LOW-THRUST VEHICLE CONCEPT STUDIES

William J. Ketchum
General Dynamics Corporation

SUMMARY

Large Space Systems (LSS) such as Geostationary Communications Platform & Space Based Radar are planned for the late 1980's and the 1990's. These are "next generation" spacecraft as large as 600 feet in size and up to 25,000 pounds in weight. Forty-seven such missions have been identified (1987-2000).

It will be advantageous to deploy and check out these expensive spacecraft in Low Earth Orbit (LEO) while still attached to the Orbiter, so any problems can be fixed, even by EVA, if necessary. The space shuttle will offer this opportunity. Once deployed and functioning, low acceleration during transfer to higher orbits (GEO) would minimize stresses on the structure, allowing larger size or lower weight spacecraft.

This report documents results of a "Low Thrust Vehicle Concept Study" conducted over a 9-month period, September 1979 - May 1980, to investigate and define new low thrust chemical (hydrogen-oxygen) propulsion systems configured specifically for low-acceleration orbit transfer of large space systems. This study for NASA/MSFC was conducted in close coordination with low-thrust engine/propulsion studies/technology efforts at LeRC and used their definitions of propulsion elements for analyses. The results of this systems/concept study are intended to help guide the propulsion technology effort already underway. This study also provides the required additional data to better compare new, low-thrust chemical propulsion systems with other propulsion approaches such as advanced electric systems.

Study results indicate that it is cost-effective and least risk to combine the low thrust OTV and stowed spacecraft in a single 65K Shuttle. Mission analysis indicates that there are 25 such missions, starting in 1987. Multiple shuttles (LSS in one, OTV in another) result in a 20% increase in LSS (SBR) diameter over single Shuttle launches.

Synthesis & optimization of the LSS characteristics and OTV capability resulted in determination of the optimum thrust-to-weight and thrust level. For the Space Based Radar with radial truss arms (center thrust application), the optimum thrust-to-weight (maximum) is 0.1, giving a thrust of 2000 lb. For the annular truss (edge-on thrust application) the structure is not as sensitive, and thrust of 1000 lb. appears optimum. For the Geoplatform, optimum T/W is.15 (3000 lb. thrust).

The effects of LSS structure material, weight distribution, and unit area density were evaluated, as were the OTV engine thrust transient and number of burns.

A constant thrust -9-burn trajectory gives better performance (and is less sensitive than constant acceleration - variable thrust) - 2-burn, and eliminates increased engine complexity (multiple low-thrust levels). Increased mission duration (3 1/4 vs 2 1/2 days total time including checkout, deployment, transfer) poses no problems for the payloads or OTV. Analysis of OTV insulation and pressurization requirements determined that propellant tank vapor residuals/pressures are little affected by engine thrust level or number of burns.

Engine thrust transient results in a dynamic factor of approximately 2. This can be reduced by using a slow, or a stepped thrust transient, but either complicates the engine, and results in little improvements in the LSS size (3%).

Distributed thrust, in addition to complicating the design of the OTV and LSS, could increase dynamic loading on the structure due to the difficulty in exact phasing of multiple thrusters.

To maximize the Orbiter payload bay volume available for the large space structure, a torus LO_2 tank is used to achieve minimum OTV length. For the 65K Shuttle, the OTV is ~18' long (allowing up to ~40' stowed payload length), having a propellant loading of 38,000 lb and a dry weight of 6000 lb.

The technology of torus tanks was investigated. A unique acquisition device was conceived that minimizes residuals no matter what the thrust offset. Only one propellant outlet is required, and no separate sumps are needed.

Several types of engines were considered; a new low-fixed thrust pump-fed engine and a low-thrust (pumped idle) mode of the OTV engine. Using 1500-lb thrust at 455 sec Isp and a 9-burn trajectory, a payload mass of ~16,000 lb can be delivered to GEO.

This study has defined an optimized low thrust OTV configured specifically for orbit transfer of large space systems. The following conclusions are made:

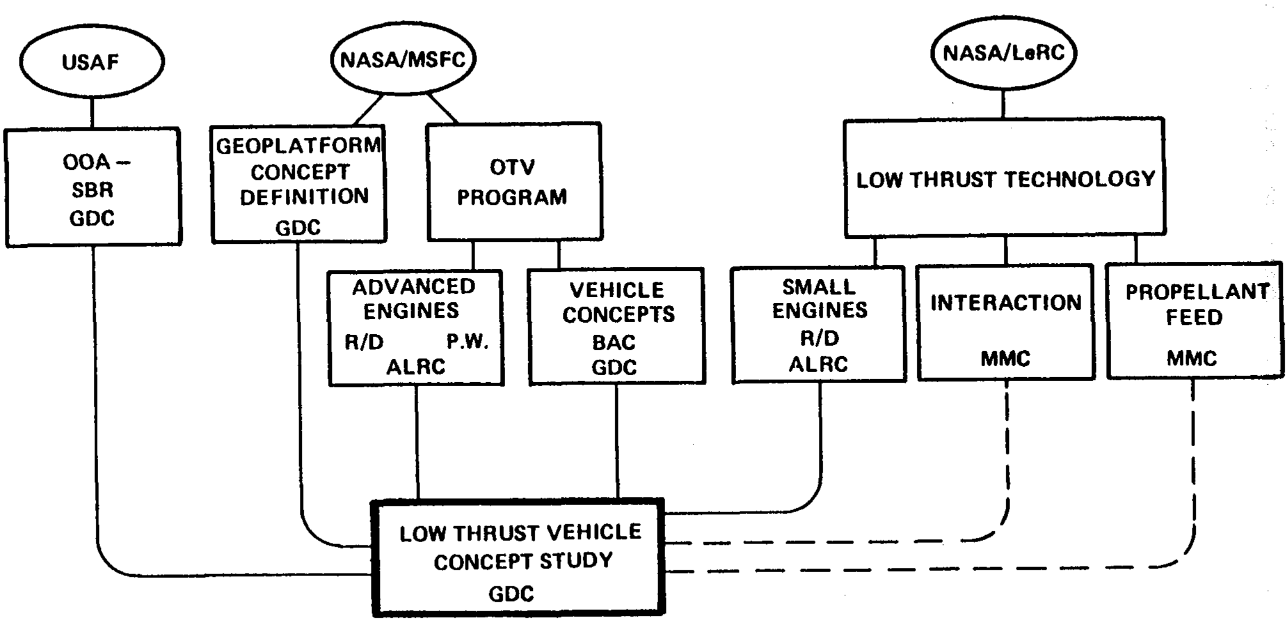
- Engine for an optimized low thrust stage
  - Very low thrust (< 1K) not required.
  - 1 -3K thrust range appears optimum.
  - Thrust transient not a concern.
  - Throttling not worthwhile.
  - Multiple thrusters complicate OTV/LSS design and aggravate LSS loads.

- Optimum vehicle for low acceleration missions
  - Single Shuttle launch (LSS and expendable OTV) most cost-effective and least risk.
  - Multiple Shuttles increase LSS (SBR) diameter 20%.
  - Short OTV needed which requires use of torus tank.
  - Propellant tank pressures/vapor residuals little affected by engine thrust level or number of burns.

Further study is needed:
- Revise results as new mission and spacecraft data beomes available (especially as the Geoplatform design evolves).
- Re-evaluate study results as LeRC low thrust engine studies produce design concepts and cost data.
- Coordinate with OTV study (NAS8-33533 follow-on).
- Further evaluate benefits of deploying LSS at LEO vs GEO.
- Evaluate how Centaur (with idle mode) could satisfy initial requirements.
- Estimate the point at which advanced electric OTV (fast transfer/MPD) might replace low thrust chemical propulsion.

Technology development:
- Hardware R&D should be undertaken for the engines and vehicle subsystems (low thrust engine, torus tank, acquisition, insulation).

LOW THRUST CHEMICAL
PROPULSION TECHNOLOGY PROGRAM



OBJECTIVES

PROVIDE THE REQUIRED ADDITIONAL DATA TO BETTER COMPARE NEW, LOW-THRUST CHEMICAL PROPULSION SYSTEMS WITH OTHER PROPULSION APPROACHES FOR TRANSFER OF LARGE SPACE SYSTEMS.

- CHARACTERIZE MISSIONS WHICH REQUIRE OR BENEFIT FROM LOW-THRUST ORBITAL TRANSFER
- IDENTIFY, DEFINE, EVALUATE, AND COMPARE CANDIDATE LOW-THRUST LIQUID PROPULSION ORBITAL TRANSFER STAGE/VEHICLE CONCEPTS
- INVESTIGATE PAYLOAD/VEHICLE INTERACTIONS AND DESIGN IMPLICATIONS
- DETERMINE PROPULSION/SYSTEM CHARACTERISTICS HAVING THE GREATEST INFLUENCE UPON SYSTEM SUITABILITY/CAPABILITY
- IDENTIFY AND DESCRIBE PROPULSION TECHNOLOGY REQUIREMENTS

WHY DEPLOY AT LEO?
(I.E., WHY LOW THRUST?)

THE STS WILL OFFER THE FIRST OPPORTUNITY TO CONTROL, CHECK OUT, AND CORRECT THE DEPLOYMENT OF SPACECRAFT TO ENSURE OPERATIONAL READINESS BEFORE TRANSFERRING THEM TO HIGHER ORBITS.

DEPLOYMENT AT LEO CAPITALIZES ON SHUTTLE CAPABILITY AND PHILOSOPHY (MAN-ASSIST).

Mission planning (NASA and DoD) information (specifically the NASA/MSFC OTV Mission Models) was used to identify potential low-thrust missions, payload characteristics, transportation needs, and schedule requirements.

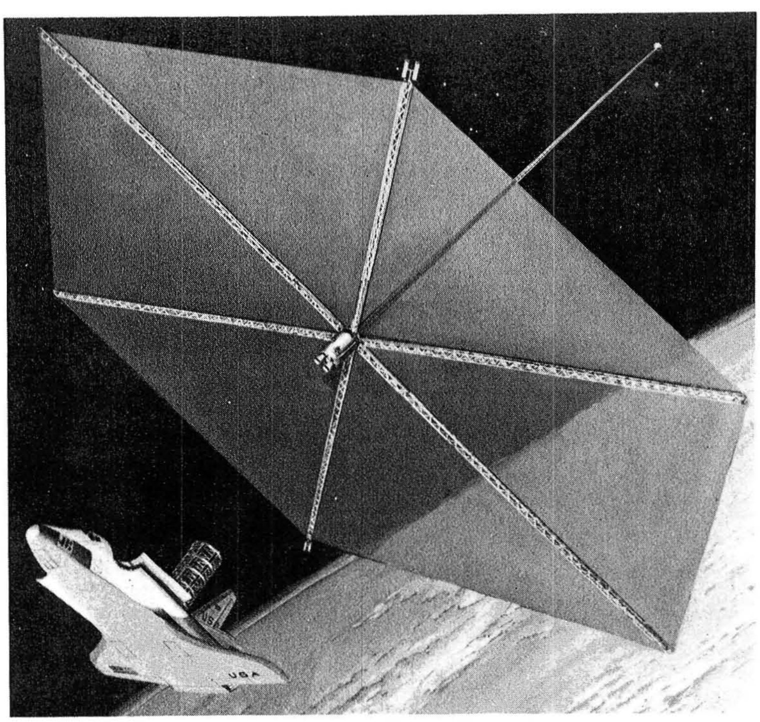
The Geoplatform Communication Antenna System, and the Space-Based Radar Antennas are the leading near-term missions. These were selected for detailed analysis. It is seen that the mission drivers are 1987 IOC; 35 ft payload; 15000 lb payload; geosynchronous mission.

A solar power array was initially considered, but was determined to be an unlikely candidate for low-thrust chemical propulsion because current concepts are designed for retraction on-orbit (protection against solar flares, etc.) and therefore it would make little sense to require transfer in the deployed condition. Future advanced (rigid-SPS, etc.) concepts will likely be self-powered (Ion or MPD engines).

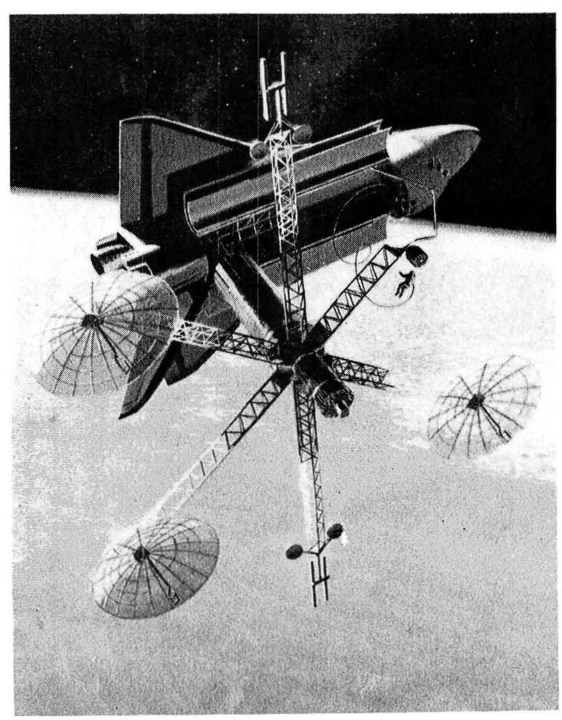
From this data, the range of requirements imposed on the OTV were determined. It is seen that for payload IOC's in the first 5 years of LSS operations (1987 - 1992) single Shuttle launches are sufficient. There are 25 such planned missions.

