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DESIGN AND DEVELOPMENT OF LARGE MODEL DUAL COMPONENT  
EXHAUST PROPULSION SYSTEMS

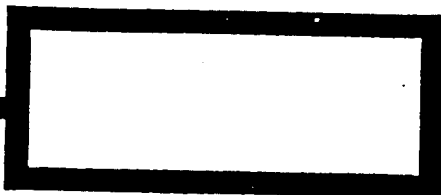
by

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## ABSTRACT

As far as super charging improvements carried out on large model dual component propulsion systems are concerned, they make the new systems completely different from the pressure regulated systems at the present time. From considerations of the three areas of thrust chamber design, performance, and system structure, operating conditions associated with new designs all have important technological advances. Test measurements have been carried out with regard to system levels through thrust chamber thermal tests. In conjunction with this, verifications have been carried forward in respect to propulsion system exhaust design life limits.

KEY WORDS Dual component Exhaust propulsion system Design Development

## FORWARD

The carrying out of pressure regulation with regard to space ship dual component propulsion systems is in order to guarantee high efficiency characteristics and stability of propellant loads. The systems in question are primarily used in the orbital entry and separation of communications satellites. There is no need for long periods of regulating operations. Shallow surface layer pressure exhausting is used during operations in orbit. However, other operations, within the whole design life limit, must consume large amounts of propellants. In this type of situation, the choice designers face is to opt for the use of complicated systems in order to increase efficiency or to opt for the use of simple systems so as to lower load efficiency. In the Luokexide (phonetic) Bus 1 carrier vehicle, option is made for the use of exhaust super charging designs in order to make use of their unique reliability, permitting a very slight reduction in propellant load efficiency.

Bus 1 requirements include long life, periodic propellant servability, three axis control, as well as compatibility with the space transport system (STS) and reusable carrier devices. Propulsion systems which the Bus 1 carrier device opts for require new software to facilitate operations. Moreover, performance is generally higher than dual component systems in the past. The biggest technological key lies in thrust chamber development. This is primarily orbital regulation and development of reaction control thrust chambers. Besides this, discussion is made of system thermal test run projects carried out at NASA's White Sands testing base, to include ignition of partial systems possessing actual fuel piping as well as thermal tests with regard to two models of thrust chamber.

## DESIGN REQUIREMENTS AND SYSTEM SELECTION

### Main Design Requirements

Primary design requirements are propulsion systems opting for the use of monomethylhydrazine (MMH) and dinitrogen tetroxide (NTO) to act as propellants, producing 13344.6 kilonewtons per second or more of impulse, completion of orbital regulation as well as reaction control functions, and lives that can reach a number of years. Thrust levels used in orbital regulation are approximately 889.6N. Thrust levels used in reaction control systems (RCS) are approximately 66.73N. Single combustion times associated with orbital regulation reach 3600 seconds. There is a requirement to be able to complete orbital regulation functions within the entire design life cycle. RCS 66.73N thrust levels are used in controlling combustion during orbital regulation. Besides this, three axis control can satisfy different operational cycles. Compatibility between STS and reusable carrier devices also influences system designs.

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### System Selection

Satellites entering into geosynchronous transfer orbits regularly make use of signal valves to isolate pressure regulator devices in systems. After that, use is made of quite a small part of the remaining propellant to carry out shallow surface layer exhausting. This type of method eliminates the inherent defeating factors in pressure regulation. However, Bus 1 designs require making use of large amounts of propellant within the limits of the entire plan life. It is a design that does not opt for the use of isolation regulators. As a result, earnest considerations must be made, and, in conjunction with that, a new type of design found in order to replace that original type of regulation system with its large numbers of numerous types of components. The exhaust design that was finally determined on was workable for the reasons that follow. First, as far as large numbers of single component propellant exhaust systems are concerned, they provided usable experience to draw on. The propellant load associated with this type of system exceeds 2270kg. Using pressurized storage tank methods increased load efficiencies. A good deal of "experience" was produced in the areas of attitude control applications in operations, propellant control, and thrust chamber operation cycle effects. Second, dual component exhaust designs went through in depth study, setting up an adequate theoretical foundation. Simulation and analysis results clearly show that residual propellant material will not be excessive. Thrust chamber operation requirements can be completely predicted. Moreover, there was already a grasp of the thermodynamic processes associated with exhaust operations. Finally, development and testing on thermodynamic processes associated with dual component thrust exhaust operations and dual component thrust chambers had already increased to a certain level, and it was worth accepting the risks in new development projects.

