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SPACE SHUTTLE PERFORMANCE CAPABILITIES REVISION 1

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Advanced Mission Design Branch

MISSION PLANNING AND ANALYSIS DIVISION

MANNED SPACECRAFT CENTER

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SHUTTLE PROGRAM

SPACE SHUTTLE PERFORMANCE CAPABILITIES REVISION 1

By Gus R. Babb
Advanced Mission Design Branch

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MISSION PLANNING AND ANALYSIS DIVISION
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
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SPACE SHUTTLE PERFORMANCE CAPABILITIES

REVISION 1

By Gus R. Babb

SUMMARY

If the goal of present studies is realized, the space shuttle will eventually assume workhorse responsibilities in space transportation from launch to low earth orbit. The shuttle alone will routinely duplicate the functions of all present launch vehicles; it will, moreover, surpass all but the Saturn V in payload delivery capability. The shuttle should be able to deliver substantial payloads to a wide range of low earth orbits. The maximum payload, on an easterly launch from Kennedy Space Center (KSC), would be at least 65 000 pounds.

To reach destinations outside the range of shuttle direct delivery, the payload may be augmented by current or proposed small, expendable propulsion stages. With this augmentation, payloads in the thousands of pounds can be delivered to high-energy transplanetary trajectories. If an even greater payload or a large ΔV is required, a series of launches will provide multiple propulsion stages.

The shuttle, then, will be highly adaptable to the needs of planned advanced missions. For realistic advanced mission planning, therefore, some knowledge of shuttle capabilities should be accessible. This document provides, in convenient form, such required information.

INTRODUCTION

The performance data in this document are projected for proposed space shuttle vehicles and supersede the data of reference 1. Continual updates and revisions will define the performance capabilities of the shuttle as significant new ground rules and design concepts are introduced.

This document shows the capability of the space shuttle (as presently conceived) as a launch vehicle. Such data are useful for making preliminary planning estimates for missions using the shuttle. The document is designed to serve those who are engaged in advanced mission planning.

SYMBOLS

ABES	air-breathing engine system
ASTS	advanced storable third stage
BLOW	booster lift-off weight
I_{sp}	specific impulse
KSC	Kennedy Space Center
LH_2	liquid hydrogen
LOX	liquid oxygen
MSC	Manned Spacecraft Center
OMS	orbital maneuvering system
SRM	solid rocket motor

SHUTTLE PERFORMANCE CONSIDERATIONS

Performance Requirements

The design performance requirements of the shuttle are given in terms of three reference missions (ref. 2).

a. Delivery of a 65 000 pound payload to a 28.5° inclination with enough orbital maneuvering system (OMS) propellant to provide 950-fps ΔV after insertion into a 50- by 100-n. mi. orbit and main tank jettison. For the current range of shuttle weights this mission requirement is the most severe of the three reference missions and therefore sizes the spacecraft.

b. Delivery of 40 000 pounds of payload to a 90° inclincation, 50- by 100-n. mi. orbit with 500 fps of OMS on board.

c. Delivery of 25 000 pounds of payload to a 55° inclination, 50- by 100- n. mi. orbit with 1500 fps of OMS on board.

Missions a and b are without an air-breathing engine system (ABES) aboard; mission c is with the ABES. The ABES is currently envisioned as an add-on system that fits in the payload bay and provides emergency go-around capability during landing. The weight of the ABES plus propellant is currently estimated at from 10 000 to 12 000 pounds. Performance data are given only for the shuttle without ABES. For missions requiring it, the ABES should be considered as part of the payload. The OMS tankage requirement is that the orbiter have sufficient integral tankage for 950 fps of OMS propellant with 65K payload on board (i.e., to perform mission a) with enough additional plug-in tanks to bring the total OMS capacity to 2500 fps. These plug-in tanks are to be carried in the payload bay.

The current design approach is for two sets of tanks integrally mounted (one on each side of the bay) having a total capacity of 950 fps with a 65K payload. Up to three more sets of these tanks, with plug-in adaptions, can be put in the payload bay to provide the required "2500-fps" capacity. Each of the three plug-in tank sets, when empty, adds 1200 pounds to the inert weight of the orbiter for a total weight increase of 3600 pounds with all three tank sets installed.

The profiles given here are based on integral tanks that hold a total of 23 500 pounds of usable OMS propellant when full. Each add-on set gives an additional 11 750 pounds of OMS capacity, with a maximum useful OMS loading of 58 750 pounds when all three extra tank sets are aboard.

Performance Calculations

The performance plots assume the vehicle has the capability to perform the most difficult design mission, in this case, the 65K payload to 28.5° inclination with 950 fps of OMS propellant on board.

Table I gives the weights and propulsion data used for the performance plots. These weights are for the referenced (65K) mission. The characteristic ΔV from the entire system (excluding OMS) normalized to a polar launch, which has no rotational component, is also given.

SHUTTLE SIZING

The shuttle performance data are based on the 040C-2 orbiter configuration with dual 156-inch solid rocket motors (SRM) burning in parallel with the orbiter main engines for the boost phase. The 040C-2 is a double delta wind shuttle configuration with external propellant (LOX/LH_2) tanks. This orbiter has three engines with 470 000 pounds of thrust (vacuum) each. The weights used (table I) are best estimates for this vehicle as of February 1972. This vehicle is currently in a preliminary design state, and the estimated weights fluctuate rather significantly with time. However, the performance given here is based on the shuttle having the capability to perform the design missions as defined. Consequently, these data are not very sensitive to shuttle weight variations if the performance and propellants are assumed to also vary to maintain design requirements.

Typically, mission requirements can be defined by spacecraft or net payload weight and by orbital specifications or space destination. The first question to be considered in planning for the use of a shuttle is whether the mission can be accomplished by means of a shuttle alone. If not, the next question is what type of additional propulsion stage ("shuttle third stage") would be required to complete the mission. To resolve these questions more easily, the data are presented in two parts.

a. Data for the planning of shuttle-only missions

b. Data for the planning of shuttle/shuttle-third-stage missions

SHUTTLE-ONLY MODE

The shuttle is designed to provide inexpensive transportation from the earth to low earth orbit. The orbits available to direct shuttle launch will be restricted to inclinations above 28.5° (i.e., above the latitude of the launch site) and to altitudes measured in hundreds of miles rather than thousands. Users with payload needs in these areas should first consider direct shuttle delivery. Payloads to be delivered beyond these regions will require a shuttle third stage.

After he has defined a mission in terms of spacecraft or net payload weight and orbital specification or destination, the prospective shuttle user would then normally estimate the additional weight of shuttle adapters. This is the extra weight requirement above the standard orbiter payload bay mounting provisions. Figure 1 shows the preliminary estimated shuttle adapter weight as a function of net payload weight. Gross payload weight is the sum of the net payload weight and the adapter weight. The net payload consists of the user's payload module, which includes the user's payload (spacecraft or cargo) and whatever adapters, equipment, and supplies are necessary to insure payload protection and proper functioning.

Shuttle adapter weights include such items as handling rings, shuttle deployment mechanism adapter, fittings, and cargo bay mounting attachments. The current concept is of "palletized" payloads. Each pallet is a unification of the payload and shuttle adapter, and will have a standard interface with the shuttle. The exact nature of the interface and the functions of the shuttle as opposed to the functions of the pallet are currently being defined and will be available at a later date.

Shuttle Delivery Capability

Once the individual mission planner has determined his gross payload, this weight can be compared with shuttle performance capabilities to determine whether the mission can be performed using the shuttle alone. Figure 2 shows shuttle gross payload capabilities as a function of inclination for various circular orbit altitudes. The OMS propellant was loaded to the extent necessary to exactly provide the on-orbit ΔV required for each mission. This ΔV is given as total OMS ΔV at the right side of the figure for each curve. At the left of each curve is given the corresponding circular orbit altitude that the shuttle can reach, circularize, and retrofire while maintaining a 120-fps reserve for rendezvous and contingencies. The OMS is not used any time in the launch phase, that is, prior to the shuttle reaching the 50- by 100-n. mi. injection orbit. The total injected weight on any given inclination is a constant and represents the maximum capability of the shuttle to that inclination. The variation in payload between altitudes is due to trading payload for OMS propellant.

Figures 3 and 4 give payload as a function of circular orbit altitude reached. Figure 3 has a 50-fps OMS ΔV reserve. Figure 4 is for a rendezvous case with a total of 120 fps of OMS ΔV held back for rendezvous and reserve. For these plots, insertion is always into a 50- by 100-n. mi. orbit. Any additional altitude is achieved by the OMS alone. All performance calculations are based upon the entire payload being carried throughout all of the ΔV maneuvers. This would allow the vehicle to deorbit in the event that the payload, for any reason, could not be jettisoned. It would also be the case if one payload was delivered to orbit and another picked up for return to earth. For these figures payload is traded directly for OMS propellant until the OMS tanks are full.

Figures 5 and 6 give the circular orbit altitude capability of the shuttle if the main orbiter engines are allowed to burn past the nominal 50- by 100-n. mi. injection orbit cutoff point and can be used to insert directly into a 50- by h-n. mi. elliptical orbit where appropriate. The main engines cannot be restarted so they are never used for circularization or retrofire. The performance is based on the assumption that the external (main) propellant tank is always jettisoned before any OMS propellant is used for ΔV. Figure 5 has a 50 fps OMS ΔV reserve, and figure 6, the rendezvous case, has a total of 120 fps for reserve and rendezvous maneuvers.

