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SATELLITE PROPULSION SYSTEM ANALYSIS

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AIR FORCE ROCKET PROPULSION LABORATORY
DIRECTOR OF LABORATORIES
AIR FORCE SYSTEMS COMMAND
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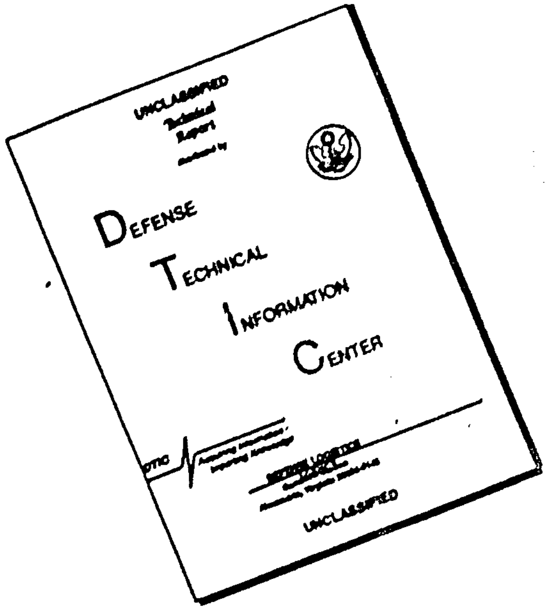

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13. ABSTRACT

Propulsion systems were studied for post-1975 geosynchronous satellites that have stringent attitude and station maintenance requirements with mission durations of up to 10 years. Systems using catalytic monopropellant, nuclear-thermal monopropellant, chemical bipropellants and electric thrusters were studied and ranked according to several analysis areas which included propulsion system weight, system reliability and costs. Areas requiring further technology development are recommended on the basis of system rankings.

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FOREWORD

This report summarizes work performed during a USAF in-house program under Project 3058, during the period October 1970 through June 1971.

The program was conducted by the Liquid Rocket Division of the Air Force Rocket Propulsion Laboratory. Captains Raymond D. Klopotek and Walden L. S. Laukhuf were the project engineers.

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This technical report has been reviewed and is approved.

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ABSTRACT

Propulsion systems were studied for post-1975 geosynchronous satellites that have stringent attitude and station maintenance requirements with mission durations of up to 10 years. Systems using catalytic monopropellant, nuclear-thermal monopropellant, chemical bipropellants and electric thrusters were studied and ranked according to several analysis areas which included propulsion system weight, system reliability and costs. Areas requiring further technology development are recommended on the basis of system rankings.

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NOMENCLATURE

$A_\perp$ = projected area in a plane normal to the line of sight, ft^2

D = diameter of satellite centerbody, feet

g = gravitational acceleration, 32.2 ft/sec^2

I_{bit} = impulse bit minimum, lb_f-sec

$I_{t_{ac}}$ = total impulse for attitude control, lb_f-sec

$I_{t_{AM}}$ = total impulse for attitude maintenance, lb_f-sec

I_{t_c} = total impulse for north-south stationkeeping, lb_f-sec

I_{t_i} = total impulse for east-west stationkeeping, lb_f-sec

$I_{t_{lc}}$ = total impulse for limit cycling, lb_f-sec

I_{t_s} = total impulse for solar pressure corrections, lb_f-sec

I_{xx} = satellite moment of inertia about x axis, slug-ft^2

I_{yy} = satellite moment of inertia about y axis, slug-ft^2

I_{zz} = satellite moment of inertia about z axis, slug-ft^2

J = polar moment of inertia, slug-ft^2

L = length of satellite centerbody, feet

M_{CB} = mass of centerbody, lb_m

M_e = mass of satellite at end of propulsion maneuver, lb_m

M_o = mass of satellite at beginning of propulsion maneuver, lb_m

M_{sp} = mass of solar panels, lb_m

P = orbital period, degrees/day

$\Delta\dot{P}$ = repositioning rate, degrees/day

NOMENCLATURE (CONT'D)

[illegible]	propellant storage tank pressure, psi
R	propellant storage tank radius, inches
r	moment arm of thruster couple, feet
$R_{F_{LT}}$	large thruster feed system reliability
$R_{F_{ST}}$	small thruster feed system reliability
$R_{S_{LT}}$	total large thruster system reliability
$R_{S_{ST}}$	total small thruster system reliability
$R_{V\text{-}TH_{LT}}$	large thruster-valve combination reliability
$R_{V\text{-}TH_{ST}}$	small thruster-valve combination reliability
T	storage tank thickness, inches
t_m	mission duration, years
V_o	nominal orbital velocity, ft/sec
ΔV	change in satellite velocity, ft/sec
ΔV_{rep}	change in velocity for repositioning, ft/sec
X	solar CP-CG offset, feet
X_{CB}	- for rectangular centerbody, the x-axis dimension, feet
X_{SP}	height of solar panel (distance parallel to centerbody, feet
Y_{CB}	for rectangular centerbody, the y-axis dimension, feet
Y_{SP}	length of solar panel (distance perpendicular to centerbody), feet
Z_{CB}	for rectangular centerbody, the z-axis dimension, feet
	deadband half-angle, degrees

NOMENCLATURE (CONT'D)

ϵ_c = drift in satellite position cross-track, nm

ϵ_i = drift in satellite position in-track, nm

$\dot{\theta}_{min}$ = satellite minimum achievable average angular rate, deg/sec

ρ = propellant storage tank material density, lb/in^3.

σ_y = yield stress of storage tank material, psi

SECTION I

INTRODUCTION

The task of evaluating future attitude control propulsion development programs for satellite applications is unwieldy due to the proliferation of systems concepts over the past 10 years. Since budgetary constraints limit the amount of dollars for new technology efforts, a method for selecting the most promising areas of future satellite propulsion work is needed. Past evaluation methods have employed fragmented examinations of various engine performance parameters such as specific impulse, pulse centroid repeatability and minimum impulse bit (Reference 1). No recent comparisons on a total system design basis for a specific mission have been made. Only one other satellite system study has been undertaken at the Air Force Rocket Propulsion Laboratory (AFRPL). This study was completed on 20 May 1968 by Mr. E. C. Barth. It was entitled "Applications of DART for Space Relay and Data Management Satellite."

The present study uses an advanced geosynchronous mission model having stringent attitude and station maintenance requirements to compare 16 satellite propulsion systems, in various phases of development, against such important system design parameters as propulsion system weight, system reliability and costs. These ranged from the conventional monopropellant hydrazine thrusters to more sophisticated electric ion thrusters.

SECTION II

APPROACH

The construction of a post-1975 satellite mission model was based primarily upon existing model availability. From the several satellite models postulated for geosynchronous orbit, the Air Force's Space and Missile System Organization (SAMSO) model pertaining to the class of satellites referred to as "SYNCSATS" was chosen as the framework for this study (Reference 2). SYNCSATS pr ovide for a wide variety of commercial and military missions, including co mmunication relays, navigation aids, and meteorological and strategic reconnaissance.

So that a large variety of satellite propulsion systems could be readily evaluated, a computer program (see Appendix A) using the SYNCSAT mission model was developed to calculate total propulsion system weight, propellant tank sizing and mission total impulse requirements. The program is also designed to size and weigh the satellite centerbody and solar panels and to compute the available on-board electrical power. Some of the SYNCSAT parameters which may be varied are the satellite life, initial gross weight, initial angular momentum, centerbody bulk density and repositioning rate.

In conjunction with the weight computer program, a reliability and cost study for each propulsion system design was undertaken. Reliability data were extracted from a recent Jet Propulsion Laboratory (JPL) report (Reference 3) which arrived at quantitative satellite propulsion component reliabilities based on a review of existing reliability studies and reported component reliability and failure rate values. Reliabilities for noncyclic components were based on a 1-year mission duration. Improving reliability figures through the use of redundancy was not assessed in this study. It is to be noted that a quantitative ranking of the components is difficult since reliability numbers for propulsion system components do not have the extensive statistical failure rate data typical of electronic components.

Development cost data for advanced propulsion systems are very difficult to obtain. Moreover, a significant portion of the development cost is expended for flight qualification. This dichotomy between development and system engineering groups compounds the total cost estimate. Instead of expending many hours in an attempt to acquire every bit of cost data, a rough cost estimate for existing propulsion systems was undertaken by using available figures from reported development and flight qualified systems. Postulated propulsion system costs were then extrapolated from these existing estimates. Although the anticipated monetary inflationary rate will alter cost estimates for post-1975 propulsion systems, the figures used for this study are based on 1971 dollars. In addition to a quantitative evaluation of system weight, reliability and cost, other tradeoff areas were qualitatively evaluated. These included plume effects, integration problems, design flexibility and ground handling requirements.

SECTION III

ANALYSIS

A. POST-1975 SYNCSATS MISSION MODEL

1. Introduction

One of the most useful satellite orbits is the "earth-synchronous" or "geosynchronous" orbit, i.e., a circular orbit in the equatorial plane with an orbital period of one sidereal day. A satellite placed in such an orbit will (ideally) remain fixed in the sky, relative to an observer on the earth. The orbital characteristics for a "geosynchronous" orbit are:

Semi-major axis,	a	=	22,808.5 nm
Eccentricity,	ϵ	=	0
Inclination,	i	=	0
Period,	P	=	24 hours

The class of satellites having the above orbital parameters are referred to as "SYNCSATS," and cover a wide variety of useful missions, both commercial and military. Many of these missions will require extremely close pointing accuracy and/or precise stationkeeping. Such requirements, coupled with a long mission duration, tax the capabilities of current propulsion technology.

A three-axis active attitude control system (ACS) was chosen for the SYNCSAT in preference to spin-stabilized or gravity gradient systems. A fully stabilized satellite presents the most demanding propulsion requirements, offers a significantly higher on-board electrical power capacity through the use of a one-degree-of-freedom, sun-oriented solar array, and can meet the close stationkeeping and tight attitude control specifications. Furthermore, the three-axis active control system does not demand the rapid pulsing capability of a spin-stabilized spacecraft and thus can utilize a wider range of propulsion concepts.

2. Satellite Geometry

An inertial model of a SYNCSAT spacecraft was formulated to permit propulsion system sizing and power allocation. The model does not represent any specific design in this family of prospective SYNCSATS, but merely a consistent set of dimensions and inertias. Geometrically, the spacecraft centerbody may assume a cylindrical, spherical or rectangular shape. The one-degree-of-freedom, articulated solar array takes the form of two rectangular solar panels symmetrically deployed on either side of the centerbody, which contains the remaining equipment. The spacecraft configuration is shown in Figure 1. This figure shows the centerbody as a cylinder. The spacecraft model incorporates both high-thrust engines of 5-pound thrust and low thrusters of less than 1-pound thrust.

For the two solar panels, an ideal specific weight is required. Combining this figure with a percent life degradation factor yields an array specific weight. A specific surface area must also be assumed.

To arrive at dimensional and inertial characteristics for the model, it was first necessary to size the solar array. The assumed available on-board power can be given as a function of initial gross weight according to the equation:

$$\text{On-Board Power (w)} = -400 + 1.25 \times \text{Initial Gross Weight } (lb_m) \qquad \text{(III-1)}$$

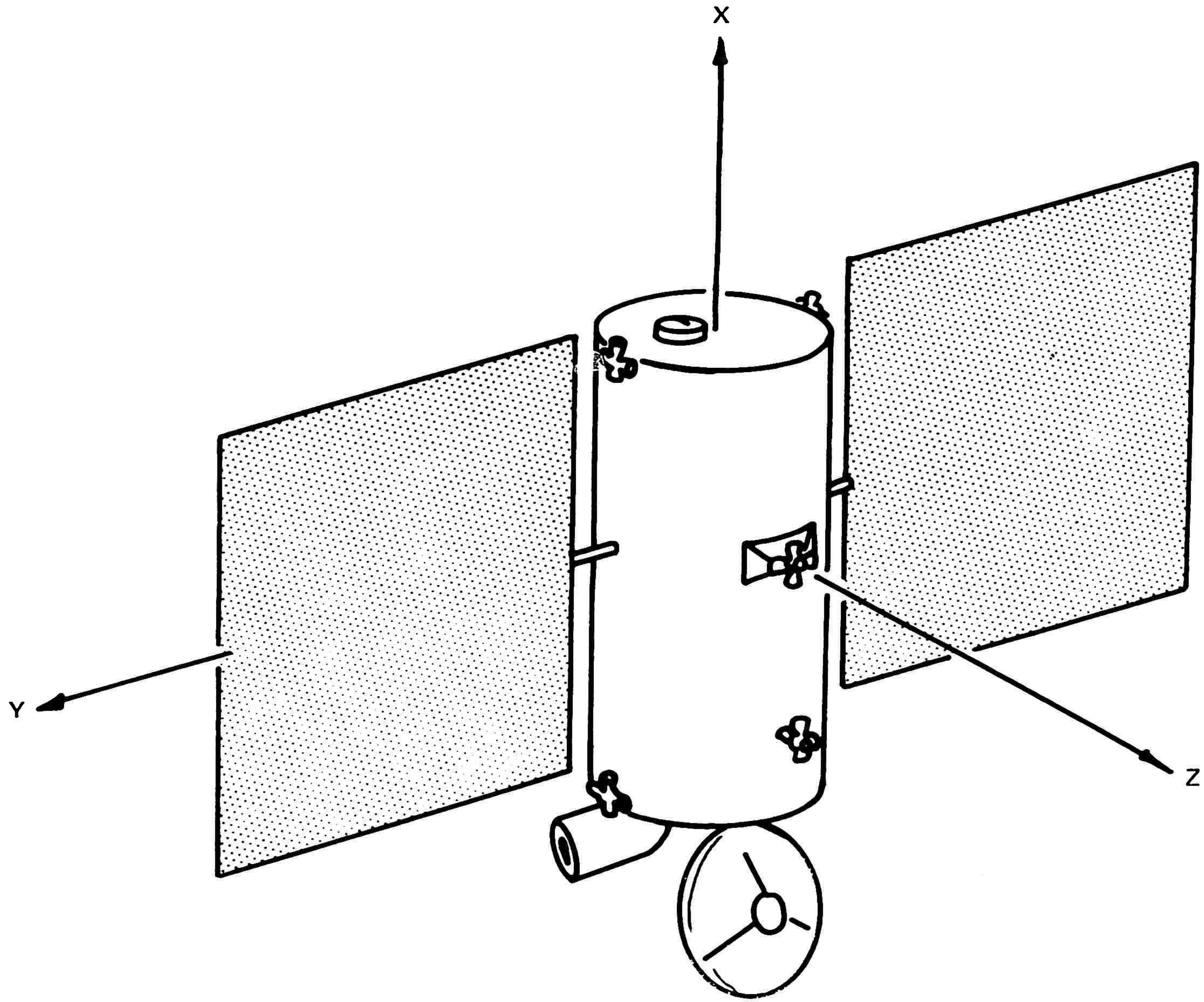


Figure 1. Spacecraft Inertial Model

Once the on-board electric power is known, then the weight and size of the two rectangular solar panels to supply this power are calculated. From the centerbody weight, density and L/D configuration, the dimensions of the centerbody are obtained. Next, calculated moments of inertia for the three principal axes are developed.

For this study, the following design information was used. The initial gross weights were assumed to be 2000 lb_m and 3000 lb_m. The centerbody assumed a cylindrical shape with an L/D of 2:1. Existing spacecraft indicate that a bulk density of 20 lb_m/ft^3 is representative for the centerbody. The solar panels were taken to be square with an ideal specific weight of 88 lb_m/kw. The percent life degradation was 80 percent and the solar panels were assumed to have a specific surface area of 100 ft^2/kw.

For the two initial gross weights assumed, Table I presents spacecraft geometry data.

TABLE I. SATELLITE MODEL GEOMETRY

Initial Gross Weight (lb_m)		2000	3000
On-board Electric Power (kw)		2.10	3.35
Centerbody Diameter (feet)		3.833	4.375
Centerbody Length (feet)		7.666	8.75
Centerbody Weight (lb_m)		1769.0	2631.5
Solar Array Area (ft^2)		210.0	234.8
Side of One Solar Panel (feet)		10.25	12.94
Maximum Projected Area (ft^2)		239.4	373.3
Moments of Inertia (slug-ft^2) (Solar Panels Deployed)	I_{xx}	378.3	889.3
	I_{yy}	382.2	779.0
	I_{zz}	800.6	1796.8

3. Mission Requirements

With the model spacecraft established, a consistent set of maneuver and control requirements were taken from Reference 2. The propulsive functions involved are of four types:

Initial positioning
Attitude maintenance
Station maintenance
Repositioning

Propulsion requirements for the foregoing maneuver and control functions are now described in detail.

a. Initial Positioning (Injection Error Corrections)

The initial positioning errors are primarily caused by the launch vehicle. Upon separating from the booster, the spacecraft will have a residual rate (tumble) in each axis which must be nulled. It will also have a terminal velocity and position error to be corrected. Eccentricity and inclination errors need to be reduced only if the resulting oscillation is greater than the allowable deadband.

Based upon existing booster performance, a ΔV allowance of 50 ft/sec for position and velocity error correction, and a 1 deg/sec residual rate correction in each axis would be nominal. For this study, the inclination and eccentricity errors were assumed tolerable, and the total impulse required to correct for the initial tumble in all three axes was taken to be a constant value of 23 lb_f/sec for both spacecraft weights.

b. <u>Attitude Maintenance</u>

Attitude maintenance comprises the limit cycling within some prescribed deadband and the correction of disturbance torques. The primary contributor of disturbance torques is solar pressure. Assuming unit reflectivity and normal incidence, the total corrective impulse which must be supplied to the spacecraft in t_m years is (Reference 2):

$$I_{t_s} = 5.91 \; t_m \sum_j \left(\frac{A_\perp X}{r} \right)_j \quad lb_f\text{-sec} \qquad \text{(III-2)}$$

where: $A_\perp$ = total satellite projected area in a plane normal to the line of sight to the sun (ft^2)

where the summation is carried out for the two axes involved. Appropriate values for the solar CP-CG offset, X, for different spacecraft were taken as in Reference 2:

$$\text{so that} \quad \sum \frac{X}{r} = \sum \frac{\text{CP-CG OFFSET}}{\text{Moment Arm}} = 0.35 \text{ in all cases.}$$

The impulse involved in limit cycling depends upon a number of factors. Maximum propellant consumption occurs in a symmetric (undisturbed) limit cycle. Although symmetric limit cycling is not truly representative for this type of spacecraft, the conservatism implicit in such an assumption does not significantly distort the results and greatly simplifies the calculations. The primary parameters in the total impulse requirements are the half-angle of the deadband, δ, and the size of the minimum impulse bit, I_{bit}. The total limit cycle impulse delivered in t_m years is (Reference 2):

$$I_{t_{lc}} = \frac{I_{bit}^2 \, t_m}{\delta} \sum_k \left(\frac{r}{J}\right)_k \quad lb_f\text{-sec} \qquad (III-3)$$

where

r = moment arm of thruster couple (feet)

J = polar moment of inertia (slug-ft^2)

down to some minimum achievable average angular rate, $\dot{\theta}_{min}$, at which point the rate limit impulse is (Reference 2):

$$I_{t_{lc_{min}}} = 4 \frac{\dot{\theta}_{min} \, t_m}{\delta} \sum_k \left(\frac{J}{r}\right)_k \quad lb_f\text{-sec} \qquad (III-4)$$

Deadband angles typically range from $\pm$ 0.125 degree in coarse mode control to $\pm$ 0.100 degree in fine mode control. This study assumed a minimum achievable average angular rate of 2×10^{-4} deg/sec and the deadband angle of $\pm$ 0.125 degree.

For satellites with relatively large surface areas and long mission durations, the effects of micrometeoroid bombardment must be assessed. Using probability theory based on the possible case, Aerospace (Reference 2) has shown that the predictable impulse for micrometeoroid impact correction is negligible. The unpredictable impulse requirement due to a large and improbable impact must be provided in the "contingency" impulse.

Other disturbances, such as torques imparted by the friction in moving telescopes or antennae, gravity gradient and earth magnetic field torques, and coupling of translation thrust into the attitude control axes caused by thruster misalignment with respect either to the spacecraft center of mass or to each other, could not be accurately estimated without a more detailed and sophisticated model. It was therefore decided to apply a generous contingency of 50 percent to the total of solar and limit cycle impulse allocations. Thus, the attitude control total impulse was assumed to be (Reference 2):

$$I_{t_{ac}} = 1.5 \left[I_{t_s} + I_{t_{lc}} \right] \quad lb_f\text{-sec} \qquad \text{(III-5)}$$

c. <u>Station Maintenance</u>

The bulk of the spacecraft's propulsion requirement is for stationkeeping. A real earth SYNCSAT tends to drift from its initial position radially, longitudinally and latitudinally (cross-track). These drifts are caused by the triaxiality (asphericity) of the earth and by the gravitational perturbations due to the sun and the moon.

At synchronous altitude, the observable angular deviation due to radial drift is negligible in any foreseeable mission. Thus, only in-track (east-west) and cross-track (north-south) stationkeeping are required. Table II lists the major perturbations on a 24-hour equatorial circular orbit which cannot be corrected by initial injection bias (as reported in Reference 4).

TABLE II. GEOSYNCHRONOUS ORBIT PERTURBATIONS

Perturbation Cause	Direction	Period	Displacement	ΔV/yr
Zonal Harmonics	-	-	-	-
Tesseral Harmonics	In-track	Secular	t^2 dependent	7.15
Solar-Lunar	Cross-track	Secular	5630 ft/day	150
Solar-Lunar	In-track (ϵ_i)	2 years	$\pm$ 14.8 nm	-
Solar-Lunar	Cross-track (ϵ_c)	24 hours	$\pm$ 8.9 nm	-

A zonal harmonic results from the terms in the gravitational potential of the earth that are dependent on latitude only and are therefore symmetrical about the equator. This is a result of the fact that the earth is not a perfect sphere. However, drifts caused by this perturbation may be corrected by injection bias. Tesseral harmonics are those resulting from the aspherical gravitation field or inhomogeneous mass distributions of the earth. Hence, one area of the earth will have a greater gravitational attraction for a satellite than another area. These areas are not symmetrical about the equator and thus produce an east-west drift upon a satellite. The solar-lunar perturbations result from the pull of the sun and the moon on the earth. A secular perturbation is one which is not periodic but is a constant perturbation dependent, for example, on the time in orbit. The periodic solar-lunar perturbations need not be corrected if the displacement shown is acceptable.

If the tolerable drift amplitude for stationkeeping is taken to be greater than or equal to the periodic perturbations shown in Table II, i.e., $\epsilon_i \geq 14.8$ nm and $\epsilon_c \geq 8.9$ nm (referred to as the critical ellipsoid), then an annual ΔV increment of about 157 ft/sec, dominated by the cross-track correction, is required. However, if a "fine" stationkeeping mode, i.e., $\epsilon_i < 14.8$ nm and $\epsilon_c < 8.9$ nm, is desired, the value for ΔV jumps to about 635 ft/sec/yr. This study will only consider an annual ΔV increment of 157 ft/sec for stationkeeping.

To account for coupling of thrust into the attitude control axes during the attitude maintenance maneuvers, 3 percent of the stationkeeping total-impulse requirement was allotted for this purpose. Thus, the attitude maintenance total impulse was taken as (Reference 2):

$$I_{t_{am}} = 1.03 \left[I_{t_i} + I_{t_c} \right] \quad lb_f\text{-sec} \qquad \text{(III-6)}$$

d. Repositioning

Post-1975 SYNCSATS must be capable of covering any global region. This implies that the satellite has the capability to perform transfers of up to 180 degrees in longitude. For any given satellite thrust-to-weight ratio and change in satellite longitudinal position, a minimum time for repositioning can be determined. The velocity increment required is a function only of the repositioning rate. The total ΔV required per reposition is given by the following equation:

$$\Delta \dot{P}_{rep} = \frac{2 \quad V_o}{3} \quad \frac{\Delta \dot{P}}{P} \qquad \text{(III-7)}$$

V_o = nominal orbital velocity (ft/sec)

P = orbital period (deg/day)

$\Delta \dot{P}$ = repositioning rate (deg/day)

For the mission study of this report, a one-time satellite repositioning maneuver was assumed to be representative for a post-1975 SYNCSAT, and repositioning rate of 15 deg/day was used. The total ΔV_{rep} required for this maneuver using equation III-7 is 280 ft/sec.