### SYSTEM DESCRIPTION

Fig.1 is a schematic diagram of the Bus 1 propulsion system. The system in question is composed of two independent systems. It is possible to cross connect between storage tanks and thrust chambers. Table 1 sets out main system components and their explanations. Propellant capacity is 5215kg. Fueling rate is 80%.

In conjunction with this, it is possible to independently repeat pressurization. The capacity of the four system storage tanks is 3491.9kg. The operating pressure range of the titanium propellant storage tanks is 0.0997 (illegible) - 2.551MPa. In conjunction with this, there is no surface tension type propellant control apparatus in order to guarantee being able--in cases at any speed--to take propellant which does not contain gases and send it to engines. 10.06m<sup>3</sup> storage tanks are appropriate for use with all

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engines and landing environments. In conjunction with this, they satisfy cracking control requirements. Opting for the use of titanium alloy storage tanks and piping is capable of insuring oxydizer compatibility during long life applications.

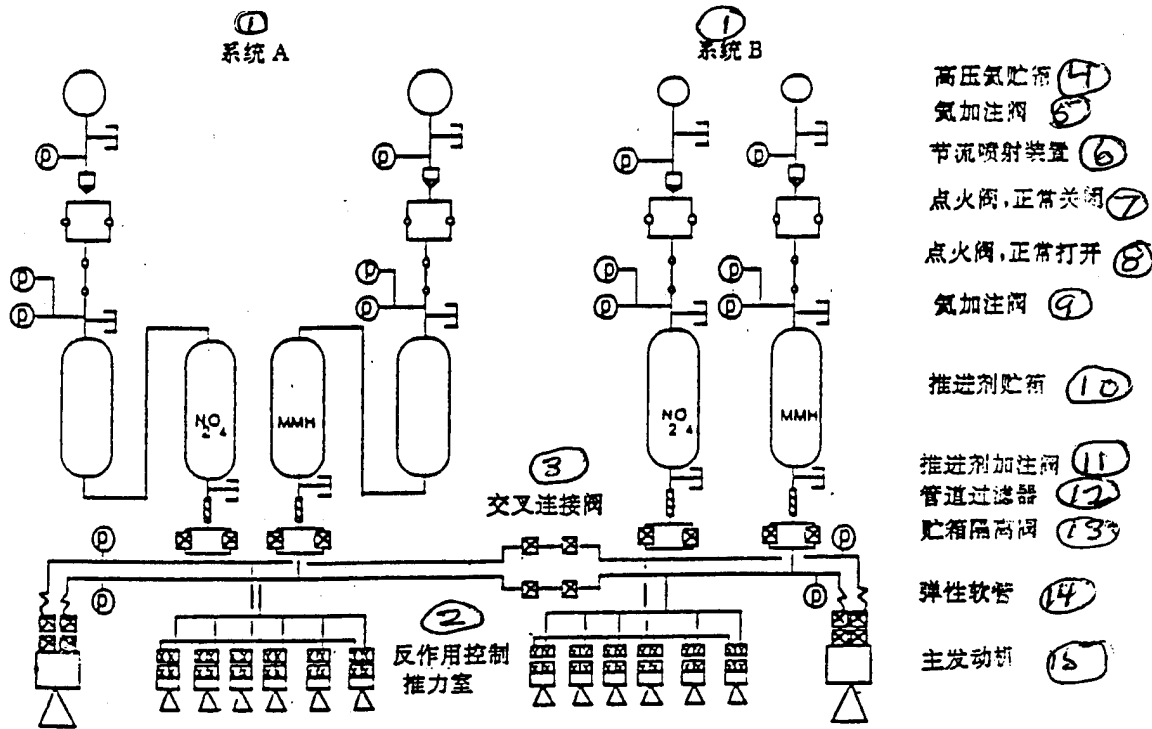


Fig.1 Bus 1 Propellant System Schematic Diagram

Key: (1) System (2) Reaction Control Thrust Chambers (3) Cross Connection Valves (4) High Pressure Helium Storage Tank (5) Helium Fill Up Valve (6) Throttle Injection Apparatus (7) Ignition Valve. Normally Closed. (8) Ignition Valve. Normally Open. (9) Helium Fill Up Valve (10) Propellant Storage Tank (11) Propellant Fill Up Valve (12) Pipe Filter (13) Storage Tank Isolation Valve (14) Soft Elastic Tubing (15) Main Engine

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Electromagnetic isolation valves associated with fueling systems are capable of controlling propellant isolation to carry out leak protection and to control storage tank shunting redundancy. In conjunction with this, cross connection is carried out between storage tanks and thrust chambers. Pressure reduction characteristics of valves are capable of guaranteeing that pipes

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and components avoid suffering the effects given rise to by overpressures. Due to the fact that cross connection is certainly not normal operation and latent leakage between systems is very serious--influencing system mixture ratios and residues--as a result, cross connection valves are connected in series. Titanium alloy elastic propellant tubing is used in regulation as well as engine calibration in order to adapt to changes in spaceship center of gravity.

