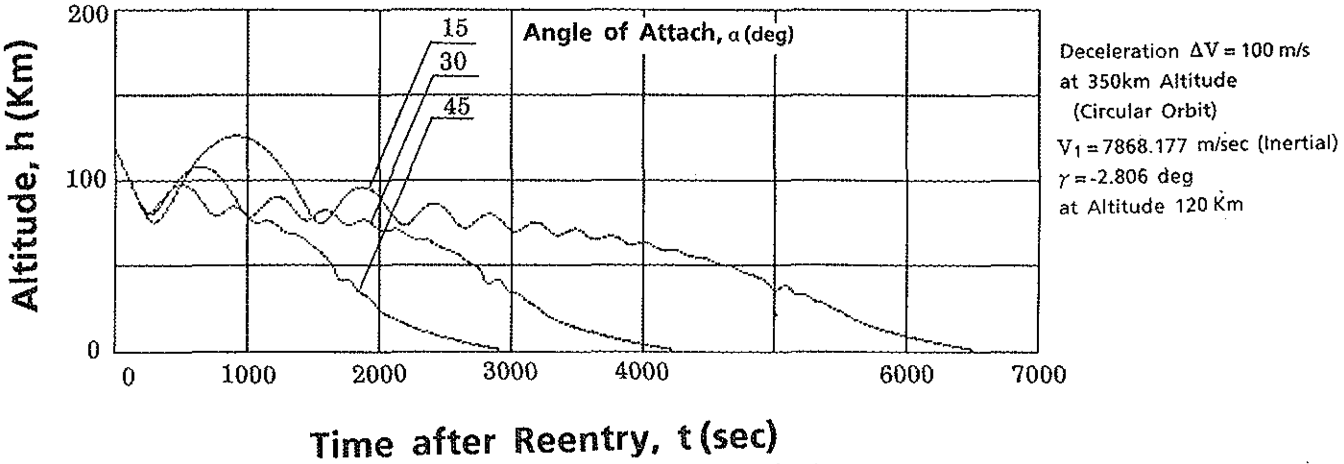


Figure 13 Reentry Flight Trajectory
(No Cryogenic Source)

The abort capabilitiy during the ascent phase were presented in Figures 7-(i) and 7-(ii) in terms of Cross Range vs Down Range and the Earth Longitude vs Latitude respectively, where abort operations were done with the unpowered flight condition by the initial bank angles of 45 degree and at optimal angle of attack for maximum L / D.(*cf.*, Figure 8 of Azimuthal Directivity of Abort Flight.)

Aborts are assumed to be due to the occurrence of the propulsions inoperation for the cases during LACE-mode ascending, scramjet engine unstarted after LACE cutoff, scram ascending, end of scram acceleration and rocket-mode LACE unstarted. The Corresponding abort locations (h, M)in terms of the altitude h (km) and flight Mach number M are (17.0, 2.0), (21.5, 5.0), (33.9, 15.0), (38.4, 20.0) and (50.0, 21.0) respectively.

Figure 9 shows the time realization of altitude for abort operation from Mach = 15.0 and altitude h = 33.9 km.

The reference reentry flight trajectory for the SSTO spaceplane is presented in Figure 10.

De-orbiting by the OME propulsion after the mission completion on the LEO, unpowered flight was assumed during re-entry phases.

The cross range capability is presented in Figure 11, where the active cooling is incorporated to the required structure. Requied cryogenic source for active cooling during return phase was estimated to be approximately of 3.9 ton. In Figure 12, the corresponding time histories of nose temperature as an example, is shown.

For the emergency case when no cryogenic source for active cooling being available, reentry and return will be done by the skipping flight with zero bank angle. The flight trajectory is shown in Figure 13 and the corresponding time histories at nose is presented in Figure 14, where the maximum temperature at nose is being kept below 1200 °K for $\alpha = 45$ deg and below 1500°K for $\alpha = 30$ deg.

V Concluding Remarks

The current activities on Spaceplane system studies and related technology research, which primarily initiated by National Aerospace Laboratory in Japan, were summarized with an emphasis on SSTO Spaceplane concept characterized by Scram / LACE hypersonic airbreathing propulsion system.

Spaceplane is the new concept for next-generation manned space tranportation system as a succesor of current STS in the 21st Century.

Leading countries in space development have been promoting the ambitious space policy and conducting the R&D efforts as their respective national programs.

However, with the consideration of the rapid changes and progress in international as well as national situations surrounding space activities, it is of great importance to enhance and integrate these R&D efforts as integrational cooperation urgently for the development the innovative Spaceplane toward 21st Century.

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