The most efficient method for repositioning is to place the satellite into an orbit with a period greater or less than 24 hours, causing a westward or eastward, respectively, drift. For example, the drift is 15 deg/day for an orbit with a 25-hour period and requires a ΔV expenditure of approximately 280 ft/sec for both high- and low-thrust devices. Using this technique, repositioning requires from a few days to approximately 2 weeks.

A summary of the mission requirements used in this study is given in Table III.

TABLE III. MISSION REQUIREMENTS

Function	ΔV Requirement	ACS Requirement
Initial Positioning		
Position/Velocity Error	50 ft/sec	
Tip-off Rate, Each of Three Axes		23 lb_f-sec
Stationkeeping	157 ft/sec/yr (E-W/N-S of $\pm$ 8.9 x 15 nm)	
Attitude Maintenance		$\pm$ 0.125-degree deadband, 2 x 10^{-4} deg/sec average rate
Repositioning	280 ft/sec	

B. SYNCSAT PROPULSION SYSTEMS

Sixteen different combinations of high and low thrusters were incorporated into the spacecraft model and evaluated. The high-thrust engines were 5 pounds and the low thrusters were less than 1 pound. The large thrusters were used for initial positioning and repositioning, while attitude maintenance was performed with the small thruster. The thruster (i.e., large or small) which had the highest performance was used for stationkeeping.

A listing of the 16 propulsion systems evaluated is presented below:

	5 lb_f Thruster	Small Thruster
1.	N_2H_4 Catalytic	N_2H_4 Catalytic
2.	N_2H_4 Catalytic	N_2H_4 Plenum
3.	N_2H_4 Catalytic	N_2H_4 Electrolytic
4.	N_2H_4 Catalytic	N_2H_4 Resistojet
5.	N_2H_4 Catalytic	N_2H_4 Radioisotope
6.	N_2H_4 Catalytic	DART
7.	N_2H_4 Catalytic	Cesium Ion
8.	N_2H_4 Catalytic	Colloid
9.	N_2H_4 Catalytic	Hg Pulsed Plasma
10.	DO Radioisotope	DO Radioisotope
11.	DO Radioisotope	Colloid
12.	H_2O Electrolysis Bipropellant	H_2O Electrolysis Bipropellant
13.	H_2O Electolysis Bipropellant	Colloid

Dioxyamine

$5\ lb_f$ Thruster	Small Thruster
14. N_2O_4/N_2H_4 Bipropellant	N_2H_4 Plenum
15. ClF_5/N_2H_4 Bipropellant	N_2H_4 Plenum
16. DART	DART

The following subsections provide a conceptual design schematic for each of the 16 propulsion systems. System description and performance data are also included.

1. Hydrazine Catalytic/Hydrazine Catalytic

The development of the Shell 405 catalyst in 1963 permitted the design of hydrazine thrusters capable of a large number of restarts without requiring the use of catalyst bed heaters or an oxidizer injection system for initiation of hydrazine decomposition. Since then, monopropellant hydrazine thrusters have become the "standard" spacecraft propulsion system for missions which do not have stringent orientation requirements and are not marginal on weight. Hydrazine has excellent storability, good compatibility with most engineering materials and is capable of repeated pulse operation.

a. $5\text{-}lb_f$ Thruster

Steady-state performance for the 5-pound hydrazine thruster, such as in Figure 2, was based upon 55 percent NH_3 dissociation, on an area ratio of 40:1 and upon 97 percent engine efficiency, giving 230 seconds of delivered specific impulse. This performance represents nearly the maximum achievable with hydrazine. Some hydrazine thrusters have demonstrated steady-state firings exceeding 2 hours. The only required power is that necessary to operate the propellant valves. However, in

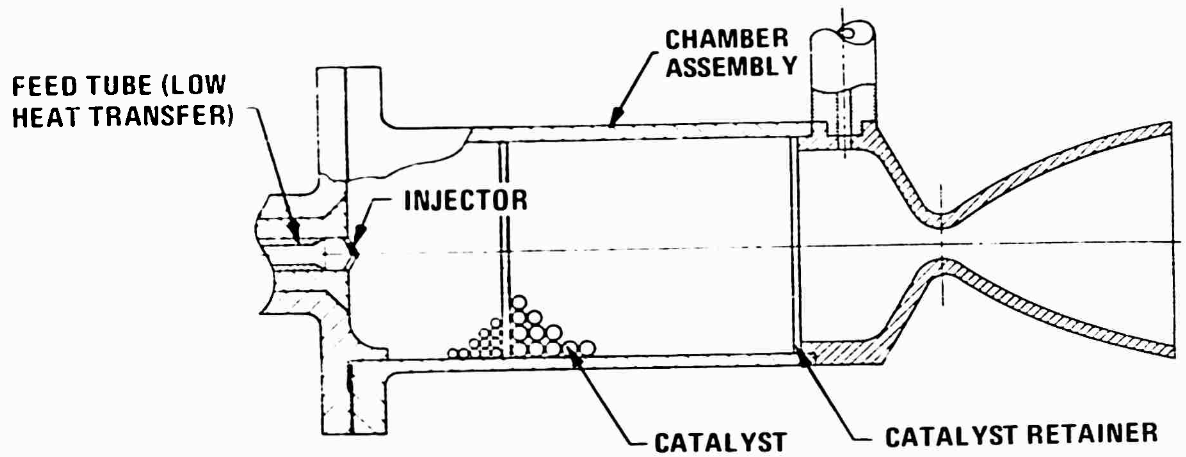


Figure 2. Catalytic Hydrazine Thruster

certain installations, the low freezing point of hydrazine (33°F) necessitates the incorporation of a 2- to 10-watt heater on each thruster.

b. 0.1-lb_f Thruster

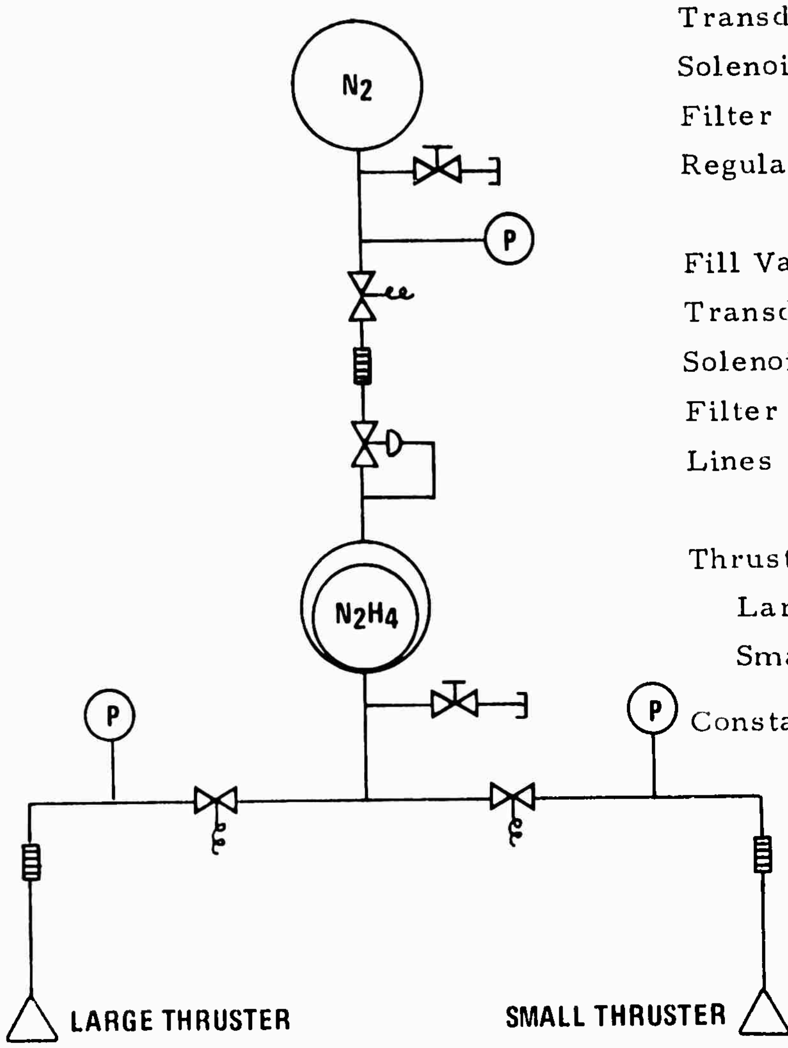
Pulse-mode performance of the small thruster was based upon the same assumptions as those for the large thruster. Assuming that heaters would be used on the catalyst pack to maintain temperature above 60°F, and using a minimum impulse bit of 4×10^{-3} lb-sec, a specific impulse of 200 seconds is achievable. Although no flight-qualified 0.1-lb_f thrusters have been built, a present NASA/Goddard development effort for the Applied Technology Satellites (ATS), Models F & G, will provide this technology. Hydrazine thrusters have demonstrated pulsing capability on the order of 1-million hot starts. Several thousand cold starts should be realizable without significant performance degradation.(Reference 3).

c. System Schematic

Figure 3 shows the system schematic.

2. N_2H_4 Catalytic/N_2H_4 Plenum

This hybrid propulsion system is a modification of the all-hydrazine catalytic system. Hydrazine plenum systems have been developed and flight qualified by Rocket Research Corporation and TRW Systems. For this design, the low-level thrusters are supplied gas from a single catalytic hydrazine gas generator which feeds an accumulator or plenum. The only system problem encountered with this hybrid system has been that of maintaining a cool plenum temperature during a long pulse duty cycle (Reference 3).



		Weight (pounds)
Fill Valve		0.25
Transducer		0.20
Solenoid		0.20
Filter		0.20
Regulator		0.3
Fill Valve		0.25
Transducer (2)		0.40
Solenoid (2)		0.40
Filter (2)		0.40
Lines		1.00
Thrusters		
Large	8(0.80) =	6.4
Small	12(0.40) =	4.8
Constant Weight		14.80

Figure 3. System Schematic for N_2H_4 Catalytic-N_2H_4 Catalytic

a. 5-lb_f Thruster

The large hydrazine catalytic thruster is identical to that described in Section III.B. 1. All performance numbers remain unchanged.

b. 0.050-lb_f Plenum Thrusters

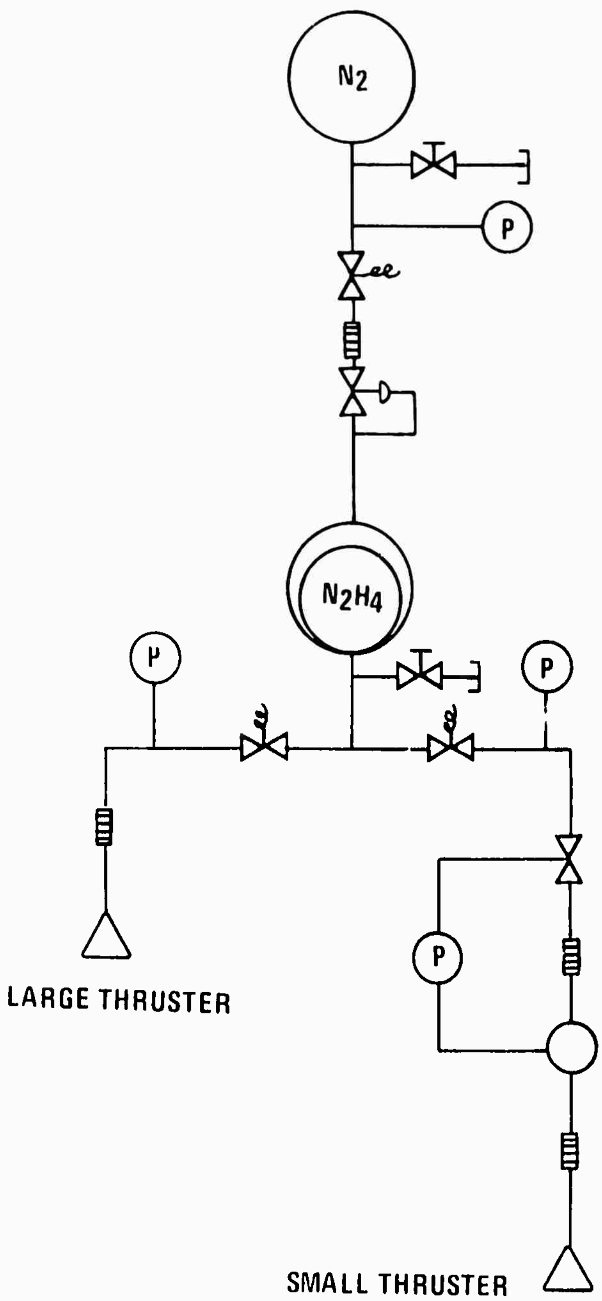
The catalytic hydrazine gas generator uses Shell 405 catalyst and feeds a plenum tank having a nominal 35-psia pressure. Specific impulse for the 50-millipound thrusters is taken to be a constant 110 seconds for this study. Actual performance data for an N_2H_4 cold gas plenum varies between 95 and 110 seconds depending upon the gas temperature. If individual heaters are used on all low-level thrusters, then the specific impulse will vary between 114 and 132 seconds, again depending upon the plenum gas temperature. A minimum impulse bit of 5×10^{-4} lb_f-sec was used.

c. System Schematic

Figure 4 shows the system schematic.

3. N_2H_4 Catalytic/N_2H_4 Electrolytic Ignition

The search for an efficient method of initiating and continuing the decomposition of hydrazine without the use of a scarce catalyst has led researchers to the concept of electrolytic ignition. The Air Force Rocket Propulsion Laboratory (AFRPL) first determined the feasibility of this approach through a contractual program with the Dynamic Science Corporation in 1969-1970 (Contract F04611-69-C-0048, Final Report AFRPL-TR-69-247). Presently, the United Aircraft Corporation Research Laboratory is under contract (F04611-70-C-0070) to AFRPL for development of an electrolytic ignition cell for use in a 0.1-lb_f thruster.



			Weight (pounds)
Fill Valve			0.25
Transducer			0.20
Solenoid			0.20
Filter			0.20
Regulator			0.30
Fill Valve			0.25
Solenoid (2)			0.40
Transducer (2)			0.40
Filter			0.20
Control Valve			0.40
Pressure Switch			0.25
Gas Generator (GG)			0.35
Plenum			0.30
Filter			0.20
Lines			1.0
Thrusters			
Large	8(0.8)	=	6.4
Small	12(0.4)	=	4.8
Total Weight			16.1

Figure 4. System Schematic for N_2H_4 Catalytic-N_2H_4 GG Plenum

Fabrication and testing of this cell have not yet begun. Since no test data are available, all performance numbers are to be considered as "best" estimates and will have to be revised in the future.

a. 5-lb_f Thruster

The large hydrazine catalytic thruster is identical to that described in Section III.B.1. All performance numbers remain the same.

b. 0.1-lb_f Thruster

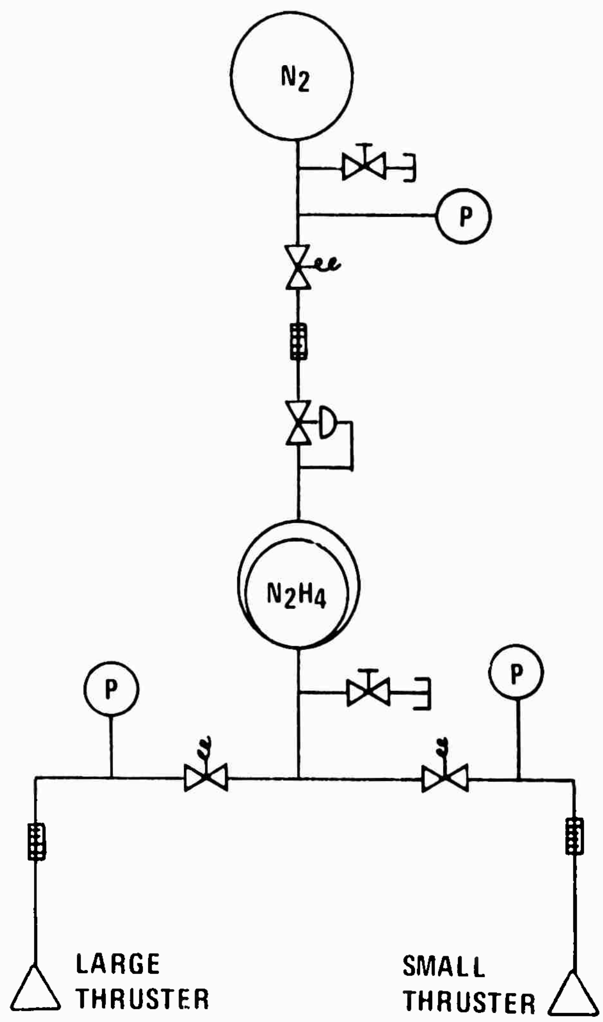
This study postulates a 0.1-lb_f hydrazine electrolytic ignition thruster having a pulse mode specific impulse of Isp = 220 seconds and a minimum impulse bit of 5×10^{-3} lb_f-sec. This size of low-level thruster will require approximately 15 watts of electrical power excluding that required for the valve. No life or reliability data are available.

c. System Schematic

The system schematic is shown in Figure 5.

4. N_2H_4 Catalytic/N_2H_4 Resistojet

The hydrazine resistojet has been under development by both AVCO (NAS 5-21080) and TRW. AVCO has built and tested a number of prototype thrusters for NASA/Goddard Space Flight Center using a porous ceramic injector configuration. Test data have shown that Isp is



	Weight (pounds)
Fill Valve	0.25
Transducer	0.20
Solenoid	0.20
Filter	0.20
Regulator	0.3
Fill Valve	0.25
Solenoid (2)	0.40
Transducer (2)	0.40
Filter (2)	0.40
Lines	1.0
Thrusters	
Large 8(0.8) =	6.4
Small 12(0.5) =	6.0
Total Weight	16.0

Figure 5. System Schematic for N_2H_4 Catalytic-N_2H_4 Electrolytic

a strong function of thrust level (N_2H_4 flow rate), so that the designer must be careful of his performance numbers. AVCO prototype data are:

Thrust (lb_f)	Isp $\left(\frac{lb_f\text{-sec}}{lb_m}\right)$
2.4×10^{-3}	120
4.6×10^{-3}	155
7.1×10^{-3}	177
9.5×10^{-3}	190
12.0×10^{-3}	200
14.4×10^{-3}	206
16.8×10^{-3}	210

Specific power for the AVCO prototype thruster is approximately 2 W/mlb$_f$ (10 mlb$_f$). TRW has completed the preliminary development of a 0.01-lb$_f$-thrust hydrazine resistojet thruster for both pulsed and steady-state operation. Reproducible impulse bits based upon pulse widths as short as 20 milliseconds have been demonstrated.

The pulsed mode specific impulse is 180 seconds; steady-state operation results in a delivered specific impulse of 200 seconds. The total power input for a 0.010-lb$_f$ thrust system is less than 5 watts, excluding the valve power.

a. 5-lb_f Thruster

The large hydrazine catalytic thruster is identical to that described in Section III.B.1.

b. 0.050-lb_f Thruster

Contractor in-house programs have arrived at a new wall injection prototype thruster design incorporating a spiral-wound heater element (Figure 6). This thruster has a moderately high chamber pressure of 8.5 atmospheres and delivers 235 seconds of steady-state specific impulse. The hydrazine resistojet can be pulsed as low as 50 milliseconds and deliver an average of 190 seconds Isp. These values yield a minimum impulse bit of 2.5×10^{-3} lb_f-sec. The new prototype thruster requires 5 watts for approximately 1 minute prior to ignition. This electrical input raises the wall temperature to $1000^{o}F$.

c. System Schematic

The system schematic is shown in Figure 7.

5. N_2H_4 Catalytic/N_2H_4 Radioisotope

Both General Electric Company and TRW have developed radioisotope thrusters using either NH_3 or H_2 as the propellant. Very little technology has been expended on a hydrazine radioisotope thruster. Since N_2H_4 decomposes exothermally, the isotope power required is considerably reduced from that of an ammonia radioisotope thruster. Therefore, thruster inert weight and power required will be less for the hydrazine system. To achieve long life, capsule temperatures will be $2000^{o}F$ or less. The design of such a thruster will be very similar to the DART system in that there is a radioisotope, re-entry heat shield, propellant flow tubes, and thermal insulation (Figure 8).

