DOUGLAS PAPER NO. 4086

SYSTEMS APPLICATIONS IN ORBITAL LAUNCH OPERATIONS

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FOR PRESENTATION TO:
AIAA THIRD ANNUAL MEETING
BOSTON, MASSACHUSETTS
NOVEMBER 29 THRU DECEMBER 2, 1966

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Abstract

The objective is to examine the technical requirements and feasibility of conducting orbital launch operations with systems now in the development phase. In order to maintain realistic constraints on the analysis, the Saturn S-IVB stage has been used as an example of present stage technology. The requirements, procedures and complexity of operations for orbital assembly and launch are discussed. The primary design requirement for orbital assembly and launch operations is increased orbital stay time (from hours to days or weeks). The S-IVB stage was examined to determine the design changes, weight increase, and performance penalties of adapting it to a 30 day orbit stay time loaded with propellants. The tradeoffs in weight and performance between an independent stage and the removal of certain stage support systems to a separate jettisonable support equipment stage is considered.

I. Introduction

Orbital launch operations with existing or in development systems will enable the performance of several new classes of missions beyond manned lunar landing. The objective of this paper is to examine the technical requirements and feasibility of conducting orbital launch operations with systems now in the development phase. In order to maintain realistic constraints on the analysis of operations and systems requirements and feasibility, the Saturn S-IVB stage has been used as an example of present stage technology.

The approach is to identify the basic functional requirements for orbital assembly and launch operations, define the basic operational modes and associated support systems, and investigate the system requirements of a representative orbital launch vehicle stage (e. g. , the S-IVB). The stage support requirements' weights and performance penalties associated with orbital assembly and launch requirements are then determined as a function of stay time in orbit and a performance tradeoff presented between the separate orbital support equipment mode (OSE) and the onboard equipment mode (independent OLV).

II. Discussion

Why OLO

Before examining the requirements for orbital assembly and launch operations (OLO), one might question the reason for considering this as yet untried and unproven operational mode in view of the already developed and sophisticated experience with ground launch modes with bigger and bigger boosters. Part of the reason is that the largest booster yet developed, the Saturn V, appears to be near the dimensional limit for handling convenience – certainly a mere increase in size, say by 30 per cent or more, in order to significantly increase mission capability would present severe handling problems as well as invalidate most all of the tremendous investment to date in facilities and equipment. Increases in propulsion systems performance and new operational modes, separately or in combination, offer potentially significant increases in mission capability within present handling and facility constraints.

OLO Mission Capability

As an example of OLO mission capability, the mission spectrum potential of the Saturn V with a combination of booster uprating and orbital assembly and launch operations is shown in Figure 1. Uprating the Saturn V shows a considerable increase in mission capability but not enough for manned planetary reconnaissance. Orbital launch operations using two or three S-IVB's allow a significant support capability for a manned lunar base and performance of limited Mars and Venus manned flybys with a standard Saturn V. Orbital launch with uprated Saturn V-3 provides ample capability in two new classes of manned missions plus considerable increase in capability for unmanned capture and landing probes to Jupiter and Mercury. An orbital launch vehicle assembled from two or three modified S-IVB stages would have a payload capability of 90 to 180 metric tons, which is sufficient for manned Mars/Venus flyby missions. By trading payload for higher velocity, 30 metric tons can be delivered at 19 kilometers per second. This is sufficient for extensive exploration of the solar system (including satellites and the outer planets) with unmanned probes.

Basic OLO Requirements

The orbital launch concept will require new development in some areas to fully exploit the systems and facilities now being constructed. For example, rendezvous and docking must be perfected within the operational constraints imposted by meeting Earth, orbit, and planetary launch window schedules. In part, this has been at least tentatively demonstrated as a feasible technique by the Gemini program (e. g. , Gemini 76, Gemini 8 and 9), although some equipment problems have limited the operations. Orbital assembly and checkout techniques must be developed and tested. The capability for man extravehicular activity (EVA) is indicated; this too, although beset by some equipment problems, has been at least tentatively demonstrated by the Gemini program. New support equipment, separate or onboard the orbit launch vehicle, will be required in orbit. Existing boost stages must be modified