Elliptical Orbits

Elliptical orbits and circular orbits for the shuttle have no simple one-to-one correspondence as far as performance is concerned. This is because entry ΔV required for a highly elliptical orbit may vary from a few hundred fps to achieve entry at perigee to several thousand fps if the entry interface is to be under the elliptical orbit apogee. Figures 7 and 8 show the apogee altitude as a function of payload that can be reached with the shuttle for a 100 n. mi. perigee. Figure 7 is for an easterly launch (28.5° inclination) and figure 8 for a launch to a polar orbit (90° inclination). These data are based on the assumption that the main engines are shut down in the nominal 50- by 100-n. mi. injection orbit. The disposable tanks are then jettisoned and the orbit raised to 100 by 100 n. mi. with the OMS system. After this is done, the OMS system is then again used to raise apogee. The upper curve assumes a direct retrofire at apogee with entry coming very near perigee. This can be done when no specific requirement exists on the positioning of the apsides of the ellipse. In that case the orientation can be selected to allow the proper apsides position for direct entry from apogee. The bottom curve is for cases in which the shuttle must recircularize at 100 n. mi. before retrofiring. This would be the case if a particular apogee position were required for the payload which resulted in the worst possible alinement of the apogee and the entry interface position, or if some factor such as entry heating limitation made direct entry from the higher ellipse impossible.

With the shuttle launched into a high ellipse, a payload satellite could be placed into a circular orbit at apogee altitude with a single burn of a third stage. This would allow the use of a single, simple propulsion stage on the payload. A stage of this type may be simpler and cheaper than the multiple-start space propulsion stages.

Entry Limitations

The mission planner should remain aware that direct entry from the highest orbits which the shuttle can attain can result in relative entry speeds from 1000 to 2000 fps higher than the nominal design entry conditions. Such entries must have various additional entry angle and range constraints imposed to insure safe entry. These constraints will depend upon the final design and are not yet well defined. In general, planning for missions requiring direct entry from the higher altitudes of shuttle capability should be coordinated with the MSC Shuttle Office to insure that such entry constraints are not violated.

General OMS ΔV Capability

Figure 9 shows the total on-orbit ΔV available from the OMS system as a function of payload. The data are given for various launch inclinations and for the cases of the additional OMS tankage sets installed. This is the total ΔV available from the OMS system at the time of main engine shutdown in the 50- by 100-n. mi. insertion orbit.

Figure 10 shows the ΔV required to reach and retrofire from circular orbits, starting from the 50- by 100-n. mi. insertion orbit. The term ΔV_1 is the ΔV required at 50 n. mi. to raise apogee to the given circular orbit altitude; ΔV_2 is the ΔV required to circulize at the desired altitude; ΔV_3 is the ΔV required to retrofire from that circular orbit to the shuttle entry target line defined by table II (ref. 3); and ΔV_{total} is the sum of $\Delta V_1 + \Delta V_2 + \Delta V_3$, or the total on-orbit ΔV required of the shuttle for that circular orbit altitude. This is the absolute minimum required for this destination and does not include any ΔV for operations such as rendezvous nor any reserves, contingencies, or gravity losses.

SPACE SHUTTLE PLUS UPPER STAGE

Missions to orbits higher than the direct shuttle capability shown in figures 2, 6, and 7 and to orbits with inclinations outside the shuttle range (less than 28.5°) will require additional propulsion. Even within the region that can be reached by the shuttle, the use of an additional stage may be more efficient and cost-effective for delivering a single heavier payload or for placing multiple payloads in slightly varying orbits.

For shuttle/shuttle-upper-stage missions (both earth-orbital and earth-escape), the shuttle orbiter will normally be placed into a 225-n. mi. circular parking orbit, since this altitude can be reached on a due east launch with the design structure limit payload of 65 000 pounds. The shuttle-upper-stage would then deliver the user's payload from this parking orbit to the final orbit or space destination. In each case, the shuttle would be launched into the appropriate inclination.

Table III lists the weight, dimension, and performance characteristics of several representative upper stages. These are separated into two basic groups, the space storable stages and the cryogenics stages.

Four basic space storable stages were considered. Three of these, the Transtage, the Agena, and the Delta, are existing hardware. The fourth, the advanced storable third stage (ASTS), is a proposed stage based on the current state of the art. It has been more properly sized to deliver the maximum geosynchronous orbit payload with the shuttle.

Figure 11 gives the payload capabilities for the shuttle coupled with various space storable third stages. The figure is based on a shuttle launched to 28.5° inclination. The payload plus the third stage and a fixed third stage adapter weight are constrained to weigh no more than the payload capability of the shuttle. The shuttle payload is further restricted to no more than the design structure limit of 65 000 pounds. Propellant is offloaded from the propulsion stage when necessary to meet this requirement. The payload given is the gross payload as defined earlier, that is, the user's payload plus payload adapter weights. The weight of the upper stage and its adapter are considered as part of the shuttle system.

The performance is given in terms of ΔV above a 225-n. mi. circular orbit. This is the ΔV that can be applied to the payload starting in a 225-n. mi. circular orbit. This 225-n. mi. orbit is the altitude the shuttle can reach with the OMS loading of the reference due east mission carrying the maximum payload (65 000 lb) that the shuttle bay structure is required to support.

As an indication of the capabilities represented by the ΔV's an equatorial synchronous orbit requires a ΔV of about 14 000 fps starting from a 30° inclination parking orbit, and 13 400 fps will reach any circular earth orbit in the launch plane. Transplanetary injection of Mars- and Venus-type missions is normally between 13 000 and 15 000 fps. Translunar injection requires 10 500 to 11 000 fps and a package can be delivered to lunar orbit for less than 14000 fps. The Grand Tour missions range from 25 000 fps to over 50 000 fps.

For payloads of only a few thousand pounds destined for high energy trajectories (such as the planetary probes), the relatively high inert weight of the propulsion stage begins to limit the performance more than the payload does. For these cases ΔV capability can be significantly improved by the addition of a small fourth stage with very low inert weight.

Figure 12 shows what can be achieved using a Beryllium Burner II fourth stage in addition to the larger third stage. The ΔV capability is increased by several thousand feet per second for the smaller payloads. For this graph, payloads of greater than 10 000 pounds are not considered, since using the Burner II for heavier payloads has little or no advantage.

Figure 13 gives the capabilities of Shuttle plus third stage when using the high energy cryogenic liquid oxygen/hydrogen stages. The two stages examined are the Centaur and GT Centaur, a version of the Centaur with propellant tanks enlarged. This tank enlargement can give considerably more performance since the stage burnout weight is only up 17 percent while propellant weight is increased 50 percent. This plot includes the stages plus the Beryllium Burner II fourth stage. The Burner II again shows considerable velocity gains for the smaller payloads.

Dual Shuttle Launch

Larger payloads can be delivered using two shuttle launches and two third stages. A partially fueled propulsion stage plus the payload is launched on the first flight. A second flight with a fully fueled propulsion stage is then launched. The two shuttles rendezvous and the stages are mated. The payload is then delivered to its ultimate destination with the two stages. The shuttle delivering the stage alone (the second launch) performs the rendezvous since it is not fully loaded.

Figure 14 shows the capabilities of this system. Only the advanced storable stage was considered, except for payloads under 10 000 pounds, where the performance with a Beryllium Burner II final stage is also shown. In this case one launch delivers the second large stage, the Burner II, and the payload.

CONCLUSION

These performance data show the tremendous potential of the shuttle vehicle. Alone, the shuttle can deliver large units (up to 65 000 lb) of payload to a wide range of low earth orbits.

Destinations outside the reach of shuttle direct delivery are accessible by adding to the payload unit one of several currently available or proposed small expendable propulsion stages. In this manner, payloads in the thousands of pounds can be delivered to high energy transplanetary trajectories. If greater payloads are required, or if larger ΔV's are necessary, multiple launches can provide multiple propulsion stages.

The result is a highly flexible space transportation system with exceptional delivery capabilities that can routinely perform all of the missions now done by using existing launch vehicles.

B

TABLE I.- 040C-2 SHUTTLE WEIGHT AND PROPULSION DATA

(PARALLEL BURN; SRM BOOST)

(a) Weight data

Booster lift-off weight (BLOW) (2-156 in solids)	2 660 000 lb
Solid boost propellant	2 397 500 lb
Orbiter lift-off weight	1 900 000 lb
Orbiter propellant	1 570 000 lb
External LOX/LH_2 tank weight (including 1 percent propellant reserve)	70 650 lb
Payload	65 000 lb
OMS propellant	23 500 lb
ΔV reference (polar launch)	32 068 lb

(b) Propulsion data

Solid booster I_{sp} (duty cycle)	259 sec
Orbiter I_{sp}:	
Boost phase (duty cycle)	430 sec
Orbiter phase	454.5 sec
OMS I_{sp}	310 sec
ΔV reference (polar launch)	32 068 fps
Solids thrust, total	5 000 000 lb
Orbiter thrust, three engines at 470K each	1 410 000 lb

TABLE II.- DELTA WING ORBITER TARGET LINE

Velocity at entry interface, fps	Flight-path angle at entry interface, deg
25 000	-0.50
25 500	-1.12
26 000	-1.67
26 500	-2.20
27 000	-2.62
27 500	-3.00
28 000	-3.29
28 500	-3.55
29 000	-3.80

Note: Entry interface altitude = 400 000 ft.