When storage tank pressures drop to precalculated values, high pressure spheres on top of the liquid surface in propellant storage tanks will open up signal valves, beginning the next interation of pressure increases.

Table 1 Propulsion System Components

Component	Explanation
Propellant Storage Tank	New Design
Super Charging Agent Storage Tank	Similar to Storage Tanks at the Present Time
Main Engine	Enlarges Engines at the Present Time
RCS Thrust Chamber Components	New Design
Isolation Valve	New Design
Soft Elastic Tubing	New Design
Fill Up/Exhaust Valve	Opts for the Use of Present Designs. Materials Are Titanium.
Signal Valve	Current Design
Pressure Sensor	Opts for the Use of Current Designs
Propellant Filter	New Design

What Fig.2 shows is a pressure discharge distribution graph as well as the status associated with opting for the use of the next interation of super charging in order to increase propellant effectiveness. Following along with the next iteration of storage tank super charging, other signal valves, which are normally open, immediately close, in order to prevent liquid or vapor seeping out of storage tanks. Thermal control of storage tanks, fluid components, and thrust chambers is completed by redundant heaters and thermostats. Systems also do not have a good number of pressure and temperature measurement devices in order to guarantee monitoring of normal operations and propellant quality status.

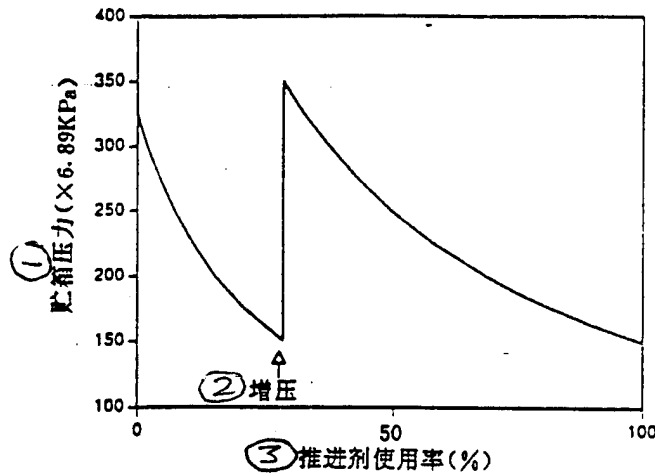


Fig.2 Pressure Discharge Distribution Graph

Key: (1) Storage Tank Pressure (2) Super Charging  
(3) Propellant Utilization Rate

The thrust range of R-42SR model main engines produced by Kaiser Marquardt is 622.74 - 1334.46N. Total impulse exceeds 13344.7kN/s.

The mean specific impulse is approximately 2972.4m/s. Jet tube surface area ratio is 164:1. Maximum combustion time can reach 3600 seconds. During ignition processes--through combustion thin film cooling and combustion chamber radiation cooling--the cooling of engines is carried out. Heaters and thermostats inside the thermal control outer shell covering the front end of engines carry out thermal control of engines in orbit. Redundant system fuel and oxydizer valves offer ideal degrees of leakage protection redundancy. RCS thrust chamber components are fitted on two AJ-220 model air jet type combustion chambers, completing structural support and thermal control. The thrust chamber constituents in question also include pressure sensors, heaters, thermostats, as/29 well as temperature monitoring devices. The thrust chamber thrust range is 44.48-97.86N or more. Thrust chamber operating life reaches 40 hours. During 66.72N thrust levels, specific impulse is approximately 2812.6m/s. Pulses are 0.02 seconds. In the same way, RCS thrust chambers also opt for the use of fuel thin film cooling. Moreover, use is made of a series of redundant valves to provide the degree of leakage protection redundancy. Propulsion systems have six thrust chamber subassemblies. Each subassembly includes a system A thrust chamber and a system B thrust chamber.

## DESIGN AND PERFORMANCE PROBLEMS

After selection of an exhaust super charging design, a number of supplementary requirements and problems are produced, influencing system development--in particular, the development of two types of thrust chambers. Pressure ranges within the entire design life cycle influence a series of factors such as the original loads and supply system fill up, as well as dynamic characteristics.