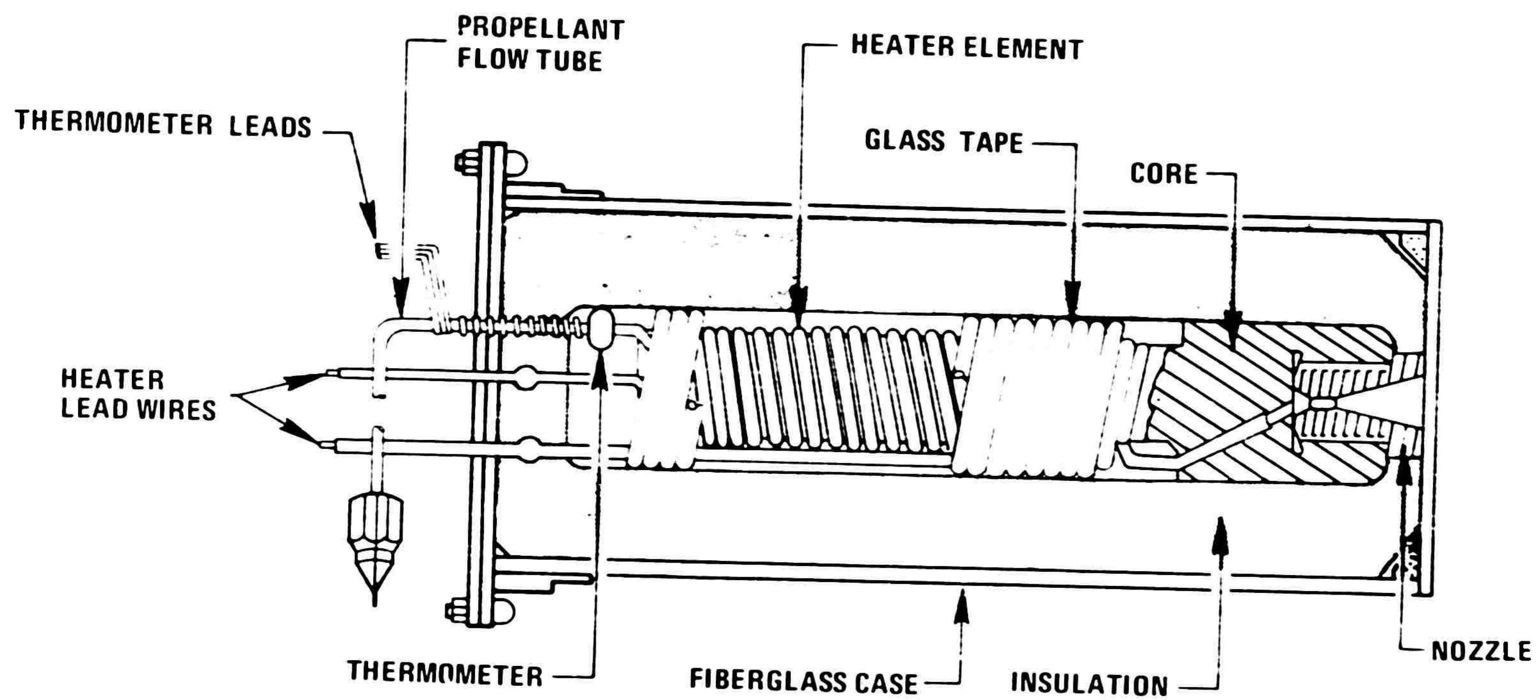
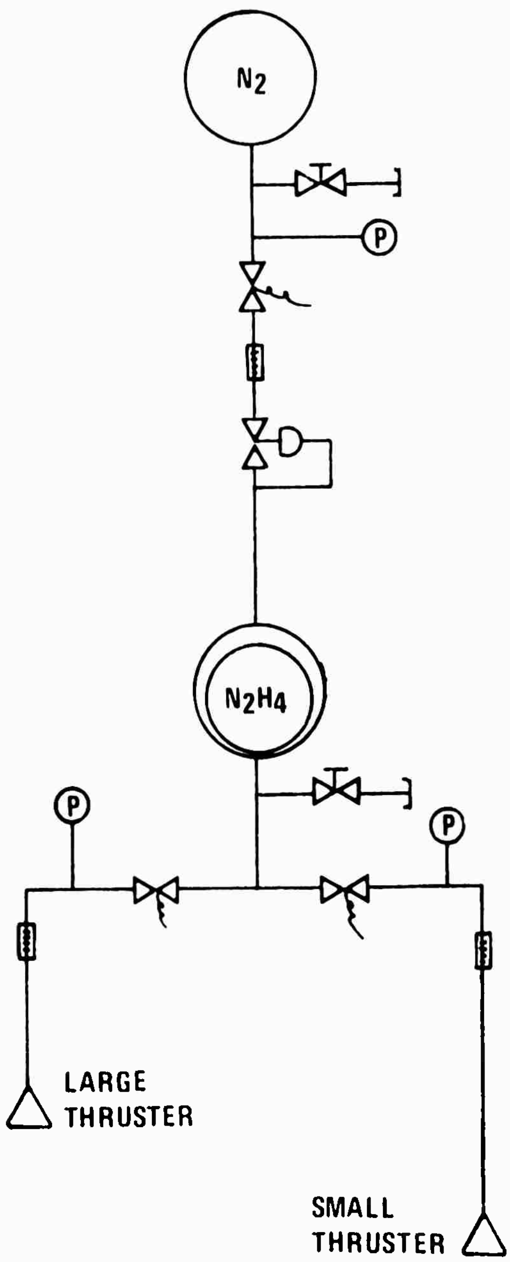


Figure 6. N_2H_4 Resistojet Thruster



			Weight (pounds)
Fill Valve			0.25
Transducer			0.20
Solenoid			0.20
Filter			0.20
Regulator			0.3
Fill Valve			0.25
Solenoid (2)			0.40
Transducer (2)			0.40
Filter (2)			0.40
Lines			1.0
Thrusters			
Large	8(0.8)	=	6.4
Small	3(0.45)	=	1.35
Total Weight			11.35

Figure 7. System Schematic for N_2H_4 Catalytic-N_2H_4 Resistojet

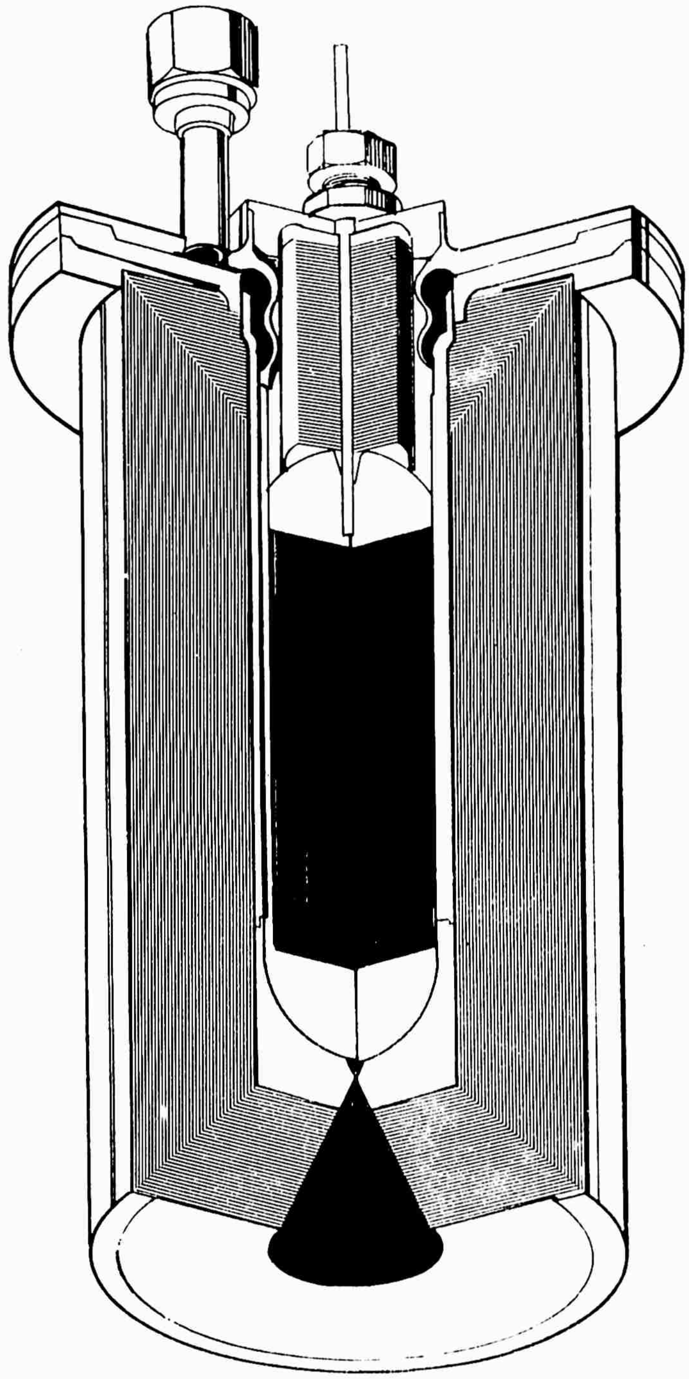


Figure 8. N_2H_4 Radioisotope Thruster

a. 5-lb_f Thruster

The large hydrazine catalytic thruster is identical to that described in Section III. B. 1.

b. 0.025-lb_f Thruster

For a thrust level of 25 millipounds, a minimum impulse bit of 5×10^{-4} lb_f-sec was used for limit cycling. Pulse mode specific impulse was taken to be 250 seconds on the basis of a capsule temperature of 2000°F. (Steady-state Isp is 220 seconds.) A vented capsule will be required to achieve the 10-year life requirement.

c. Conceptual Schematic

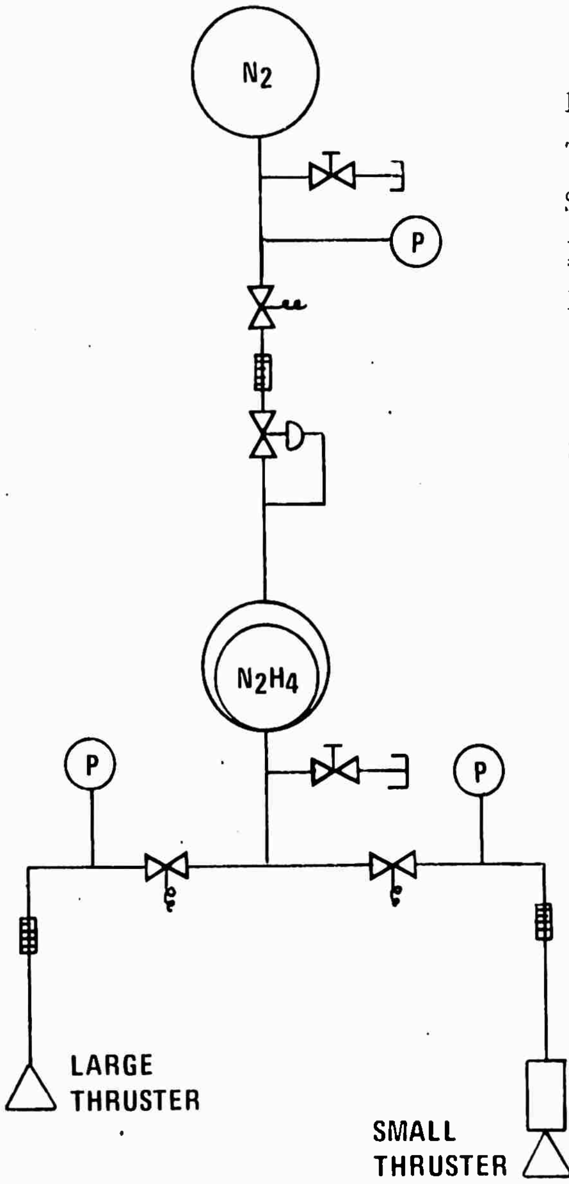
Figure 9 shows the conceptual schematic.

6. N_2H_4 Catalytic/DART

The decomposed ammonia radioisotope thruster (DART) has been under AFRPL-sponsored development with TRW since 1965 (AF04(611)-11536). A DART prototype thruster was demonstrated at the AEC Mound Laboratory in January 1967. An advanced DART prototype has been designed by the Los Alamos Scientific Laboratories and is presently undergoing evaluation. Since 1969, DART has been a part of the SAMSO ADP for Advanced Satellite Propulsion, and a current $50,000 study is concerned with problems associated with spacecraft integration.

a. 5-lb_f Thruster

The large hydrazine catalytic thruster is identical to that described in Section III. B. 1.



			Weight (pounds)
Fill Valve			0.25
Transducer			0.20
Solenoid			0.20
Filter			0.20
Regulator			0.30
Fill Valve			0.25
Solenoid (2)			0.40
Transducer (2)			0.40
Filter (2)			0.40
Lines			1.00
Thrusters			
Large	8(0.8)	=	6.40
Small	12(1.5)	=	18.00
Total Weight			28.00

Figure 9. System Schematic for N_2H_4 Catalytic-N_2H_4 Radioisotope

b. 0.025-lb_f Thruster

Performance for DART was based upon a capsule temperature of 2500°F. For a thrust level of 25 millipounds, a minimum impulse bit of 5×10^{-4} lb_f-sec was used for this study. Specific impulse numbers are 310 seconds pulsed, and 280 seconds at steady-state.

c. Design and Conceptual Schematic

Figure 10 shows the thruster design and Figure 11 is the conceptual schematic.

7. N_2H_4 Catalytic/Cesium Bombardment Ion

The electron bombardment engine uses an anode-cathode arrangement to ionize a propellant such as mercury or cesium. The ions are accelerated in an electrostatic field and neutralized as they are emitted to avoid the limitations of space charge flow (Figure 12). While the ionization potential for cesium is less than that of mercury, the cross section for electron-atom interactions for mercury is greater than for cesium. The result is that both propellants are equally easy to ionize.

NASA/Lewis Research Center mercury bombardment thrusters (Kaufman thrusters) have flown on SERT-I and SERT-II satellites. An Electrical Optical Systems (EOS) cesium bombardment ion engine has been tested as an experiment aboard an Air Force satellite. Cesium is easily handled by passive zero-g feed systems (Figure 13) and has a high mass utilization efficiency as long as the cesium is kept above its freezing point. Due to long start and shutdown transients, high-frequency pulsing is not practical for the ion engine. Also, power requirements are extremely sensitive to thrust and range from 15 watts at 10 $\mu\text{-lb}_f$ to 1300 watts at 10 mlb_f thrust.

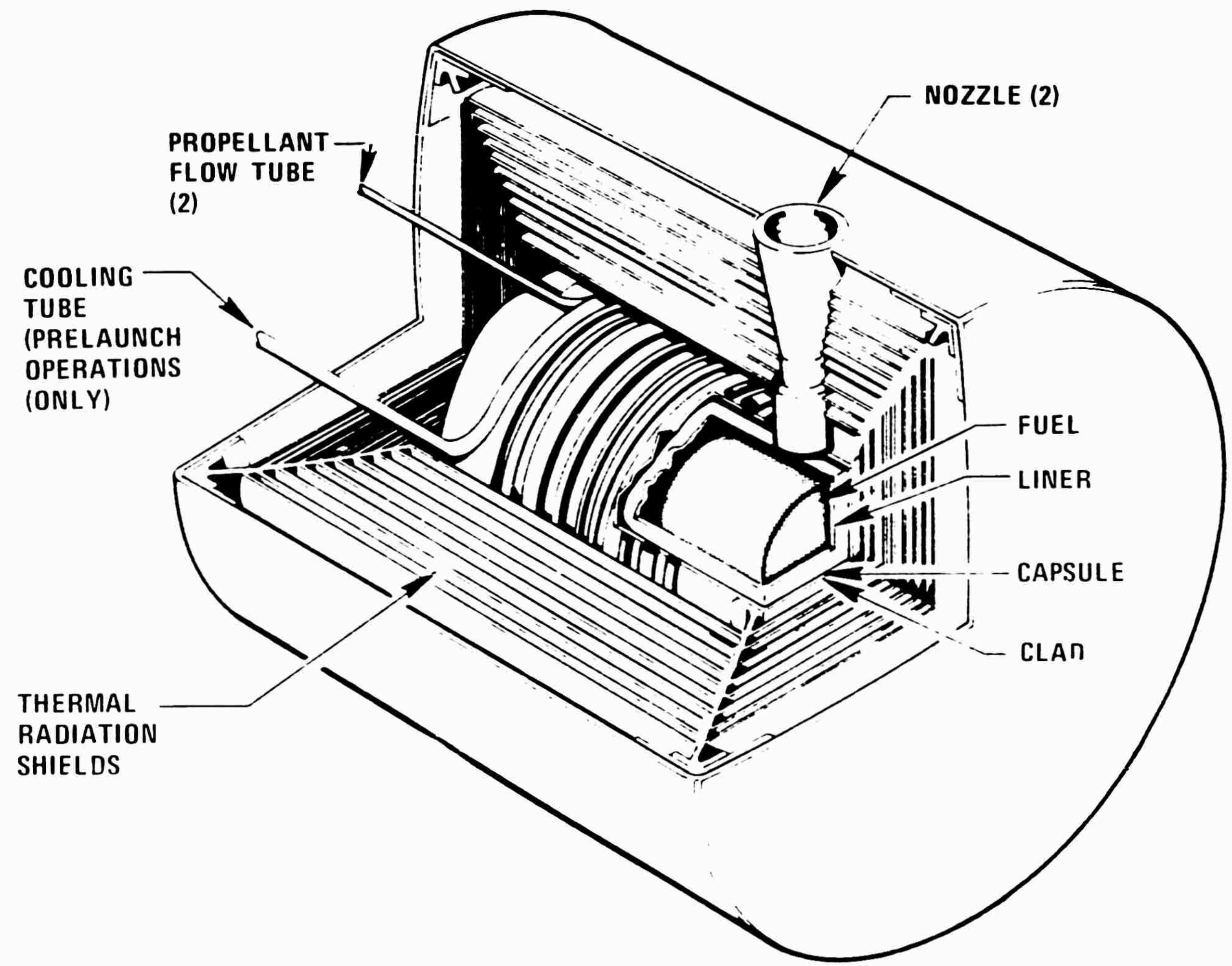
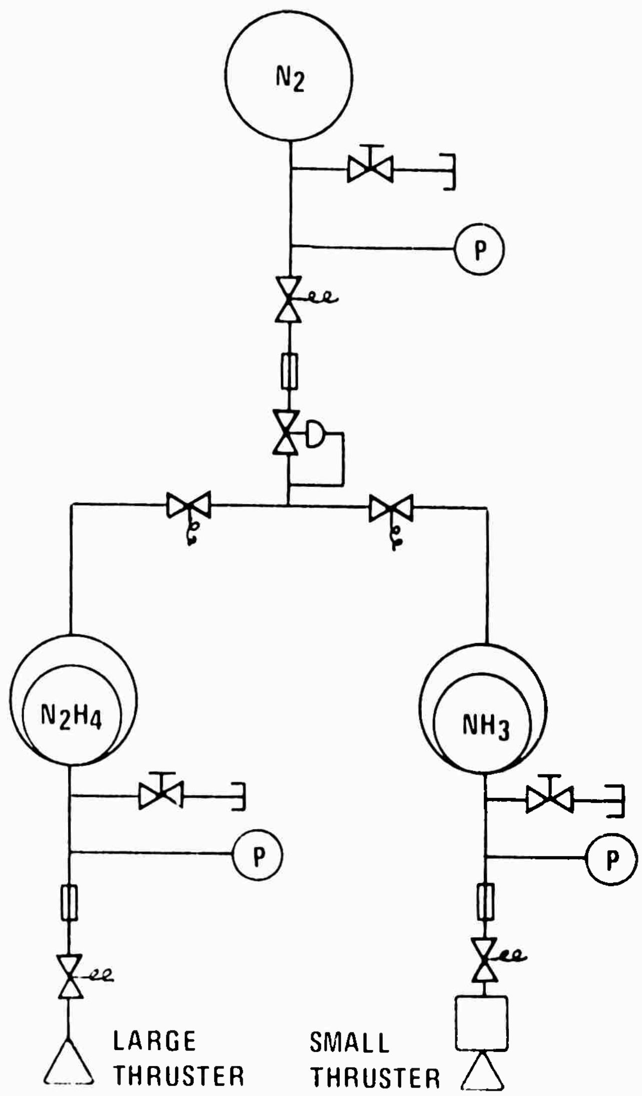


Figure 10. DART Thruster



			Weight (pounds)
Fill Valve			0.25
Transducer			0.20
Solenoid			0.20
Filter			0.20
Regulator			0.30
Solenoid (2)			0.40
Fill Valve (2)			0.50
Transducer (2)			0.40
Filter (2)			0.40
Solenoid (2)			0.40
Lines			1.0
Thruster			
Large	8(0.8)	=	6.4
Small	3(12)	=	36.0
Total Weight			46.65

Figure 11. System Schematic for N_2H_4 Catalytic-DART

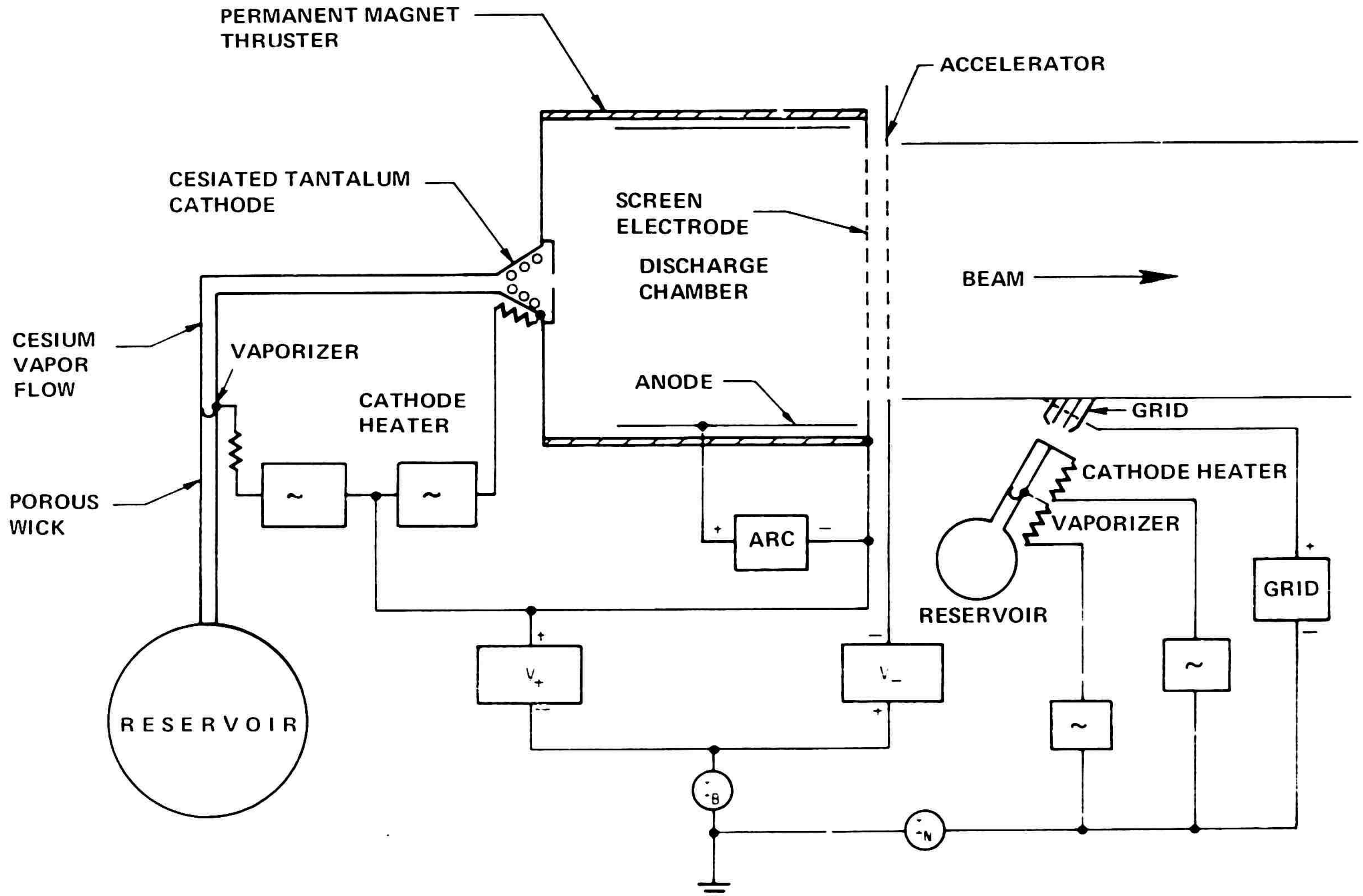


Figure 12. Cesium Ion Engine Schematic

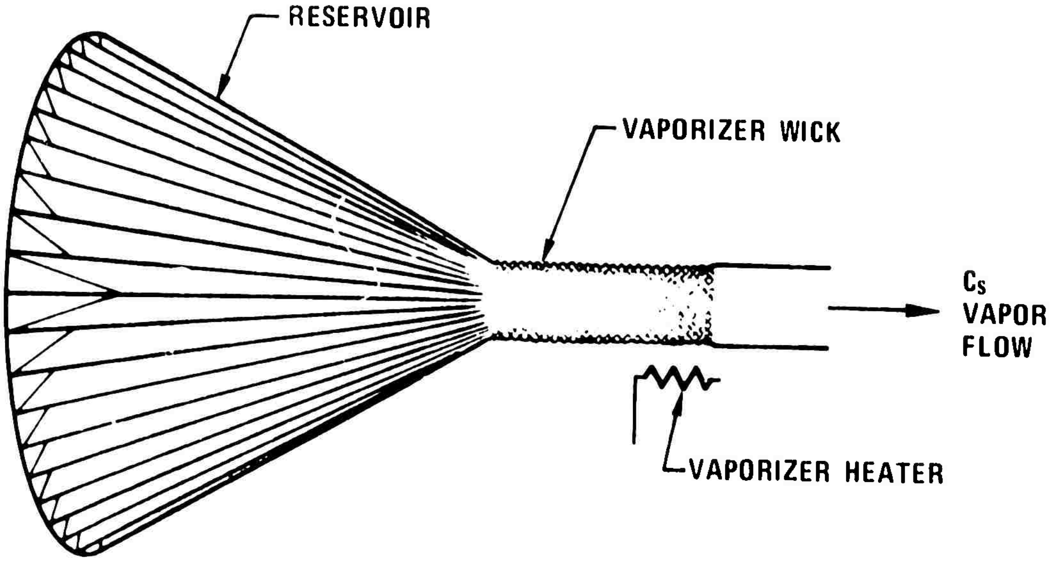


Figure 13. Cesium Feed System

a. 5-lb_f Thruster

The large hydrazine catalytic thruster is identical to that described in Section III. B. 1.