TABLE III.- SHUTTLE EXPENDABLE UPPER STAGES

Stage	Type	Dimensions diameter/length, ft	Burnout weight (including adapters), lb	Usable propellant weight, lb	I_{sp}, sec
Beryllium Burner II	Solid	6/6	450	2 435	306
Delta	Storable	4.8/9.6	2000	10 500	271
Agena	Storable	5/21	1600	13 000	298
Transtage	Storable	10/14	4500	23 000	302
Advanced storable third stage	Storable	14/21	2700	52 000	298
Centaur	Cryogenic (LOX/H_2)	10/30	5000	30 000	440
GT Centaur	Cryogenic (LOX/H_2)	14/32	5850	45 000	440

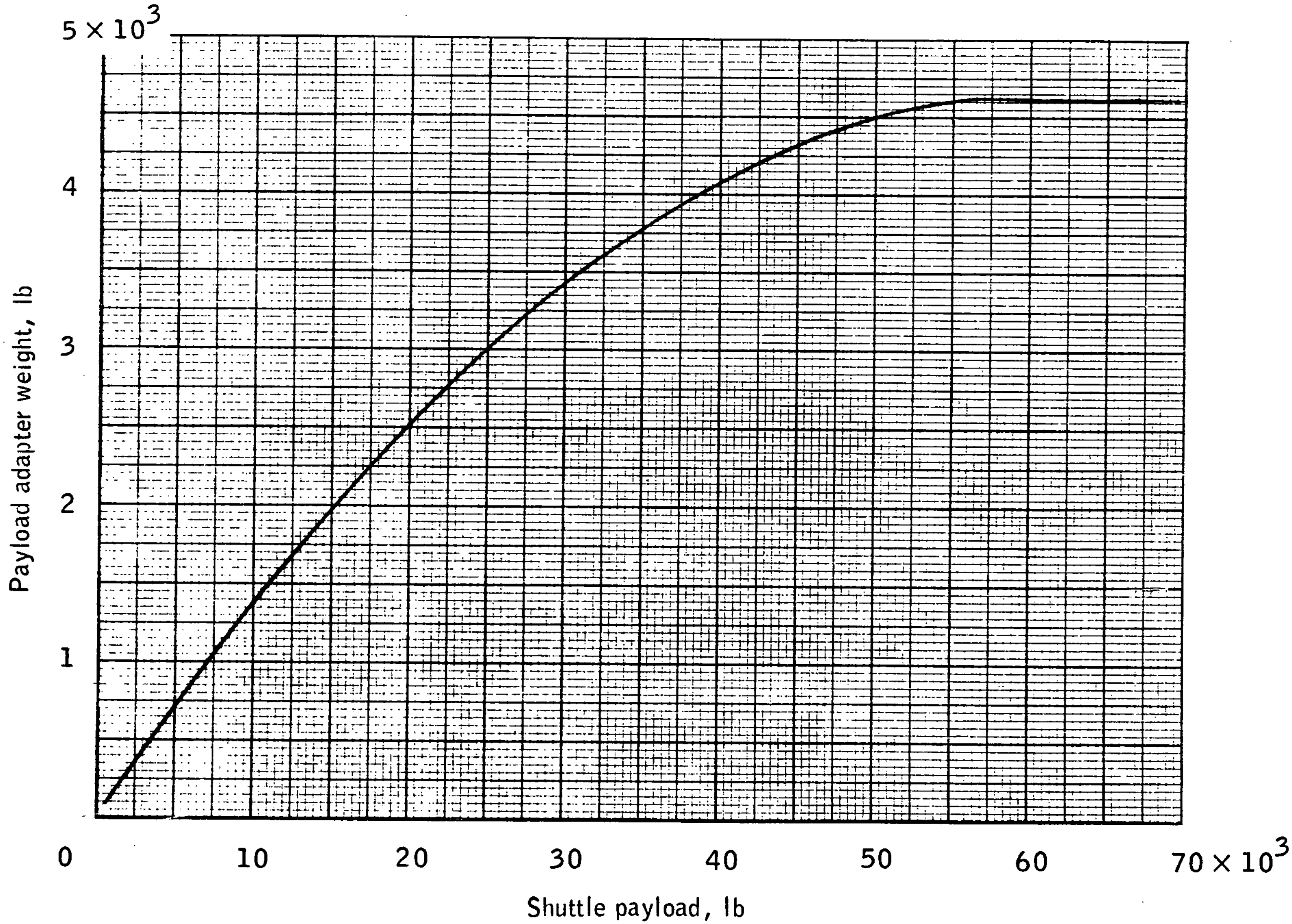

Figure 1.- Shuttle payload adapter weight.

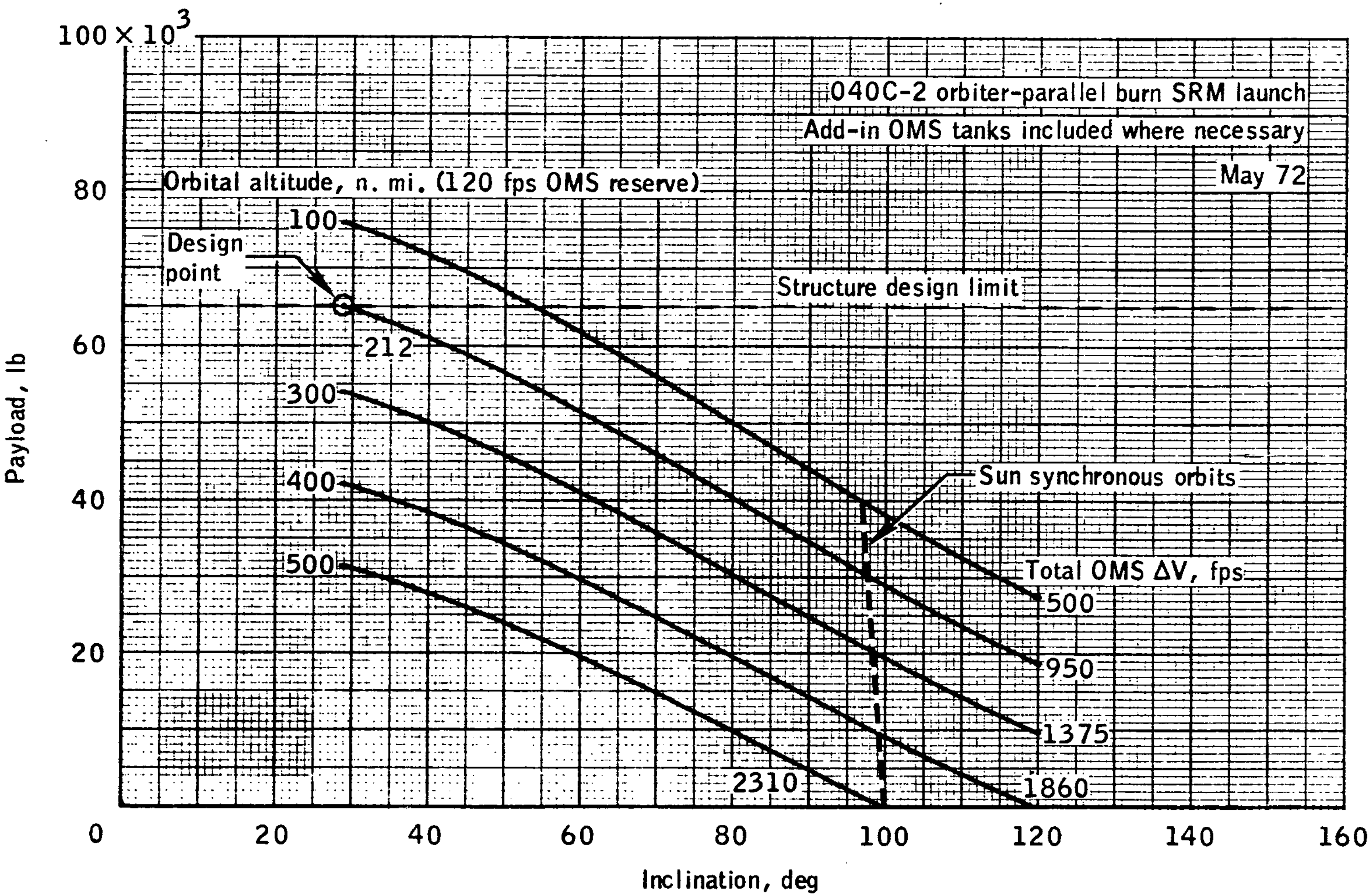

Figure 2. - Space shuttle payload to different inclinations.