SATURN V MISSION SPECTRUM MAP

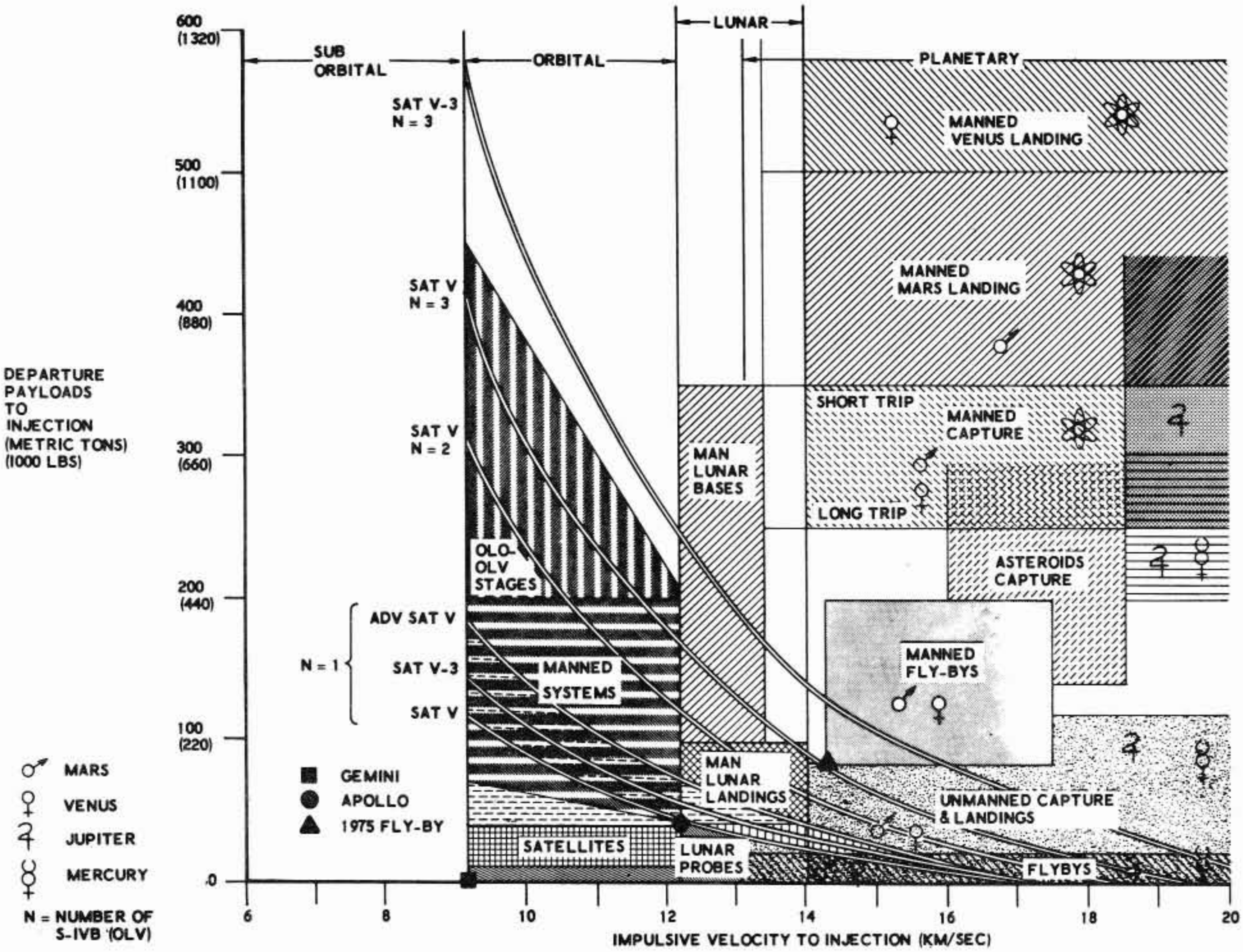

FIGURE 1.

to extend their orbit stay time and provide a rendezvous, docking, assembly and checkout capability.

The basic requirements for orbital launch operations may be grouped into five broad categories as noted in Figure 2. The components must be launched into orbit to build-up the orbit launch vehicle. These components must be maintained in orbit until the operations are completed and the orbit personnel (assembly crews, checkout crews, and the mission crews) must be accommodated. When the build-up is completed, preparation must be underway to perform the launch within the mission window constraints. Most of these task requirements are applicable to orbit launch of any vehicle. The particular manner in which the orbital operations tasks are performed will depend in part on the basic operational mode selected.

Operational Modes

There are three basic operational modes associated with orbital assembly and launch operations. These are termed the Independent Orbit Launch Vehicle, the Temporary Orbital Support Equipment, and the Permanent Orbital Launch Facility, and are defined below. Obviously, it is possible to combine certain aspects of each of the three basic modes to create several alternate modes with varying degrees of vehicle dependency and support and operational capability.

ORBIT LAUNCH OPERATIONS (OLO) REQUIREMENTS

PERSONNEL

- CREWS ACCOMMODATIONS AND SAFETY
- CREW TRANSFER

BUILD UP

- LOGISTICS
- RENDEZVOUS
- DOCKING
- ASSEMBLY
- FABRICATION
- PROPELLANT TRANSFER

PREPARATIONS

- COMMAND AND CONTROL
- CHECKOUT
- FAULT DETECTION
- REPAIR AND REPLACE
- COMMUNICATIONS
- DATA EVALUATION

MAINTAIN

- PROPELLANT CONTROL
- ENVIRONMENT CONTROL
- ATTITUDE CONTROL
- MAINTENANCE AND SUPPORTING SUPPLIES

LAUNCH

- COUNTDOWN AND LAUNCH
- LAUNCH WINDOWS
- EMERGENCIES AND ABORT
- TRACKING AND NAVIGATION

FIGURE 2.

Independent OLV. OLO support provided by utilizing the orbital launch vehicle (OLV) itself without any supporting orbiting hardware. The spacecraft must be orbited manned in the mode and must perform all the necessary orbital operations with onboard systems. Some of these might be jettisoned prior to orbit launch.

Temporary OSE. OLO support provided in terms of checkout and maintenance crews, spares, equipment, etc., by individual support vehicles launched as required from earth - known as "Service Vehicle" or "Temporary Vehicle" mode.

Permanent OLF. OLO support provided by a "Permanent Facility" mode whereby a manned station serves as a base of operations and provides housing for the required support crews and specialized OSE is supplied similar to the "Temporary OSE" mode.

The three basic modes are presented in concept in Figure 3, engaged in OLV buildup operations. For the independent OLV concept the mission spacecraft is shown on a docking approach to an OLV booster assembled from three tandem stacked stages - stage support packs are indicated on each booster stage and on the nose of the spacecraft. Strictly speaking, the spacecraft must be orbited manned in this mode and must perform all of the orbital operations. It is possible that portions of the stage support equipment may be jettisoned at orbital launch, but their weight represents a decrease in the usable propellant aboard the OLV (due to Saturn V booster limits). The temporary OSE concept is illustrated by an Apollo C/M plus S/M docking the spacecraft to OLV stages supported by an unmanned OSE module. Operations crews and mission crew life support are largely limited to that available in an Apollo Command Module (C/M). The permanent OLF adds a manned station (which can have several other missions between launches beside OLO support) for command and control base and crew housing. In addition, a specialized manned orbital tug concept is shown removing a rendezvous kick stage from a docked OLV stage. Stage support equipment similar to the temporary OSE is employed to maintain and supply the OLV.

Since these operational modes differ primarily in the nature of the resources provided in orbit for meeting the orbit launch vehicle systems requirements and the orbital assembly and launch operations requirements, these requirements must be examined in order to properly evaluate and compare the feasibility of the various modes.

Orbit Launch Vehicle System Requirements

In order to identify the OLV stage requirements, a specific Saturn V stage was selected for analysis. The S-IVB/Saturn V stage because of its six hour orbit stay capability, restart capability, and mission profile for the Apollo LOR Program, is most similar to an OLV and was selected as a prototype stage for the requirements analysis.