b. 0.001-lb_f Thruster

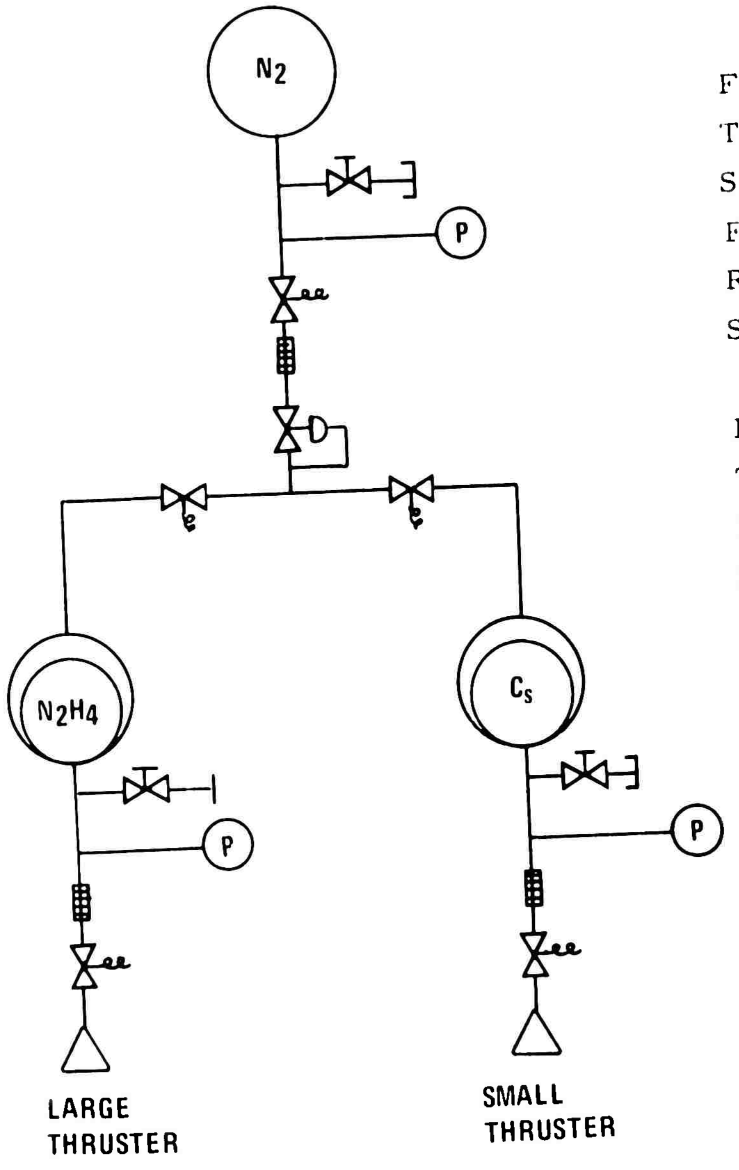
The 1-millipound thrust size for the low-level thruster was chosen to keep the power requirements around 150 watts. Although EOS life-tested two 8-millipound bombardment ion thrusters, their power consumption was on the order of 1 kilowatt. For a 1-millipound thruster and 150 watts power, a specific impulse of 3000 seconds is projected. A minimum impulse bit of 1×10^{-3} lb_f-sec was considered reasonable, based on a 1-second minimum pulse width. (The above performance goals were obtained from Dr. Fritz, AFAPL/POP-2 of the Air Force Aero Propulsion Laboratory.)

c. Conceptual Schematic

Figure 14 shows the conceptual schematic.

8. N_2H_4 Catalytic/Colloid

The basis for the colloid engine (Figures 15 and 16) is an electrically conducting propellant subjected to a high electric field established between the propellant and an extractor electrode. The extractor electrode has historically been a small-diameter (4-mil bore) capillary needle, but recent development effort has been expended on a linear slit geometry electrode version. Once the electrode field is established, field emission ionization of small-diameter (100 Å) droplets occurs at the needle tip or linear slit. The same field which produces ionization also accelerates the charged droplets to produce thrust. Since the charged droplets may be positive or negative depending on the polarity of the potential applied to



		Weight (pounds)
Fill Valve		0.25
Transducer		0.20
Solenoid		0.20
Filter		0.20
Regulator		0.3
Solenoid (2)		0.4
Fill Valve (2)		0.50
Transducer (2)		0.40
Filter (2)		0.40
Solenoid (2)		0.40
Lines		1.0
Thrusters		
Large	8(0.8) =	6.4
Small	12(5.5) =	66.0
Total Weight		76.65

Figure 14. System Schematic for N_2H_4 Catalytic-Cs Ion

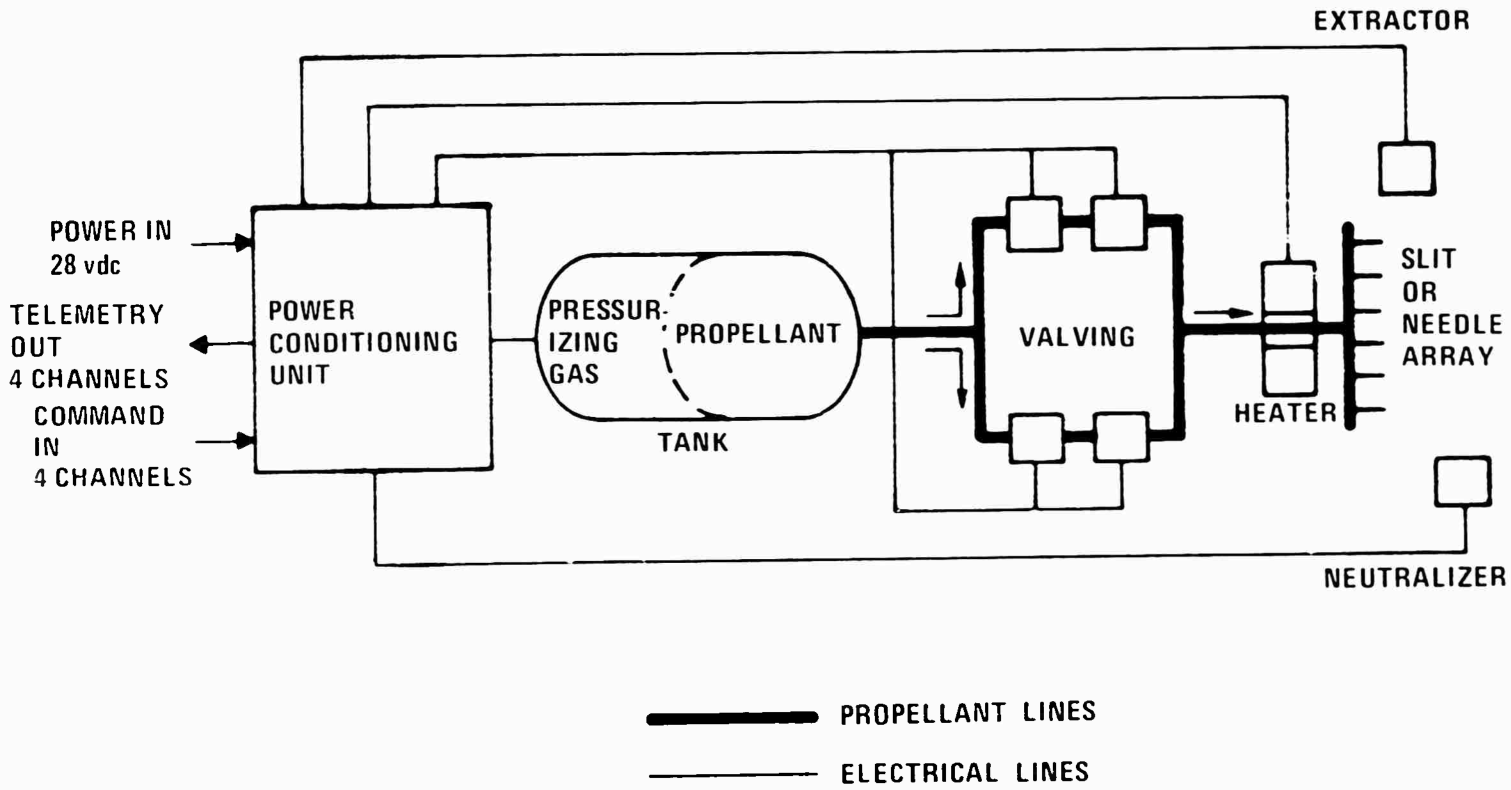


Figure 15. Colloid Engine Schematic

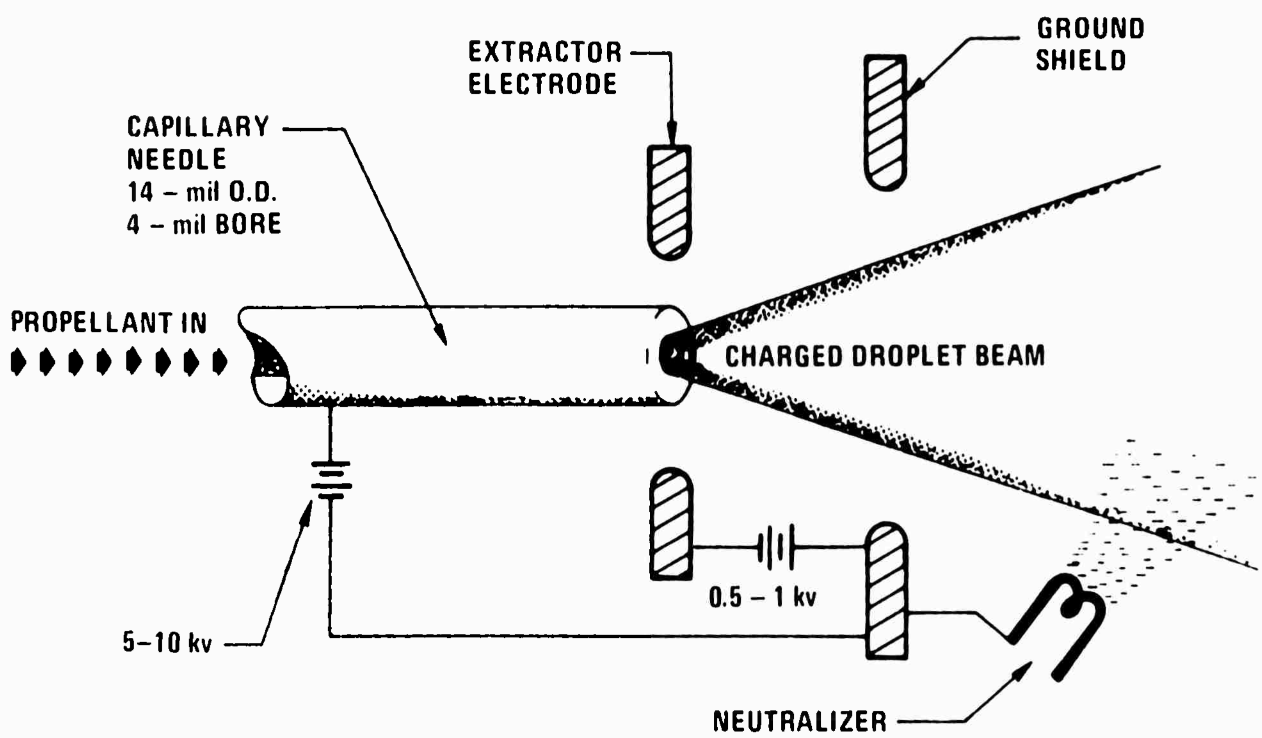


Figure 16. Colloid Thruster Concept

the needles, a neutralizer is necessary to neutralize the beam. The masses of the charged droplets are generally greater than the masses of ions produced in ion engines.

Although the colloid engine is degraded by the randomness of the particle formation and the manner of inducing the charge, it alone, of the electrostatic engines, has the most efficient formation of charged particles.

The most successful colloid engine work has been performed by TRW Systems for the Air Force Aero Propulsion Laboratory (AFAPL). TRW built a Colloid Microthruster Experiment (CMF) for the AFAPL in support of the DODGE-II satellite, which was cancelled. The CMF flight hardware was subsequently tested for 1000 hours during 1969.

Since 1969, the TRW colloid thruster has been part of the SAMSO ADP for Advanced Satellite Propulsion. In December 1970, TRW was awarded a 56-month contract by SAMSO for development of a 1-millipound-thrust colloid thruster. The thruster, resembling a 10-inch cube with 12 individual thrusting modules, will weigh about 20 pounds and carry some 25 pounds of propellant, mainly glycerol with sodium iodide. At the 1-millipound thrust level, the colloid engine will have a specific impulse of 1500 seconds and deliver about 35,000 lb_f-sec of total impulse. The contract calls for ground testing of three flight qualified thrusters for 10,000 hours and delivery of three systems for satellite flight testing to provide satellite stationkeeping for 7 years.

a. 5-lb_f Thruster

The large hydrazine catalytic thruster is identical to that described in Section III.B.1.

*Space Business Daily, 2 December 1970

b. 0.001-lb_f Thruster

The current SAMSO ADP for colloid propulsion was used to obtain propulsion system characteristics. For this study, thrust level was 1 millipound, Isp was 1500 seconds and minimum impulse bit was 1×10^{-4} lb_f-sec. The propellant is 20 percent NaI and 80 percent glycerol (percent by weight).

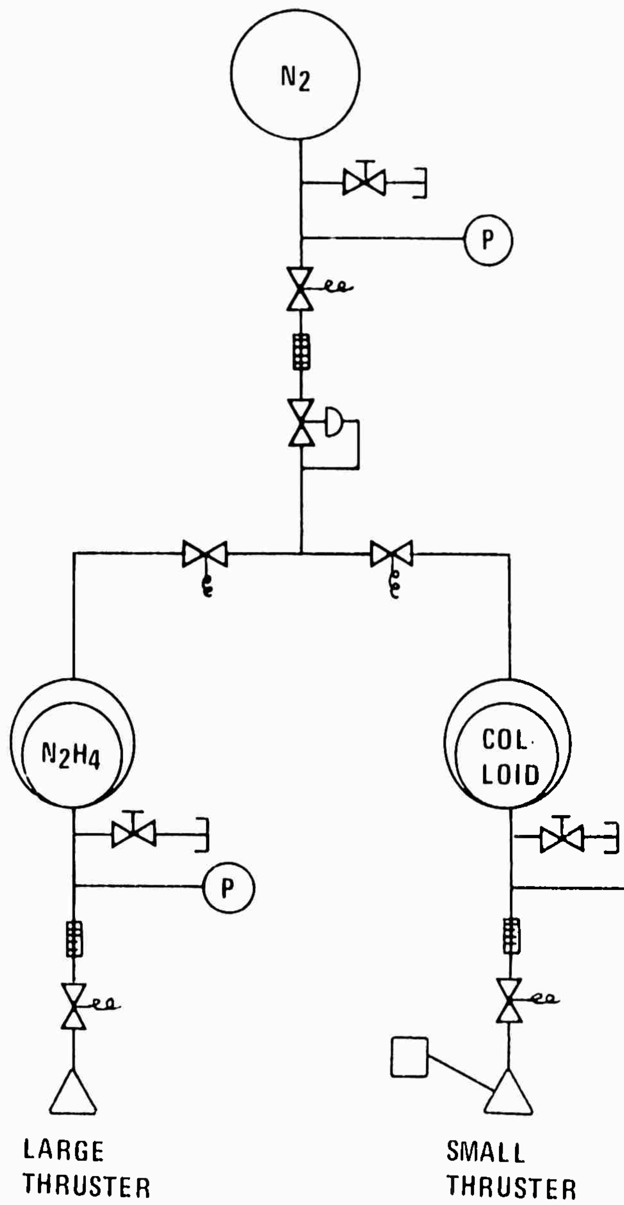
A lightweight and reliable feed system remains the largest development effort. No pulse tests have been performed on the linear slit to date. The needle has been pulsed between 1 and 3 pulses/sec in duty cycles of 10 and 30 percent. Although the low power required (70 watts) for the colloid thruster is favorable, the linear slit requires between 14 and 16 kilovolts for operation and is the weak point in the system.

c. Conceptual Schematic

Figure 17 shows the conceptual schematic.

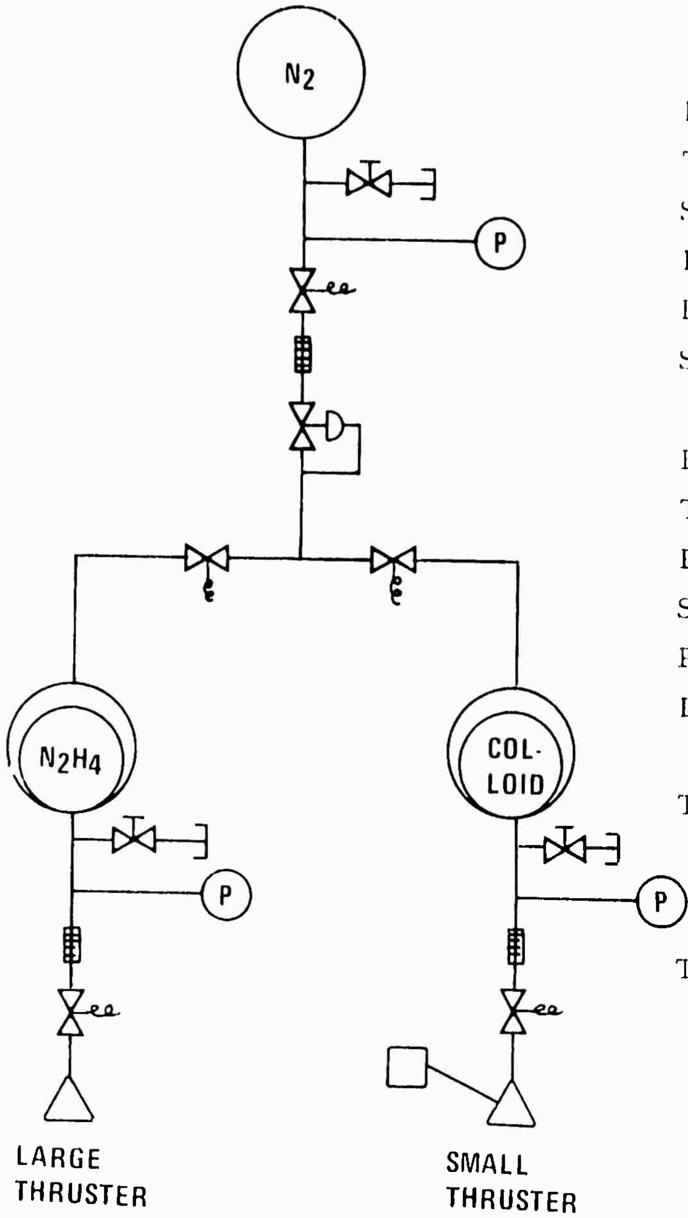
9. N_2H_4 Catalytic/Hg Pulsed Plasma

Although several types of pulsed plasma thrusters have been undergoing exploratory development (Figure 18), only the pulsed vacuum arc thruster (Figure 19) being developed by Cornell Aeronautical Laboratories uses a liquid propellant (mercury) which permits this system to achieve a total impulse level required for a SYNCSAT (USAF Contract No. F33615-67-C-1579, Report AFAPL-TR-68-92). The general mode of operation is for mercury to be ionized by a high-voltage discharge and accelerated by the interaction of the discharge current with its own magnetic field. The PVAT produces only discrete impulses, the effective "thrust" being governed by the size of these impulse bits and the repetition rate. Typical impulse-per-pulse figures range from 10^{-6} to 10^{-5} lb_f-sec while repetition rates from zero to 50 pulses/sec are readily attainable.



	Weight (pounds)
Fill Valve	0.25
Transducer	0.20
Solenoid	0.20
Filter	0.20
Regulator	0.30
Solenoid (2)	0.40
Fill Valve (2)	0.50
Transducer (2)	0.40
Filter (2)	0.40
Solenoid (2)	0.40
Power Conditioner	11.00
Lines	1.00
Thruster	
Large 8(0.8) =	6.40
Small 12(0.8) =	9.60
Total Weight	31.25

Figure 17. System Schematic for N_2H_4 Catalytic-Colloid



	Weight (pounds)
Fill Valve	0.25
Transducer	0.20
Solenoid	0.20
Filter	0.20
Regulator	0.30
Solenoid (2)	0.40
Fill Valve (2)	0.50
Transducer (2)	0.40
Filter (2)	0.40
Solenoid (2)	0.40
Power Conditioner	11.00
Lines	1.00
Thruster	
Large 8(0.8) =	6.40
Small 12(0.8) =	9.60
Total Weight	31.25

Figure 17. System Schematic for N_2H_4 Catalytic-Colloid

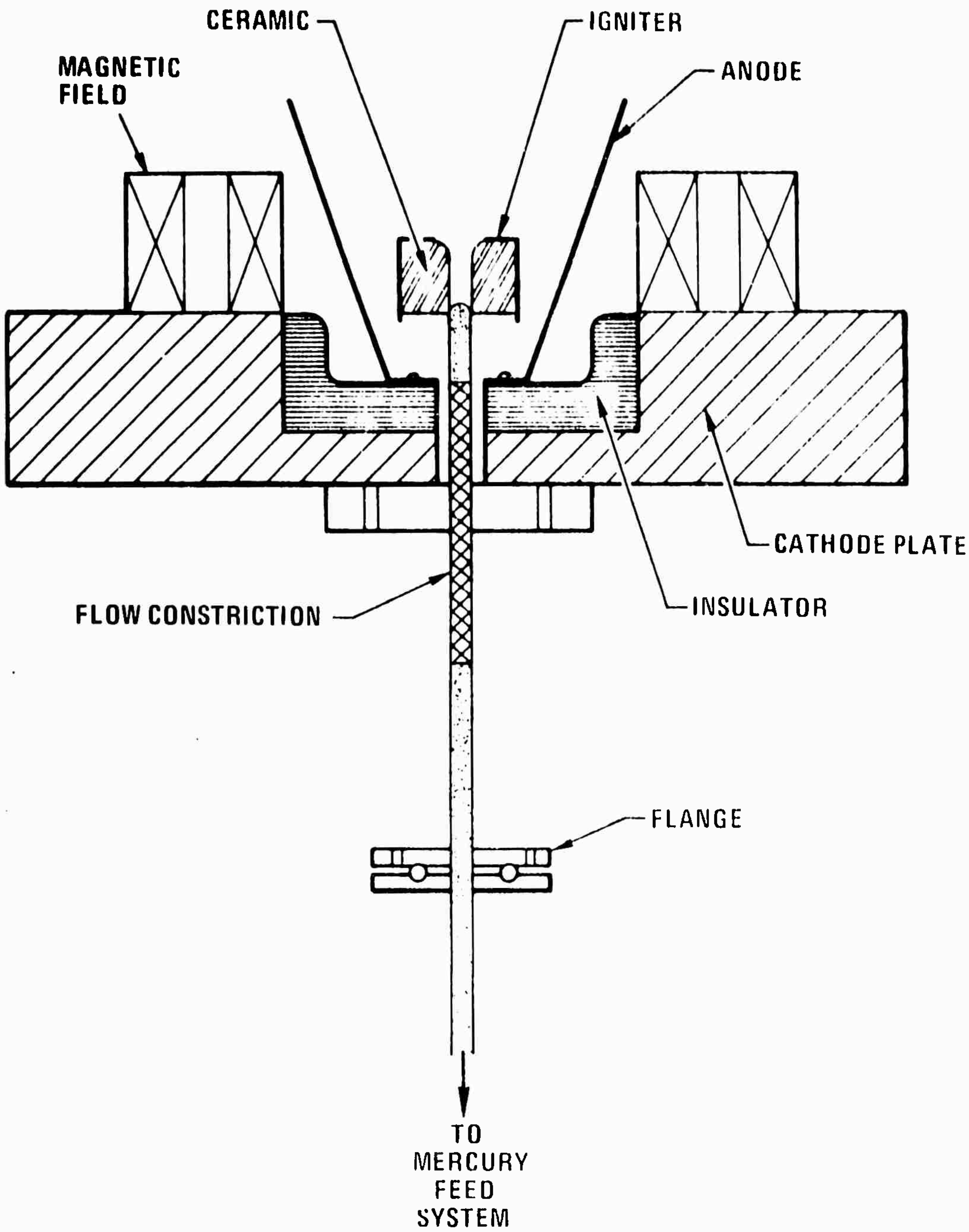


Figure 19. Pulsed Vacuum Arc Thruster

Lifetimes up to 6 x 10^7 pulses have been demonstrated on several pulsed vacuum arc thrusters (PVATs). To date, the mercury-cathode PVAT, however, has been run for only about 4 x 10^5 pulses because of feed system problems.

a. 5-lb_f Thruster

Performance for the N_2H_4 thruster was Isp = 230 seconds steady-state vacuum. All members are identical to those previously used in Section III. B. 1.

b. 0.00001-lb_f Thruster

Data used in this study were based on the PVAT being developed by Cornell Aeronautical Laboratories. This study used a thrust level of 10 micropounds force, a specific impulse of 1500 seconds and a minimum impulse bit of 5 x 10^{-6} lb_f-sec.