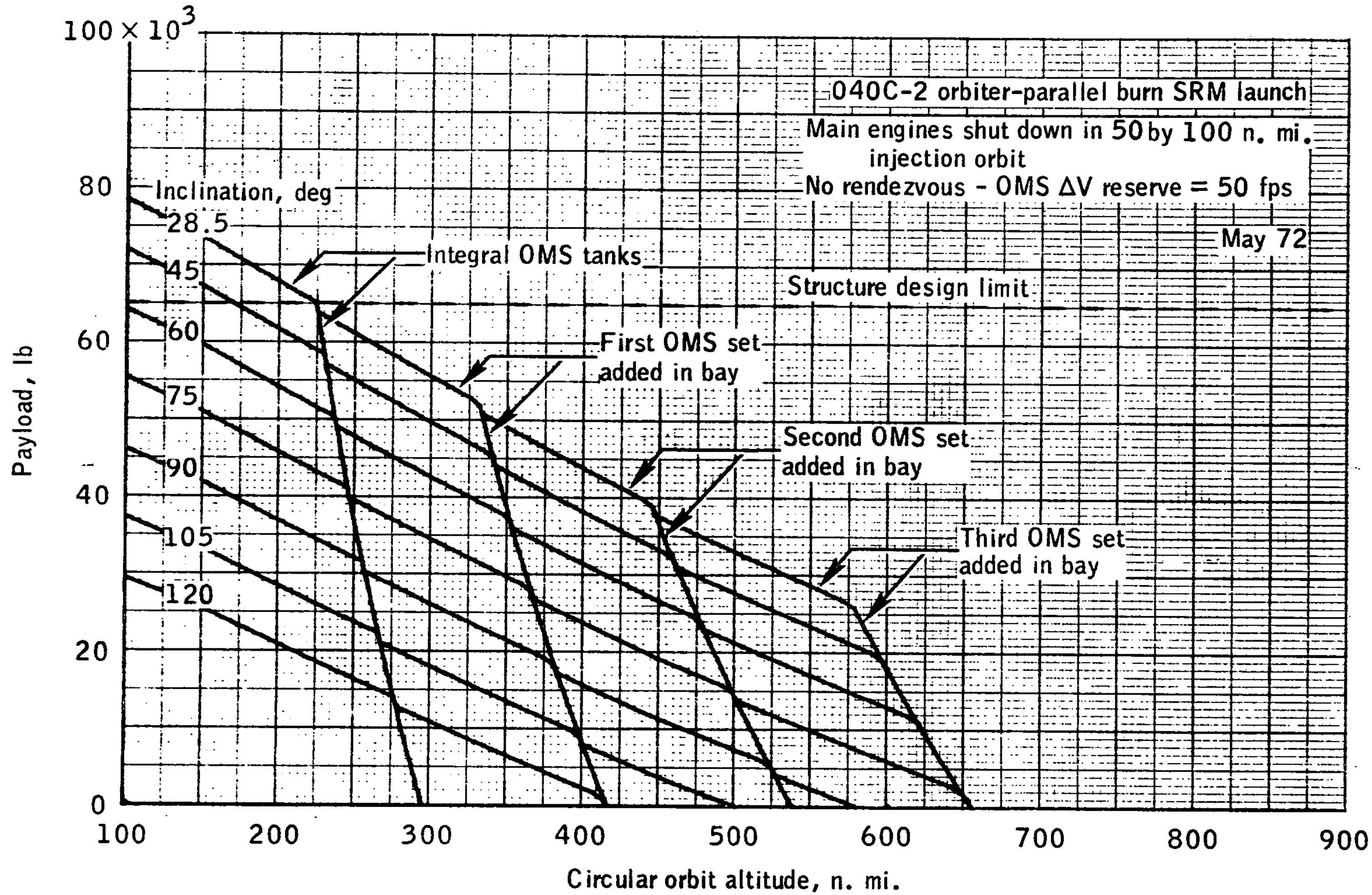

Figure 3.- Space shuttle payload to circular orbits - without rendezvous.

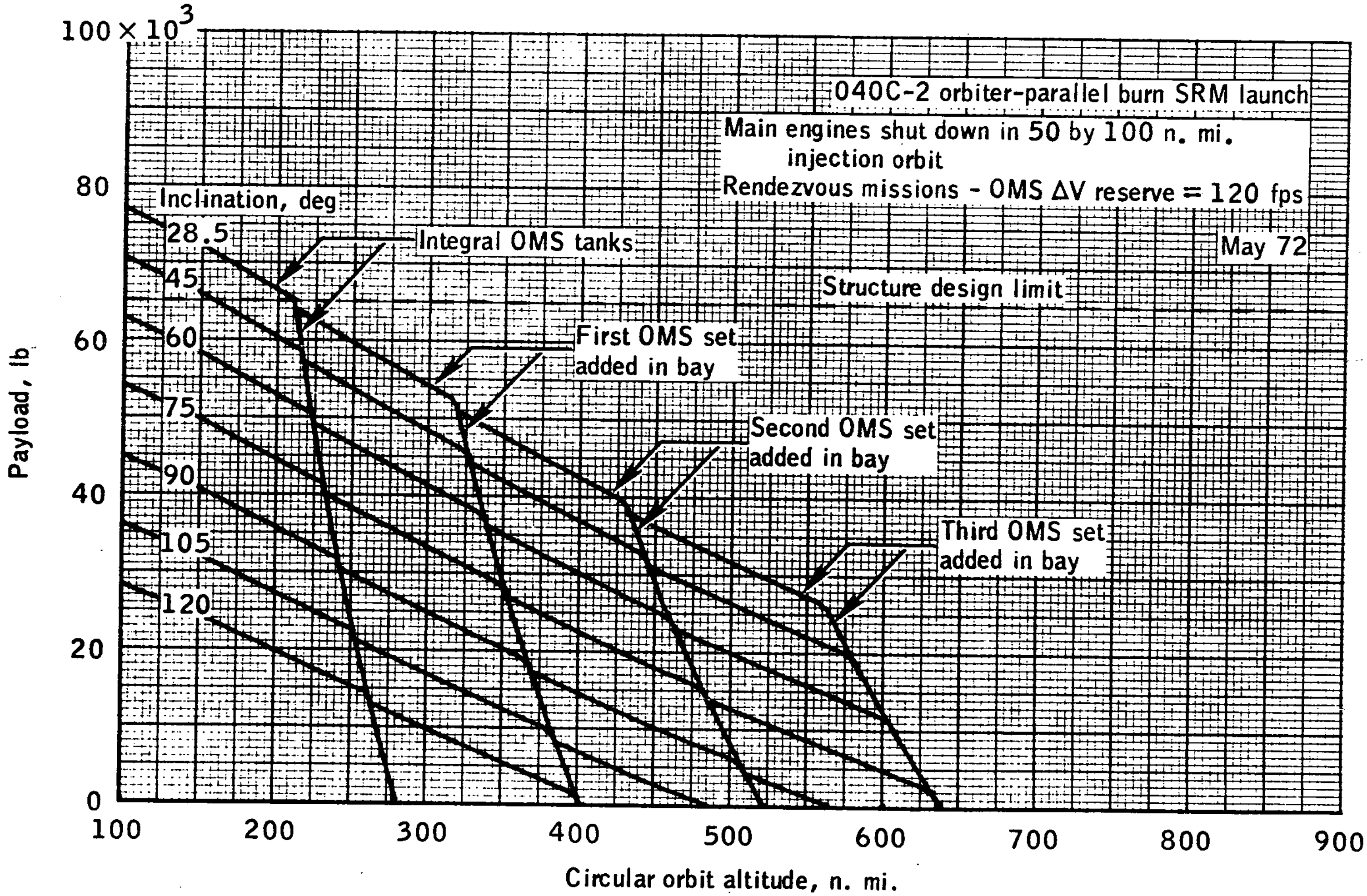

Figure 4.- Space shuttle payload to circular orbits with rendezvous.