An analysis of the S-IVB for the Orbit Launch Vehicle (OLV) booster stage indicates that neither fabrication or propellant transfer operations are required. The standard Saturn V booster can deliver a modified OLS-IVB to the assembly orbit with sufficient propellant (85 per cent) onboard to perform useful orbit launch missions using orbital assembly only. Moderate uprating of the Saturn V (250K uprated J-2) can deliver the OLS-IVB docked and unfired with 95 per cent of propellant load (a rendezvous kick stage is required for the Gemini style rendezvous gross maneuvers in any case). These figures include the weight penalty of 7,000 pounds per OLS-IVB stage mandatory for cryogenic insulation, meteoroid shielding, and docking structures.

Figure 4 is a list of increased or new system requirements which must be provided to adapt or convert an earth launch stage to an orbit launch stage. Many of these system requirements are due to the time required for orbital buildup of the OLV and the desire to provide sufficient orbit hold time to mitigate launch window constraints on the operations schedule. A nominal stay time of 20 days was indicated from the example mission timeline analysis and a design stay time of 30 days selected for system criteria. Performance and control requirements for rendezvous and docking, along with a desire to maintain the main stage propulsion system in a "buttoned-up" condition until orbit launch (improving orbit stay time, OLV performance, safety, and checkout capabilities), led to separate propulsion systems tailored to these functions. A rendezvous kick stage can perform the major velocity injections (plane change, slow catch up injection, and near circularization) of a quasi-Gemini rendezvous technique.

OLO MODES

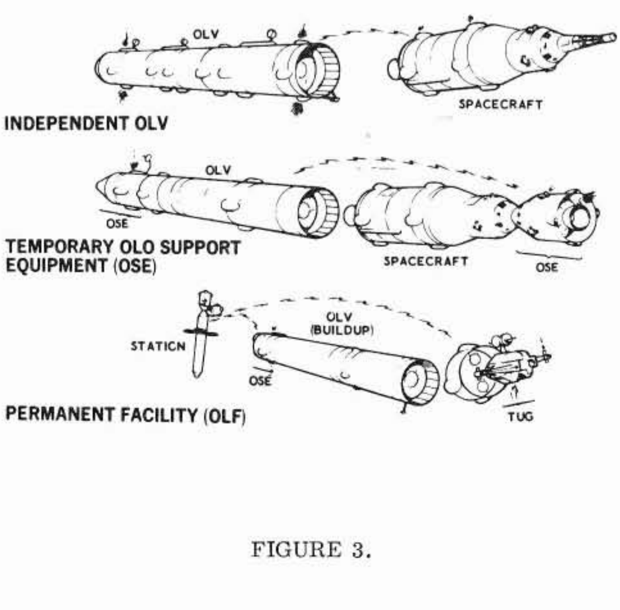

FIGURE 3.

ORBIT LAUNCH VEHICLE (OLV) SYSTEM REQUIREMENTS

PROPULSION

- • RENDEZVOUS SYSTEM
- • DOCKING SYSTEM
- ▲ • ATTITUDE CONTROL SYSTEMS
- ▲ • PROPELLANT CONTROL SYSTEM (VENT & SETTLE)
- • ABORT & DEBRIS RETRO MOTORS
- • STEP T/W≧~0.7
- • RESTART (S)
- • HIGH ENERGY PROPELLANTS (MAIN STAGE)

STRUCTURES

- • DOCKING STRUCTURES (MALE AND FEMALE)
- • INSULATION AND HEAT BLOCKS
- • MICROMETEROID SHIELDS
- • ORBIT HANDLING AND ATTACH PTS.
- • REPAIR & REPLACE ACCESS
- • UMBILICAL TUNNEL
- • ADDED SUPPORT STRUCTURES AND BRACKETRY

MECHANICAL

- • DOCKING ACTUATORS
- • ASSEMBLY LATCHES
- △ • ORBIT UMBILICAL CONNECTORS AND ACTUATORS
- ▲ • PNEUMATIC SUPPLY INCREASE
- △ • SPACE RADIATORS
- △ • THERMAL CONTROL PANELS (AND BLANKETS)

ELECTRICAL/ELECTRONIC

- • ADDED COMMAND MODES
- • TRACKING TRANSPONDERS
- ▲ • POWER SUPPLY (DURATION INCREASE)
- △ • HORIZON AND STAR SEEKERS
- • INCREASED SEQUENCER PROVISIONS
- △ • COMMUNICATION LINKS (COMMAND AND CONTROL)
- △ • DIGITAL COMPUTER
- △ • DOCKING SENSORS
- △ • UMBILICAL CONNECTORS AND CARRY-THRU
- • ADDED PROPELLANT MONITORING AND CONTROL ELECTRONICS
- • RENDEZVOUS STAGE ELECTRONICS AND INTERFACE
- • DOCKING ELECTRONICS (APS)
- • ENVIRONMENTAL CONTROL SENSORS
- • SAFETY MONITOR SENSORS
- △ • CHECKOUT INTERFACES
- • ORBIT F/D TEST POINTS
- • ORBIT ABORT SENSING AND CONTROL

▲ REQUIREMENTS WHICH CAN BE MET OR SUPPLEMENTED (△) BY OSE

FIGURE 4.

Added APS (Auxiliary Propulsion System) modules provide rendezvous attitude control, final circularization, and docking propulsion. Propellant control systems are needed to settle the main stage propellants for venting (thermal control, etc., are designed to allow at least a 24-hour span between vent operations to minimize interference with orbit operations) and for launch. Abort motors are required to retro the OLV stages away from the manned spacecraft for a launch abort.

Step thrust to weight ratio of 0.7 or greater is desired to minimize gravity losses at orbit launch (first stage thrust to weight should exceed 0.25). Restart is desired to increase the orbital launch window even with a multistage OLV (a 40 second burn at apogee of the intermediate escape elliptical orbit allows about 6 degrees to 8 degrees plane change prior to final injection near perigee). High energy propellants are desirable for OLV stages to minimize OLV growth factor.