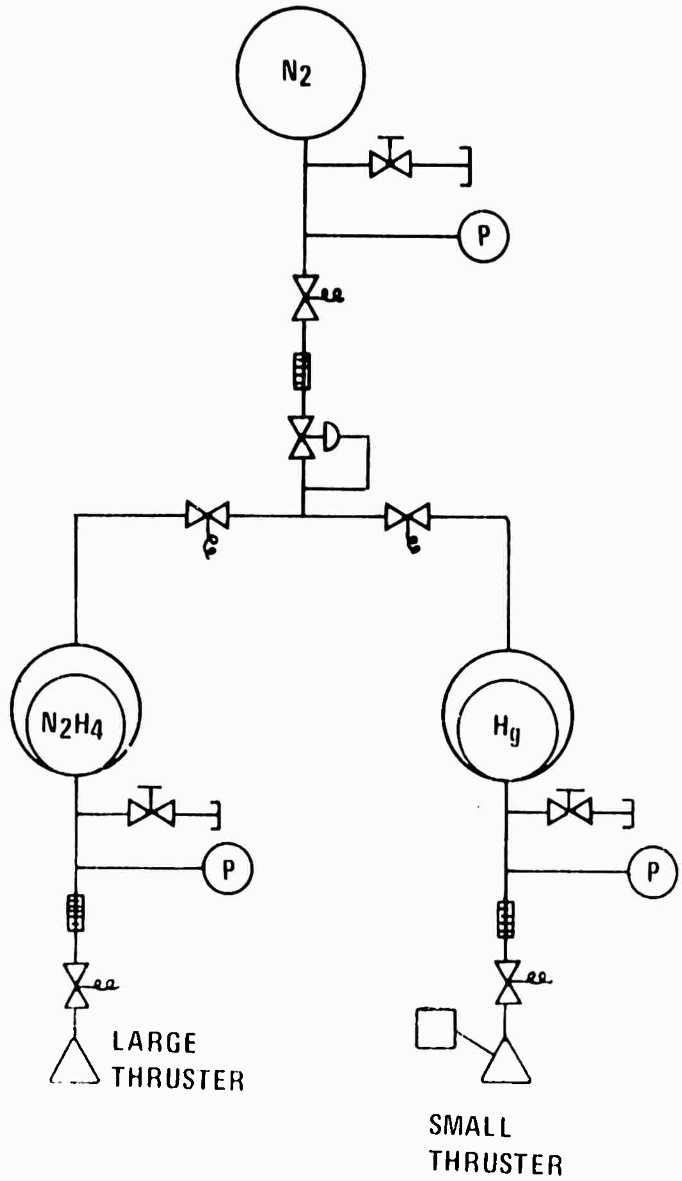
The PVAT still needs considerable development in the feed system area and more life testing of an integrated system. For the SYNCSAT, power requirements are on the order of 100 watts for each PVAT.

c. Conceptual Schematic

Figure 20 shows the conceptual schematic.

10. DO Radioisotope/DO Radioisotope

DO (dioxyamine) is a new type of monopropellant presently being characterized by the AFRPL. Because of the high (2600°F) equilibrium flame temperature of DO, it is difficult to project the early development of a catalyst and substrate to decompose DO. For this reason, a radioisotope capsule is envisioned as the ignition scheme to initiate thermal decomposition for the purposes of this study.



	Weight (pounds)
Fill Valve	0.25
Transducer	0.20
Solenoid	0.20
Filter	0.20
Regulator	0.30
Solenoid (2)	0.40
Fill Valve (2)	0.50
Transducer (2)	0.40
Filter (2)	0.40
Solenoid (2)	0.40
Power Conditioner	5.0
Lines	1.0
Thrusters	
Large 8(0.8)	6.4
Small 12(2)	24.0
Total Weight	39.65

Figure 20. System Schematic for N_2H_4 Catalytic-Hg Pulsed Plasma

The AFRPL performance calculation computer code (ODIE) was used to calculate a theoretical altitude performance number for DO using a combustion chamber pressure of 100 psia, a nozzle expansion ratio of ε 40 and a 55 percent NH_3 dissociation. These inputs gave a theoretical steady-state altitude specific impulse of 283 seconds. Using a 94 percent efficiency factor, a realizable specific impulse of 265 seconds might be obtained.

a. 5-lb_f Thruster

Steady-state performance for the 5-pound DO thruster was taken as 265 seconds, as mentioned above. This number is based on 94 percent engine efficiency and is a "best" estimate. No engine data are available.

b. 0.025-lb_f Thruster

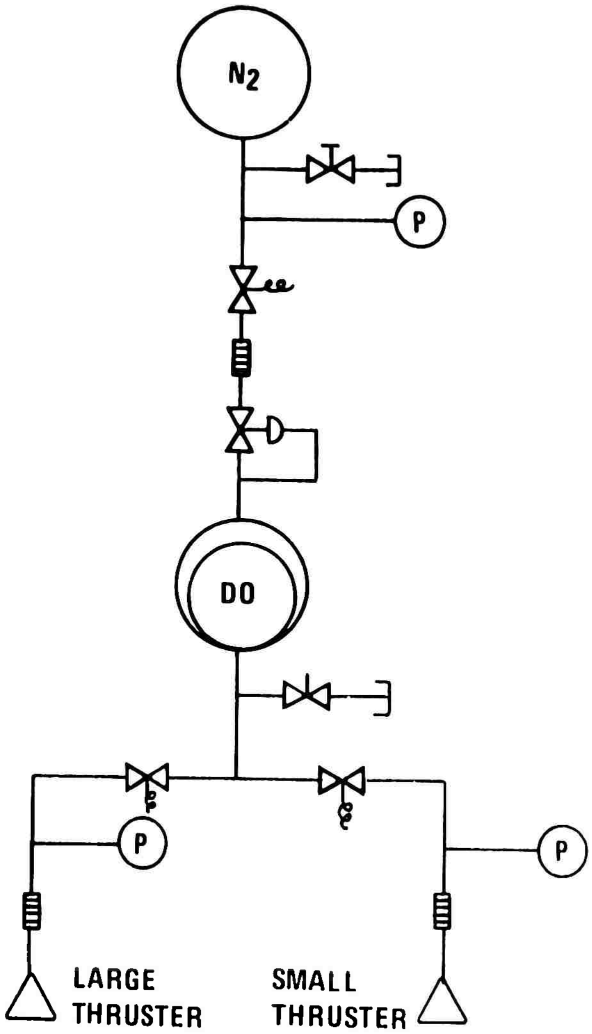
For the 25-millipound thruster, a minimum impulse bit of 5×10^{-4} lb_f-sec was assumed, based on the DART ADP goals. Pulse mode performance is Isp = 238 seconds based on a capsule temperature of 2500 °F. No test data are available.

c. Conceptual Schematic

Figure 21 shows the conceptual schematic.

11. DO Radioisotope/Colloid

This is a hybrid propulsion system comprised of two previously described units. A radioisotope thermal decomposition ignition system is postulated for the 5-lb_f DO thruster. The colloid thruster is of 1-millipound thrust with performance numbers as described in the SAMSO ADP for the NaI plus glycerol colloid propulsion development effort.



		Weight (pounds)
Fill Valve		0.25
Transducer		0.20
Solenoid		0.20
Filter		0.20
Regulator		0.30
Fill Valve		0.25
Solenoid (2)		0.40
Transducer (2)		0.40
Filter (2)		0.40
Lines		1.
Thrusters		
Large	8(2) =	16.0
Small	12(1.5) =	18.0
Total Weight		37.6

Figure 21. System Schematic for DO-DO

a. 5-lb_f Thruster

The large DO radioisotope thruster is identical to that described in Section III. B. 10.

b. 0.001-lb_f Thruster

The small colloid thruster is identical to that described in Section III. B. 8.

c. System Schematic

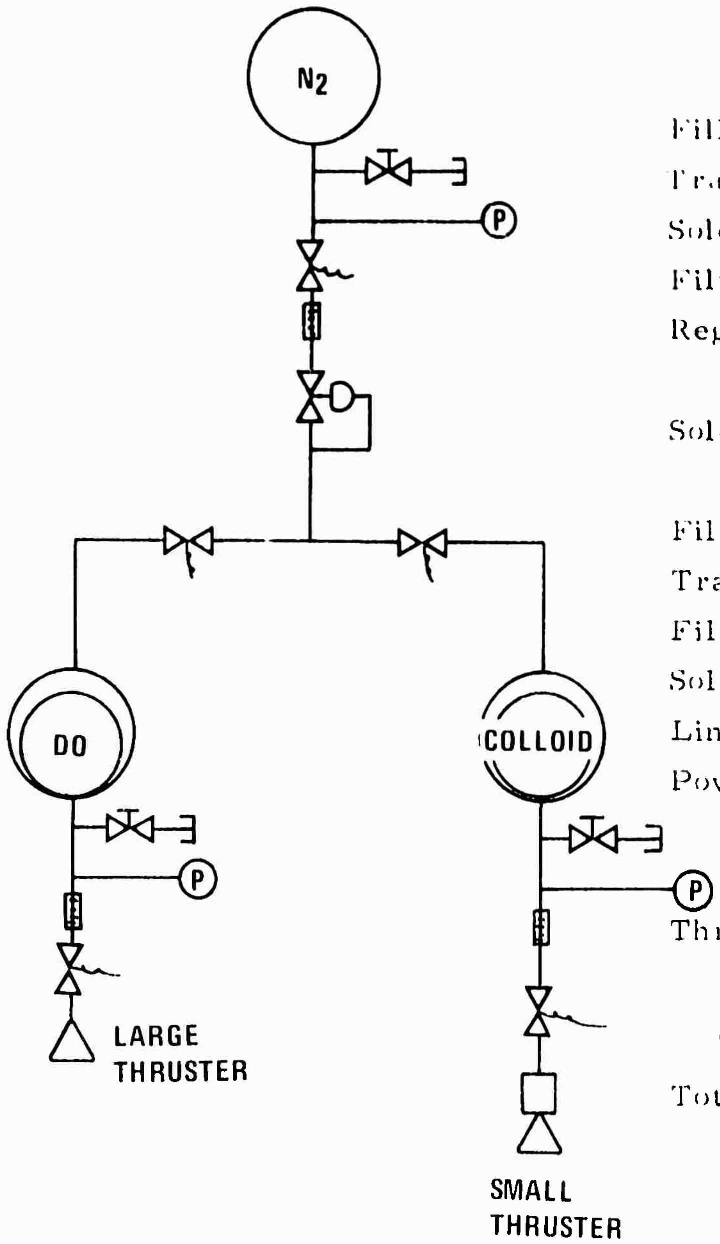
Figure 22 shows the system schematic.

12. H_2O Electrolysis/H_2O Electrolysis

The water electrolysis propulsion system employs liquid water as the propellant in the storage mode and gaseous hydrogen and oxygen for the bipropellant rocket thrusters. A zero-g water electrolysis unit provides the separated gases for the engine. This scheme permits storing liquid water at low pressure and reduces the total system weight in this manner. A recent AFRPL contract (F04611-71-C-0055) to the Marquardt Corporation provides for the development and testing of a bipropellant 5-lb_f thruster and a bipropellant 0.1-lb_f thruster using gaseous hydrogen and oxygen. General Electric is the subcontractor for the zero-g water electrolysis unit. Twenty watts of continuous power are required.

a. 5-lb_f Thruster

Steady-state performance for the large 5-lb_f GH_2/GO_2 engine (Figure 23) was based on Marquardt prototype test data. This number is Isp = 350 seconds with a thrust coefficient equal to 1.6. A pulsing performance of Isp = 310 seconds was assumed for this thruster. GH_2/GO_2 thrusters provide high performance and highly reproducible pulses.



			Weight (pounds)
Fill Valve			0.25
Transducer			0.20
Solenoid			0.20
Filter			0.20
Regulator			0.30
Solenoid (2)			0.40
Fill Valve (2)			0.50
Transducer (2)			0.40
Filter (2)			0.40
Solenoid (2)			0.40
Lines			1.00
Power Conditioner			11.00
Thruster			
Large	8(2)	=	16.0
Small	12(.8)		9.60
Total Weight			40.85

Figure 22. System Schematic for DO-Colloid

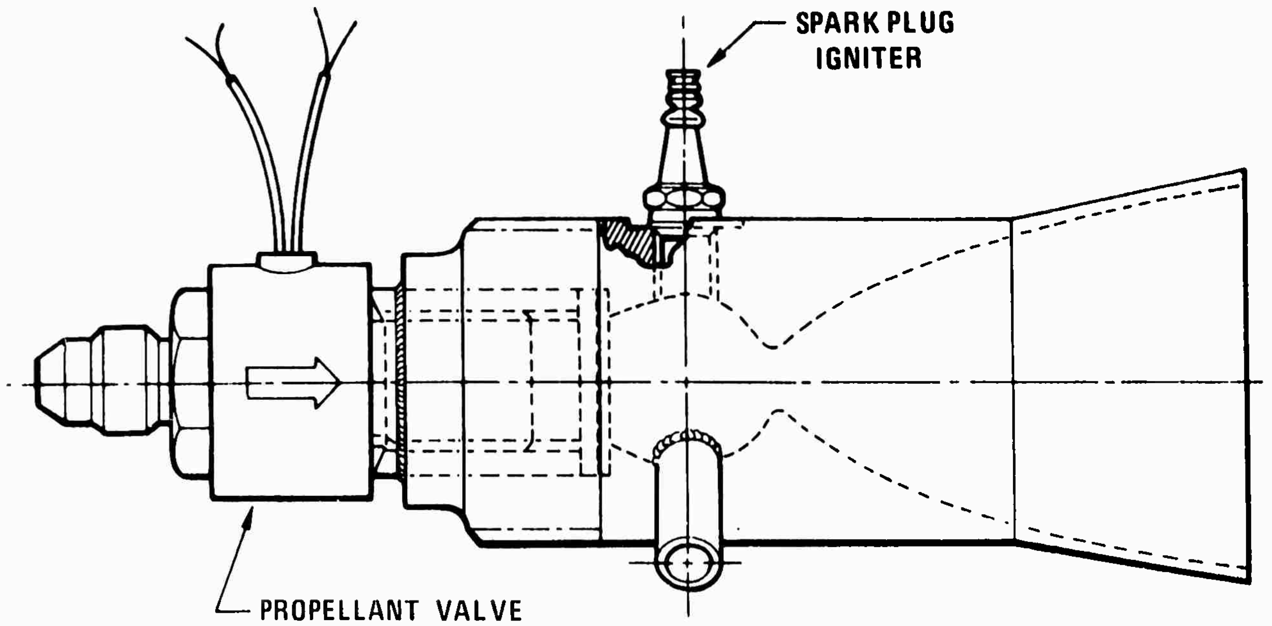


Figure 23. Water Electrolysis Bipropellant Thruster

b. 0.1-lb_f Thruster

The small thruster pulse mode Isp was assumed to be 280 seconds. Using a 25-millisecond pulse width, a minimum impulse bit of 2.5×10^{-3} lb_f-sec was taken. Steady-state performance for the 0.1-lb_f thruster was assumed to be Isp = 310 seconds.

In general, this system lacks feed system and integration testing. System weight reduction is at the expense of system complexity. A high system reliability must be demonstrated early in its development.

c. Conceptual Schematic

Figure 24 shows the conceptual schematic.

13. H_2O Electrolysis/Colloid

This hybrid propulsion system is designed to provide a high-performance chemical rocket engine with electrical colloid thruster. Both units have been described previously.

a. 5-lb_f Thruster

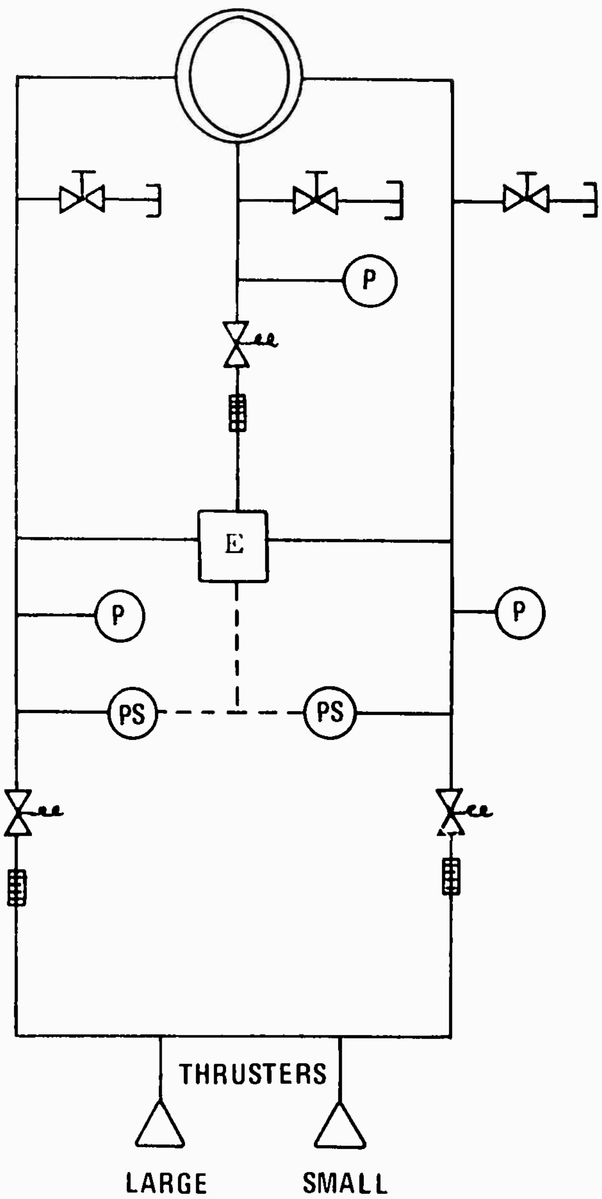
The large GH_2/GO_2 bipropellant thruster is identical to the water electrolysis system described in Section III. B. 12.

b. 0.001-lb_f Thruster

The small colloid thruster is identical to that described in Section III. B. 8.

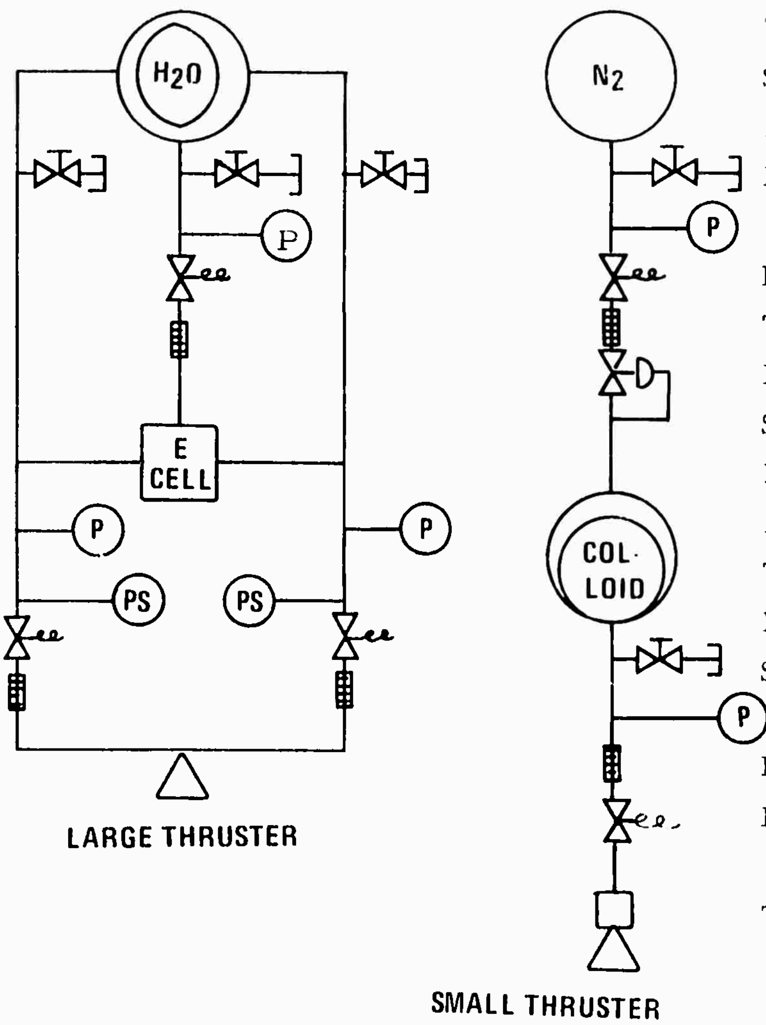
c. Conceptual Schematic

The conceptual schematic is shown in Figure 25.