Starting in 1991, longer (60') and heavier (25K) payloads will require multiple Shuttle operations and use of the larger OTV being defined in a separate study (NAS8-33533).

MISSIONS/PAYLOADS



SPACE BASED RADAR



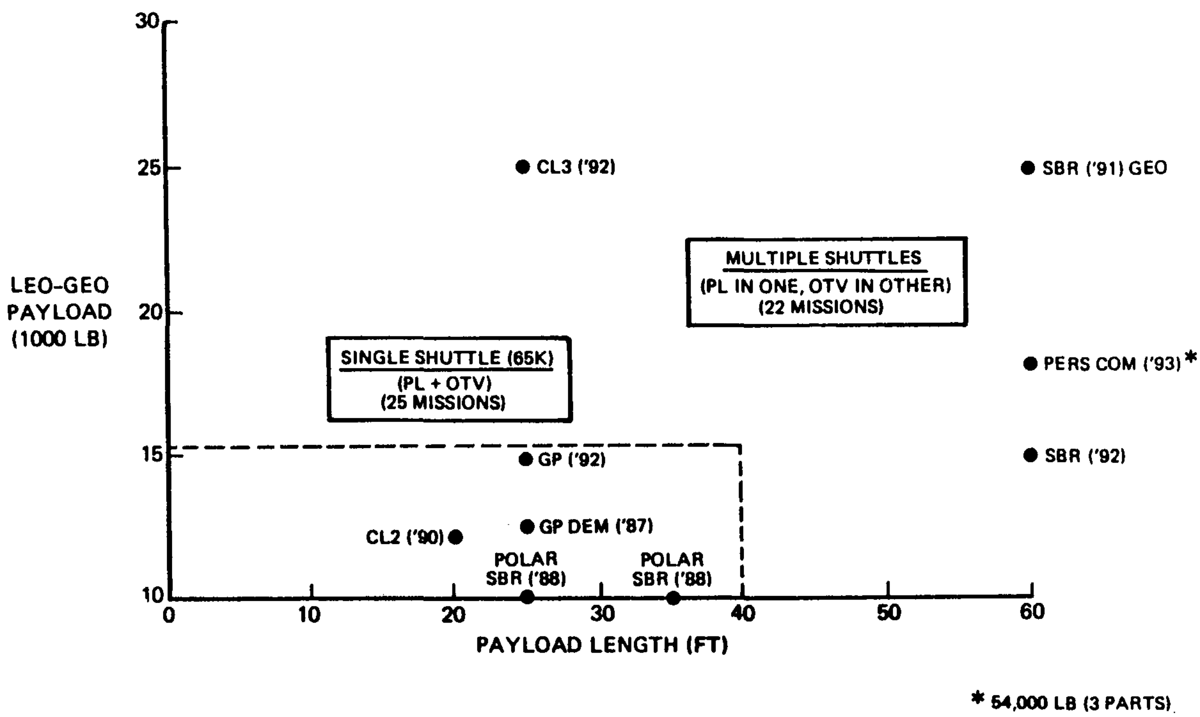
GEOPLATFORM

POTENTIAL MISSIONS/PAYLOADS FOR LOW THRUST PROPULSION

	NUMBER	IOC	
GEO-PLATFORM DEMO - 12,500 LB × 25 FT	1	1987	NOMINAL MODEL
GEO-PLATFORM - 15,000 LB × 25 FT	12	1992	NOMINAL MODEL
SPACE BASED RADAR			NOMINAL MODEL
POLAR - 10,000 LB × 25-35 FT	8	1988	NOMINAL MODEL
GEO - 15,000 - 25,000 LB × 60 FT	2	1991	NOMINAL MODEL
DOD CLASS 2 - 12,000 LB × 20 FT	4	1990	NOMINAL MODEL
DOD CLASS 3 - 25,000 LB × 25 FT	8	1992	NOMINAL MODEL
PERS COMM - 54,000 LB (3 PARTS) EACH - 18,000 LB × 60 FT	12	1993	NOMINAL MODEL
	47		
X-RAY TELESCOPE/GRAVITY WAVE INTERFEROMETER (SPACE FAB)		1997	MAX MODEL
SOLAR POWER DEMO (SPACE FAB)		1995	MAX MODEL

(REF NASA MSFC 29 FEB 1980)

PAYLOAD ALLOCATION



DESIGN & OPERATIONAL CHARACTERISTICS OF SELECTED PAYLOADS

	SBR		GP	
	POLAR	GEO	EXPER	OPR
DESIGN CHARACTERISTICS				
WEIGHT (LB)	10,000	15,000-25,000	12,500	15,000 (NOM)
STOWED LENGTH (FT)	25-35	60	25	25
OPERATIONAL CHARACTERISTICS				
MISSION	5600 N. MI. POLAR	GEO	GEO	GEO
IOC	1988	1991	1987	1992
FUNCTION	AIRCRAFT SHIP, GROUND VEHICLE SKIN TRACKING	SAME	ADVANCED COMMUNICATION AND EARTH OBSERVATION	ADVANCED COMMUNICATION AND EARTH OBSERVATIONS
LIFE	10 YR	10 YR	5 YR	16 YR (NOM)
SERVICING	NO	NO	TEST	EVERY 1-1/2 YR

(circled) IMPACTED BY OTV REF: NASA/MSFC 29 FEB 1980

SELECTED MISSIONS ARE THE GEOPLATFORM AND SPACE BASED RADAR. DRIVING REQUIREMENTS ARE: 1987 IOC; 25-35 FT PAYLOAD LENGTH; 15,000 LB PAYLOAD WEIGHT TO GEOSYNCHRONOUS ORBIT.

GEOSTATIONARY PLATFORM PROGRAM

MISSION GOALS

- MAXIMIZE EFFICIENT USE OF AVAILABLE FREQUENCY SPECTRUM THROUGH FREQUENCY REUSE AND OTHER ADVANCED TECHNOLOGIES.
- REDUCE CONGESTION IN THE GEOSYNCHRONOUS ORBITAL ARC.
- REDUCE COSTS BY SUBSYSTEM SHARING AND "ECONOMY OF SCALE".
- USED PRIMARILY FOR COMMUNICATIONS (COMMERCIAL, NASA, AND DOD) BUT ALSO OFFERS TENANCY AND SUPPORT FOR EXPERIMENTS, ETC.

BACKGROUND

- NASA/MSFC PHASE A CONCEPTUAL DEFINITION CONTINUING BY GDC WITH COMSAT, COORDINATED WITH COMMERCIAL INTERESTS.

CONCEPTS

- RANGE FROM VERY LARGE, DOCKED MODULES TO A GROUP OF PLATFORMS "FLYING IN FORMATION".
- RANGE IN WEIGHT FROM 12,500 TO 37,000 POUNDS REQUIRING 25 TO 60 FEET STOWED LENGTH.
- EARLY EXPERIMENTAL PLATFORM PLANNED FOR 1987; OPERATIONAL UNITS BY 1992.

SPACE-BASED RADAR

MISSION GOALS

- WOULD PRECLUDE NEED FOR EXPENSIVE UPKEEP OF DEW LINE AND AWACS FLIGHTS
- CAN PROVIDE EARLIER ADVANCE WARNING

BACKGROUND

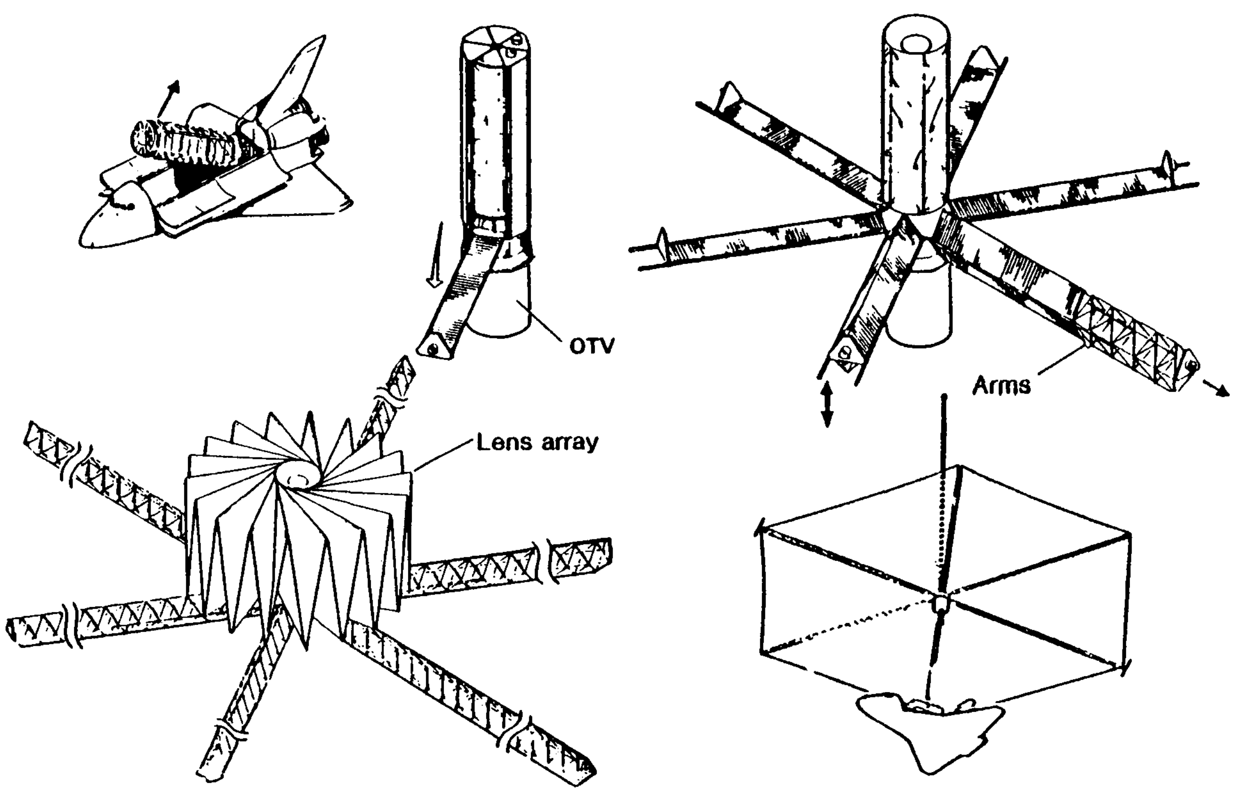
- TEN YEARS OF U.S. NAVY FEASIBILITY STUDIES OF OCEAN SURVEILLANCE SENSORS
- "ON-ORBIT ASSEMBLY" STUDIES FOR SAMSO IN 1978.
- DARPA TECHNOLOGY UNDERWAY, INCLUDING NEW GDC LENS STUDY
- RECENT NASA/MSFC RFP FOR FLIGHT EXPERIMENT OF LARGE DEPLOYABLE ANTENNA

CONCEPTS NOTE: RADAR AND IR SENSORS MAY BE COMBINED IN ONE NETWORK OR ON ONE SPACECRAFT

- POLAR ORBIT
  - ▲ APPROXIMATELY 200 FT DIAMETER GIVES GOOD RESOLUTION
  - ▲ 6 TO 12 SPACECRAFT GIVE COVERAGE
  - ▲ IOC COULD BE AS EARLY AS 1988
  - ▲ EACH SPACECRAFT WEIGHS ~10,000 POUNDS AND REQUIRES ABOUT 25-35 FT STOWED LENGTH
- GEO ORBIT
  - ▲ 300 TO 600 FT DIAMETER NEEDED FOR RESOLUTION
  - ▲ 1 OR 2 SPACECRAFT REQUIRED
  - ▲ IOC PROBABLY WOULD FOLLOW POLAR-ORBIT CONCEPT
  - ▲ EACH SPACECRAFT WEIGHS 15,000-25,000 POUNDS AND REQUIRES ABOUT 60 FT STOWED LENGTH