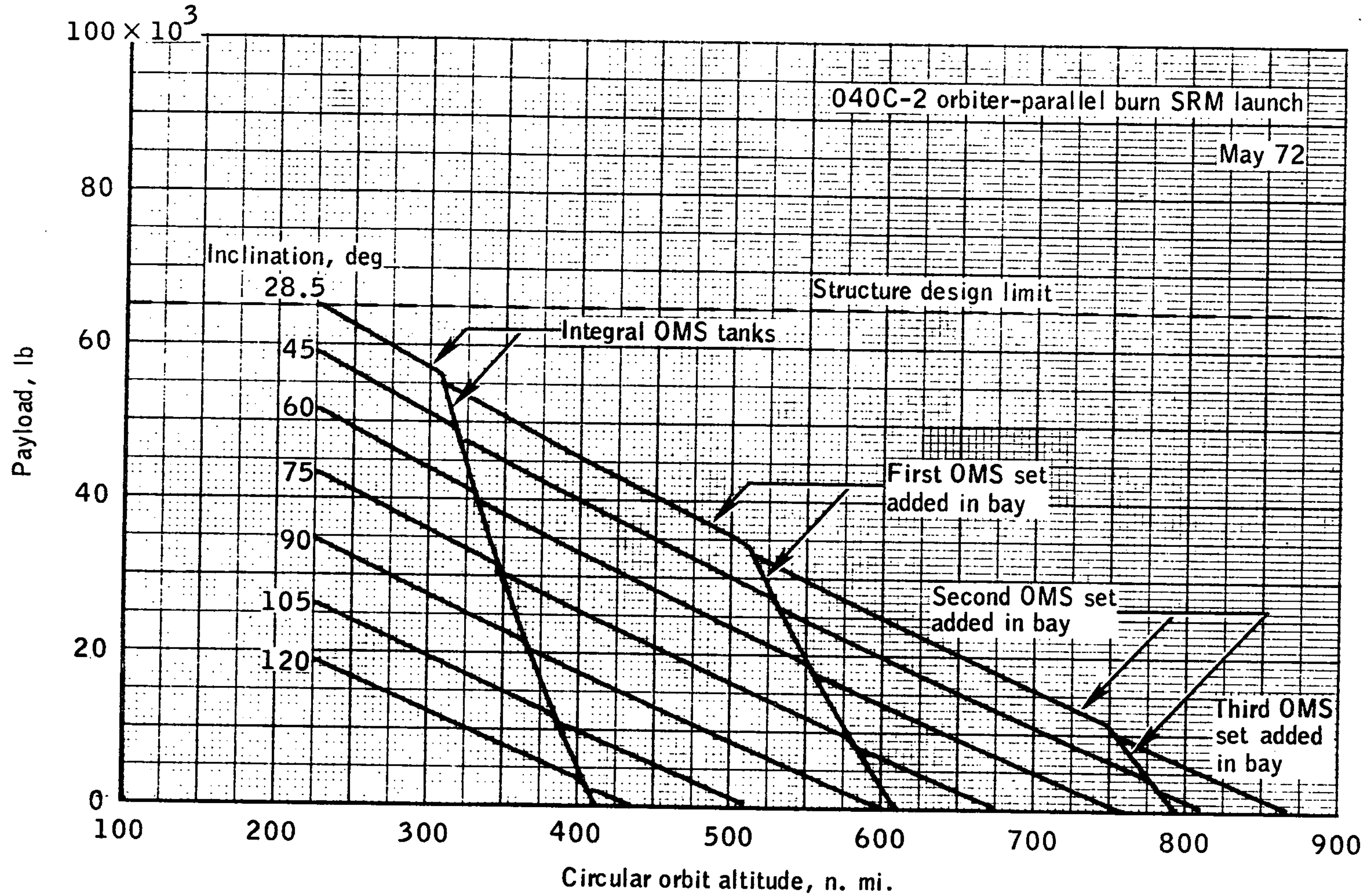

Figure 5.- Space shuttle payload to circular orbits - direct injection to 50 by h n. mi. with main engines (no rendezvous - OMS reserve = 50 fps).

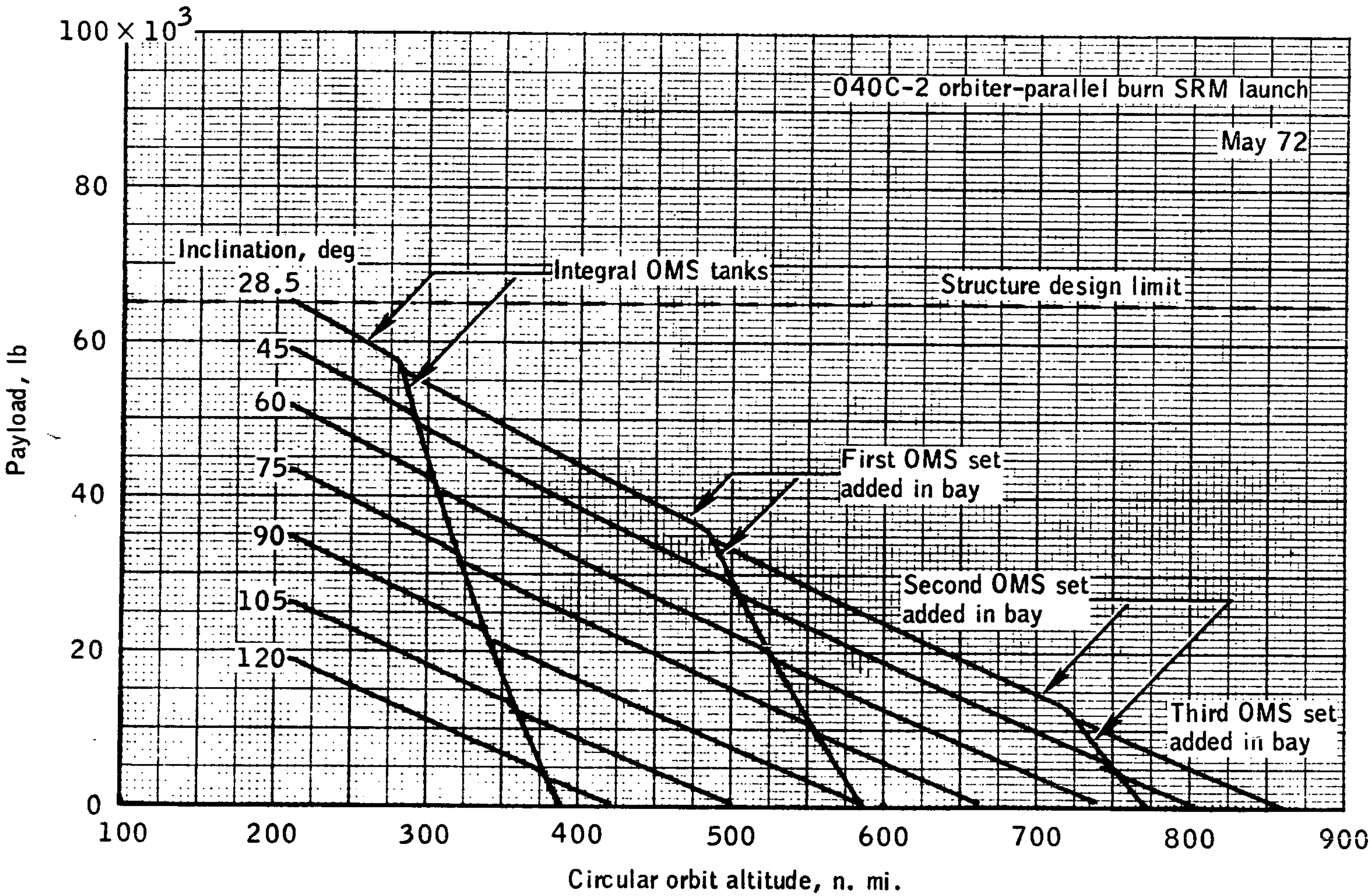

Figure 6.- Space shuttle payload to circular orbit - direct injection to 50 by h n. mi. with main engines (rendezvous - OMS reserve = 120 fps).

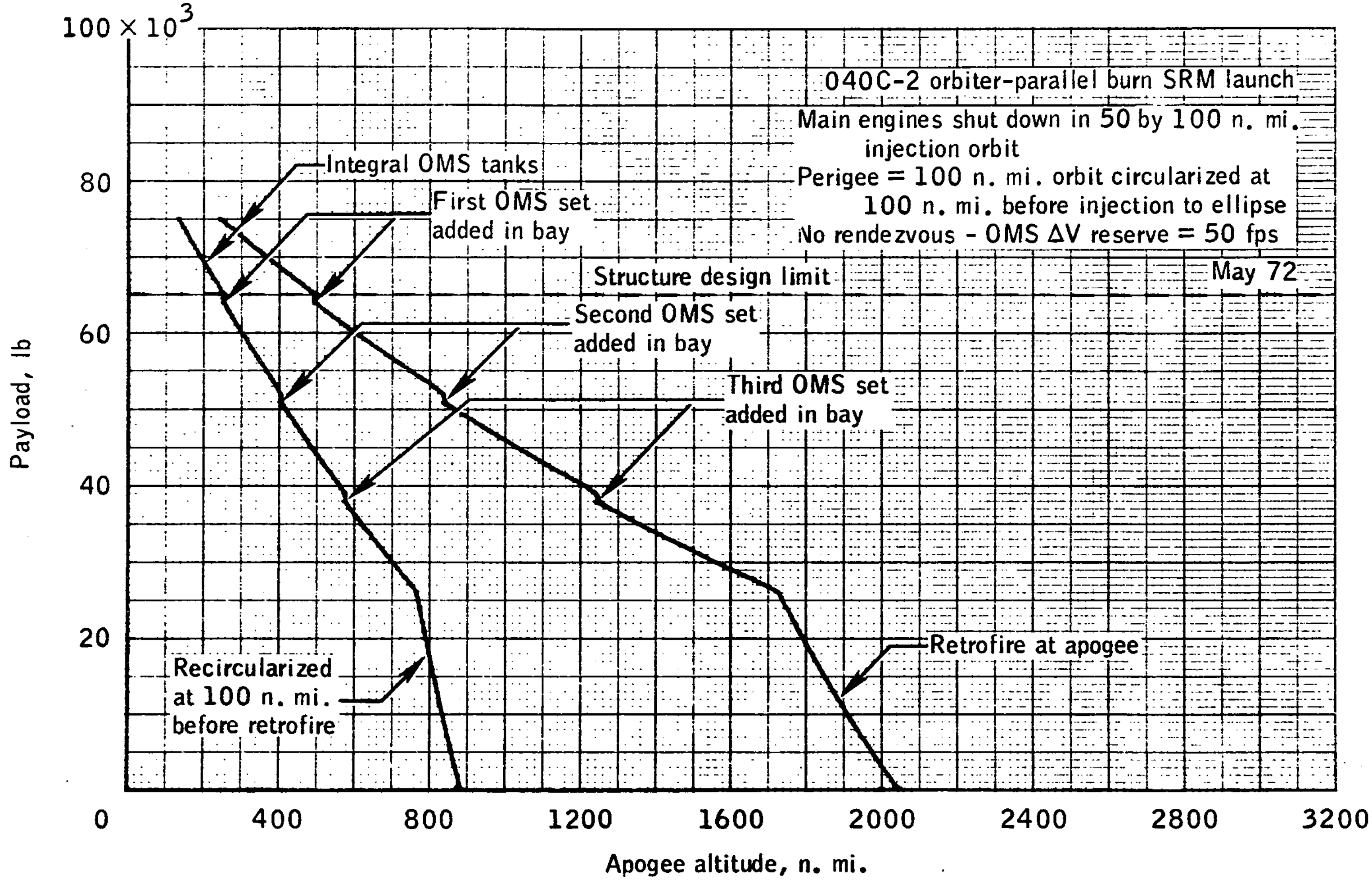

Figure 7.- Space shuttle payload to elliptical orbit - 28.5° inclination.