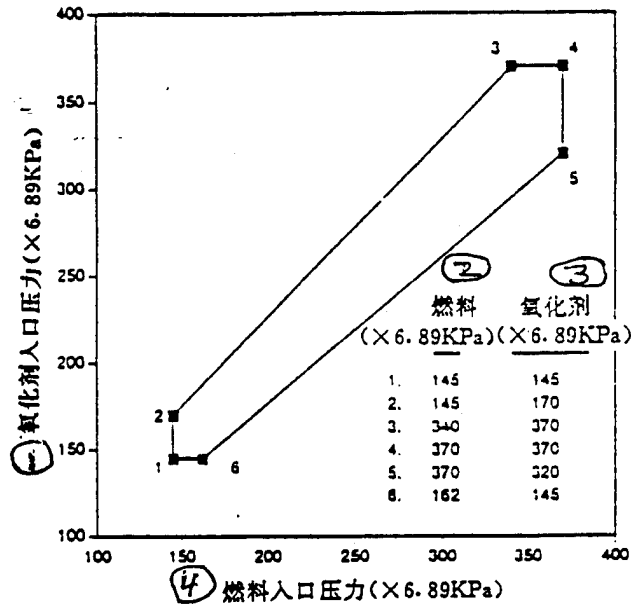


Fig.3 Thrust Chamber Operation Envelope Curve

Key: (1) Oxydizer Inlet Pressure (2) Fuel (3) Oxydizer  
(4) Fuel Inlet Pressure

### Thrust Chamber Problems

The primary design problems associated with Bus propulsion systems center on operational adaptability under a series of conditions produced by main engine and reaction control thrust chamber discharges. In computer models, programed super charging characteristics, supply system design plans, and thrust chamber performance characteristics are used in order to determine thrust chamber operating envelope curves--including all possible parameters--for example, load instability. The envelope curve is shown in Fig.3. The difficulty lies in maintaining good performance within pressure and mixture ratio ranges--at the same time, avoiding sensitivities associated with excessively high thrust chamber temperatures and operating periods. The elastic deformation and flexible deformation shown by thrust chambers do not fit with the requirements of regulating operations. What is

particularly worthy of attention is the thermal stability of reaction control systems in subassemblies.

After making use of a series of redundant valves--at fuel and oxydizer outlet valve seats down the flow in tubing--there is a latent danger of leakage. There is a requirement to verify that a damaging ignition peak pulse will not be produced. The other parameter that needs to be verified is the thrust chamber stability parameter. Large pressure ranges as well as changes in mixture and degree of helium saturation also require further consideration.

Even if helium saturation in propellants is not figured as a unique situation, exhaust operational configurations, however, will influence levels of saturation. In situations of exhaust super charging, long periods of ignition will reach supersaturated conditions. Besides this, because of opting for the use of dual system structures, there is a requirement--as far as thrust chambers are concerned--to be able to carry out helium gas absorption when the propellant is exhausted. After that, cross connecting to the other propulsion system, normal operations are carried out.

#### System Problems

Exhaust super charging operations require having some increases. Storage tank pressure maximum values increase to 2.55 MPa, meaning that system components must be correspondingly higher than pressures associated with normal values. Speaking in terms of Bus 1 structures, operational as well as protective pressures are required to be subject to the influences of supply system isolation valves as well as thrust chamber valve designs. For example, when system pressures reach maximum values and isolation valves are closed, maximum static pressures will be produced at thrust chamber valves. Thrust chambers must bear storage tank pressures as well as supplementary pressures produced by isolation valve pressure reductions. Because valve seats up the flow also possess pressure reduction characteristics, pressure status is, therefore, the worst inside the cavity areas in series of redundant thrust chamber valves. Besides static pressure requirements, systems must endure water hammer effects within the entire pressure zone. /30

Another problem is the problem of filling up STS carrier vehicle supply systems. Even after systems go through regulation, when the pressures in propellant storage tanks are very low, it is still possible to complete fill up. However, once isolation valves are open--in particular, when supply piping is evacuated or at relatively low pressure--super charging systems associated with storage tank initial pressures that are comparatively high will produce pressure fluctuations.

## THRUST CHAMBER DEVELOPMENT TESTS

This section lays primary stress on a number of technological problems and solution methods. It certainly does not aim at completely describing development or evaluation processes.