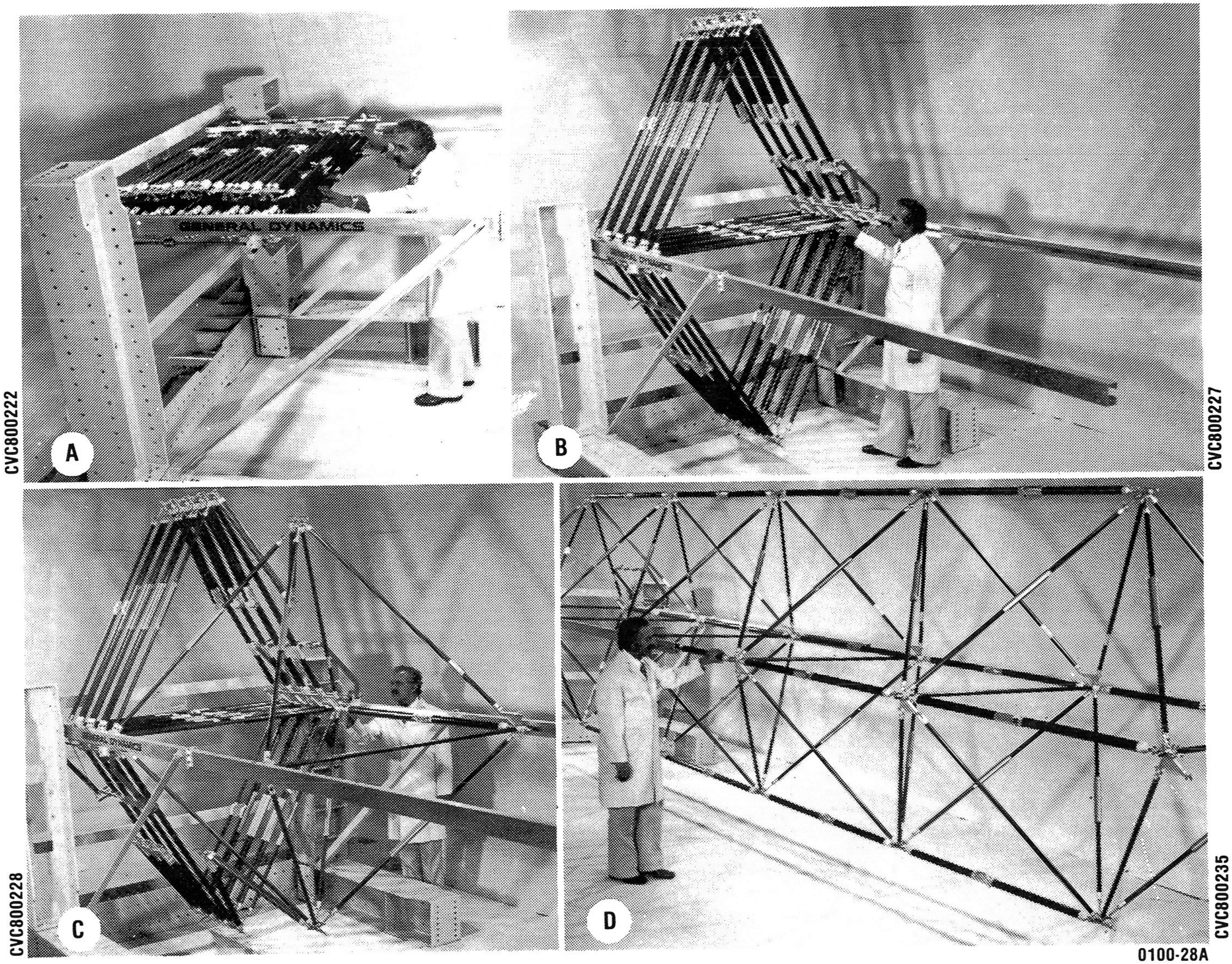
SPACE-BASED RADAR

TETRAHEDRAL TRUSS ARM DEPLOYMENT SEQUENCE



GDC TETRAHEDRAL TRUSS DEMONSTRATION

(GY70/X-30 TUBES)



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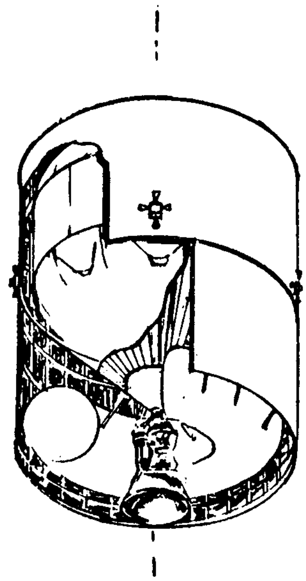
ORBIT TRANSFER VEHICLES/PROPULSION SYSTEMS



RANGE OF REQUIREMENTS IMPOSED ON OTV

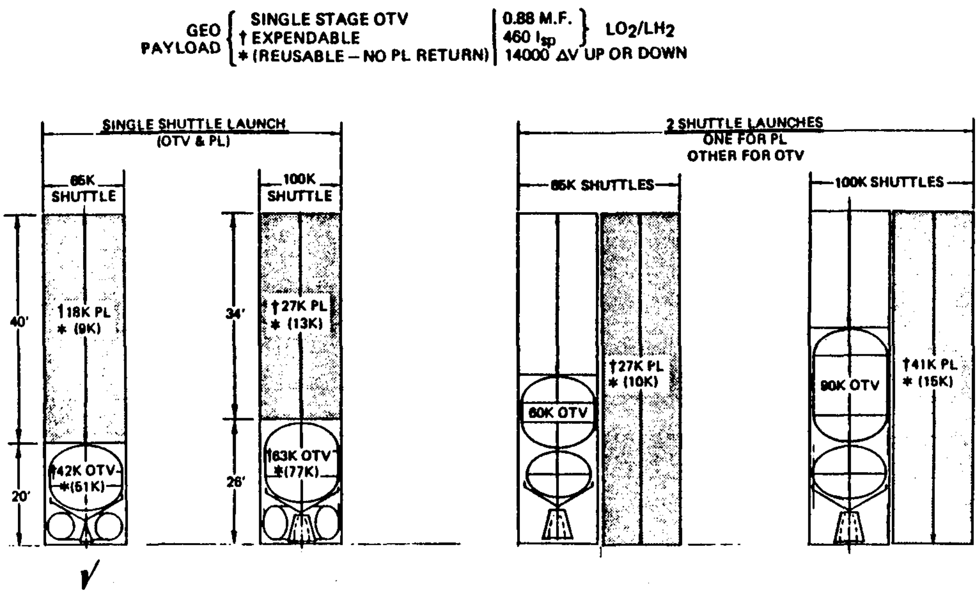
NUMBER	IOC	PAYLOAD WEIGHT	PAYLOAD LENGTH	
13	1987 - 1990	10,000 - 12,500 LB	20-35'	SINGLE SHUTTLE OK
12	1992	15,000 LB	25'	
14	1991 - 1993	15,000 - 25,000 LB	60'	MULTIPLE SHUTTLES REQD
8	1992	25,000 LB	25'	

> STARTING IN 1987, THERE ARE [IN THE NASA/MSFC MISSION MODEL FOR OTV STUDY (NAS8-33533)] 25 MISSIONS WHICH BENEFIT FROM LOW THRUST - THAT CAN BE LAUNCHED WITH AN OTV IN A SINGLE SHUTTLE LAUNCH - ENCOURAGING A SHORT OTV.

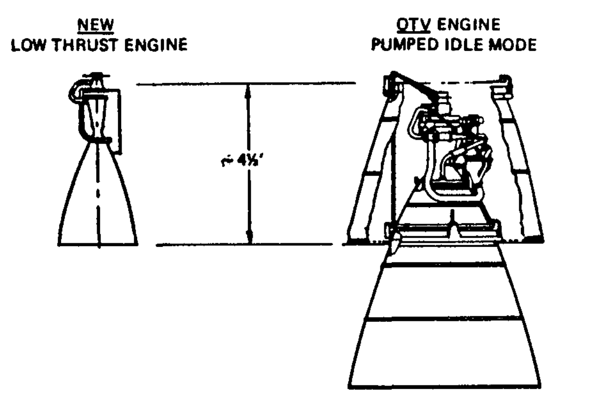
Analysis was conducted for expendable vs. reusable, single stage vs. 2-stage, single vs. multiple Shuttle launches, and 65K vs. 100K Shuttles. The most cost-effective option is the single Shuttle, expendable OTV. This option was selected for primary study.

To obtain the shortest possible stage to allow maximum payload length, the torus LO_2 tank configuration is selected since it is superior to all others (conventional suspended tanks, nested tanks). A savings of 9' in length is realized over conventional tanks.

CANDIDATE OTV CONCEPTS



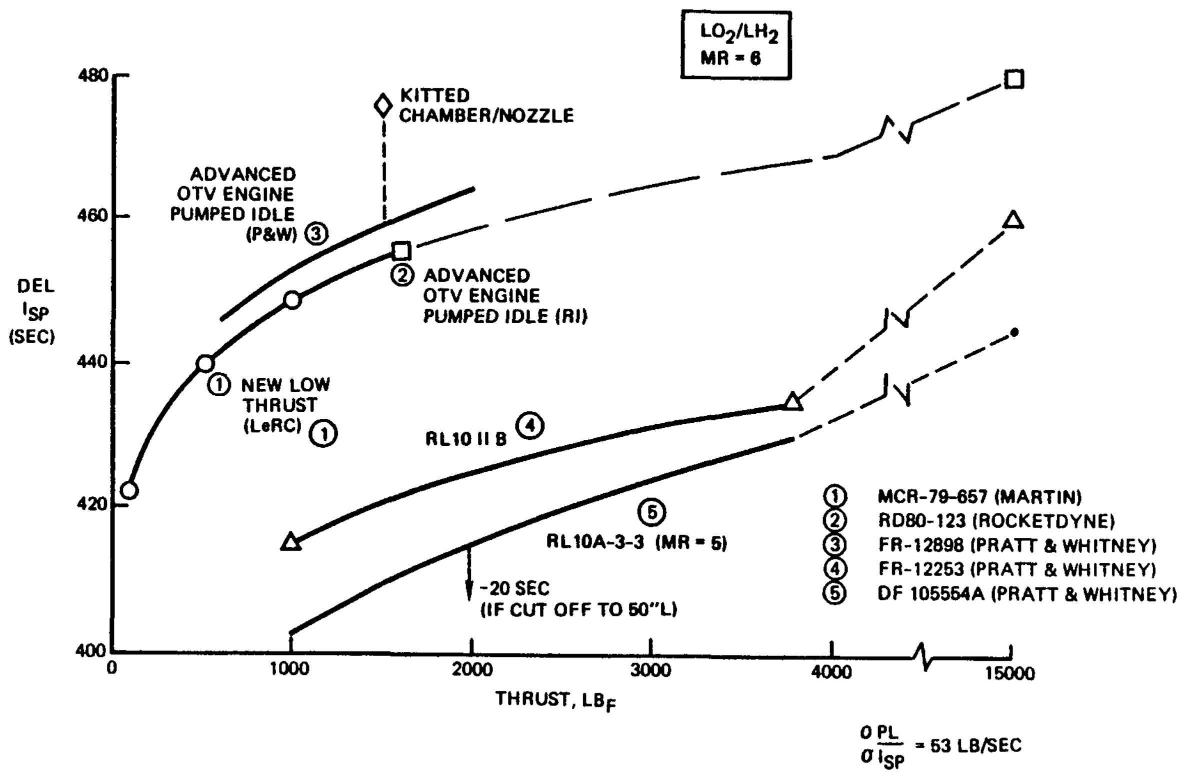
ENGINE OPTIONS



		NEW	NEW + KIT*	RL10 II B
THRUST, LB	1500	1500	1500	3500
I_{SP}, SEC	455	455	470	435

*CHAMBER/NOZZLE (SMALLER THROAT, COUNTERFLOW NOZZLE)