	Weight (pounds)
Fill Valve (3)	0.75
Transducer	0.20
Solenoid	0.20
Filter	0.20
Electrolysis Cell	15.0
Transducer (2)	0.40
Pressure Switch (2)	0.50
Solenoid (2)	0.40
Filter (2)	0.20
Lines	1.00
Thrusters	30.00
Total Weight	49.05

Figure 24. System Schematic for H_2O-H_2O



	Weight (pounds)
Fill (4)	1.00
Transducer (2)	0.40
Solenoid (2)	0.40
Filter (2)	0.40
Regulator	0.30
Electrolysis Cell	15.00
Transducer (2)	0.40
Pressure Switch (2)	0.50
Solenoid (2)	0.40
Fill Valve	0.25
Filter (2)	0.40
Transducer	0.20
Filter	0.20
Solenoid	0.20
Power Conditioner	11.00
Lines	2.00
Thrusters	
Large	15.00
Small	9.6
Total Weight	57.65

Figure 25. System Schematic for H_2O-Colloid

14. N_2O_4/N_2H_4 Bipropellant/N_2H_4 GG Plenum

Although a 5-lb_f bipropellant thruster using N_2O_4 and hydrazine has not yet been developed, a large number of 5-lb_f engines using N_2O_4/MMH and N_2O_4/50 percent N_2H_4-50 percent UDMH have been built and tested. This system is designed to use the common hydrazine tank for both the high and low thrusters, thereby providing for simplicity and weight reduction. The earth storable bipropellants are well defined in terms of properties and characteristics. The only required power is that needed to operate the propellant valves.

a. 5-lb_f Thruster

Since no 5-lb_f thrust N_2O_4/N_2H_4 test data were available, steady-state 5-lb_f thruster performance numbers for N_2O_4/MMH were used. This yielded steady-state operation at Isp = 280 seconds for an area ratio of 40:1 at a mixture ratio of 1.40.

b. 0.050-lb_f Thruster

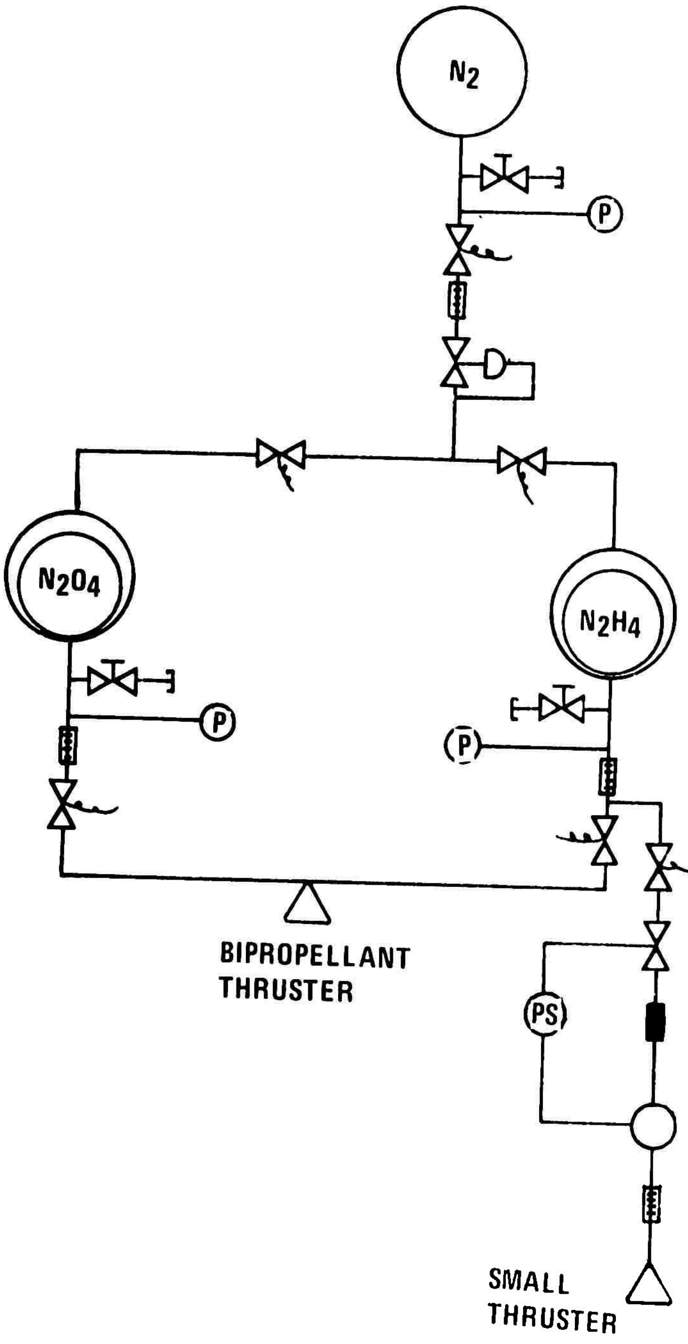
The low-thrust hydrazine gas generator plenum system was capable of giving Isp = 110 seconds and a minimum impulse bit of 5×10^{-4} lb_f-sec. These numbers are identical to the hydrazine plenum system described in Section III.B.2.

c. Conceptual Schematic

Figure 26 shows the conceptual schematic.

15. ClF_5/N_2H_4 Bipropellant/N_2H_4 GG Plenum

This bipropellant system is similar to the N_2O_4 system described in Section III.B.14, except that care must be exercised in the selection of a ClF_5 storage tank. A tank material compatibility problem exists which



		Weight (pounds)
Fill Valve		0.25
Transducer		0.20
Solenoid		0.20
Filter		0.20
Regulator		0.3
Solenoid (2)		0.4
Fill Valve (2)		0.50
Transducer (2)		0.40
Filter (2)		0.40
Solenoid (3)		0.60
Control Valve		0.40
Press. Switch		0.25
G G		0.35
Plenum		0.30
Filter		0.20
Lines		1.00
Thruster		
Large	8(1.30) =	10.4
Small	12(0.4) =	4.8
Total Weight		21.15

Figure 26. System Schematic for N_2O_4/N_2H_4-N_2H_4 GG Plenum

was not experienced with N_2O_4. No performance data for a 5-lb$_f$ ClF_5/N_2H_4 thruster are available. The only required power is that needed to operate the propellant valves.

a. 5-lb$_f$ Thruster

For this study, a 10-second specific impulse gain above the N_2O_4/N_2H_4 system was assumed. Therefore, steady-state performance was Isp = 290 seconds at a mixture ratio of 2.0.

b. 0.050-lb$_f$ Thruster

Once again, the hydrazine gas generator plenum performance numbers were identical to those used previously in Section III.B.2.

c. Conceptual Schematic

Figure 27 shows the conceptual schematic.

16. ADP DART/ADP DART

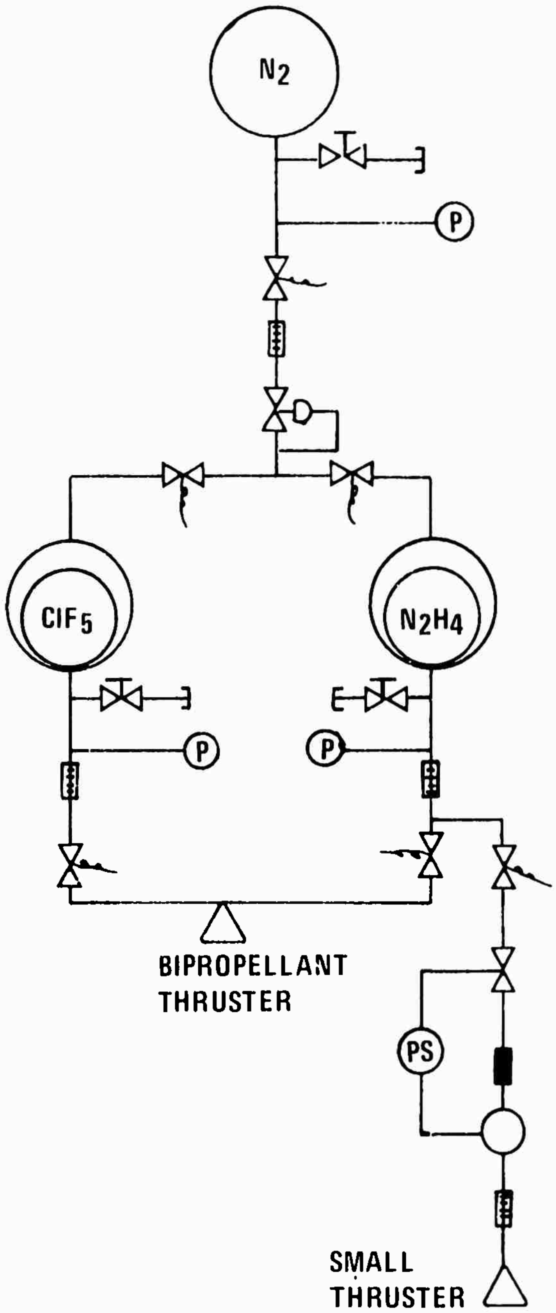
The development status of the decomposed ammonia radioisotope thruster (DART) has been described under Section III.B.6. The all-DART concept has been favored by the AFRPL since 1968, and an in-house study was accomplished by Mr. E. Barth to detail its potentials and mission applications (Reference 5).

a. 5-lb$_f$ Thruster

There is no 5-lb$_f$ engine in this concept. All engines are of the 0.025-lb$_f$ class. Repositioning may pose a problem.

b. 0.025-lb$_f$ Thruster

The ADP DART performance goals were used for the all-DART system. Thrust level was 25 millipounds and a 20-millisecond pulse



			Weight (pounds)
Fill Valve			0.25
Transducer			0.20
Solenoid			0.20
Filter			0.20
Regulator			0.3
Solenoid (2)			0.4
Fill Valve (2)			0.50
Transducer (2)			0.40
Filter (2)			0.40
Solenoid (3)			0.60
Control Valve			0.40
Pressure Switch			0.25
G G			0.35
Plenum			0.30
Filter			0.20
Lines			1.00
Thrusters			
Large	8(1.30)	=	10.4
Small	12(.4)	=	4.8
Total Weight			21.15

Figure 27. System Schematic for ClF_5/N_2H_4-N_2H_4 GG Plenum

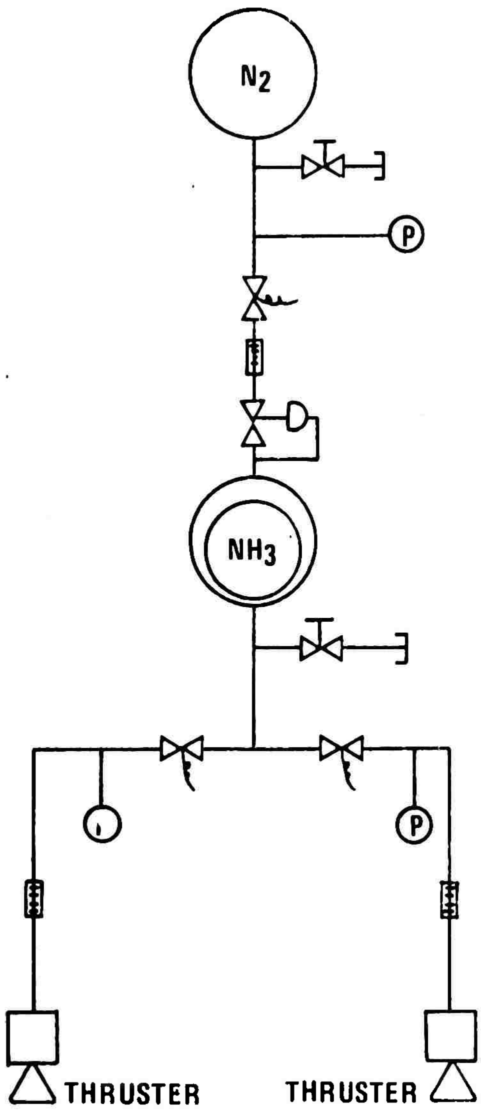
produced a minimum impulse bit of 5×10^{-4} lb_f-sec. Pulse mode Isp = 310 seconds and steady-state Isp = 280 seconds were used, based on a capsule gas temperature of 2500°F.

c. Conceptual Schematic

Figure 28 shows the conceptual schematic.

C. PROPULSION SYSTEM WEIGHT

A computer program was developed to facilitate the task of calculating spacecraft geometry, weighing the propellant required and sizing propellant tankage and pressurization systems. This program will weigh the entire propulsion system for a geosynchronous orbit with up to 10 different propulsion functions being performed. The program will accept variations in the following parameters: (1) satellite parameters such as initial gross weight, life, initial angular momentum and repositioning rate, (2) centerbody parameters such as bulk density, geometry (i.e., spherical, cylindrical or rectangular) and L/D ratios, (3) solar panel variables such as ideal specific weight, percent life degradation, specific surface area and height-to-length ratio, and (4) parameters for the small thrusters such as minimum thrust level, minimum pulse width, deadband half-angle for accuracy and the minimum average angular rate for limit cycling. In addition to these, data on the propellant storage tank materials and their properties and storage pressures are required. The Isp which would be realized during each propulsion requirement for a given propellant or propellant combination is also required. Information obtained from the program is: (1) solar panel and centerbody dimensions and weights, (2) onboard power, (3) satellite moments of inertia, (4) impulse, ΔV and propellant amounts for each propulsion requirement, (5) total impulse, ΔV and propellant required for the mission, and (6) storage tank sizes and weights and the amount of pressurant required along with a tank to store it.



	Weight (pounds)
Fill Valve	0.25
Transducer	0.20
Solenoid	0.20
Filter	0.20
Regulator	0.30
Fill Valve	0.25
Solenoid (2)	0.40
Transducer (2)	0.40
Filter (2)	0.40
Lines	1.00
Thrusters	
5(12) =	60
Total Weight	63.60

Figure 28. System Schematic for DART-DART

For this study, four different missions were analyzed. These were:

1. 10-year life, 3000-pound satellite performing north-south stationkeeping. (This mission will be designated as 10-3NS.)

2. 10-year life, 3000-pound satellite not performing north-south stationkeeping. (This mission will be designated as 10-3.)

3. 5-year life, 2000-pound satellite performing north-south stationkeeping. (This mission will be designated as 5-2NS.)

4. 5-year life, 2000-pound satellite not performing north-south stationkeeping. (This mission will be designated as 5-2.)

Values assumed for other spacecraft parameters which remain constant from system to system in this study have been discussed in Sections III-A-2 (Satellite Geometry) and III-A-3 (Mission Requirements). Tables IV, through VII present the results from the computer for the above four missions. These tables give the propellant weight, inert weight, total weight of the propulsion system without a power penalty, power penalty and the total system weight with the power penalty.

All of the systems investigated in this study require some power; some require more than others. All systems have solenoid valves in the feed systems and these require power to operate them. Since the power levels of these are so small, these power requirements were ignored in assessing a power penalty. It was also assumed that the hydrazine systems would not require heaters to keep the hydrazine as a liquid. Therefore, power penalties were assessed upon the water electrolysis, hydrazine resistojet, colloid, cesium and mercury pulsed plasma systems. Power penalties used are presented in Table VIII.

TABLE IV. PROPULSION SYSTEM WEIGHT FOR 3000-POUND SATELLITE WITH A 10-YEAR LIFE PERFORMING NORTH-SOUTH STATIONKEEPING

High Thruster	Low Thruster	Propellant Weight	Inert Weight	Total Weight W/O Power	Power Penalty	Total Weight With Power
H_2O	Colloid	200.638	65.604	266.242	94.6	360.842
N_2H_4 Cat.*	Cs Ion	188.820	89.097	277.917	198.0	475.917
DO	Colloid	227.357	54.655	282.012	92.4	374.412
N_2H_4 Cat.	Colloid	243.969	47.083	291.052	92.4	383.452
N_2H_4 Cat.	Hg P.P.**	243.969	50.181	294.150	132.0	426.150
H_2O	H_2O	622.212	66.969	689.181	2.2	691.381
DART	DART	621.055	112.420	733.475	-	733.475
N_2H_4 Cat.	DART	640.693	97.554	738.247	-	738.247
N_2H_4 Cat.	N_2H_4 Radioisotope	751.936	65.551	817.487	-	817.487
ClF_5/N_2H_4	N_2H_4 GG Plenum	776.006	57.489	833.495	-	833.495
N_2O_4/N_2H_4	N_2H_4 GG Plenum	794.055	60.957	855.012	-	855.012
N_2H_4/Cat.	N_2H_4/Resistojet	826.525	51.933	878.458	6.6	885.058
DO	DO	850.282	73.368	923.650	-	923.650
N_2H_4/Cat.	N_2H_4 Cat.	1013.323	62.811	1076.134	-	1076.134
N_2H_4 Cat.	N_2H_4 Electrolytic	1031.291	64.715	1096.006	19.8	1115.806
N_2H_4 Cat.	N_2H_4 GG Plenum	1070.732	66.732	1137.086	-	1137.086

* N_2H_4 Catalytic

** Hg Pulsed Plasma

TABLE V. PROPULSION SYSTEM WEIGHT FOR 3000-POUND SATELLITE WITH A 10-YEAR LIFE NOT PERFORMING NORTH-SOUTH STATIONKEEPING

High Thruster	Low Thruster	Propellant Weight	Inert Weight	Total Weight W/O Power	Power Penalty	Total Weight With Power
H_2O	Colloid	107.713	60.893	168.606	94.6	263.206
DO	Colloid	135.291	49.997	185.288	92.4	277.688
N_2H_4 Cat.	Colloid	152.436	42.461	194.897	92.4	287.297
N_2H_4 Cat.	Hg. P.P.	152.436	49.425	201.861	132.0	333.861
N_2H_4 Cat.	Cs Ion	142.634	86.946	229.580	198.0	427.580
H_2O	H_2O	203.515	57.556	261.071	2.2	263.271
DART	DART	204.642	83.397	288.039	-	288.039
DO	DO	240.824	50.624	291.448	-	291.448
N_2H_4 Cat.	N_2H_4 Radioisotope	250.217	43.493	293.710	-	293.710
N_2H_4 Cat.	DART	227.546	66.941	294.487	-	294.487
N_2H_4 Cat.	N_2H_4 Resistojet	298.369	29.162	327.531	6.6	334.131
ClF_5/N_2H_4	N_2H_4 GG Plenum	337.498	41.189	378.687	-	378.687
N_2O_4/N_2H_4	N_2H_4 GG Plenum	341.879	42.098	383.977	-	383.977
N_2H_4 Cat.	N_2H_4 GG Plenum	374.084	37.432	411.516	-	411.516
N_2H_4 Cat.	N_2H_4 Cat.	410.020	37.760	447.780	-	447.780
N_2H_4 Cat.	N_2H_4 Electrolytic	480.295	42.078	522.373	19.8	542.173

TABLE VI. PROPULSION SYSTEM WEIGHT FOR 2000-POUND SATELLITE WITH A 5-YEAR LIFE PERFORMING NORTH-SOUTH STATIONKEEPING

High Thruster	Low Thruster	Propellant Weight	Inert Weight	Total Weight W/O Power	Power Penalty	Total Weight With Power
H_2O	Colloid	95.842	60.788	156.630	94.6	251.230
DO	Colloid	113.987	49.070	163.057	92.4	255.457
N_2H_4 Cat.	Colloid	125.266	40.955	166.221	92.4	258.621
N_2H_4 Cat.	Hg P. P.	125.266	47.071	172.337	132.0	304.337
N_2H_4 Cat.	Cs Ion	107.001	84.902	191.903	198.0	389.903
ClF_5/N_2H_4	N_2H_4 GG Plenum	293.170	37.867	331.037	-	331.037
N_2H_4 Cat.	DART	260.949	70.897	331.846	-	331.846
DART	DART	246.654	86.588	333.242	-	333.242
H_2O	H_2O	275.462	59.459	334.921	2.2	337.121
N_2O_4/N_2H_4	N_2H_4 GG Plenum	300.932	39.578	340.510	-	340.510
N_2H_4 Cat.	N_2H_4 Radioisotope	300.454	45.910	346.364	-	346.364
DO	DO	331.742	54.365	386.107	-	386.107
N_2H_4 Cat.	N_2H_4 Resistojet	377.696	32.846	410.542	6.6	417.142
N_2H_4 Cat.	N_2H_4 GG Plenum	412.496	39.171	451.667	-	451.667
N_2H_4 Cat.	N_2H_4 Cat.	512.553	42.285	554.838	-	554.838
N_2H_4 Cat.	N_2H_4 Electrolytic	565.962	45.784	611.746	19.8	631.546

TABLE VII. PROPULSION SYSTEM WEIGHT FOR 2000-POUND SATELLITE WITH A 5-YEAR LIFE NOT PERFORMING NORTH-SOUTH STATIONKEEPING

High Thruster	Low Thruster	Propellant Weight	Inert Weight	Total Weight W/O Power	Power Penalty	Total Weight With Power
H_2O	Colloid	64.581	58.712	123.293	94.6	217.893
DO	Colloid	83.015	47.013	130.028	92.4	222.428
N_2H_4 Cat.	Colloid	94.475	38.910	133.385	92.4	225.785
N_2H_4 Cat.	Hg P. P.	94.475	46.711	141.186	132.0	273.186
DO	DO	114.763	44.932	159.695	-	159.695
N_2H_4 Cat.	N_2H_4 Radioisotope	123.835	36.944	160.779	-	160.779
ClF_5/N_2H_4	N_2H_4 GG Plenum	138.901	31.038	169.939	-	169.939
N_2O_4/N_2H_4	N_2H_4 GG Plenum	141.611	31.698	173.309	-	173.309
N_2H_4 Cat.	DART	117.022	57.894	174.916	-	174.916
N_2H_4 Cat.	Cs Ion	91.535	83.931	175.466	198.0	373.466
DART	DART	101.587	74.993	176.580	-	176.580
H_2O	H_2O	130.146	55.364	185.510	2.2	187.780
N_2H_4 Cat.	N_2H_4 GG Plenum	160.191	27.020	187.211	-	187.211
N_2H_4 Cat.	N_2H_4 Resistojet	192.057	23.933	215.990	6.6	222.590
N_2H_4 Cat.	N_2H_4 Cat.	299.488	32.664	332.152	-	332.152
N_2H_4 Cat.	N_2H_4 Electrolytic	373.085	37.286	410.371	19.8	430.171

TABLE VIII. POWER PENALTY

System	Penalty (pounds)
Electrolytic	19.8
Resistojet	6.6
Cs Ion	198.0
Colloid	92.4
Hg P.P.	132.0
H_2O	2.2

The ideal method of assessing a power penalty would be based on the continuous power required by a thruster. However, thruster requirements are given as, say, 100 watts. It is not stated if this is a continuous requirement or one that is required just during the pulse itself. Also, no information is given as to power required between pulses nor the amount of "warm-up" time required by a particular thruster. Therefore, power penalties were assessed on the basis of the amount of power required by a thruster times the number of thrusters onboard. The weight of a solar panel which would then provide this power was added to the propulsion system weight. In this manner, the maximum power penalty has been assessed upon the systems.

Figures 29 through 32 present the total propulsion system weights graphically. Figures 29 and 30 have no power penalties whereas Figures 31 and 32 include them. It should be noted that in each figure, the systems are arranged in order of increasing total weight for the mission with north-south stationkeeping.

Several observations are to be made from the two figures without power penalty. The most important is the large weight saving obtained when the small thruster is of the electric type and the mission requires north-south stationkeeping. In the case of a 10-year, 3000-pound satellite, this saving stands to be as much as 871 pounds between the N_2H_4 catalytic-N_2H_4 gas generator (GG) plenum system and the H_20 electrolysis-colloid system, and as little as 395 pounds between the all-H_20 electrolysis system and the N_2H_4 catalytic-Hg pulsed plasma system. This weight jump between electric and chemical small thrusters is not very large for a mission which does not require north-south stationkeeping, but there still are savings with electric propulsion. It is interesting to note that in all four missions, the H_20 electrolysis-colloid is the lightest propulsion system combination. For missions 10-3NS and 10-3 (i.e., 10 years, 3000 pounds, with and without north-south), the all-water electrolysis system is the lightest of the chemical systems.