### Main Engines

The starting point for development of engines with thrusts of 889.6N is the current 489.3N thrust design (model R-4D-11). The design selected expands the dimensions of the current plan. At the same time, it maintains the original injector design. In conjunction with this, it opts for the use of the same engine valves. Speaking in terms of the 489.3N thrust chambers, thrust chamber temperatures will follow along with rises in inlet pressures and increase. 889.6N thrust designs also display the same kind of tendency. The result is that temperatures at the high pressure end of super charging zones are very high, influencing thrust chamber coating life. Through tests with regard to changes and errors in flow amounts associated with injectors, methods were selected increasing fuel film cooling levels. After option is made for the use of super charging methods, performance shows some losses. Specific impulses drop approximately 68.6m/s. Performance characteristics are shown in Fig.4.

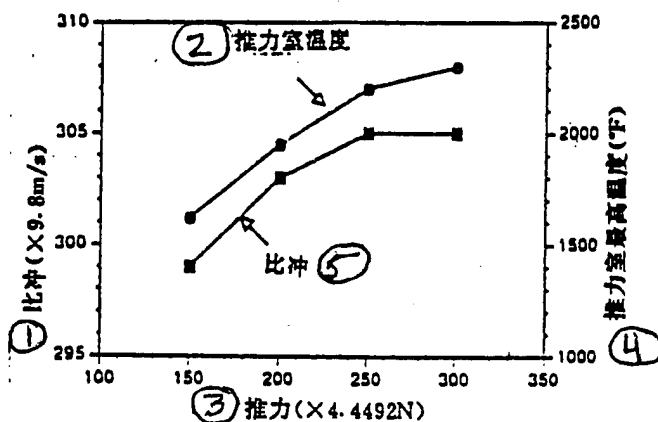


Fig.4 Main Engine Performance

Key: (1) Specific Impulse (2) Thrust Chamber Temperature  
 (3) Thrust (4) Thrust Chamber Maximum Temperature (5) Specific Impulse

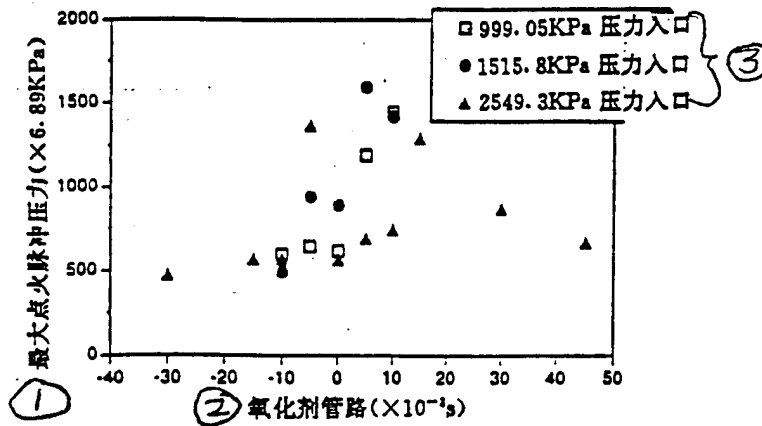


Fig.5 Main Engine Ignition Peak Pulse

Key: (1) Maximum Ignition Pulse Pressure (2) Oxidizer Pipe  
(3) Pressure Inlet

Another thing that needs to be brought up is thrust chamber stability problems. Going through a series of inlet pressure, mixture ratio, gas absorption, as well as degree of helium saturation tests, satisfactory performance characteristics were produced. When test chamber temperatures were lower than the triple point of MMH, high altitude ignition tests were carried out, doing test measurements of thrust chamber overpressure potentials. Test parameters included inlet pressure, propellant temperature, injector temperature, thrust chamber temperature, as well as fuel or oxidizer tubing systems. Test results are shown in Fig.5. The largest thrust chamber pressures recorded are lower than thrust chamber static impulse energies. Tests show that leaks in valve seats in the lower flow will not produce damage in fuel or oxidizer tubing.

#### Reaction Control Impulse Chamber Subassemblies

Development of 66.72N thrust chambers is different from the 22.246N thrust designs associated with the plate layer injectors used at the present time. Injector design as well as repetitive testing are used in order to reach ideal performance within operating ranges--at the same time, avoiding excessively high thrust chamber temperatures. Relatively high inlet pressures require percentages associated with fuel thin film cooling to be somewhat higher, thereby slightly lowering design requirements. Fig.6 shows performance characteristics. In order to reduce /31 thermal transfer within upper stream pulse operating cycles, after

intentionally blocking injector acoustic cavities, high frequency instability is produced. It can be seen that acoustic cavities can be used in increasing stability margins. This is particularly important when inlet pressures are relatively high. High altitude combustion tests associated with fuel and oxydizer tubing are similar to the same type of tests on main engines. Tests clearly show that lower flow valve seat leakage will not produce harmful ingition peak pulses.