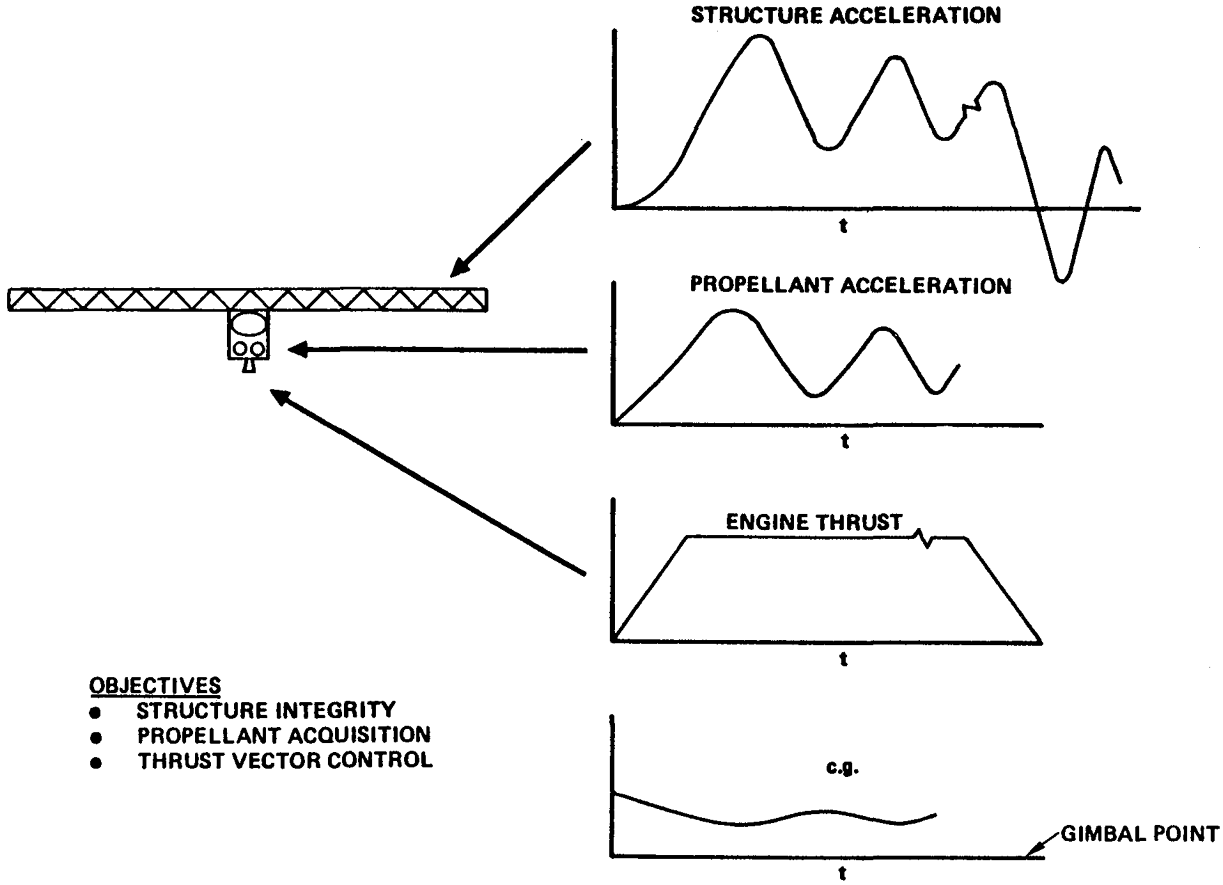
LOW THRUST ENGINE PERFORMANCE



LOW THRUST ENGINE TECHNOLOGY

	NEW LOW THRUST	PUMPED IDLE (OTV ENGINE)
TECHNOLOGY CONCERNS —	— SMALL PUMPS, COOLING, AND PERFORMANCE	— PERFORMANCE AND STABILITY AT 10% THRUST
SIZE —	— SMALLER	— LARGER
WEIGHT —	— LESS	— HEAVIER
REC. COST —	— TBD	— TBD
DEV. COST —	— TBD	— TBD

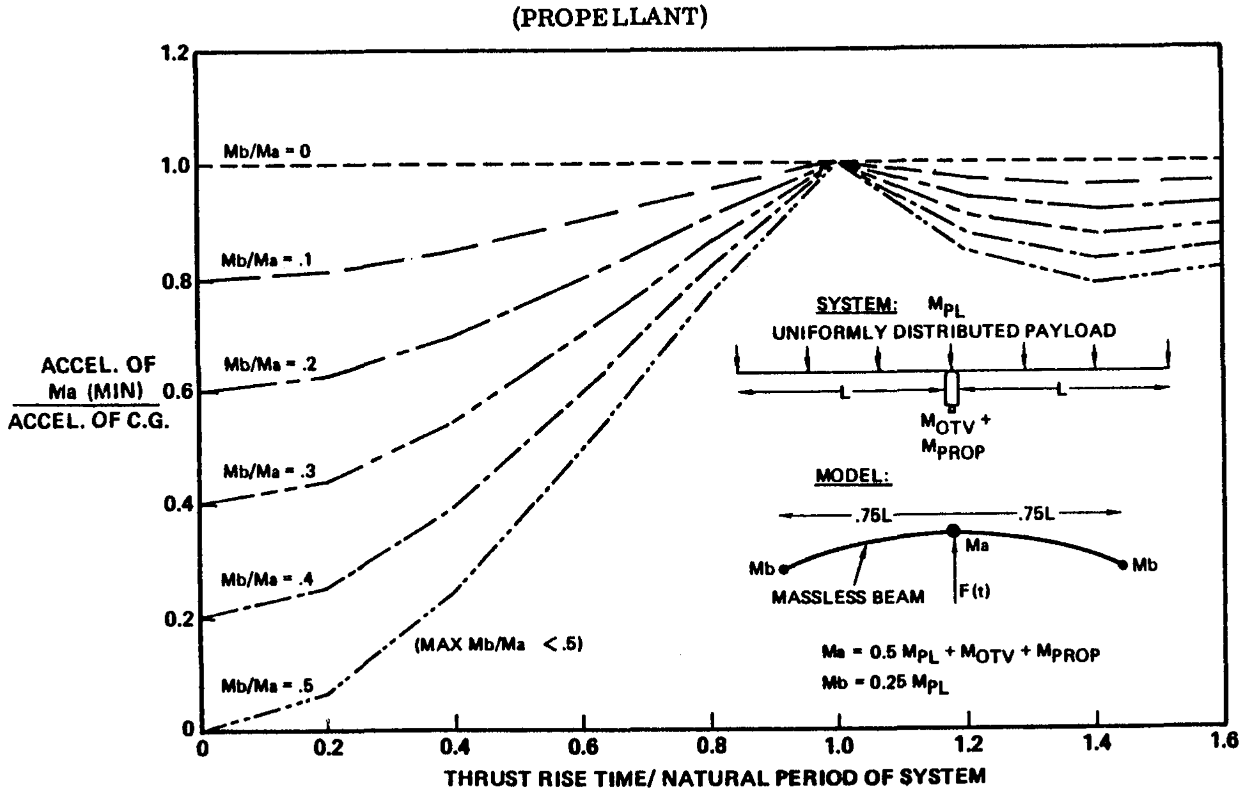
THRUST TRANSIENT INTERACTION



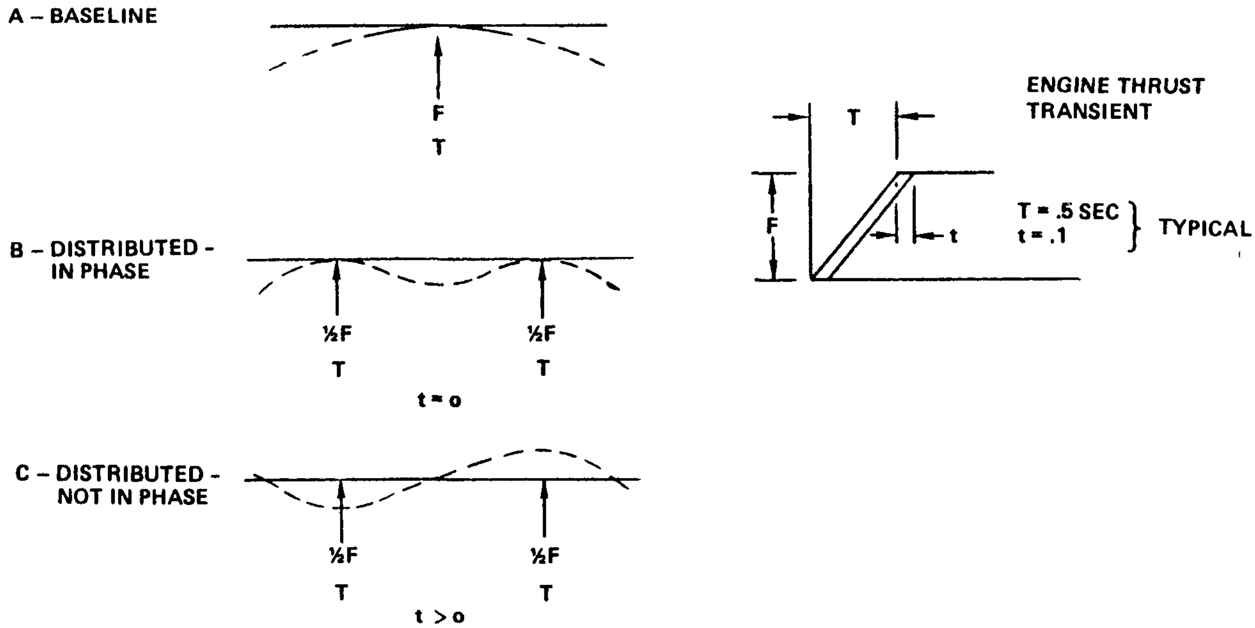
OBJECTIVES
- STRUCTURE INTEGRITY
- PROPELLANT ACQUISITION
- THRUST VECTOR CONTROL

MINIMUM DYNAMIC RESPONSE

(PROPELLANT)



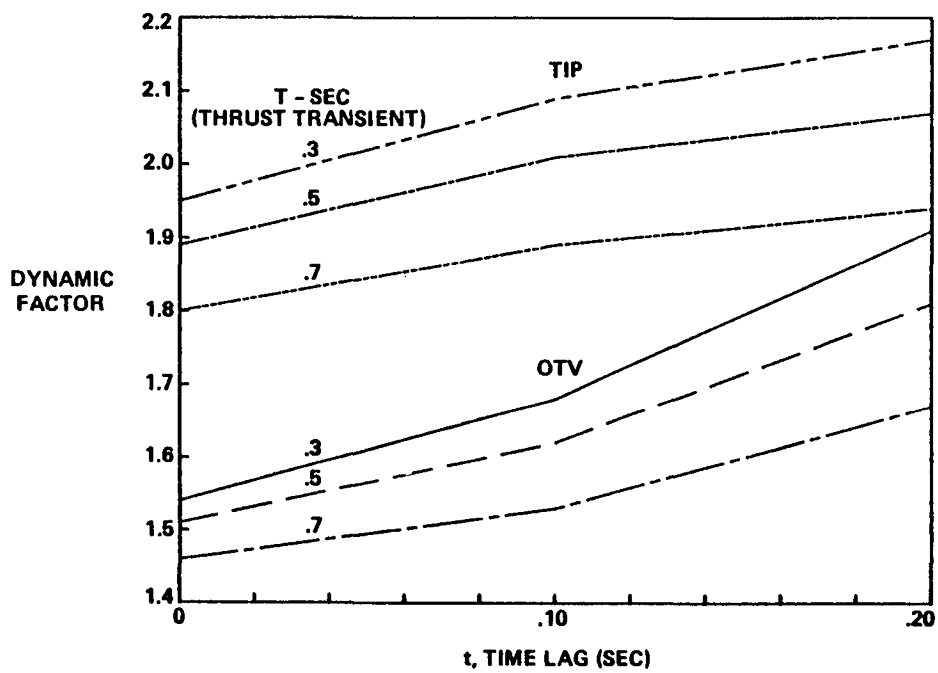
DISTRIBUTED THRUST



DISTRIBUTED THRUST COMPLICATES OTV/LSS DESIGN/DEPLOYMENT. DIFFICULTY IN PHASING THRUSTERS CAN INCREASE DYNAMIC LOADING.

DISTRIBUTED THRUST

(EFFECT ON DYNAMIC FACTOR)



The GDC computer program is both a synthesis and optimization program for parametric and trade studies of LSS and OTV configurations operating out of the Shuttle. The program has the following features.

It accepts LSS truss structure material properties, and minimum member size and gage limitations. For purposes of this analysis, graphite composite having an $E = 40 \times 10^6$ psi and an $F_{cy} = 37,000$ psi, and aluminum (6061-T6) having an $E = 10^7$ psi and $F_{cy} = 35,000$ psi are used. Minimum tube diameter and thickness are 2 and .05 inches, respectively.