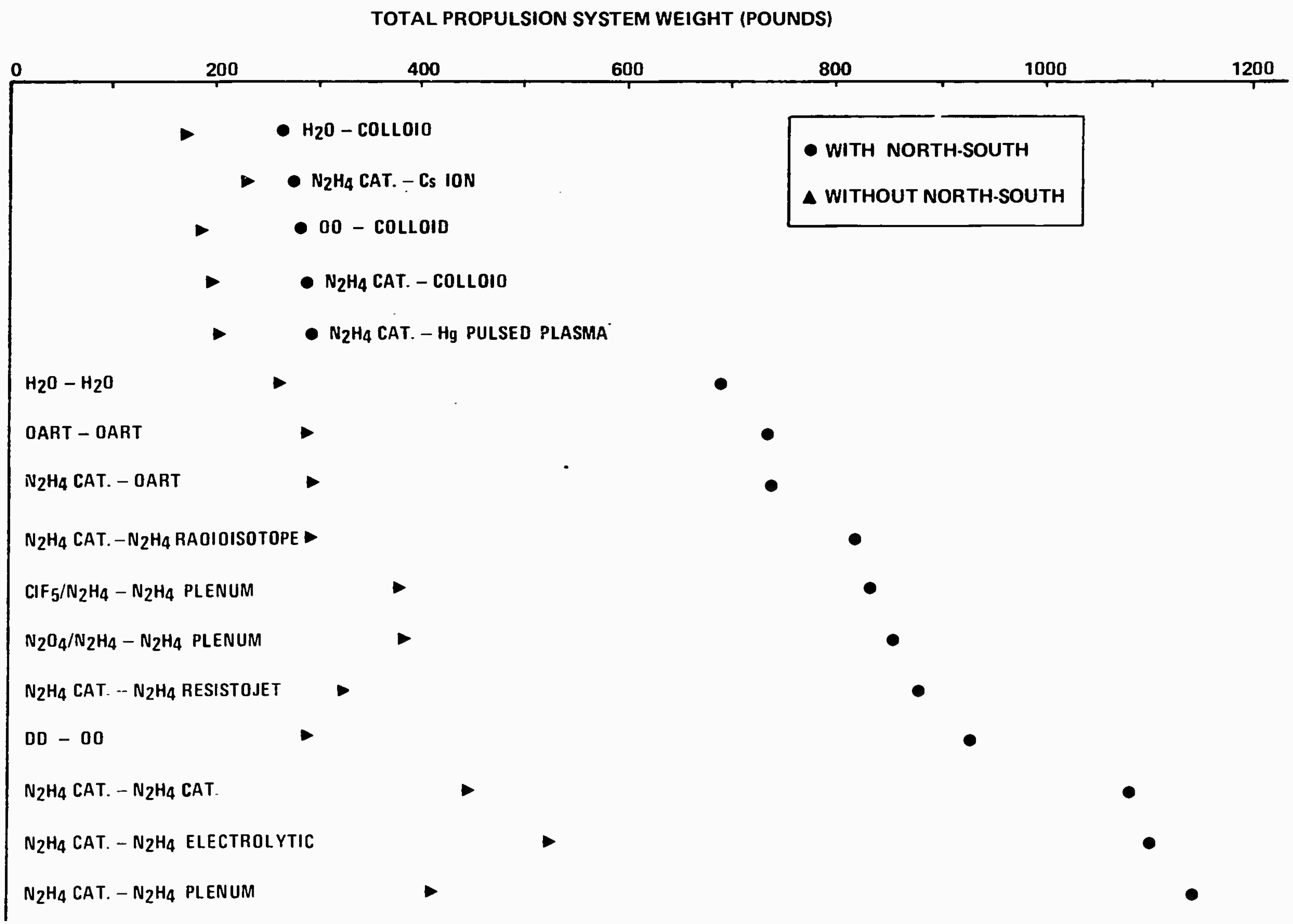


Figure 29. Propulsion System Weight for 3000-Pound, 10-Year Satellite Without Power Penalty

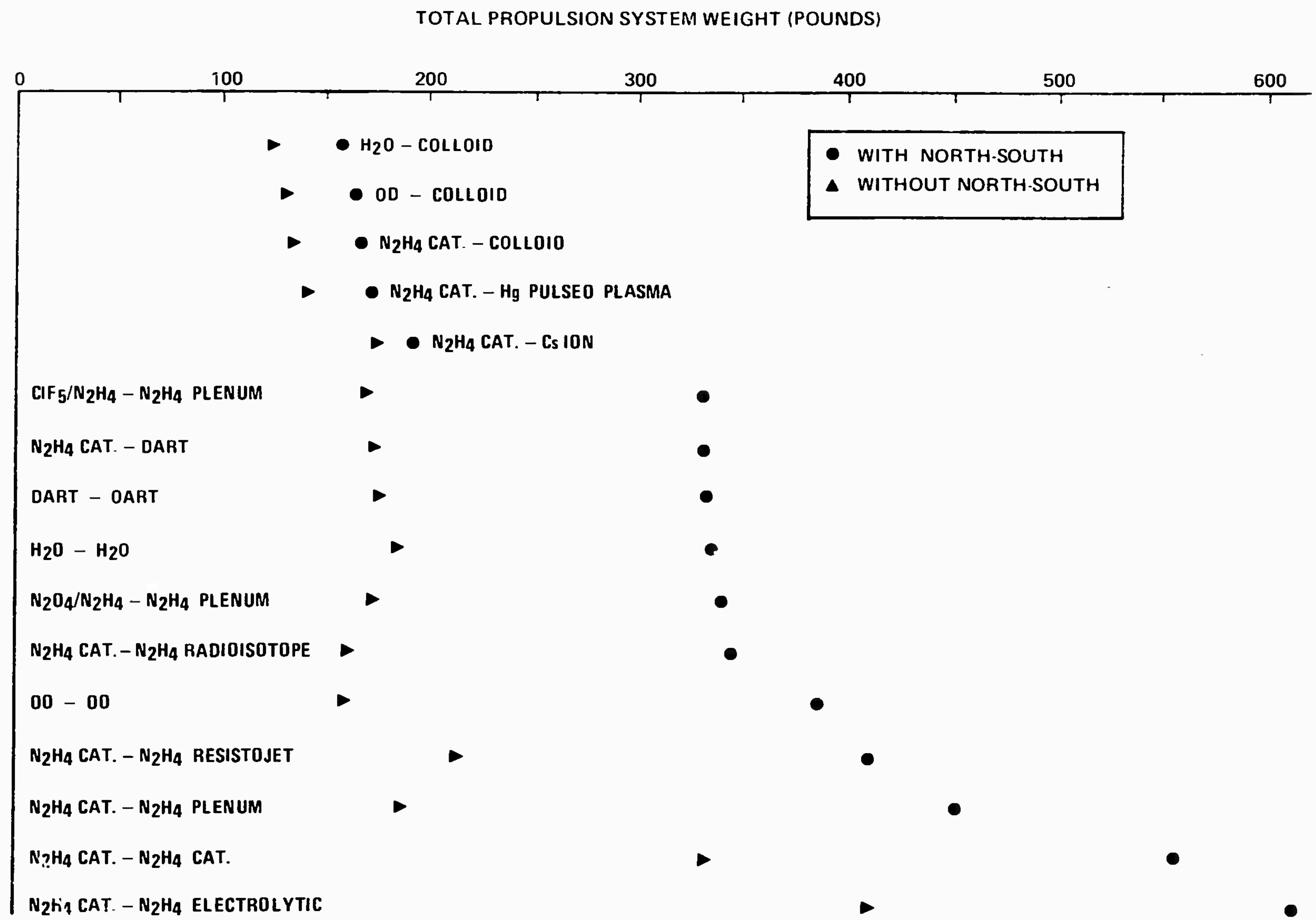


Figure 30. Propulsion System Weight for 2000-Pound, 5-Year Satellite Without Power Penalty

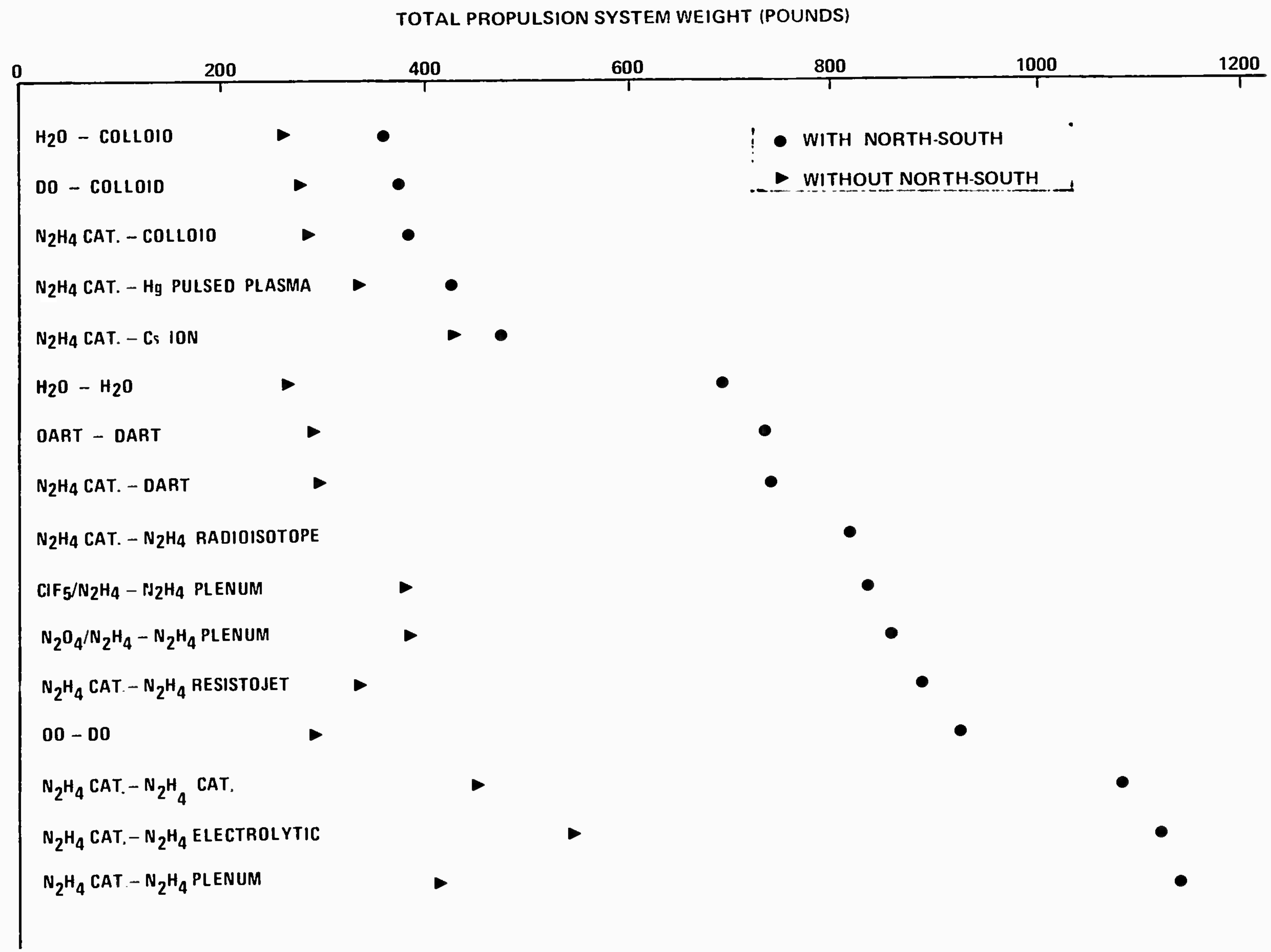


Figure 31. Propulsion System Weight for 3000-Pound, 10-Year Satellite With Power Penalty

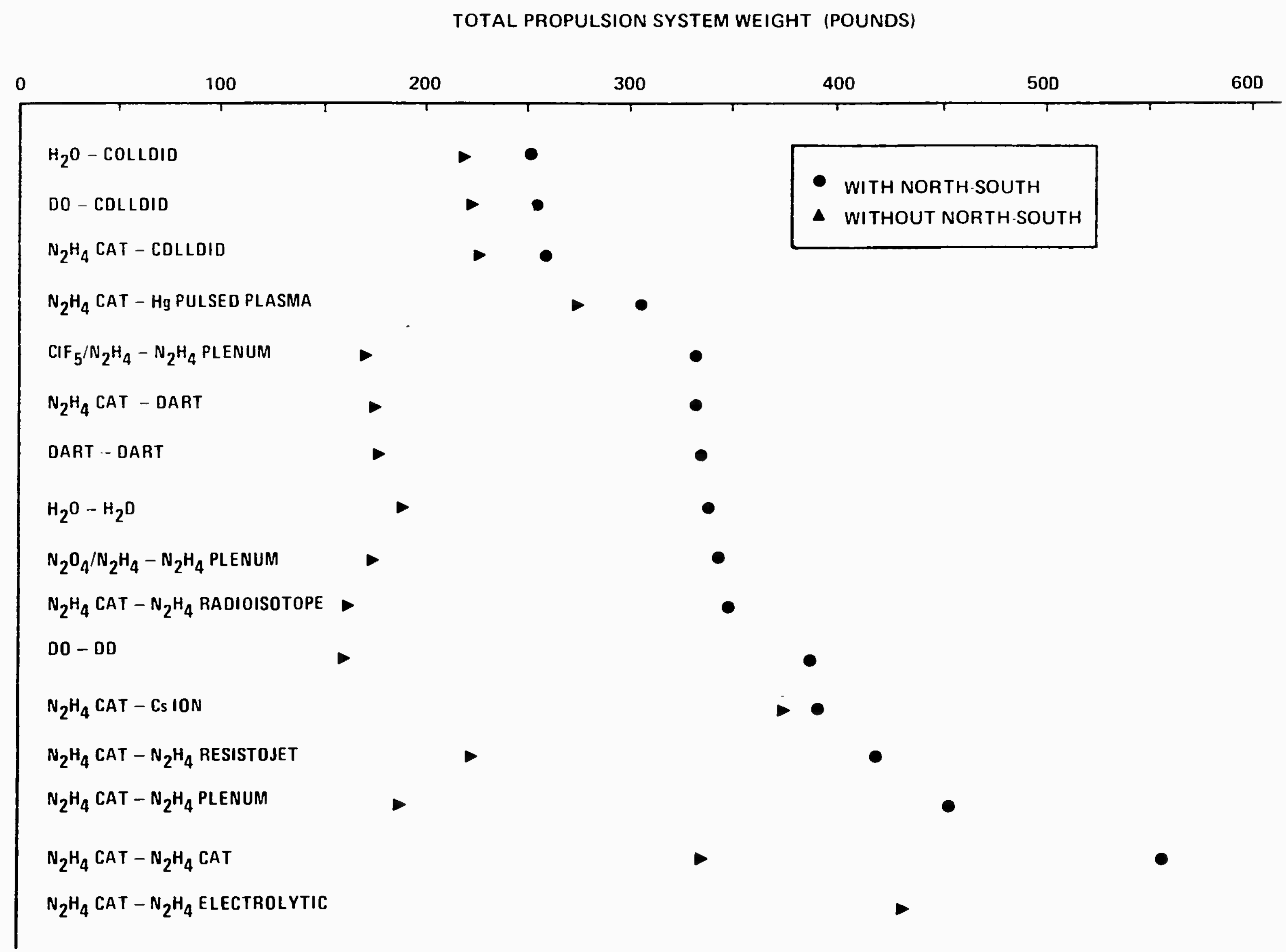


Figure 32. Propulsion System Weight for 2000-Pound, 5-Year Satellite With Power Penalty

For Mission 5-2NS, this system lacks only 4 pounds of being the lightest of all chemical systems. There are some systems which possess properties that translate themselves into total propulsion system weight handicaps for some of the missions investigated.

For Mission 10-3NS, the three systems, all N_2H_4 catalytic, N_2H_4 catalytic-N_2H_4 electrolytic and N_2H_4 catalytic-N_2H_4 GG plenum, have approximately the same total propulsion system weight. However, this trend disappears in Mission 5-2NS and 5-2. For these missions, the N_2H_4 catalytic-N_2H_4 GG plenum system is considerably lighter than the other two combinations. This is a result of the large minimum impulse bits required for N_2H_4 catalytic or N_2H_4 eletrolytic small thrusters. Hence, for either of these two systems to be competitive for the less strenuous missions, i.e., without N-S stationkeeping, the minimum impulse bit must be reduced.

A similar circumstance occurs with the electric thrusters and in particular the N_2H_4 catalytic-Cs ion system. However, in this case, the inert weight of the Cs ion thrusters and power-conditioning equipment is the reason for the increased weight. For the less strenuous missions, this inert weight begins to overshadow the propellant savings obtained with the large Isp of the Cs thruster when compared with the other electric systems.

There are several different observations to be made if a power penalty is included in the total system weight. These results are shown in Figures 31 and 32. The jump in system weight is not as large when going from electric to chemical. For Mission 10-3, there are several chemical systems which weigh less than the Hg pulsed plasma or cesium ion systems. For these two missions with the power penalty, the water electrolysis system is the lightest chemical system.

For Missions 5-2NS and 5-2, the effect of the power penalty on the Hg pulsed plasma and cesium ion engines is quite evident from Figure 32. For Mission 5-2NS, the weight of these two systems is comparable with the chemical systems whereas in Mission 5-2, most of the all-chemical systems weigh less than the electric systems. The water electrolysis-colloid system is the lightest for Mission 5-2NS, but for Mission 5-2, the all-DO system weighs less than any other one.

It is interesting to note that for all four missions investigated, the N_2H_4 catalytic-N_2H_4 electrolytic system requires the most total impulse to do the same mission. It also requires the most ΔV for mission accomplishment. The N_2H_4 catalytic-N_2H_4 GG plenum will accomplish all four missions while expending the least amount of total impulse.

D. SYSTEM COSTS

The cost of a propulsion system is an important and integral part of a total system analysis. The development cost data for an advanced propulsion system are very difficult to obtain. In addition, a significant portion of the development cost is expended for flight qualification. The cost of a system not previously developed for a similar application will necessarily be higher than that of a system already flown. Therefore, the costs shown here reflect the total system cost even though it may have already been spent. Therefore, all values shown have a common basis. It should be stressed that these are rough cost estimates and should be considered as such. These estimates do have value in that they provide a relative ranking of a system's cost. Table IX provides the costs for the individual thruster concepts, while Table X gives the cost for an et. ire propulsion system combination.

E. SYSTEM RELIABILITIES

Reliability data and combining techniques were used as suggested by a recent JPL report (Reference 2). Data presented in that report were derived from a review of previous reliability studies, reported component reliabilities and failure rate values. However, no failure rate data were included. Reliabilities for the noncyclic components were based on a 1-year mission duration, and the cyclic component reliabilities were used based on 10,000 cycles. Reliabilities were not improved through use of redundancy. A listing of component reliabilities used is provided in Table XI. Reliabilities used for the valve-thruster combinations are shown in Table XII.

TABLE IX. THRUSTER COSTS

	Thruster	Cost	Where Obtained
a.	Large Thruster	Million	
	N_2H_4 Cat.	2.5	AFRPL best estimate
	DO	3.0	AFRPL best estimate
	H_2O	5.0	Marquardt Corp. contract and AFRPL best estimate
	N_2O_4/N_2H_4	3.6	AFRPL best estimate
	ClF_5/N_2H_4	4.5	AFRPL best estimate
	DART	4.7	AFRPL best estimate and Reference 3
b.	Small Thruster		
	N_2H_4 Cat.	3.0	AFRPL best estimate
	N_2H_4 GG Plenum	3.5	AFRPL best estimate
	N_2H_4 Electrolytic	1.0	AFRPL best estimate

TABLE IX. THRUSTER COSTS (Cont)

Thruster	Cost	Where Obtained
b. Small Thruster		
N_2H_4 Resistojet	2.6	AFRPL best estimate and Reference 3
N_2H_4 Radioisotope	3.5	Reference 3
DART	4.7	AFRPL best estimate and Reference 3
Cs	4.0	AFAPL best estimate
Colloid	5.5	SAMSO ADP
Hg P. P.	4.85	AFAPL best estimate
DO	3.5	AFRPL best estimate
H_20	5.5	Marquardt Corp. contract and AFRPL best estimate

TABLE X. TOTAL PROPULSION SYSTEM COST

	Large Thruster	Small Thruster	Total System Cost (millions)
I	N_2H_4 Cat.	N_2H_4 Cat.	3.0
II	N_2H_4 Cat.	N_2H_4 GG Plenum	3.5
III	N_2H_4 Cat.	N_2H_4 Electrolytic	3.5
IV	N_2H_4 Cat.	N_2H_4 Resistojet	5.1
V	N_2H_4 Cat.	N_2H_4 Radioisotope	6.0
VI	N_2H_4 Cat.	DART	7.2
VII	N_2H_4 Cat.	Cs	6.5
VIII	N_2H_4 Cat.	Colloid	8.0
IX	N_2H_4 Cat.	Hg P.P.	7.35
X	DO	DO	3.5
XI	DO	Colloid	8.5
XII	H_20	H_20	5.0
XIII	H_20	Colloid	10.5
XIV	N_20_4/N_2H_4	N_2H_4 GG Plenum	7.1
XV	ClF_5/N_2H_4	N_2H_4 GG Plenum	8.0
XVI	DART	DART	4.7

TABLE XI. PROPULSION SYSTEM COMPONENT RELIABILITIES

<u>Noncyclic Components</u>	
Filter	0.9999
Propellant Tank	0.9999
Plenum Tank	0.99988
Pressurization Gas Tank	0.99988
Line Heater	0.99985
Pressure Transducer	0.99980
Bladder	0.99968
Fill Valve	0.99910
Lines and Manifolds	0.99850
<u>Cyclic Components</u>	
Gas Generator	0.9942
Electrolysis Cell	0.9925
Pressure Switch	0.9925
Relief Valve	0.9925
Regulator	0.9900
Solenoid Valve	0.9871
Bipropellant Solenoid	0.9830

TABLE XII. VALVE-THRUSTER RELIABILITY

Catalytic Monopropellant	0.9958
H_2 Electrolysis	0.9960
Bipropellant	0.9958
DART	0.9976
Monopropellant Plenum	0.9958
Electric Types	0.9970
Radioisotope Types	0.9976

The method used to obtain the reliability of each feed system employed the normal equation which is the product of all the component reliabilities raised to a power equal to the number of times that particular component appears in the system. The JPL report then suggests the following equations for the total system reliability.

1. The large thruster doing stationkeeping

$$R_{S_{LT}} = R_{F_{LT}} \, R^{4}_{V-T_{LT}}$$

where:

$R_{S_{LT}}$ = total large thruster system reliability

$R_{F_{LT}}$ = large thruster feed system reliability

$R_{V-T_{LT}}$ = large thruster - valve combination reliability

2. The large thruster not doing stationkeeping

$$R_{S_{LT}} = R_{F_{LT}} \, R^{2}_{V-T_{LT}}$$

3. The small thruster doing stationkeeping

$$R_{S_{ST}} = R_{F_{ST}} \; R_{V-T_{ST}}^{4}$$

here:

$R_{S_{ST}}$ = total small thruster system reliability

$R_{F_{ST}}$ = small thruster feed system reliability

$R_{V-T_{ST}}$ = small thruster valve combination reliability.

4. The small thruster not doing stationkeeping

$$R_{S_{ST}} = R_{F_{ST}} \; R_{V^{2}-T_{ST}}$$

Therefore, using these equations, a reliability for both the large thruster system and the small thruster system was obtained for each propulsion scheme. The propulsion systems can thus be ranked either according to the reliability of the large thruster or the reliability of the small thruster.

Table XIII shows the reliabilities for the large and small thruster feed systems and the total large and small thruster system. It should be pointed out that these numbers are based on the conceptual system schematics in the previous section, and therefore, are "conceptual reliabilities" only. However, they are useful from the standpoint of obtaining a relative ranking of the various propulsion schemes.

From Table XIII, the reliability ranking (high to low) for the large thruster feed systems may be summarized as in Table XIV.