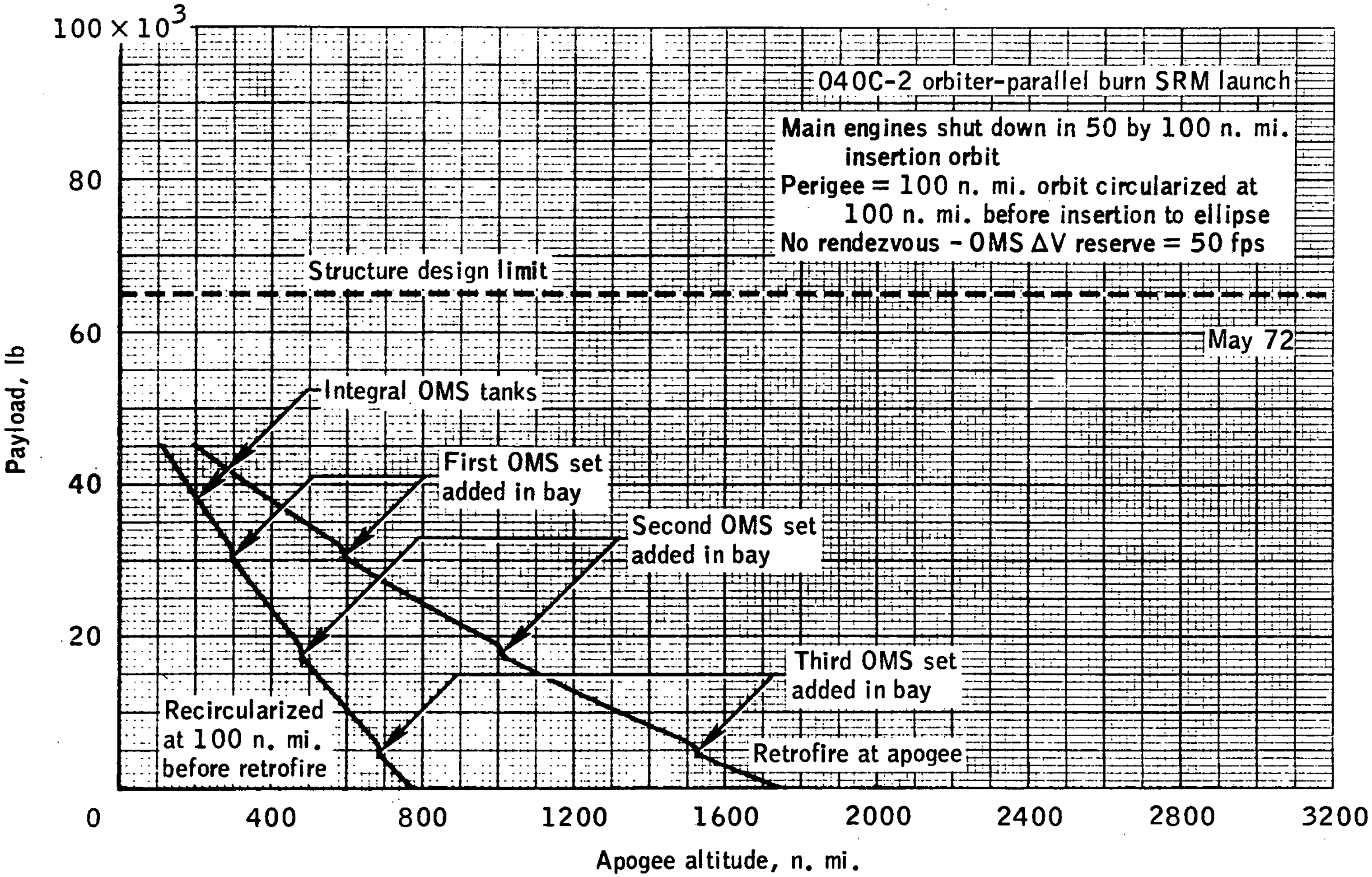

Figure 8.- Space shuttle payload to elliptical orbit 90° inclination.

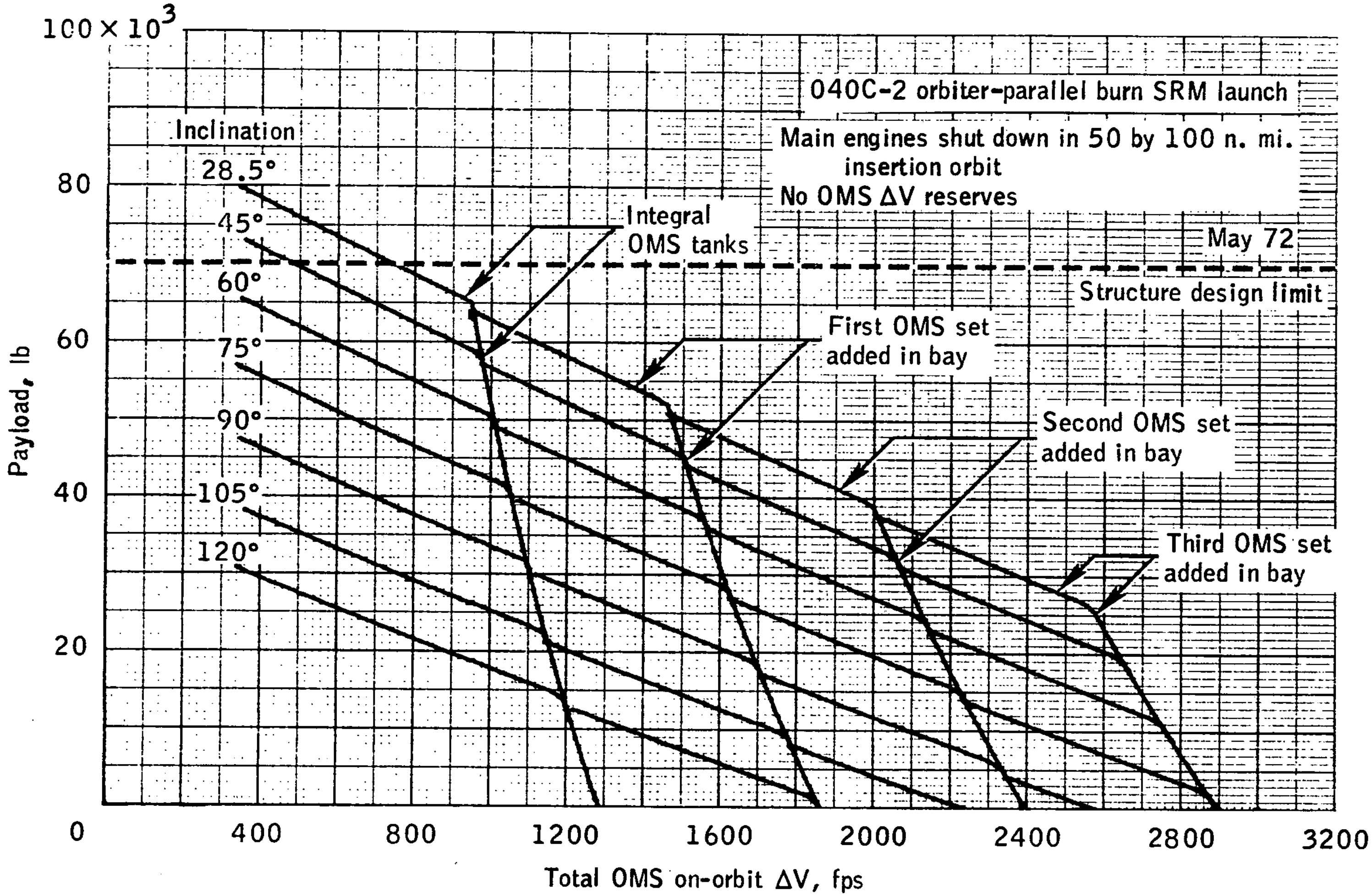

Figure 9.- Space shuttle payload versus OMS ΔV.