The added structure requirements listed in Figure 4 are largely self explanatory – an exception might be the umbilical tunnel. The dynamics and structure problems of removing long umbilical lines (from the OSE, if used, to each OLV stage) with either flexible or rigid "arms" indicates the desirability of a built-in umbilical tunnel on each stage with automatic connections from stage to stage. This also provides flight hardwire connections between stages. Use of the standard ground umbilical plate for stage interface does not appear adaptable to a dual purpose (ground and orbit) interface. Proper minimization and selection of umbilical lines and the use of staggered stacking connections minimized the penalty thus incurred. This added burden to the orbital launch vehicle (OLV) was considered acceptable in order to minimize the control dynamics and debris problem at launch and simplify the orbital assembly operations. Pneumatic supply must be increased to perform periodic valve "dither" to ensure valves do not become "frozen" during the several weeks in orbit. This can be accomplished by added onboard cold helium storage tanks in the LH_2 tank or by pneumatic supply lines from the OSE to the stage pneumatic vent valve downstream of the regulator. Thermal control requirements of the stage systems, subsystems, and components can best be met by a combination of coolant mounting plates (cold plates) and electrical heating elements (blankets). These will require space radiators on the stage. Heat injection from the coolant should employ a secondary closed loop space radiator rather than the present secondary open loop water sublimation. The hydraulic fluid temperature control can best be maintained by electrical heating blankets and line insulation combined with limited operation of the auxiliary pump for fluid circulation. The present coolant pump in the IU has a 900 hour life which is marginal for the 30 day mission.

Numerous control and sensor electronics are needed to perform the orbital operations. A major electrical requirement is the long duration power supply and possible load increases. A brief comparison with the S-IVB coast mode and expected OLO requirement indicates that the orbit stay - from post-docked to pre-launch - load profile will average 1.5 to 2.0 KW with peaks of 4KW per OLS-IVB stage. Power supply for the OLV stage while docked in orbit can be supplied by an onboard system or by a system on separate OSE. Stage power systems must be modified to meet the increased requirements during orbital rendezvous and possibly during orbital launch.

Orbital umbilical interface must be incorporated in the power, command, and data systems. A checkout interface between the stage system and the checkout system must be incorporated. The checkout system could be incorporated in the IU system or in a separate OSE stage.

These system requirements present a brief description of the necessary added weight and complexity of a stage to achieve a true orbit assembly and launch capability. If propellant transfer were employed, several additional systems and modifications would be required. It appears feasible to meet each of these requirements by modifying and adding systems to a suitable existing ground launch stage (e.g., the S-IVB). By developing separate orbit support equipment many of the requirements could be met with a minimum of weight penalties to the orbit launch vehicle. Figure 5 indicates the orbit support functional requirement which could be provided by a separate orbital support equipment stage, here termed SORD for "Supporting Orbital Dock."

Example of Separate Orbit Support Mode

The basic functions of the Supporting Orbital Dock (SORD) are grouped into six categories illustrated in Figure 5; docking, attitude control, OLS-IVB system support, checkout and monitor status, acceleration of the OLV, and launch countdown and positioning. The use of the SORD relaxes the OLV requirements and provides increased orbital support and stay time for the OLV. Without the SORD, most, or all, of these functions would have to be performed by each OLS-IVB and the OLV. The SORD concept is here illustrated in connection with a manned orbital station to comprise a "Permanent OLF" mode.

The SORD contains OLV pneumatic supply, electrical power supply, a stability and control system, reaction control and translation propulsion (possibly derived from the S-IVB APS modules), command, control, and data interfaces with the OLV systems, communication and control links with the station, part of the system for computerized orbital evaluation (SCORE) for OLV stages checkout, a female docking cone and OLV orbital umbilical interface, limited environment control for certain SORD systems, and rendezvous, docking, and station keeping systems. It also has a docking face for the orbital tug, if employed.

This concept represents the approach of minimizing the weight penalty to the OLV stage due to orbital stay time (system support, e.g., thermal control, gas use and leakage, electrical power, etc.) and operations (system functions, e.g., attitude control, ullage, etc.). It remains to be determined whether the associated weight-and-payload penalties of the non-SORD (Independent OLV) system are severe enough to warrant a separate OSE stage such as the SORD.

Dependent Orbital Launch S-IVB Description (SORD Supported)

The orbit launch version of the S-IVB stage is illustrated in Figure 6 in the configuration as launched on the Saturn V Earth Launch Vehicle (ELV). The modified S-IVB, the rendezvous kick stage, and nose cone comprise the payload to be injected to rendezvous orbit by a modified Saturn V.

The J-2 engine is uprated to 250 Klbs thrust to ensure adequate first stage thrust-to-weight ratio in multiple tandem assembled OLS-IVB's for the orbital launch vehicle. The propulsion system and thrust structure must be modified to accommodate the modified engine. The OLS-IVB can perform orbit launch missions with the 200K/J-2 engine but at marginal performance for a manned planetary reconnaissance mission. Three tandem OLS-IVB/250K/J-2 stages can boost an 86 metric ton (190,000 pounds) spacecraft into the heliocentric trajectory.

The LH_2 tank was lengthened 4.75 feet to increase LH_2 volume and allow the vent cycle (with the added external installation and heat blocks) to be increased from