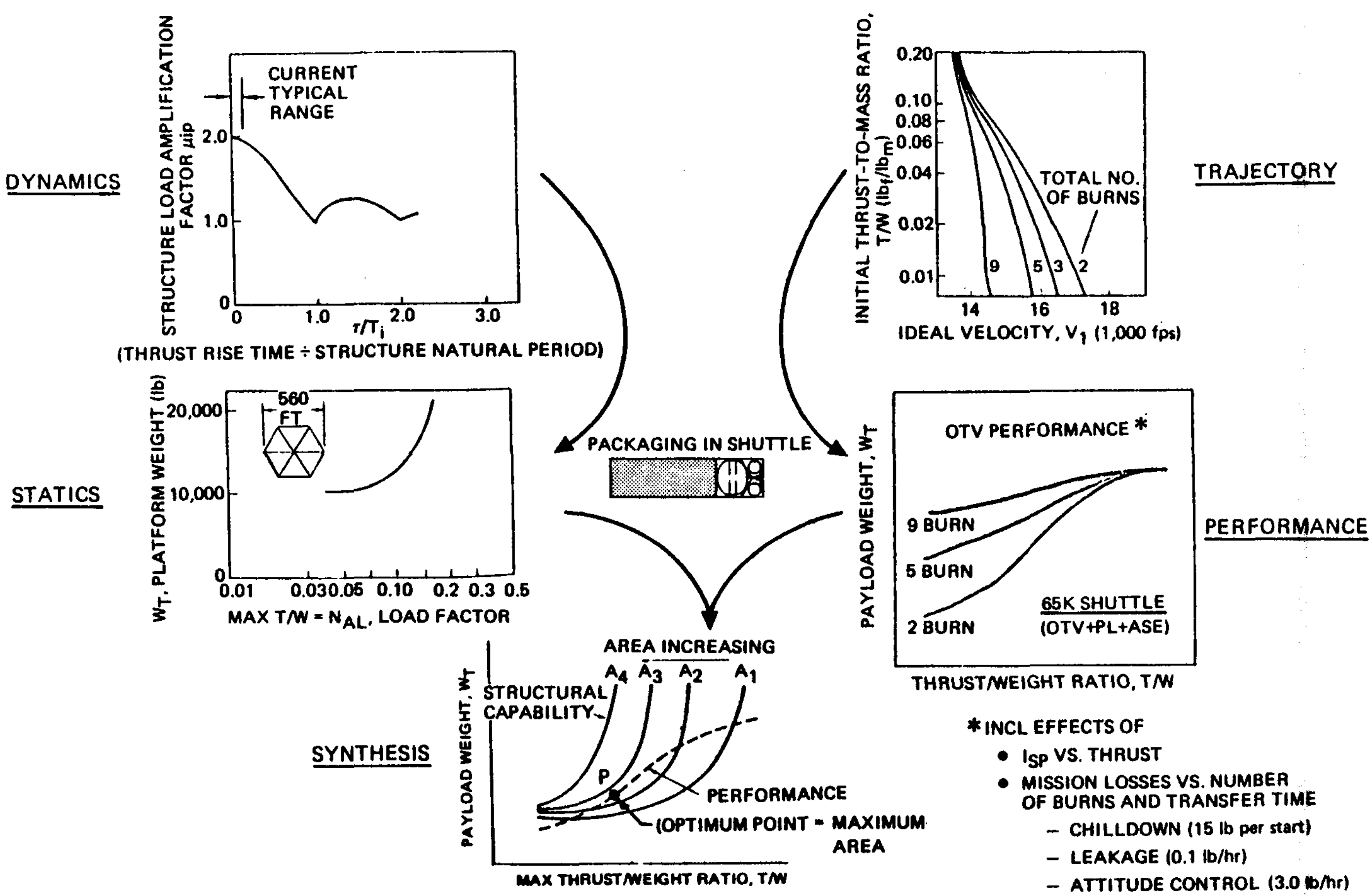
The program accounts for the Shuttle payload weight and volume constraints as well as the configuration of the OTV (i.e., mass fraction and length vs. propellant weight) and its propulsion system I_{sp} vs. thrust characteristics.

The input also includes factors for weight of joints, the LSS hub weight, dynamic amplification factors, and number of burns.

Through an iterative computational process the program computes stowed and deployed sizes as well as structural and mass properties. It checks critical stresses including Euler column buckling of truss member tubes and also radar-array-membrane stresses. If stresses are unacceptable, the tube diameters are first iteratively increased up to the point at which volume limitation constraints are encountered. After this, the tube wall gages are increased as necessary up to the point at which weight limitation constraints are encountered. It then computes OTV length, mass, and performance parameters. To perform these analyses, it must compute ΔV impulse velocity requirements to achieve orbital transfer for the selected input number of burns and initial acceleration.

Fit checks are performed to determine for a given T/W and structure size if the payload and volume limitations of the Shuttle are met and if the OTV payload capability matches the actual payload weight. The structure size is then systematically increased until either volume and/or weight limitations are encountered, at which point the maximum LSS size is assumed to have been achieved. The T/W is next increased and the above process is repeated to generate data for LSS size vs T/W. For each T/W all characterizing parameters of the LSS and OTV are computed and printed out along with a factor for the fraction of the total Shuttle cargo bay length utilized. In all cases the full payload capabilities of the Shuttle are used.

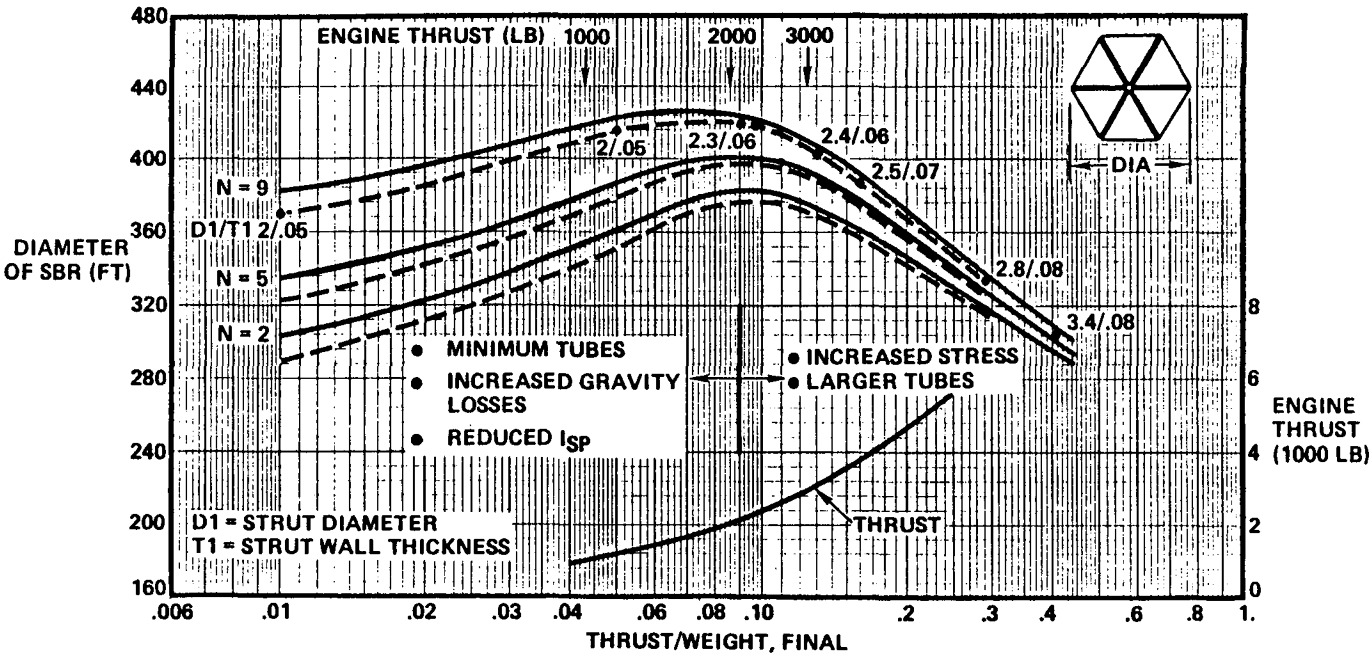
PERFORMANCE ANALYSIS



*INCL EFFECTS OF

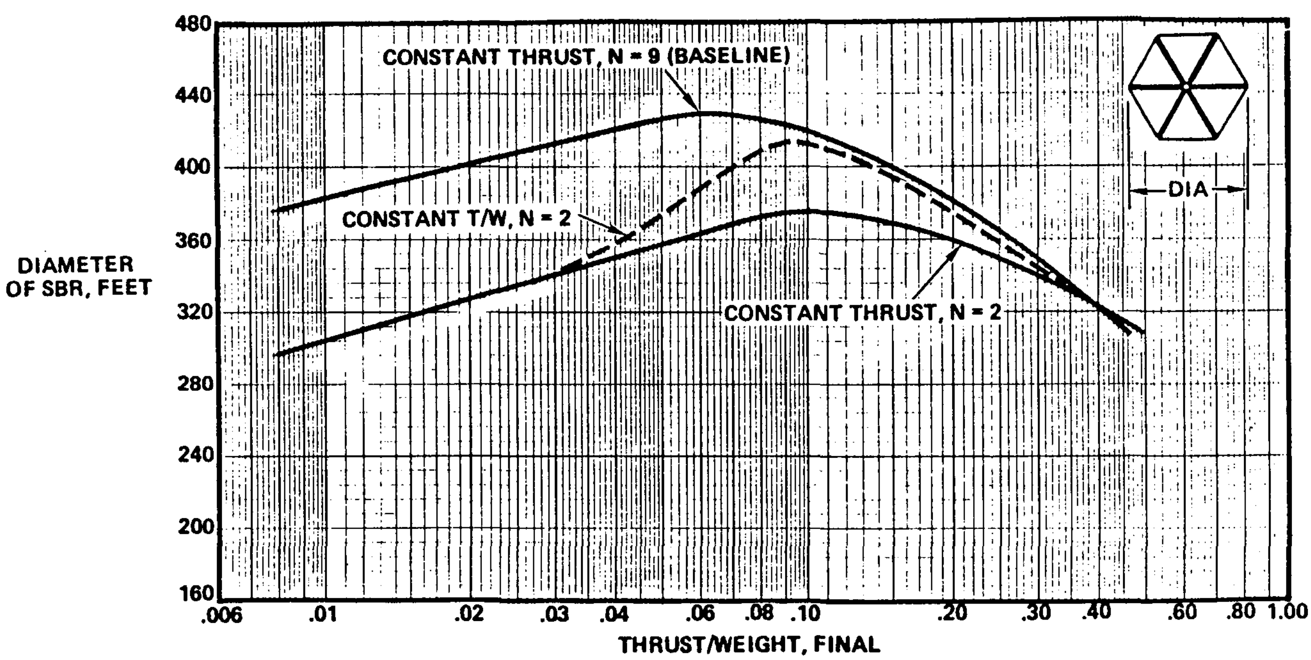
- I_{SP} VS. THRUST
- MISSION LOSSES VS. NUMBER OF BURNS AND TRANSFER TIME
  - CHILLDOWN (15 lb per start)
  - LEAKAGE (0.1 lb/hr)
  - ATTITUDE CONTROL (3.0 lb/hr)
  - POWER (0.5 lb/hr)
  - BOILOFF (MAX) (1.0 lb/hr)