The most important technical problem is--when carrying out pulse operations in super charged working environments--how to carry out satisfactory thermal control with regard to thrust chambers and subassemblies. Tests show that at the time of pulses, thermal control is very greatly influenced by inlet pressures, mixture ratios, pulse widths and operating periods. Fig.7 shows operating period sensitivities when inlet pressures are low and mixture ratios are high. There is need for a very effective test program in order to check on different operating periods, and, in conjunction with that, check out various types of solution designs that have been proposed. Increasing injector fuel thin film cooling efficiencies and, at the same time, reducing thrust chamber wall thickness, it is possible to prevent the heating of back surfaces orientating toward thrust chamber head sections. Opting for the use of relatively numerous effective shunts is capable of transmitting amounts of heat from thust chambers to various subassemblies. Besides this, due to tests showing relatively large pulse widths, it is possible to more effectively maintain thin film cooling efficiency. As a result--in situations where maintenance and other controls require consistency--it is possible to select maximum values.

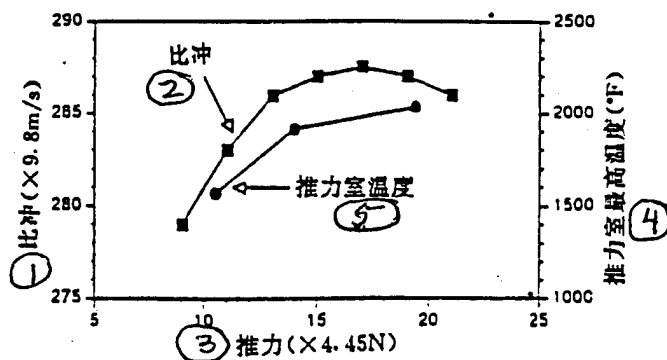


Fig. 6 Reaction Control Thrust Chamber Performance

Key: (1) Specific Impulse (2) Specific Impulse (3) Thrust  
 (4) Thrust Chamber Maximum Temperature (5) Thrust Chamber Temperature

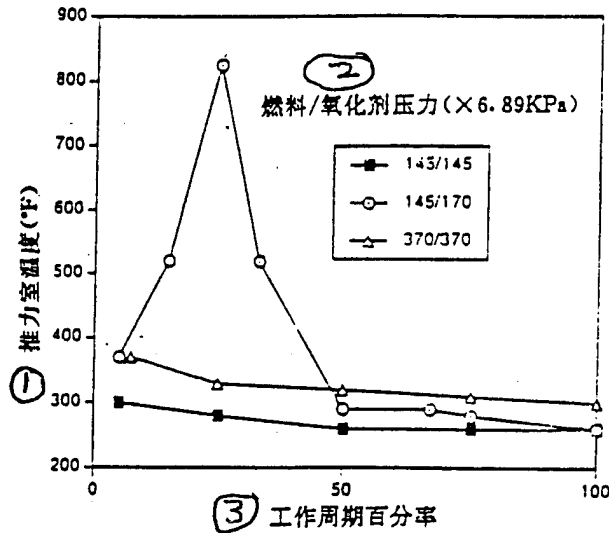


Fig.7 Typical Example of Operating Period Sensitivities

Key: (1) Thrust Chamber Temperature (2) Fuel/Oxydizer Pressure  
(3) Operating Period Percentage

#### SYSTEM TESTS

If it is desired to carry out ideal appraisals of system levels, it is then necessary to consider a series of problems. In particular, attention must be paid to such characteristics as propellant load, super charging, pressure transfer, and so on, in such situations as propellant fill up, thrust chamber operation, helium saturation effects, and gas absorption. The important point is to set up a workable fill up system and procedure. Propellant sampling and filter evaluations will verify system and propellant compatibility. In conjunction with this, contamination levels are quantified.

#### Test Description

The tested body was a fully welded flight propulsion system made of titanium. Option is made for the use of flight model components as well as tubing system apparatus. Fuel storage tanks include a full propulsion management device (PMD). However, oxydizer storage tanks are empty shells. This type of design cuts costs. It provides an opportunity to evaluate PMD thermal effects.