SORD FUNCTIONS

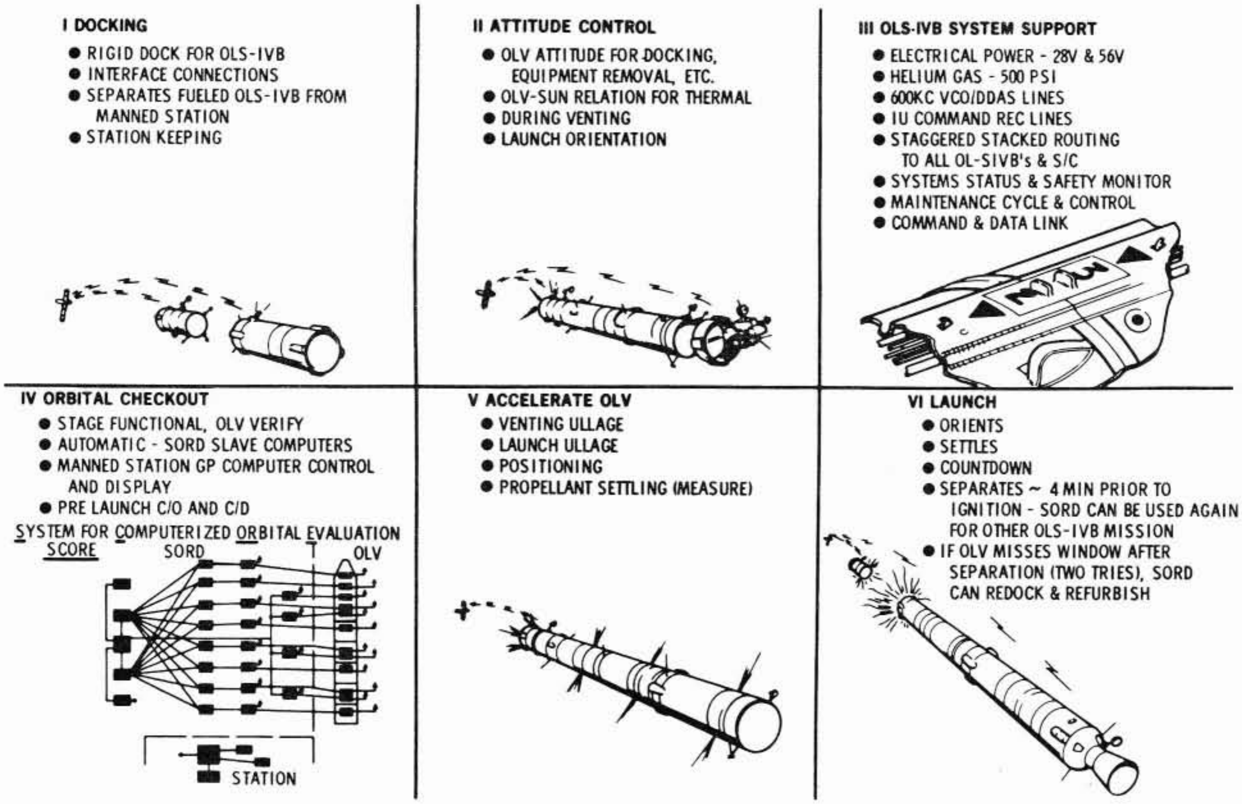

FIGURE 5.

10 hours to 24 hours. This decreased the settling and venting operations required during orbit buildup and preparation. A separate (third) bulkhead was required to isolate the LO_2 tank from the LH_2 tank to reduce heat transfer and LH_2 boiloff. The LO_2 tank pressure was increased to meet uprated J-2 engine requirements.

Docking structures are added with a male frustrum (1050 lbs) on the stern and a female frustrum (2600 lbs) on the bow. External insulation is added to the LH_2 tank walls and additional structural heat blocks incorporated to reduce thermal input to the LH_2 tank to .6 million BTU in 30 days, limiting LH_2 boiloff to 6800 lbs (227 lbs/day). A meteoroid shield is added to limit meteoroid penetration to a .99 probability of no more than one penetration of the shield itself during a 30 day stay in Earth orbit.

These stage modifications are necessarily integral modifications and result in an estimated dry weight increase of 7000 lbs for the dependent OLS-IVB stage to a total dry weight of 34,164 lbs (excluding IU and APS). The nose fairing, 1770 lbs, is jettisoned during ascent and is not included in the above weight.

Eight auxiliary propulsion modules are added to each stage to provide attitude control during rendezvous, docking and launch, and to provide translational acceleration during final circularization, docking, and orbit launch ullage. All but the four aft modules on the orbital launch vehicle first and third stages are removed in the orbit assembly operations prior to orbital launch. The aft APS modules and propellants weigh 3420 lbs and the forward APS module and propellants weigh 4180 lbs after docking is completed; this includes sufficient propellant for the orbital launch flight profile. During orbital rendezvous and docking, 9130 lbs of APS propellants are expended.

The Instrument Unit (IU) is retained with each S-IVB stage throughout the orbital operations and launch. It is an integral part of the S-IVB command and control, environmental control, and orbital checkout systems. During orbit launch, guidance and control commands are generated by the uppermost instrument unit with the other systems (first and second stages) slaved to it. This approach imposes a 4000 lb inert weight penalty which might be eliminated if more extensive stage modifications were acceptable. However, it was deemed easier to provide slightly higher propulsion performance capability to compensate for retaining the instrument unit system intact at orbit launch.

The rendezvous kick stage consists of an LO_2/LH_2 propellant and pressurization system, two RL-10 engines, and interfaces with the S-IVB stage instrument unit and power supply (including emergency batteries). It is mounted on the bow of the S-IVB (the stage is docked stern first) and jettisoned or removed by the assembly crew after the stage is docked. This stage is estimated at 10,000 lbs, including 7000 lbs of useful propellant.

With 208,175 lbs of LO_2/LH_2 OLS-IVB propellant loaded (205,800 useful at orbital day T_o), this requires a 274,839 lb injected useful payload weight into the rendezvous phasing orbit. This is within the capability of the standard two stage Saturn V modified to the 250K uprated J-2 on the S-II stage. After rendezvous and docking, the useful weight docked is 249,739 lbs, including the aft APS modules. Three of these stages can inject a 190,000 lb spacecraft (plus 7090 lb spacecraft docking-adapter structure and APS modules) into a 1977 Mars flyby trajectory from a 200 nautical mile launch orbit (ΔV impulse = 16,985 fps and using a third stage coast in an eight hour