EFFECT OF ENGINE THRUST & NUMBER OF BURNS ON SIZE OF SBR-A

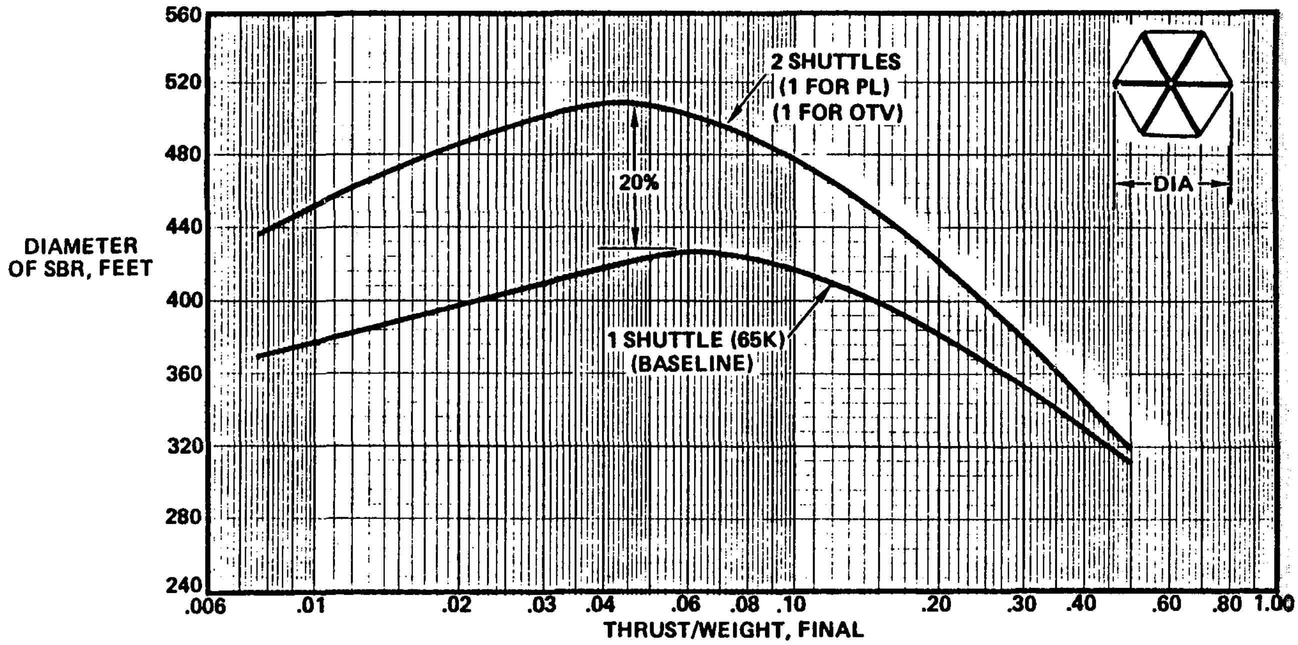


— — — WITH MISSION LOSSES

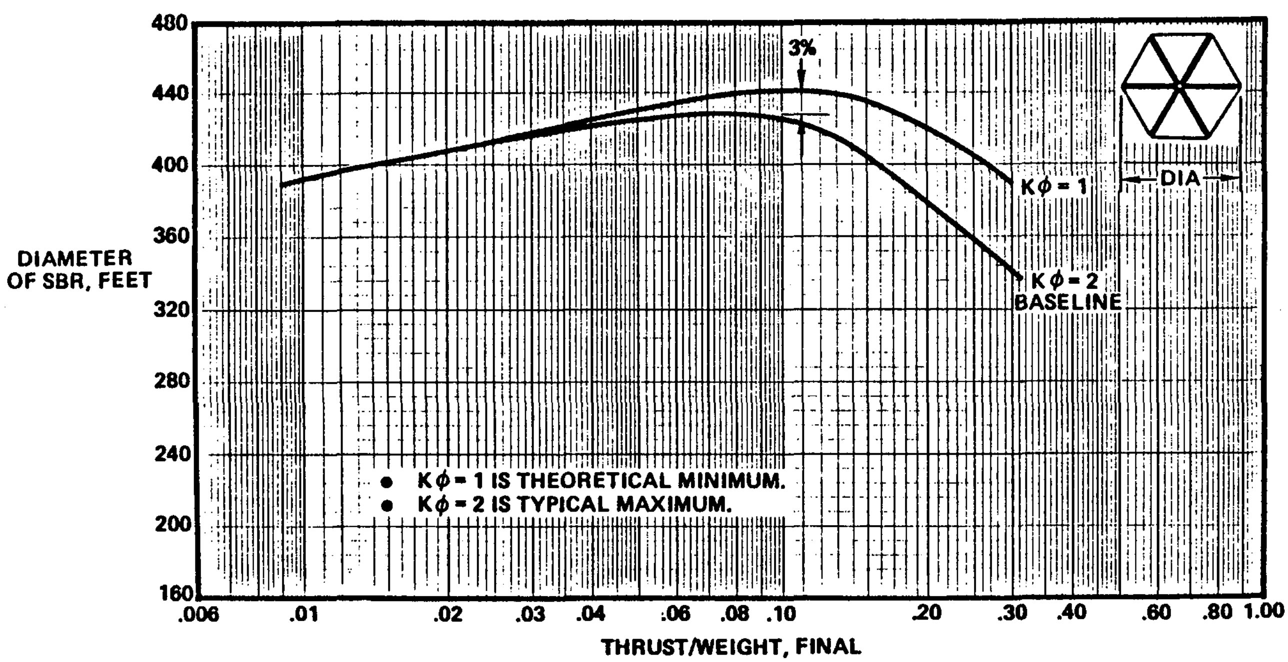
EFFECT OF CONSTANT ACCELERATION (VARIABLE THRUST) ON SIZE OF SBR-A



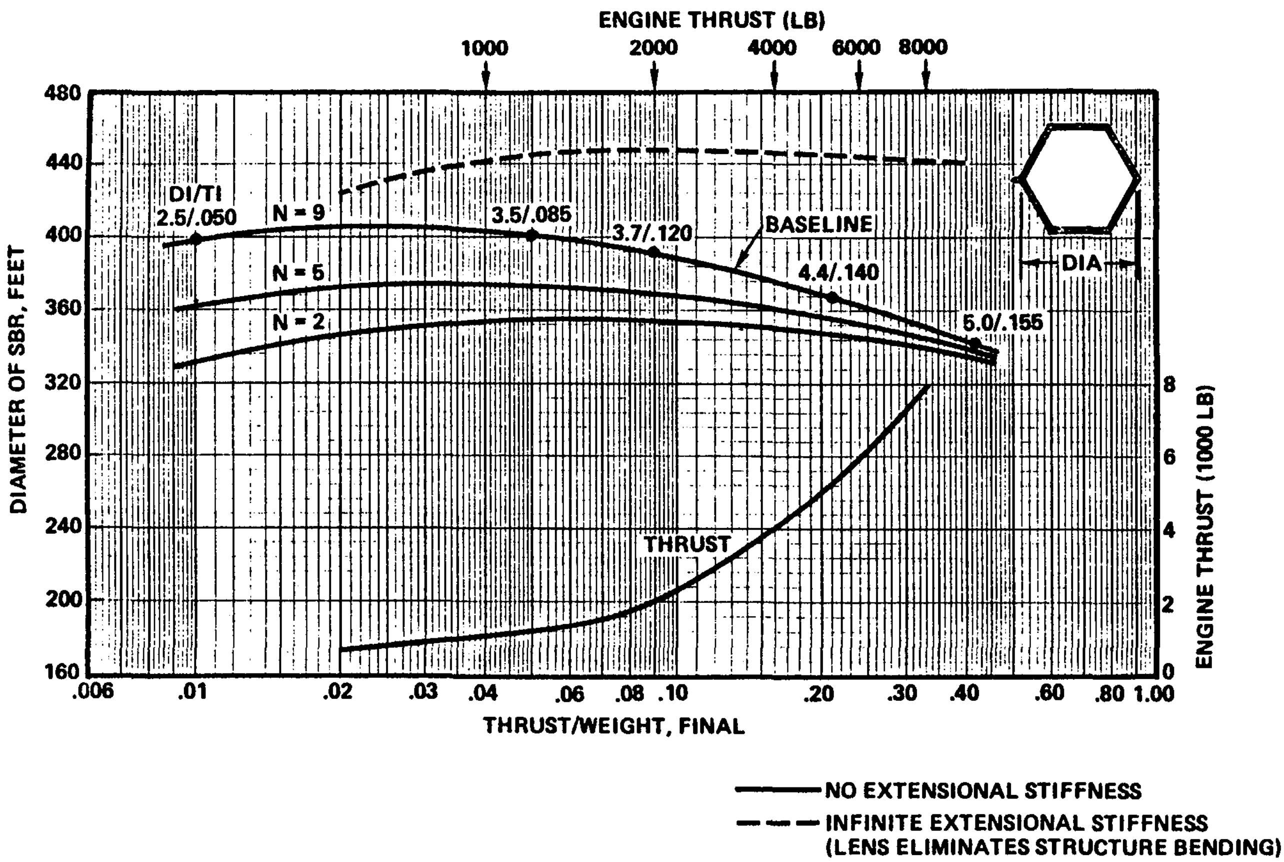
EFFECT OF NUMBER OF SHUTTLES ON SIZE OF SBR-A



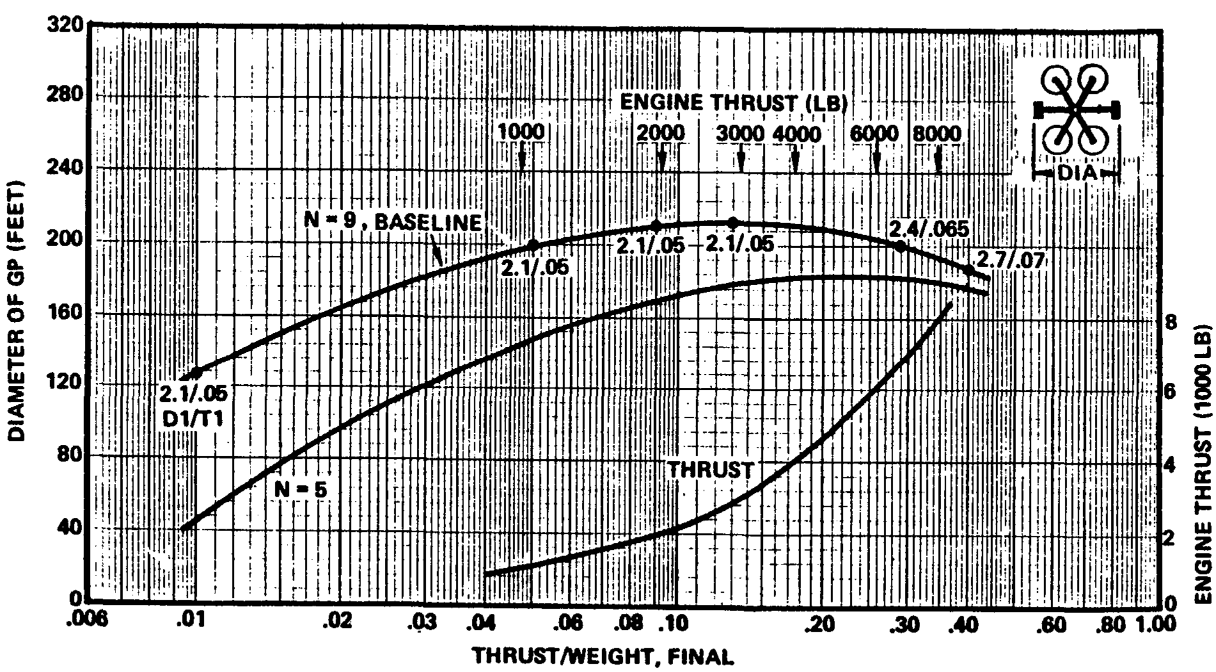
EFFECT OF DYNAMIC FACTOR (Kϕ) ON SIZE OF SBR-A



EFFECT OF ENGINE THRUST & NUMBER OF BURNS ON SIZE OF SBR-R



EFFECT OF ENGINE THRUST & NUMBER OF BURNS ON SIZE OF GEOPLATFORM



INTERACTION RESULTS

SUMMARY

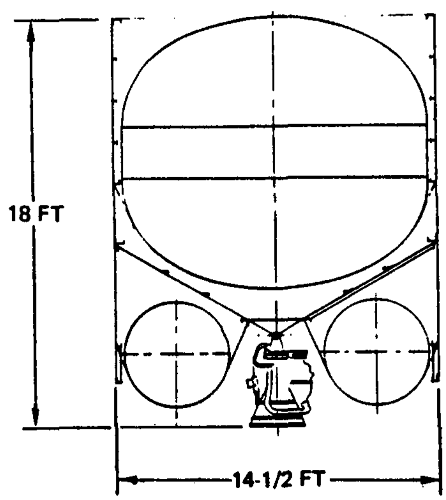
- OPTIMUM THRUST

SBR-A	2000 LB_F	(MOST SENSITIVE)
SBR-R	1000 LB_F	(LEAST SENSITIVE)
GP	3000 LB_F	

- THRUST TRANSIENT NOT A CONCERN
- CONSTANT THRUST (9-BURN) BEST

1500 LB_F THRUST LEVEL SELECTED FOR BASELINE

BASELINE DESIGN DEFINITION

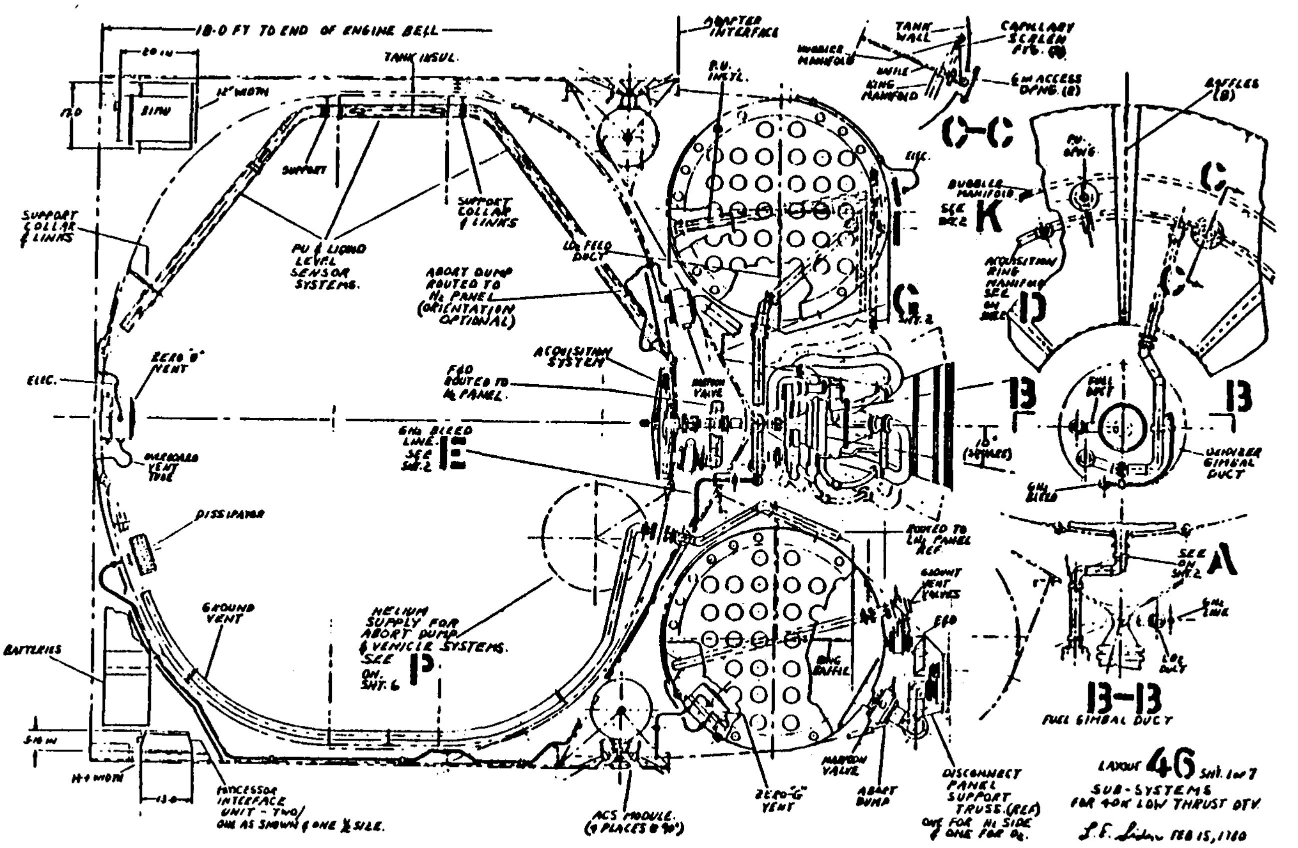


(DESIGNED FOR 3 g IN SHUTTLE).