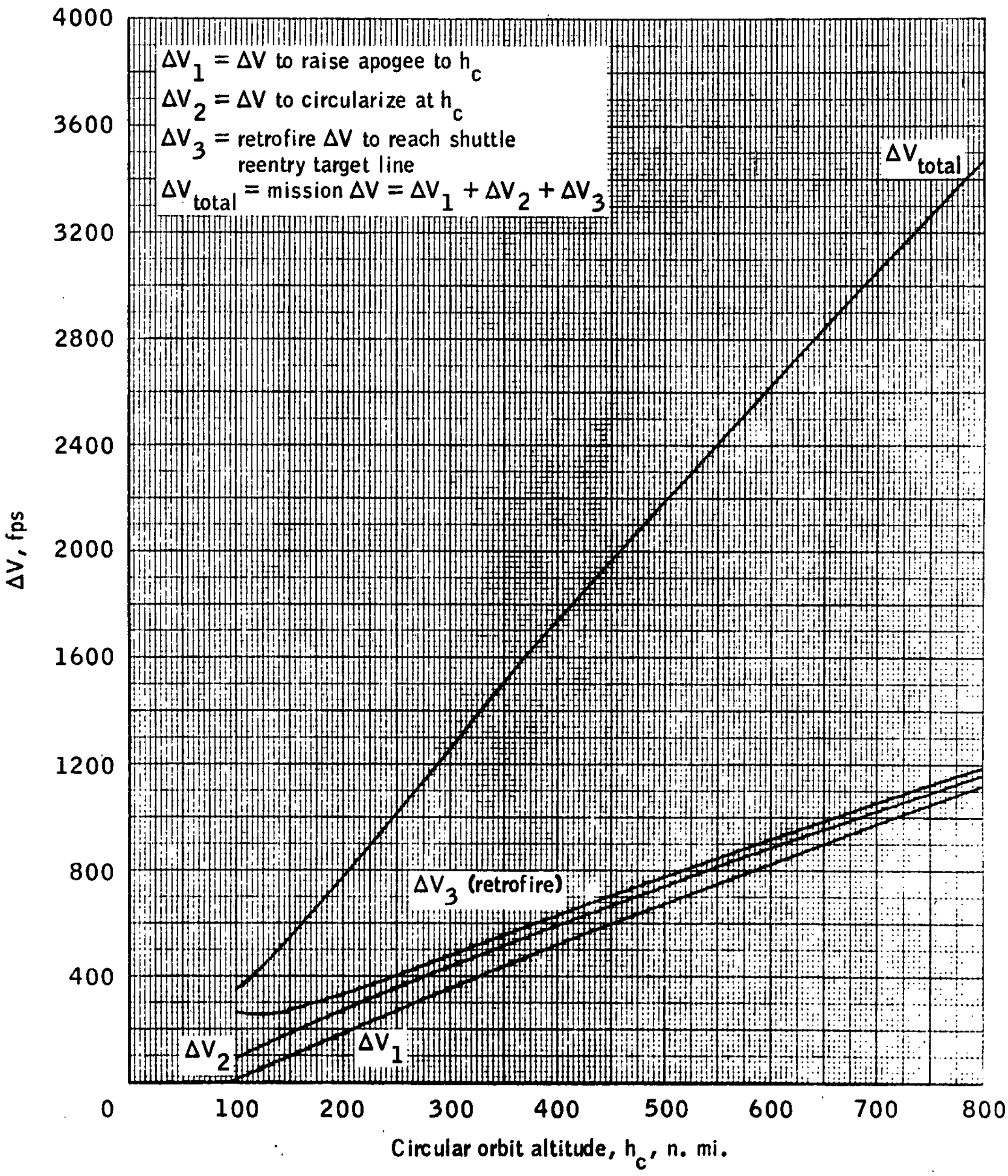

Figure 10.- Shuttle on-orbit ΔV for operation to circular orbits - starting from 50 by 100 n. mi. insertion orbit.

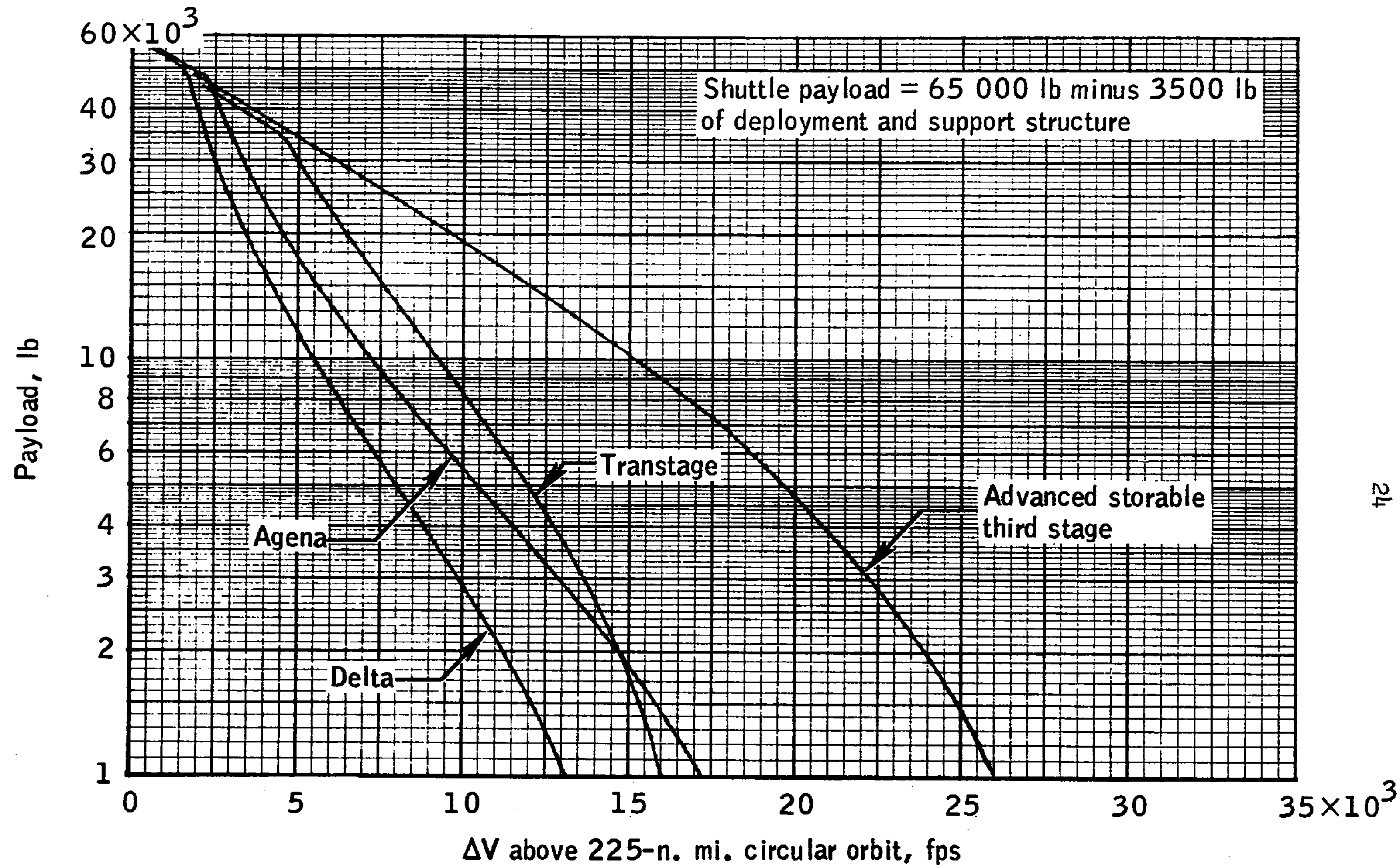

Figure 11.- Space shuttle plus storable third stages - single shuttle launch.

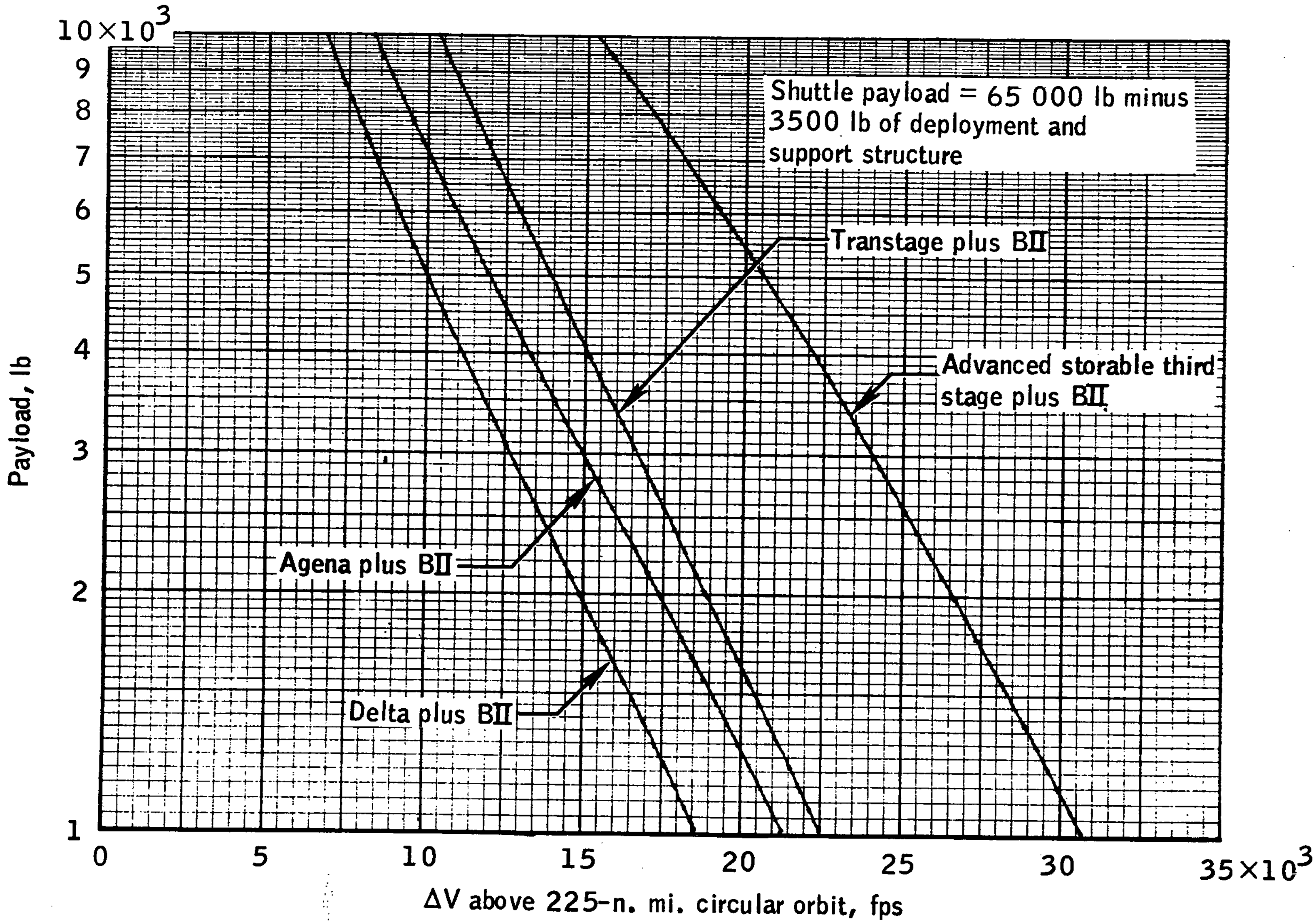

Figure 12.- Space shuttle plus storable third stages with Beryllium Burner II fourth stage - single launch.