ELV S-IVB STAGE LAUNCH

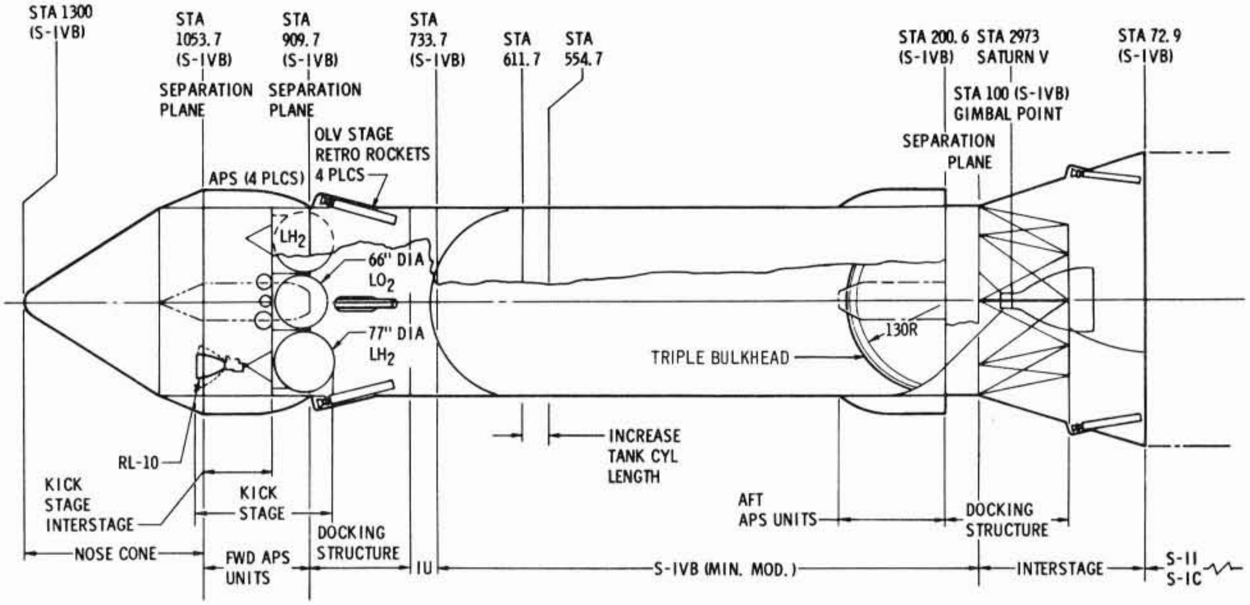

FIGURE 6.

elliptical intermediate departure orbit). This then defines the nominal weight and performance for the dependent OLV stage. For the independent OLV, the approach is to keep total OLV stage weight constant, subtracting the weight of added stage support systems from the useful propellant onboard and determine the new allowable spacecraft weight. Addition of orbit support equipment (power systems, etc.) will result in increased OLV inert weight at orbit launch (and thus lower performance), whereas certain support items (e.g., attitude control propellants) are expended during the orbit stay and thus merely reduce performance by detracting from useful propellant onboard.

Independent Orbital Launch S-IVB

The primary factor in orbit support systems weight, and thus performance penalties, is stay time in orbit. The four basic support requirements are: (1) control and pressurization helium, (2) electrical power; (3) APS propellants for attitude control and for venting and launch ullage; and (4) stage checkout equipment.

Control and pressurization helium requirements are as follows:

1. Main stage propellant pressurization - no additional helium is required over that provided for the S-IVB launch, i.e., no support stay time requirement.

2. Maintenance and Leakage - the operation of certain pneumatic valves is anticipated during orbit stay to prevent them from becoming "frozen" and to check systems - this requirement, plus system leakage, is estimated at 1.5 lbs/day.

3. APS propellant pressurization - the expulsion of APS propellants will require 0.36 lbs of ambient helium per day - approximately 0.3 lbs of this is expended during the APS operation (135 lbs of propellants) for four minutes of axial acceleration during the daily hydrogen venting cycle.

4. Checkout and launch control helium - this is required only two to three times during the orbit stay to provide added (above present stage requirements) checkout with onboard helium - one pound (total) is sufficient.

Total orbit stay support helium requirements then amount to between 1.5 and 2 lbs per day. Storage at 3000 psi ambient was investigated but resulted in high tank weights and considerable volume requirements (600 lbs and 5 two foot diameter tanks per stage for 20 days in orbit). As a result, helium storage tanks at 40° R and 3000 psi inside the LH_2 tank (as the present S-IVB stage employs) was considered. Figure 7 presents the system weight and volume requirements for orbit stay cold helium storage as a function of days in orbit for use rates of 1.5 and 2.0 lbs per day. Tank weight (46 lbs) is the major item - each is loaded with 40 lbs of cold helium at 3000 psi, of which 25 lbs can be used (500 psi lower limit). Figure 7 indicates that use of cold helium limits added stage weight to 200 lbs and volume requirements to 2 two foot diameter tanks in the LH_2 tank. However, an added requirement is to convert this to ambient temperatures (500° R) for use, particularly for the APS propellant tanks pressurization at 40 psi. The maximum demand rate here is for about 0.33 lbs of ambient helium converted from the cold helium in four minutes - once a day. This requires about 1 Kw of electrical power for heating (it is possible this might be reduced by bootstraping heat from the APS engines). This capacity is included in the electrical power supply requirements. The added weight of the converter was not determined but is estimated as a very minor weight item.

ORBITAL STAY S-IVB CONTROL HELIUM REQUIREMENTS

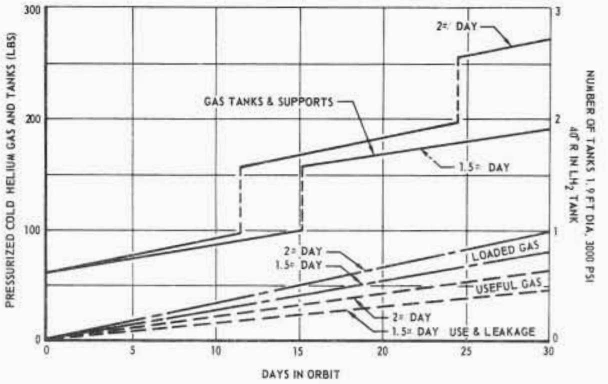

FIGURE 7.