EXPENDABLE LOW THRUST OTV
(38K PROPELLANT @ MR = 6)

- PUMP FED (1.5K) ENGINE
  - ▲ ENGINE-MOUNTED/DRIVEN PUMPS (NO VEHICLE – MOUNTED BOOST PUMPS)
  - ▲ 16 PSIA MIN INLET PRESSURE
  - ▲ NPSH
    - LO_2 – 1 PSI
    - LH_2 – 0.5 PSI
  - ▲ AUTOGENOUS H_2 BLEED
- COMPOSITE STRUCTURE
- ALUMINUM TANKS
- PROPELLANT ACQUISITION
  - ▲ PARTIAL SETTLING
  - ▲ SCREENS
- MLI TANK INSULATION (15 LAYERS)
- PRESSURIZATION
  - ▲ HELIUM PRE-PRESS; O_2 RUN
  - ▲ AUTOGENOUS H_2 RUN
- ZERO-G VENT/MIXER
- FILL AND DRAIN } THROUGH SIDES OF ORBITER
- 300 SEC ABORT DUMP } THROUGH SIDES OF ORBITER
- N_2H_4 ATTITUDE CONTROL
- FUEL CELL POWER (1 KW)
- MISSION
  - ▲ 40–HR ORBITER C/O
  - ▲ 24–HR TRANSFER
  - ▲ 9 BURNS
  - ▲ 5 HR BURN TIME

BASELINE
LOW THRUST OTV

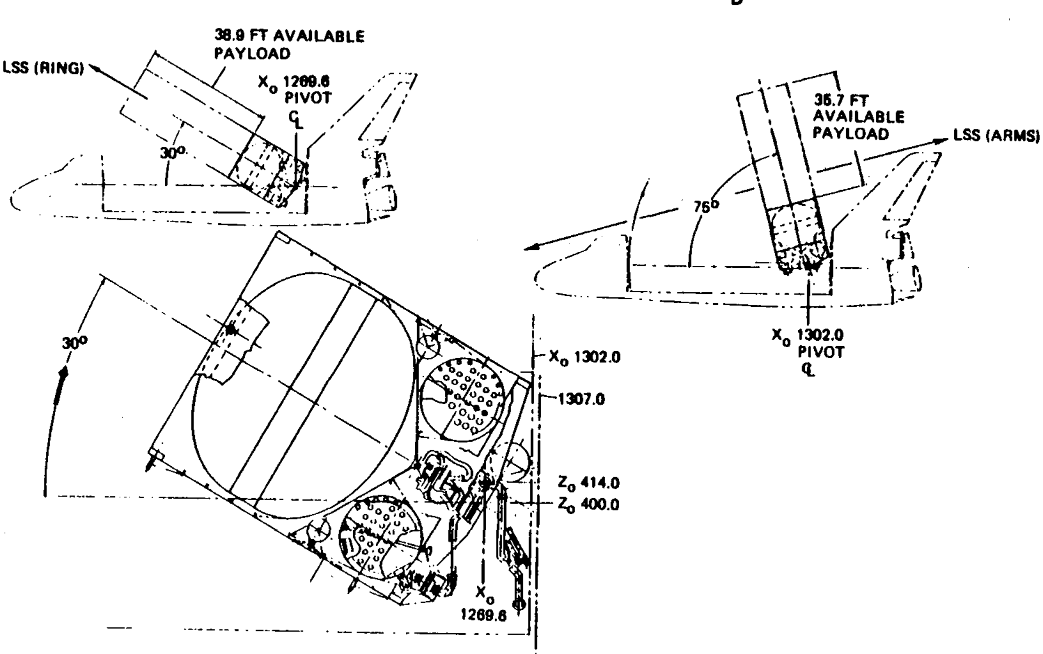


NOTE: SHORT RL10 USED TO DEFINE INTERFACES

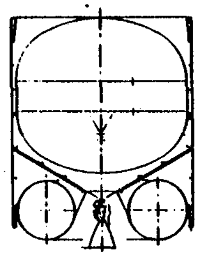
DEPLOYMENT

A -

B -

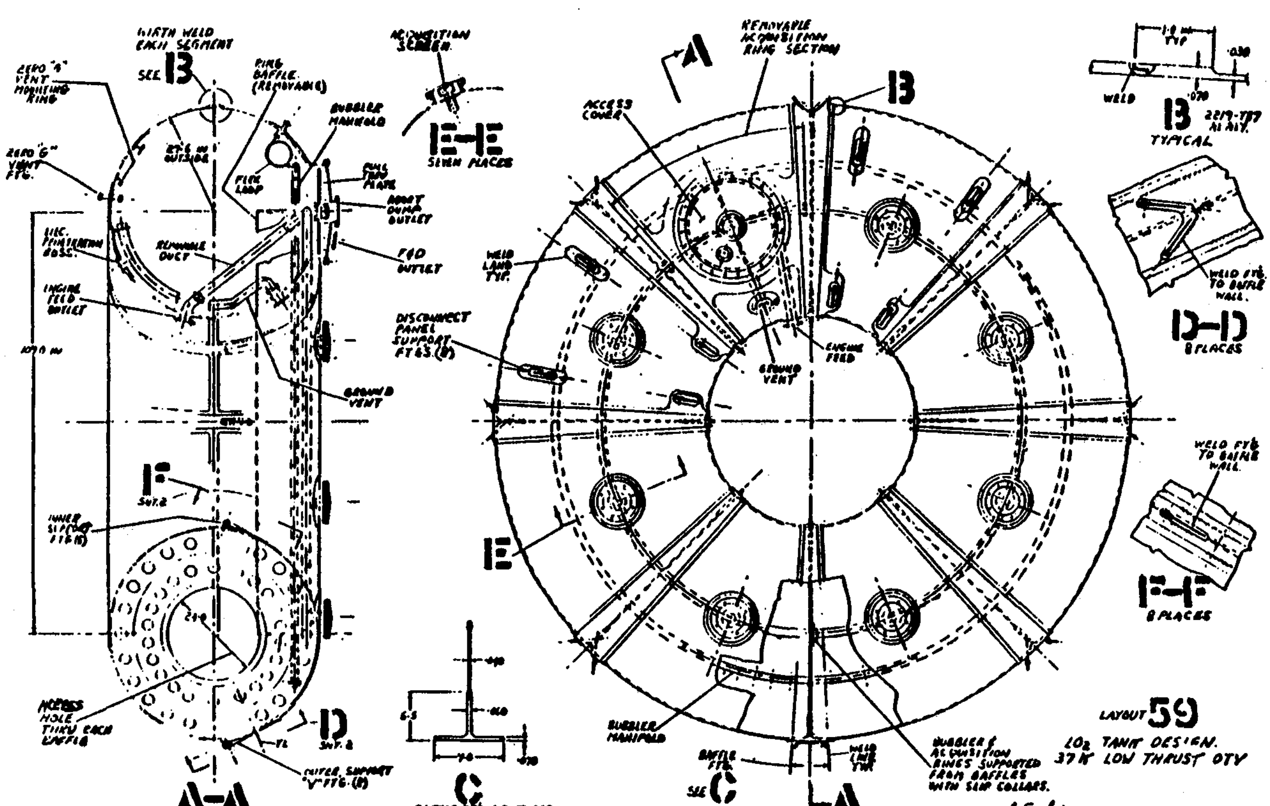


WEIGHT SUMMARY
LOW THRUST OTV

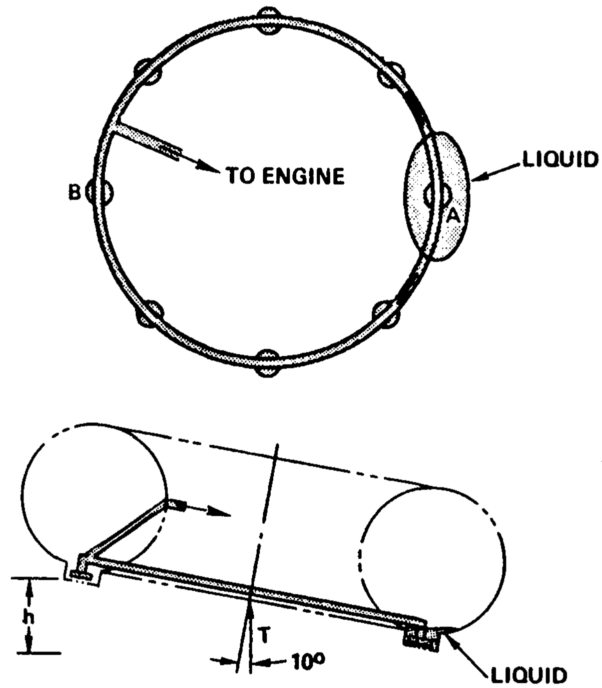


WEIGHT DATA (LB)	
STRUCTURE	2,177
THERMAL CONTROL	535
MAIN PROPULSION	762
ATTITUDE CONTROL	206
AVIONICS	396
ELECTRICAL POWER	380
CONTINGENCY	668
TOTAL DRY WEIGHT	5,124
RESIDUALS	382
RESERVES	430
BURNOUT WEIGHT	5,936
INFLIGHT LOSSES	319
MAIN IMPULSE PROPELLANT	37,434
ACS PROPELLANT (INCL DISPOSAL ΔV)	551
STAGE TOTAL WEIGHT	44,240
PAYLOAD TO GEOSYNCHRONOUS ORBIT (MAX)	15,760
STAGE PLUS PAYLOAD WEIGHT	60,000
AIRBORNE SUPPORT EQUIPMENT	5,000
TOTAL LAUNCH WEIGHT	65,000
MASS FRACTION	0.856