Another independent subassembly includes a second super charging component as well as propellant supply system and thrust chamber. Supply system tubing apparatus strictly simulates spacecraft tubing designs. In conjunction with this, it includes propellant filters, propellant isolation valves, as well as soft elastic tubing made of titanium in the upper flow of main engines. Instrument systems are installed at different positions of the supply system. High

sensitivity Kulite sensors are used in order to monitor transient pressure characteristics. Gas absorption tubing set ups are at isolation valves in the lower flow. /32

Due to tests not being carried out in vacuum conditions, as far as main engines are concerned, option is, therefore, made for the use of cross cut jet tube heads, used in sea level operations. Test measurement devices include a thrust chamber pressure sensor and two valve temperature thrust chambers. Moreover, tests clearly show that, so long as one accurately simulates actual tubing supply systems, the installation of three active thrust chambers is adequate to reach testing objectives. These thrust chambers also possess their respective cross cut jet tube heads. Each reaction control thrust chamber has a pressure sensor as well as specialized valve and flange temperature sensors.

### Test Results

The system tests carried out at NASA's White Sands testing base lasted seven months. Storage tank super charging was carried out in order to precisely specify the expected operating trends. Finally, preliminary helium absorption tests lasting 14 days were implemented. Monitoring was carried out with regard to temperature and pressure. The pressure attenuation characteristics displayed in Fig.8 clearly show that the solubility of oxydizer is relatively great. Finally, in storage tanks equipped with PMD systems, oxydizer is added in again to carry out tests. The results clearly show that making use of PMD systems can slightly reduce helium absorption rates.

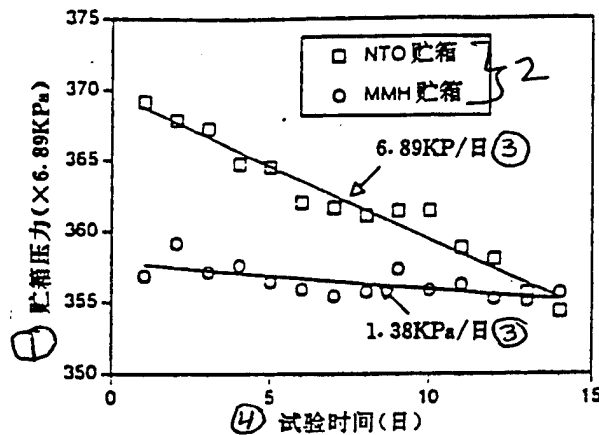


Fig.8 Helium Absorption Test Results

Key: (1) Storage Tank Pressure (2) Storage Tank (3) Day  
(4) Test Time (Days)

In order to obtain system dynamics data--at the same time dropping storage tank pressures during tests--ignition tests were carried out on thrust chambers. There was a total number of 1198 main engine ignitions. Ignition time was 2027 seconds. Water

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hammer effect tests were carried out within large storage tank pressure ranges and different levels of helium saturation. It was discovered that unstable pressure values do not exceed predicted ranges and do not influence normal operations. As was forecast, the highest pressures exist at the comparatively smaller radii in the vicinity of thrust chambers. However, pressure peak values will be approximately 25% lower than analytically predicted values.

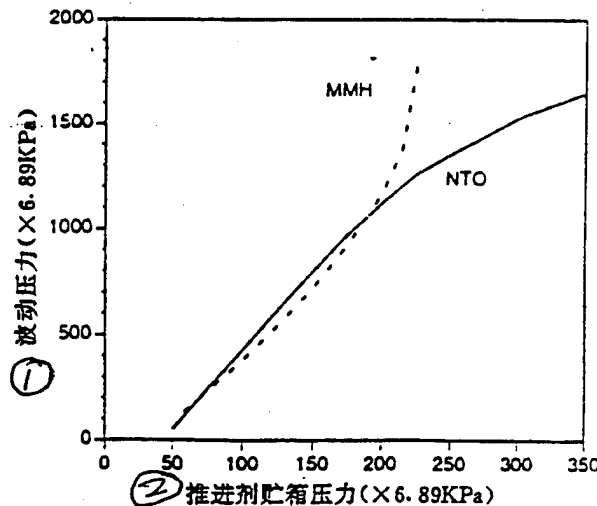


Fig.9 Pressure Fluctuations in Evacuation Tubing

Key: (1) Fluctuating Pressures (2) Propellant Storage Tank Pressures

The most important part of test programs is determining pressure instabilities produced by isolation valves operating on supply systems during fill up. Evaluations are done of pressure fluctuation test data in order to determine the ability to satisfy system safety requirements--at the same time, preventing basic conditions associated with pressure fluctuations doing harm in supply system fill ups. Fig.9 shows pressure peaks in the upper flow incessantly increasing following along with a succession of tests. It has already been determined not to continue increasing upper flow pressures associated with fuel storage tanks in order to guard against hardware damage. In lower flow tubing structures, option is made for the use of completely gas as well as gas-liquid mixtures of different ratios to carry out a series of tests. What Fig.10 shows is that the status of fuel storage tank pressures and the status of oxydizer storage tank pressures are similar. The biggest discoveries associated with pressure fluctuation tests are:

- (1) During lower flow evacuation states, the largest pressure fluctuations are produced. [(2)] On the oxydizer side, due to the fact that vapor pressures are relatively high and flow speeds are comparatively low, pressure fluctuations are the largest. (3) Speaking in terms of a given lower flow pressure, fluctuation

pressures in completely gas states are minimal. Pressures follow along with increases in the ratio of liquid added in and increase. (4) In completely gas cases, it is possible to produce very high pressure fluctuations. This is due to the fact that lower flow initial pressures are very sensitive to thermal changes in tubing.

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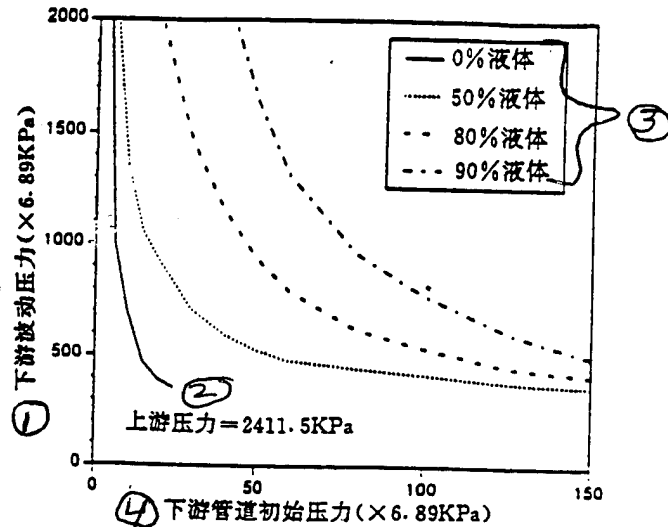


Fig.10 Fuel Fill Up Characteristics

Key: (1) Lower Flow Pressure Fluctuations (2) Upper Flow Pressure (3) Liquid (4) Lower Flow Initial Tubing Pressure

On the basis of fluctuation test results, it was determined that the liquid ratio associated with initial flight operating configurations is 75%. Helium pressures are 1.655MPa. Despite the fact that the completely gas state should be the best choice, due to gas leakage, however, tubing evacuation and potential destructive pressure fluctuations will be produced. As a result, this type of selection is discarded. Liquid present in tubing has a sealing effect, thus preventing supply system gas leakage. Opting for the use of this design, there is no need to add new components (for example, special exhaust valves).

Going through measurements and checks after tests, system propellant compatibility and purity levels were confirmed. A grand total of 884.3kg of oxydizer and 594.08kg of fuel went through filters. In conjunction with that, there were no blockages. With regard to the system as a whole, main engines as well as isolation valve filters had checks carried out on them. In conjunction with them, there was no contamination. In the area of hardware--contrary to expectations--influences of inlet pressures on isolation valve pressure reductions were discovered. Moreover, there was no way to reach pressure requirements of 3.1-3.31MPa. Through the carrying out of closure control on elevation valves and corrugated tubes, it is possible to guarantee that pressure

reduction operations will not be subject to inlet pressure influences.

During tests, the most severe problems discovered were errors existing between actual fuel usage and predicted values. That is, actual oxydizer usage was lower than that predicted by 11%. However, fuel usage, by contrast, was higher than predicted by 4%. The causes lie in main engine thrust chamber pressures gradually dropping, showing the appearance of abnormalities. Besides this, after experiments, leak tests were immediately carried out showing that leakages associated with oxydizer valve seats in the upper flow were far, far higher than parameter requirements. Analysis indicates that, when heating back plates were heated up, interior cavity pressures with long term oxydizer exposure increased, leading to the expansion and deformation of polytetrafluoroethylene (plastic) valve seats. Flow amount surface area reductions as well as propellant saturation together led to upper flow oxydizer valve fluids producing cavitation. Moreover, flow amounts were reduced. Improvement designs included enlarging valve strokes, correcting upper flow valve seats, and increasing temperatures when carrying out polytetrafluoroethylene processing to produce valves.

#### BRIEF SUMMARY

Successfully carrying out the development and appraisal of Bus 1 propulsion systems clearly shows that, using dual element super charging designs, it is possible to extend the lives of spacecraft.

A number of new technical and design problems were discovered and solved. New models of thrust chamber were developed, capable of operating under a wide range of working environments. Option was made for the use of flight model components to carry out system tests. Test results are influencing the guiding methods associated with system design.

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