Electrical Power Requirements

Based upon studies of S-IVB coast, electrical power requirements are about 47 Kwh/day with 4 Kw peaks. Although distribution of power may be modified (e.g., substitution of a hydraulic fluid electrical heating blanket instead of heating with the auxiliary motor, reduction of continuous telemetry, addition of electrical heater for converting cold helium to ambient, etc.), the total power load should remain roughly equal, or about 1.5 Kw average with 4 Kw peaks. Figure 8 presents the resulting power supply system weights per stage as a function or orbit stay time for (1) Apollo type fuel cells, (2) stage oriented silicon solar cells with chargeable batteries for nightside and peak loads, and (3) a Brayton system with peak batteries and a radioisotope heat source. Most of the fuel cell system is fixed equipment weights (non-expended) with reactant consumption at about 34 lbs/day. The solar cell system is based on mounting directly to the exterior of the interstage and docking structure in a circumferential mount about 21 feet along the length of the stage. It requires stage orientation normal with the sunline – at least during the sunside passage – to keep incident light within ±15 per cent of normal. Without this orientation the solar cell system would require rather complex and heavy steerable panels or about four times as much area and weight as well as more batteries (it is assumed that the stage stabilizes in a vertical position reducing incident solar energy per orbit by about a factor of two). Obviously, the choice of a stage electrical power supply for the expected 20 to 30 days in orbit falls to either the solar cells/chargeable batteries system (910 lbs) or the radioisotope/Brayton/chargeable batteries systems (470 lbs). Advantages and disadvantages are associated with both systems other than simple weight comparisons. No attempt was made to discriminate, rather it was elected to employ the heavier and more constraining concept, the solar cell system, with 100 per cent attitude control.

APS propellant requirements are summarized in Figure 9 on a per stage basis. Note that the pure attitude control requirements, 44/lbs day for control 24 hours a day, 21/lbs day average for control only during certain operations such as docking, venting, inspection, etc., or about 2.5 hours per day, are small compared to total requirement of about 180 lbs per day (24 hours/day control) due to the axial acceleration of 5×10^{-4} g's provided by the APS for about four minutes each day to settle and maintain propellants during hydrogen venting. The acceleration is applied normal to the orbit plane and reversed on alternate vents to minimize orbit perturbations (4 fps per vent cycle). This identifies the venting ullage propellant as the heaviest single orbital support requirement. The linear acceleration method is considered rather than some of the more exotic and promising zero g vent systems because it is the only one within the existing state-of-the-art and most in accord with stage tank and vent systems geometry. The primary question is not, "Will it work?" but rather, "at what level of acceleration will it work?" Estimates and calculated values range for 10^{-2} g's to 10^{-4} g's over periods of seconds to minutes. At 5×10^{-4} g's (125 lbs thrust) the stage is translated the length of the LH_2 tank in 70 seconds. This would seem adequate to settle the propellant; however, more sophisticated analyses considering viscosity and buoyancy as well as some limited experimental data indicate that a factor of 2.5 should be applied to the settling time ($2.5 \times 70 =$ 175 seconds). The value assumed here is 190 seconds to settle at 5×10^{-4} g's (125 lbs thrust) and an additional 50 seconds at this level to vent 227 lbs of gaseous hydrogen per S-IVB stage (once a day cycle).

The attitude control propellant requirements are based on 8 lb-sec minimum impulse engines, 5400 seconds of ±1 degree control per day, three daily convergences (at 3 lbs propellants each), and 2100 seconds of ±5 degrees control for the 10 per cent case, of 22.5 hours of ±5 degrees control for the 100 per cent case (24 hours/day control) in a 200 n. mi. circular orbit and

ORBITAL STAY S-IVB POWER REQUIREMENTS

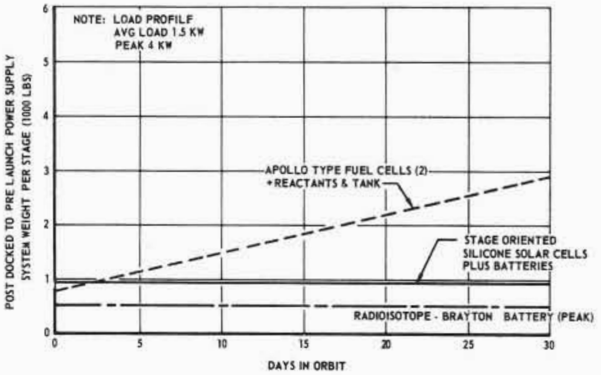

FIGURE 8.

ORBITAL STAY S-IVB ATTITUDE CONTROL AND VENTING ULLAGE PROPELLANT REQUIREMENTS

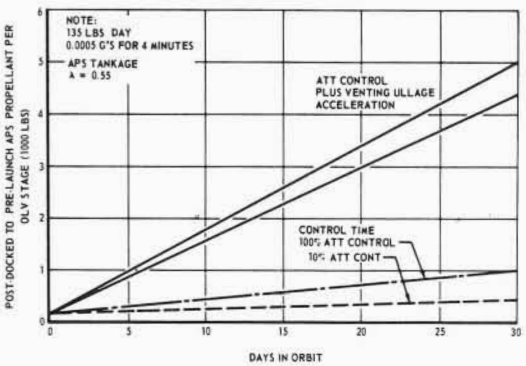

FIGURE 9.

near sunline normal orientation. Stage moments of inertia and APS locations result in consumption rates for the 8 lb-sec impulse limit of about 5 lbs/hour at ±1 degree and 1 lb/hour at ±5 degrees. For a rough approximation these values may be extended to the assembled orbital launch vehicle (3 OLS-IVB in tandem) by multiplying by three. This was done to simplify the analysis and appears to be a conservative approximation.

The amount of APS propellant indicated in Figure 9 is not the total system requirement since expulsion tankage, support structure, etc., must be added to hold the additional propellant. The estimated propellant mass fraction, λ', in this case is 0.55 (e.g., 4000 lbs of additional APS propellant requires a total added weight of $4000/0.55 = 7,270$ lbs).

Checkout requirements for the stage can largely be met by adding about a hundred pounds of computer racks, sequencer modules, and a few hundred pounds of necessary sensors, switching, and cabling to the IU and stage systems. This was considered within the allowed weight for the IU (4000 lbs) and was not added as a weight penalty to the independent OLV.