TORUS LO_2 TANK DESIGN

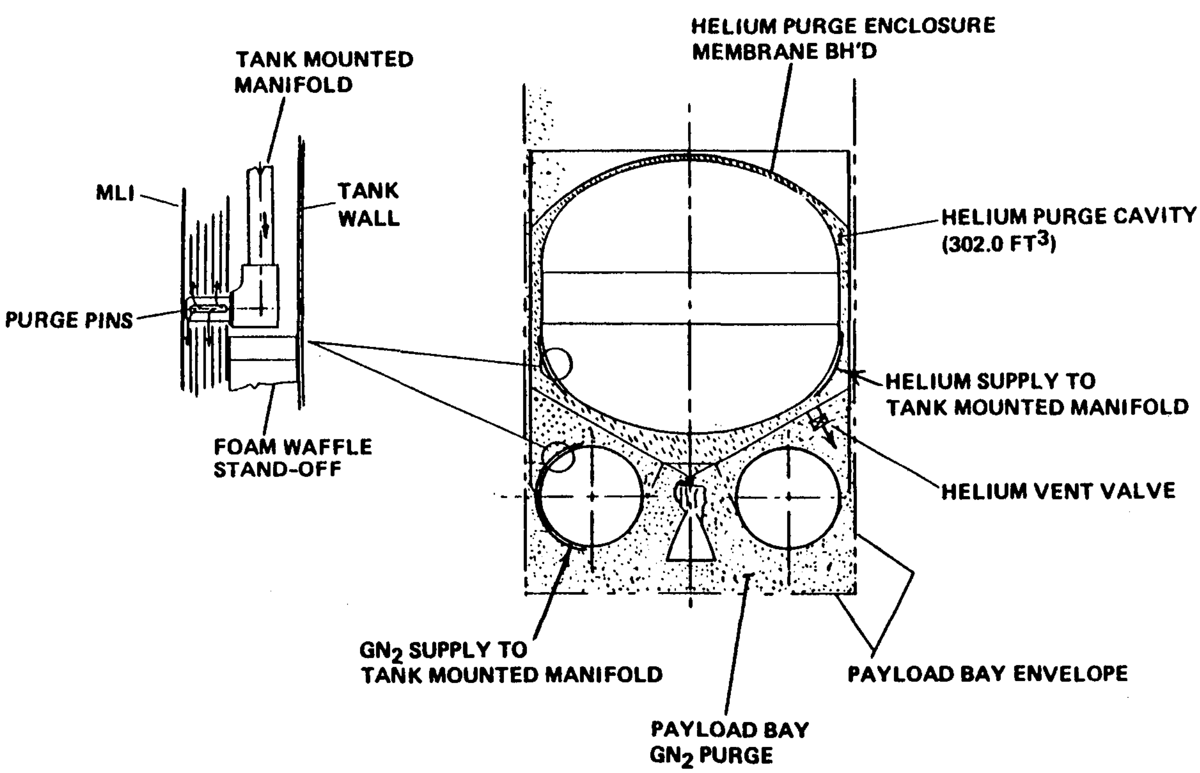


LO_2 ACQUISITION WITH THRUST MISALIGNMENT

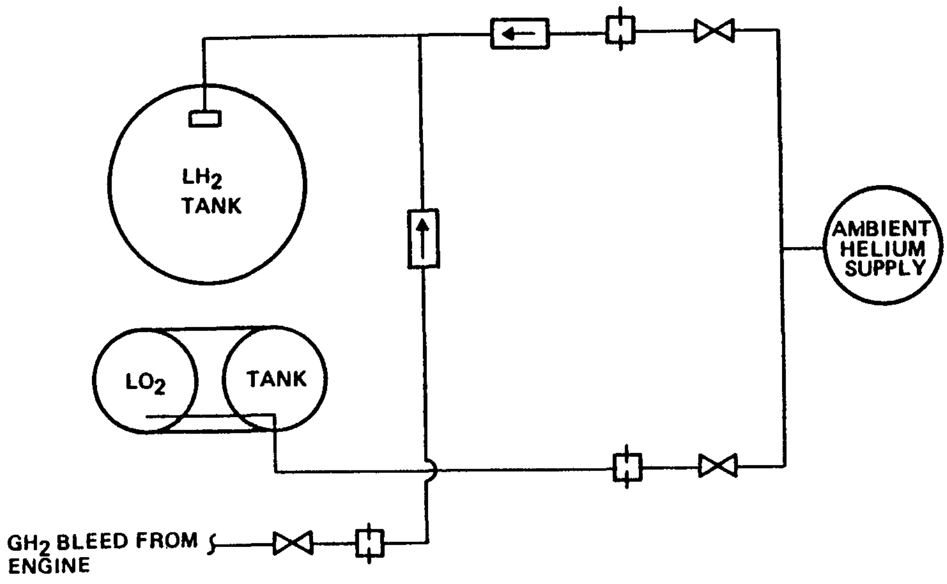


TORUS PROPELLANT ACQUISITION DEVICE MINIMIZES RESIDUALS WITH C.G. MISALIGNMENT.

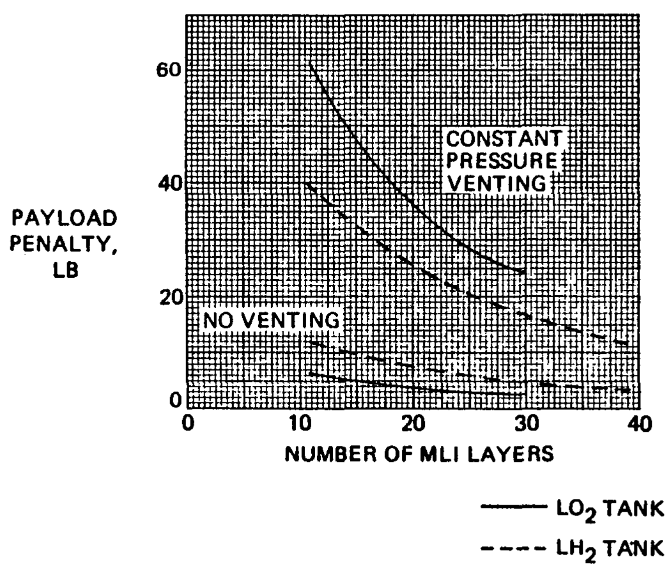
PURGE SYSTEM ENCLOSURE



PROPELLANT TANK PRESSURIZATION SYSTEM



40-HR CHECKOUT (PAYLOAD PENALTY)



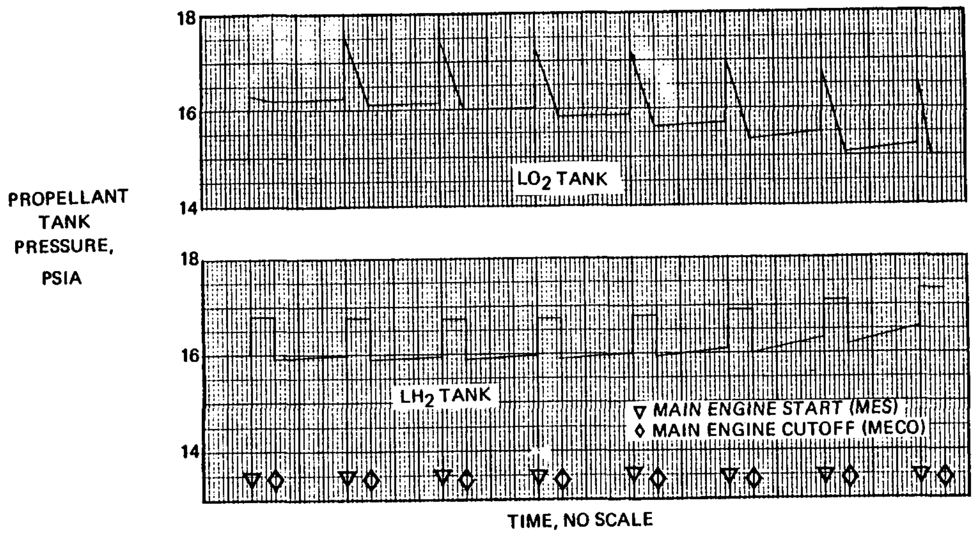
NO VENT CONDITION – PRESSURES DO NOT EXCEED DESIGN VALUES (SET BY ABORT DUMP REQUIREMENTS)

19 PSIA – LH_2
25 PSIA – LO_2

ZERO "G" VENT/MIXER

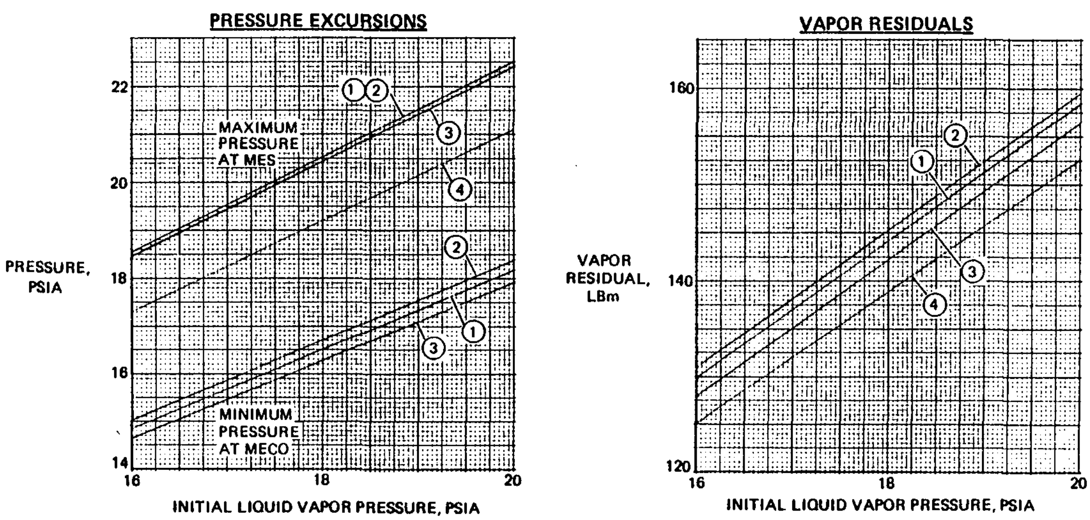
PAYLOAD PENALTY FOR 40-HR CHECKOUT AT LEO IS MINIMIZED WITH NO VENT OPTION

PROPELLANT TANK PRESSURE HISTORIES FOR EIGHT-BURN OTV MISSION



- LO_2 TANK PRESSURIZED WITH HELIUM FOR ENGINE START AND ENGINE BURN
- LH_2 TANK PRESSURIZED WITH HELIUM FOR ENGINE START; AUTOGENOUS PRESSURIZATION FOR ENGINE BURN
- ENGINE NPSP REQUIREMENT
  - ▲ 1.0 PSI LO_2
  - ▲ 0.5 PSI LH_2

OTV MISSION PARAMETERS INFLUENCE UPON LO_2 TANK



(1) 8-BURN, 1000 LB_F
(2) 8-BURN, 300 LB_F
(3) 5-BURN, 1000 LB_F
(4) 2-BURN, 3000 LB_F

> LO_2 TANK VAPOR RESIDUALS OR PRESSURES LITTLE AFFECTED BY MISSION – ENGINE THRUST OR NUMBER OF BURNS

TECHNOLOGY DEVELOPMENT

TECHNOLOGY DEVELOPMENT SHOULD BE UNDERTAKEN FOR ENGINE AND VEHICLE SYSTEMS
ESTIMATED INVESTMENT NEEDED

TORUS TANK	—	\$3-5M	FABRICATION AND TEST
PROPELLANT ACQUISITION	—	\$1M	FABRICATION AND TEST
INSULATION	—	\$0.5M	FABRICATION AND TEST
LOW THRUST ENGINE	—	\$3-7M	BOTH NEW LOW THRUST AND PUMPED IDLE
TOTAL		\$7-14M	

TECHNOLOGY INVESTMENT IS NEEDED FOR LOW THRUST OTV

CONCLUSIONS

THIS STUDY HAS DEFINED AN OPTIMIZED LOW THRUST OTV CONFIGURED SPECIFICALLY FOR ORBIT TRANSFER OF LARGE SPACE SYSTEMS - WITH THE FOLLOWING CONCLUSIONS:

ENGINE FOR OPTIMUM LOW THRUST VEHICLE

- VERY LOW THRUST (< 1K) NOT REQUIRED.
- 1 - 3K THRUST RANGE APPEARS OPTIMUM.
- THRUST TRANSIENT NOT A CONCERN.
- THROTTLING NOT WORTHWHILE.
- MULTIPLE THRUSTERS COMPLICATE OTV/LSS DESIGN AND AGGRAVATE LSS LOADS.
- NEW LOW THRUST ENGINE HAS ADVANTAGES OVER OTV PUMPED IDLE ENGINE.

OPTIMUM VEHICLE FOR LOW ACCELERATION MISSIONS

- SINGLE SHUTTLE LAUNCH (LSS AND EXPENDABLE OTV) MOST COST-EFFECTIVE AND LEAST RISK (ADEQUATE FOR 25 LSS MISSIONS).
- MULTIPLE SHUTTLES INCREASE LSS DIAMETER 20%.
- SHORT OTV NEEDED WHICH REQUIRES USE OF TORUS TANK
- PROPELLANT TANK PRESSURES/VAPOR RESIDUALS LITTLE AFFECTED BY THRUST LEVEL OR NUMBER OF BURNS.

RECOMMENDATIONS

FURTHER STUDY

- REVISE RESULTS AS NEW MISSION AND SPACECRAFT DATA BECOME AVAILABLE (ESPECIALLY AS THE GEOPLATFORM DESIGN EVOLVES).
- REEVALUATE STUDY RESULTS AS LeRC LOW THRUST ENGINE STUDIES PRODUCE DESIGN CONCEPTS AND COST DATA.
- COORDINATE WITH OTV STUDY (NAS8-33533 FOLLOW-ON).
- FURTHER EVALUATE BENEFITS OF DEPLOYING LSS AT LEO VS GEO.
- EVALUATE HOW CENTAUR (WITH IDLE MODE) COULD SATISFY REQUIREMENTS.
- ESTIMATE THE POINT AT WHICH ADVANCED ELECTRIC OTV (FAST TRANSFER/MPD) MIGHT REPLACE LOW THRUST CHEMICAL PROPULSION.

TECHNOLOGY

- UNDERTAKE TECHNOLOGY DEVELOPMENT FOR THE ENGINES AND VEHICLE SUBSYSTEMS (LOW THRUST OPTIONS. TORUS TANK, ACQUISITION, INSULATION).