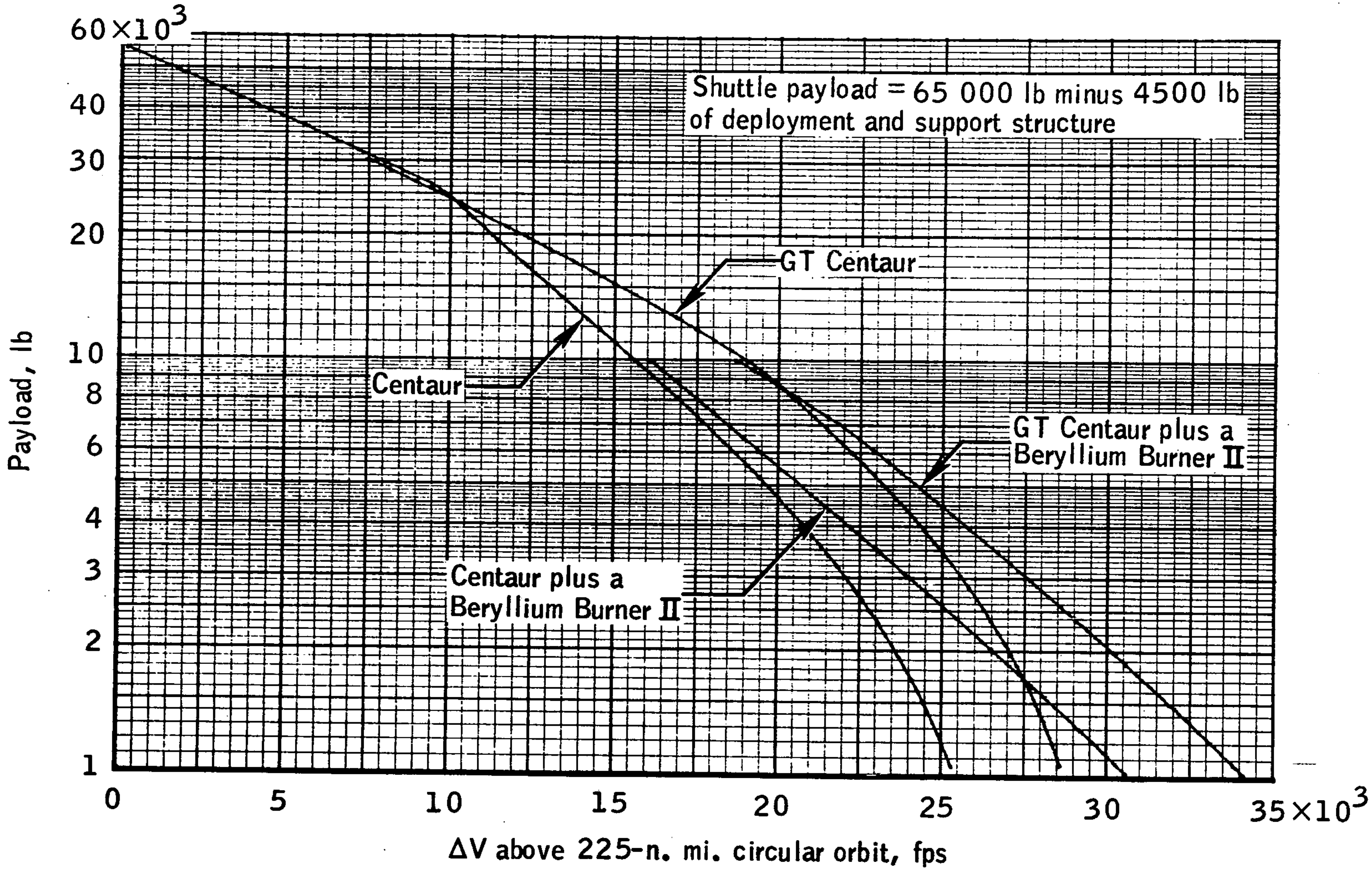

Figure 13.- Space shuttle plus cryogenic third stages - single shuttle launch.

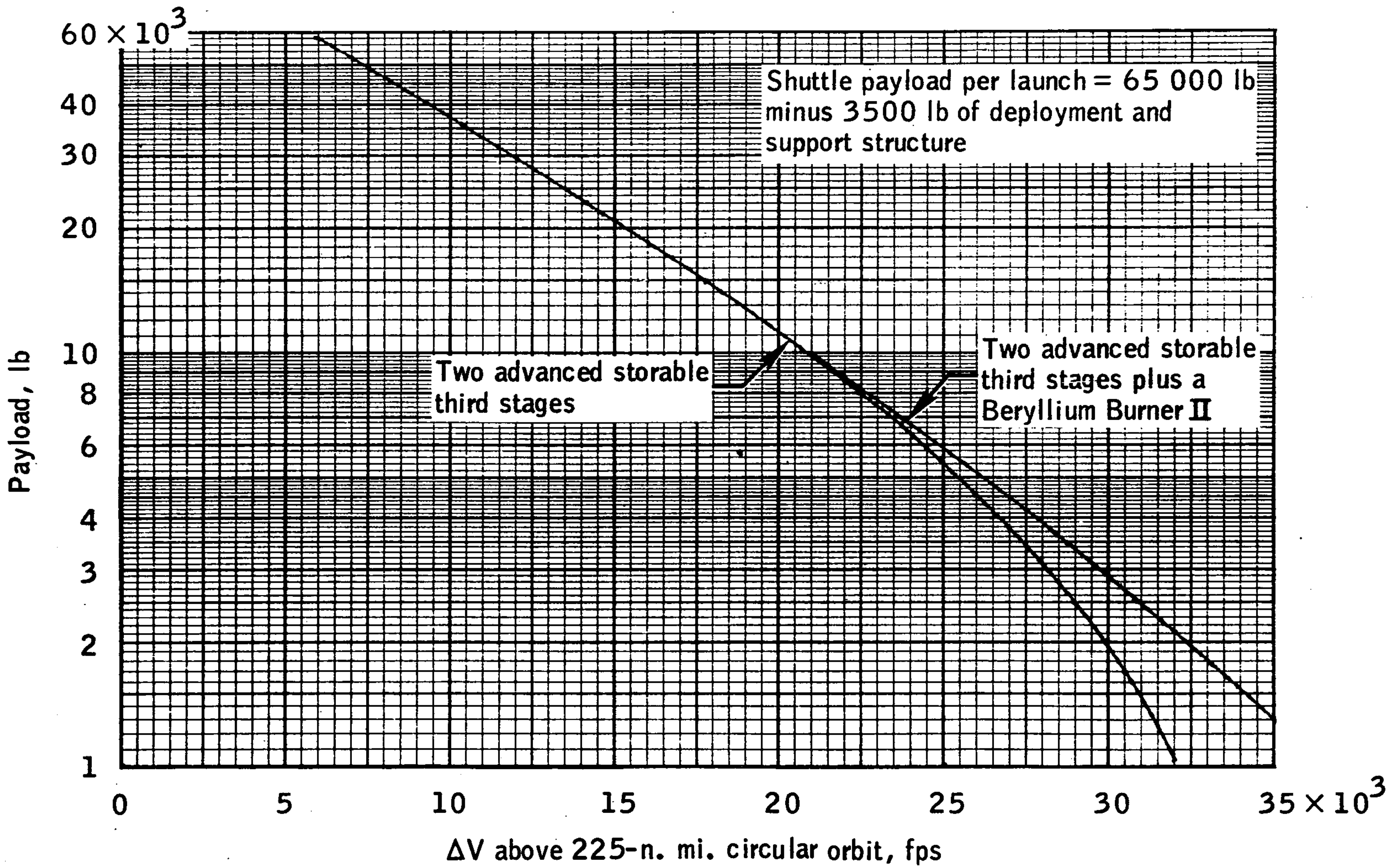

Figure 14.- Space shuttle plus storable third stages - dual shuttle launches.

REFERENCES

1. Babb, Gus R.: Space Shuttle Performance Capabilities. MSC IN 71-FM-350, Sept. 16, 1971.

2. Space Shuttle Program Request for Proposal no 9-BC421-67-2-40P.

3. Harpold, Jon C.: Preliminary Entry Target Line for Mission Planning Activities on the Delta Wing Orbiter. MSC IN 71-FM-156, Apr. 27, 1971.