Orbit Launch Vehicle Performance

The useful mission payload weight which can be injected onto a 1977 Mars flyby heliocentric trajectory by a constant gross weight into orbit (752,957 lbs on day zero) orbit launch vehicle is presented in Figure 10 as a function of days in orbit (stay time) and for various levels of onboard versus separate OLV support. As previously indicated, the dependent OLV which has separate orbit support equipment (separately launched into orbit and jettisoned at orbit launch) typified by the SORD concept has a useful payload of almost 190,000 lbs after maximum stage time in orbit of 5 days. This value decreases as LH_2 boiloff reduces the available propellant in orbit at about 227 lbs/stage/day in orbit (LO_2/LH_2 loading is proportioned to provide the proper mixture ratio after the nominal stage time in each case). After twenty days since the first OLS-IVB was docked in orbit (based upon an assumed 4 days in this case between launches into orbit), the useful payload is reduced to 187,200 lbs; after thirty days, to 185,800 lbs (16,280 lbs of LH_2 vented overboard out of a total of 116,480 lbs orbited). Timing provides for a total of five launches (3 OLS-IVB's + backup + spacecraft) plus one time interval (1 to 6 days) for final orbit preparations.

The effect of increasing onboard OLV support (eliminating separate OSE) is presented in incremental fashion. It is seen that addition of onboard orbit stay control helium has very little effect on payload ($\Delta PL = -316$ lbs at 20 days). Addition of the solar cells/batteries stay time electrical power supply has a more significant effect, reducing payload by -1970 lbs in all cases (note this is a constant weight with stay time item). Addition of onboard attitude control during orbit stay (100 per cent of time as required to orient the solar cells) leads to further moderate reductions in payload, down 2170 lbs at twenty days to a total of 182,800 lbs for orbit stay control helium, electrical power, and attitude control onboard.

The major payload degradation for the independent OLV is due to the daily venting ullaging APS propulsion requirements – this one requirement exceeds the combined payload reduction of the other orbit support requirements. At twenty days in orbit the payload is reduced a further 7800 lbs for a total reduction from the dependent OLV of about 12,200 lbs or from 187,200 lbs down to 175,000 lbs. It is possible that combining all the ullaging propulsion propellants and systems onto the first stage (first OLS-IVB orbited) and taking all the useful propellant penalty on this lowest growth factor stage will mitigate this payload penalty. In addition, by combining all ullaging propulsion requirements on the first stage it would be possible to achieve a better ullaging propulsion system mass fraction (lower inert weight) and/or possibly stage the spent system at launch.

Dependent/Independent OLV Comparison

The useful payload for the fully independent OLV is compared in Figure 11 to the useful payload of the dependent OLV using SORD type OSE as a function of stay time in orbit. The resulting payload loss ranges from less than 3 per cent at 5 days to only 9 per cent at 30 days. These results indicate that from a vehicle performance criterion the independent OLV is an acceptable operational mode. That is, it may be easier to moderately uprate the Saturn V (and thus useful OLV propellant) a further 5 per cent to provide a 190,000 lb payload than to develop and launch a separate orbit support stage (e.g., SORD).

EFFECT OF ORBITAL STAY AND SUPPORT REQUIREMENTS ON OLV (3 S-IVB) PAYLOAD

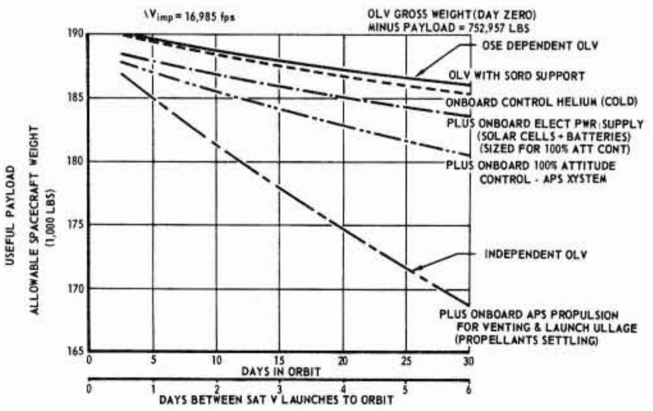

FIGURE 10.

EFFECT OF OLV-OSE SUPPORT ON PAYLOAD CAPABILITY

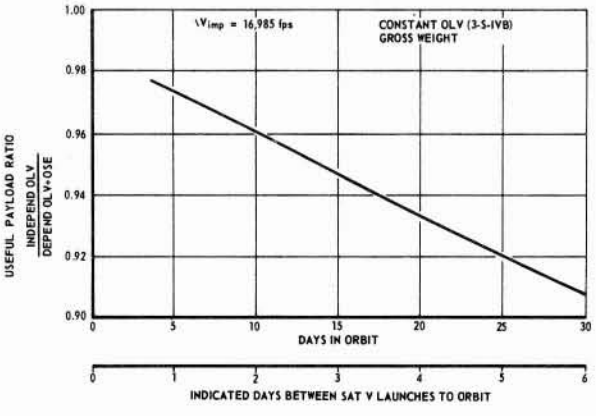

FIGURE 11.

Conclusions

Based upon the limited analysis presented, the following conclusions are made in regard to orbital launch operations with existing or in development stages.

Technology Requirements

1. Maintaining stage integrity during the long stay times in orbit is the major OLO design requirement.
2. Certain requirements are necessarily integral to the OLV stage, e.g., thermal insulation, micrometeoroid protection, docking structures, etc.
3. Other support requirements may be onboard the stage (independent OLV) or located in a separate orbit support equipment stage (e.g., SORD) - these are: control helium, electrical power, attitude control propulsion, propellant ullage propulsion (for vent cycles and launch), and system checkout computers and logic.
4. The major support requirement from a weight penalty criterion is propulsion for venting ullage.

Feasibility

1. Present stage technology (as represented by the S-IVB + IU) is adaptable to orbital assembly and launch operations; however, several significant stage modifications and the addition or orbital support equipment (onboard and/or separate) are necessary, requiring some new development engineering and testing.
2. The Independent OLV mode is feasible and does not present excessive performance penalties in comparison with the separate OSE supported OLV, i.e., the SORD is not required.

The conclusions presented here are in addition to and supersede those presented earlier by the author in Reference 1. The depth and scope of the analysis performed for this paper were necessarily limited and the conclusions presented, therefore, should be construed as tentative pending further study. Concurrent with the presentation of this paper, the Douglas Aircraft Company is performing a contracted study for NASA on the application of the S-IVB as an orbital launch vehicle stage; this study should provide much more substantial and definitive results and conclusions.

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