TABLE XIII. SYSTEM RELIABILITY

Large Thruster	Small Thruster	Large Thruster Feed System	Large Thruster Total System	Small Thruster Feed System	Small Thruster Total System
N_2H_4 Cat.	N_2H_4 Cat.	0.95891	0.95087	0.95891	[illegible]
N_2H_4 Cat.	N_2H_4 Plenum	0.95891	0.94290	0.93899	[illegible]
N_2H_4 Cat.	N_2H_4 Electrolytic	0.95891	0.95087	0.95891	[illegible]
N_2H_4 Cat.	N_2H_4 Resistojet	0.95891	0.95087	[illegible]	[illegible]
N_2H_4 Cat.	N_2H_4 Radioisotope	0.95891	[illegible]	0.95891	[illegible]
N_2H_4 Cat.	DART	0.94654	0.93860	0.94654	0.93748
N_2H_4 Cat.	Cs Ion	0.94654	0.93860	0.94658	[illegible]
N_2H_4 Cat.	Colloid	0.94654	0.93860	0.94654	[illegible]
N_2H_4 Cat.	Hg Pulsed Plasma	0.94654	0.93860	0.94654	[illegible]
DO	DO	0.95891	0.94973	0.95891	[illegible]
DO	Colloid	0.94654	0.94200	0.94654	[illegible]
H_20	H_20	0.93202	0.91720	0.93202	0.92458
H_20	Colloid	0.93202	0.92458	0.95891	[illegible]
N_20_4/N_2H_4	N_2H_4 Plenum	0.91940	0.90405	0.92678	0.91901
ClF_5	N_2H_4 Plenum	0.91940	0.90405	0.92678	0.91901
DART	DART	0.95891	0.95431	0.95891	[illegible]

TABLE XIV. LARGE THRUSTER FEED SYSTEM RELIABILITY RANKING

Type	Propellant
Monopropellant	Same as in small thruster
Monopropellant	Different than in small thruster
Water Electrolysis	Same as in small thruster
Bipropellant	Fuel is same as small thruster propellant

A similar ranking for the small thruster feed system is in Table XV.

TABLE XV. SMALL THRUSTER FEED SYSTEM RELIABILITY RANKING

Type	Propellant
Monopropellant	Same as in large thruster
Monopropellant	Different than in large thruster
Plenum	Same as in monopropellant large thruster
Water Electrolysis	Same as in large thruster
Plenum	Same as fuel in bipropellant large thruster

These rankings serve to reiterate the obvious, that the more complicated or the more components in the feed system, the lower the reliability of that feed system. In like manner, large and small thruster total system reliability rankings may be obtained from Table XIII. For the large thruster, this ranking is shown in Table XVI.

TABLE XVI. TOTAL LARGE THRUSTER SYSTEM RELIABILITY RANKING

Type	Perform North-South	Propellant
Nuclear Thermal	No	Same as in small thruster
Catalytic	No	Same as in small thruster
Nuclear Thermal	Yes	Same as in small thruster
Catalytic	Yes	Same as in small thruster
Nuclear Thermal	No	Different than in small thruster
Catalytic	No	Different than in small thruster
H_2O Electrolysis	No	Different than in small thruster
H_2O Electrolysis	Yes	Same as in small thruster
Bipropellant	Yes	Fuel same as propellant in small thruster

The ranking for the small thruster system is in Table XVII.

TABLE XVII. TOTAL SMALL THRUSTER SYSTEM RELIABILITY RANKING

Type	Perform North-South	Propellant
Nuclear Thermal	No	Same as in large thruster
Nuclear Thermal	Yes	Same as in large thruster
Electric	Yes	Same as in large thruster
Catalytic	Yes	Same as in large thruster
Nuclear Thermal	Yes	Different than in large thruster
Electric	Yes	Different than in large thruster
Plenum	No	Same as in monopropellant large thruster
H_2O	No	Same as in large thruster
Plenum	No	Same as fuel in bipropellant large thruster

These total system rankings once again point out the fact that the simpler the conceptual diagram, the more reliable the system should be. In addition, the nuclear thermal thruster is more reliable than the catalytic systems. It must be pointed out, however, that there is probably a difference in the reliability of the thrusters for the DO, DART and N_2H_4 radioisotopes even though the value used for each is the same. The same applies to the electric-type thrusters. Common values were used because of the lack of data on these new thrusters. Therefore, care must be used in extracting just a number from these tables.

F. PLUME EFFECTS, INTEGRATION AND HANDLING

There are several other areas where the different combinations may be compared on a qualitative basis. One of these is plume effects. Two areas within plume effects warrant discussion. These are the signature of the plume and contamination of solar panels, and sensing devices by the plume. Table XVIII shows the propellants, their signatures and possible contaminations.

TABLE XVIII. PLUME EFFECTS

Propellant	Signature	Contamination
N_2H_4	Low	Low for short term; has not had long term studies done
NH_3	Low	Low
H_2O	High	High because of frozen water
N_2O_4/N_2H_4	High	High
ClF_5/N_2H_4	High	High
Cs	Low	Thought to be high but little data are available
Hg	Low	Same as Cs
Colloid	Low	Same as Cs
DO	High	High? No studies made

It must, however, be kept in mind that the contamination from any one of these propellants may be lowered by appropriate positioning of the thrusters or by careful tailoring of operating conditions. If the thrusters are pointed away from the solar panels and the sensors on the satellite, then there may be essentially no contamination from any of them. However, from a plume effects standpoint, the all-hydrazine or ammonia systems will produce the least plume effects whereas the bipropellants and the water systems probably produce the worst effects. The cesium, mercury and colloid may produce the worst contaminations of all but this isn't really known because no real in-depth studies have been made using the propellants. In addition, since two of the missions investigated here are 10 years in length, it should be pointed out that no work has been done on long-term plume effects of this duration.

Integration and handling are two other areas where comparisons are required. The systems employing a radioisotope for a heat source have unique problems in that they require special handling both on the ground and within the spacecraft. Adequate shielding presents a problem because of the excessive weight buildup of the containers. ClF_5 also has a ground-handling problem as a result of its corrosive and toxic nature.

Certain systems have inherent problems or lack flexibility. The cesium system is one of these because the entire feed system must be kept warm (above 83.3°F) to avoid the problem of frozen cesium in the feed lines. If the cesium freezes, then the wicking process of feeding the thruster will not work. Hence, there are inherent problems in the feed system. Because of the electrolysis cell in the H_2O electrolysis system, there is very little flexibility. The cell must be sized to accomplish the task and cannot be split up in order to redistribute the weight throughout the satellite. Also, the storage of gaseous hydrogen and oxygen in the mixed condition presents a potentially explosive problem. Care must be exercised in this area.

The electrical systems (Cs, Hg and colloid) are very complex systems. They require large voltages and power. In addition, the action of the accelerated particles can degrade and limit the life of some of the engine parts.

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

Based upon the calculated data, several conclusions may be made. Conclusions as to system weight will be based on data including power penalty.

1. For the more strenuous missions, i.e., with north-south stationkeeping, the systems using an electric small thruster have a considerable weight saving. This is particularly true if the electric concept is a colloid system. The cesium and mercury pulsed plasma do not offer as large a weight saving, and in one case, none at all (cesium on a 5-year satellite).

2. For missions requiring no north-south stationkeeping, the electric systems offer no advantage from a weight standpoint. If the mission life is for 5 years or less, a considerable weight disadvantage is incurred as a result of the power penalty required.

3. The water electrolytis or nuclearthermal systems appear to offer some weight savings over the other "all-chemical" systems for the more strenuous missions. For the less strenuous mission, these systems are comparable in weight.

4. Although the all-hydrazine catalytic systems appear to offer no weight savings, the effect of the hydrazine plume is less than all other systems. Furthermore, because of the number of currently operational catalytic systems, further development and flight qualification are minimized.

5. If the actual power penalty is anywhere near that estimated, the electric systems offer no advantage for missions not requiring north-south stationkeeping.

6. The weight savings obtained for missions with no north-south stationkeeping indicate that development of an all-DO system is warranted.

7. The nuclearthermal systems appear to have very good reliability whereas the bipropellants and the water electrolysis system have worse reliabilities.

8. The reliabilities for solenoid valves are very poor and additional development in this area is needed. Also, considerable reliability work and life testing must be done in the electric thruster area.

9. The hydrazine electrolytic system suffers from a poor minimum impulse bit of 0.005 lb_f-sec. If this could be reduced to 0.004 lb_f-sec, then this concept may compare more favorably with the hydrazine catalytic systems.

10. The nuclearthermal systems have an integration and handling problem which must be solved.

The following recommendations are thus put forward.

1. Advanced development of the electric thrusters and, in particular, the colloid thruster

2. Life and reliability work on electric thrusters

3. Reduction of the power requirement of the electric thrusters

4. Development of the water electrolysis thrusters

5. Reduction of minimum impulse bit for the hydrazine electrolytic and the cesium ion thrusters

6. Development of DART and DO nuclearthermal thrusters

7. Improvement of valve reliability

APPENDIX A

SATELLITE PROPULSION SYSTEM WEIGHT PROGRAM DESCRIPTION

The computer program can be divided into 15 distinct sections. This is shown on the overall logic diagram on the next page. The program calculates certain data in each of these sections. The flow through these sections is as shown in the diagram. Following the diagram is a short description of the calculations in each section.

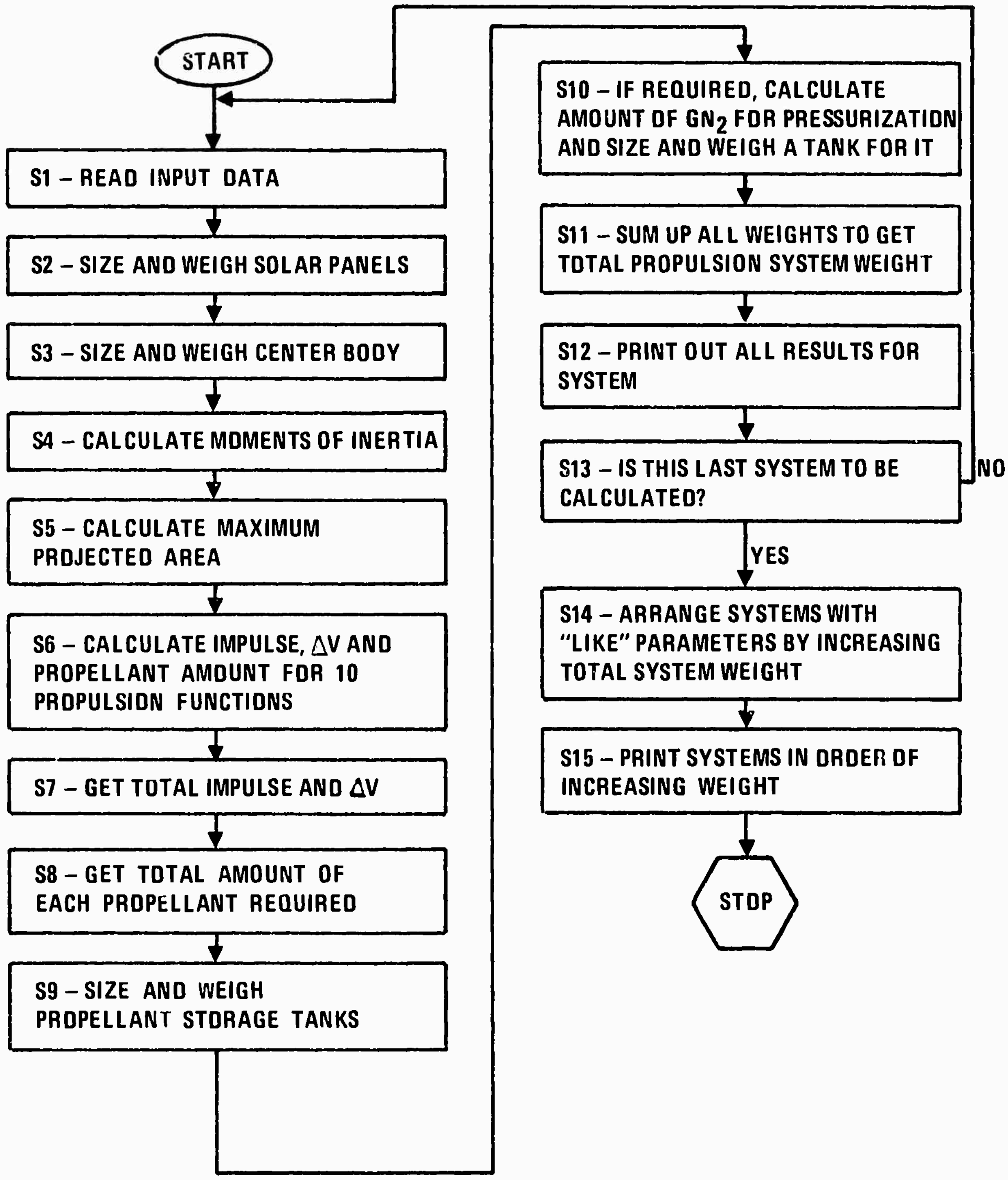


Figure 33. Logic Diagram for Computer Program

S1 - READ INPUT DATA

The data cards for a particular system are read into the computer.

S2 - SIZE AND WEIGHT SOLAR PANELS

The initial gross weight of the satellite is used to determine the onboard power from the solar panels using equation III-1 in the main body of this report. The panels are then sized and weighed using the ideal specific weight, percent life degradation, specific surface area and height-to-length ratio.

S3 - SIZE AND WEIGH CENTERBODY

The centerbody weight is equal to the initial gross weight minus the weight of the solar panels. The centerbody can then be sized using the bulk density, centerbody shape code and the dimension ratios supplied as input.

S4 - CALCULATE MOMENTS OF INERTIA

The moments of inertia for the spacecraft are calculated here. Referencing the axis system as set up around the spacecraft in Figure 1 of the main body of this report, the equations for the moments of inertia in slug-ft^2 are:

For spherical centerbody:

$$I_{xx} = \frac{2\,M_{CB}}{5g}\left(\frac{D}{2}\right)^2 + \frac{2\,M_{SP}}{3g}\,Y_{SP}^2 + \frac{2\,M_{SP}}{g}\left(\frac{D}{2}\right)^2 \qquad (A-1)$$

$$I_{yy} = \frac{2\ M_{CB}}{5g} \left(\frac{D}{2}\right)^2 + \frac{2\ M_{SP}}{3g} X_{SP}^2 - \frac{2\ M_{SP}}{g} \left(\frac{X_{SP}}{2}\right)^2 \qquad \text{(A-2)}$$

$$I_{zz} = \frac{2\ M_{CB}}{5g} \left(\frac{D}{2}\right)^2 + \frac{2\ M_{SP}}{12g} \left(Y_{SP}^2 + X_{SP}^2\right) + \qquad \text{(A-3)}$$

$$\frac{2\ M_{SP}}{g} \left(\frac{D}{2} + \frac{Y_{SP}}{2}\right)^2$$

where: M_{CB} = mass of centerbody

M_{SP} = mass of solar panel

D = centerbody diameter

Subscript CB = centerbody

SP = solar panel

For cylindrical centerbody:

$$I_{xx} = \frac{M_{CB}}{2g} \left(\frac{D}{2}\right)^2 + \frac{2\ M_{SP}}{3g} Y_{SP}^2 + \frac{2\ M_{SP}}{g} \left(\frac{D}{2}\right)^2 \qquad \text{(A-4)}$$

$$I_{yy} = \frac{M_{CB}}{4g} \left[\left(\frac{D}{2}\right)^2 + \frac{L^2}{3}\right] + \frac{2\ M_{SP}}{3g} X_{SP}^2 - \qquad \text{(A-5)}$$

$$\frac{2M_{SP}}{g} \left(\frac{X_{SP}}{2}\right)^2$$

$$I_{zz} = \frac{M_{CB}}{4g}\left[\left(\frac{D}{2}\right)^2 + \frac{L^2}{3}\right] + \frac{2\,M_{SP}}{12g}\left(Y^2_{SP} + X^2_{SP}\right) \qquad \text{(A-6)}$$

$$+ \frac{2\,M_{SP}}{g}\left(\frac{D}{2} + \frac{Y_{SP}}{2}\right)^2$$

For rectangular centerbody:

$$I_{xx} = \frac{M_{CB}}{12g}\left(Z^2_{CB} + Y^2_{CB}\right) + \frac{2\,M_{SP}}{3g}\,Y^2_{SP} + \qquad \text{(A-7)}$$

$$\frac{2\,M_{SP}}{g}\left(\frac{Y_{CB}}{2}\right)^2$$

$$I_{yy} = \frac{M_{CB}}{12g}\left(X^2_{CB} + Z^2_{CB}\right) + \frac{2\,M_{SP}}{3g}\,X^2_{SP} - \qquad \text{(A-8)}$$

$$\frac{2\,M_{SP}}{g}\left(\frac{X_{SP}}{2}\right)^2$$

$$I_{zz} = \frac{M_{CB}}{12g}\left(X^2_{CB} + Y^2_{CB}\right) + \frac{2\,M_{SP}}{12g}\left(Y^2_{SP} + X^2_{SP}\right) \qquad \text{(A-9)}$$

$$+ \frac{2\,M_{SP}}{g}\left(\frac{Y_{CB}}{2} + \frac{Y_{SP}}{2}\right)^2$$

S5 - CALCULATE MAXIMUM PROJECTED AREA

This area is required in the calculation of solar pressure corrections and is the area seen when looking along the Z axis in Figure 1, including solar panel and centerbody projected area.

S6 - CALCULATE IMPULSE, ΔV AND PROPELLANT AMOUNT FOR TEN MISSION FUNCTIONS

The ten mission functions are calculated in the following order where it has been assumed that the satellite is repositioned halfway through its lifetime. It is possible, however, to eliminate any number of these functions. In such a case, the computer automatically sets the impulse, ΔV and propellant required to zero.

1. Despin
2. Tipoff
3. Injection
4. One-half of the total E-W stationkeeping
5. One-half of the total N-S stationkeeping
6. One-half of the total attitude maintenance, i.e., solar pressure, limit cycle and contingency.
7. Repositioning
8. One-half of the total E-W stationkeeping
9. One-half of the total N-S stationkeeping
10. One-half of the total attitude maintenance
11. Stationkeeping contingency

The method for calculating the impulse, ΔV and amount of propellant for each propulsion function is as follows:

1. DESPIN

The impulse is calculated by dividing the satellite initial angular momentum by half the maximum distance between thrusters in the x-y plane (Figure 1). If the centerbody is a sphere or a cylinder, then this maximum distance is the diameter. If a rectangle, then use the largest dimension (y or z) of the centerbody.

The amount of propellant equals this impulse divided by the Isp for this function, and the ΔV required is obtained from the normal equation.

$$\Delta V = g\ Isp\ \ln\ (M_o / M_e) \qquad (A-10)$$

where: M_o = mass of satellite at beginning of maneuver

M_e = mass of satellite at end of maneuver

2. TIPOFF RATE

The impulse for tipoff is read into the computer as input data. The amount of propellant and ΔV are then calculated as for Despin.

3. INJECTION ERROR

The ΔV for this is read in as input data. The amount of propellant is determined through the use of equation A-10 and the impulse by multiplying the amount of propellant by the Isp.

4. EAST-WEST STATIONKEEPING

From Table I, the ΔV is equal to

$$\Delta V = 7.15\ t_m \qquad (A-11)$$

where t_m is the satellite life in years. The impulse and propellant are then calculated as an Injection Error.

5. NORTH-SOUTH STATIONKEEPING

From Table II, the ΔV is equal to

$$\Delta V \quad 150\ t_m$$

Impulse and propellant are as in east-west stationkeeping.

6. STATIONKEEPING CONTINGENCY

The amount of impulse is equal to 3 percent of the sum of the east-west impulse and the north-south impulse. ΔV and propellant are then calculated as in Tipoff Rate.

7. SOLAR PRESSURE

The impulse is calculated from equation III-2 in the form

$$I_{t_s} = 5.91\, t_m\, (0.35)\, A_\perp$$

where $A_\perp$ = maximum projected area, ft^2. The ΔV and propellant are then calculated as in Tipoff Rate.

8. LIMIT CYCLE

A value is calculated from both equation III-3 and equation III-4. The impulse required for limit cycling is then the larger of the two numbers. ΔV and propellant are then calculated as in Tipoff Rate.

9. ATTITUDE MAINTENANCE CONTINGENCY

The impulse is calculated as per equation III-5 with ΔV and propellant as per Tipoff Rate.

10. REPOSITIONING

The ΔV is determined from equation III-7. Impulse and propellant are then calculated as per Injection Error.

S-7 - GET TOTAL IMPULSE AND ΔV

The total impulse and ΔV are obtained by summing the impulse and ΔV from each of the ten propulsion functions.

S-8 - GET TOTAL AMOUNT OF EACH PROPELLANT REQUIRED

In this section, the amount of each propellant used for the ten propulsion functions is summed. This section has the capability of handling a bipropellant large thruster. By using the mixture ratio on this, the two propellants can be split out to give correct propellant sums. An ullage of 1.5 percent is then added to each propellant sum.

S-9 - SIZE AND WEIGHT, PROPELLANT STORAGE TANKS

Spherical tanks are designed for propellant storage. They are sized by getting the total volume required from knowing the total propellant and the propellant density. The tanks are then weighed using the equation

$$\text{weight} = \frac{2\pi}{0.9} \frac{\mathbb{P} R^3}{\sigma_y} \rho \qquad \text{(A-12)}$$

where: $\mathbb{P}$ = operating pressure, psi
R = tank radius, inches
ρ = tank material density, lb/in^3
σ_y = yield stress of tank material, psi

A safety factor of 1.25 is used in this calculation. From this weight, the thickness of the tank is determined. This thickness is then compared with that coming from the normal stress equation

$$T = \frac{\mathbb{P} R}{2\sigma_y} \qquad \text{(A-13)}$$

The largest thickness is then selected and compared with the minimum average workable thickness (input data) for that particular metal. The largest of the three thicknesses is selected and the tank reweighed using this thickness. Then 15 percent of this weight is added to account for fittings, flanges and attachment points. The program has the ability to not design a tank for any particular propellant if so desired.

S-10 - PRESSURIZATION SYSTEM

The program can design a pressurization tank, weigh it and weigh the gaseous nitrogen placed in it if so desired. It is also set up to pressurize only some of the propellant tanks. To simplify the calculations, an isothermal expansion of the GN_2 was assumed.

S-11 - SUM UP ALL WEIGHTS TO GET A TOTAL PROPULSION SYSTEM WEIGHT

All weights are summed.

S-12 - PRINT OUT ALL RESULTS FOR SYSTEM

The results for the particular system just calculated are printed out.

S-13 - IS THIS LAST SYSTEM TO BE CALCULATED?

A check is made to see if there are more systems to be calculated. Up to 99 systems may be calculated with one computer run.

S-14 - ARRANGE SYSTEMS WITH "LIKE" PARAMETERS BY INCREASING TOTAL SYSTEM WEIGHT

Systems with common parameters (i.e., doing the same propulsion functions, having same initial gross weight and satellite life, etc.) are ranked according to increasing total propulsion system weight. If the computer received no inert weights (pipes, valves, thrusters, etc., as input data) for a particular system, then this system's total weight will appear as zero in the listing.

S-15 - PRINT SYSTEMS IN ORDER OF INCREASING WEIGHT

This increasing total weight listing is printed out.

APPENDIX B
SATELLITE PROPULSION SYSTEM WEIGHT PROGRAM USER MANUAL

This section describes the procedure for writing the input required to use the computer to weigh the total propulsion system to accomplish the proposed post-1975 mission model. Twelve different types of input data cards are required to manipulate the program. Cards 2 through 12 describe any particular high-low thruster combination desired. Card 1 tells the computer how many such cases or combinations will be investigated. Up to 99 different combinations may be calculated during one computer run. However, a complete set of data cards (cards 2 through 12) must be furnished for each case. In the event of a special study involving relatively few changes on repeated cases, the original data deck for that case must be reproduced and only those cards containing changes must be repunched and inserted.

The input variables required by the program are defined on the following pages. This is followed by a listing of card formats and input instructions. Also included is a list of suggested values for some of the variables required by the program.

TABLE XIX. COMPUTER INPUT VARIABLES

C(i)	The Chemical used in a thruster
DBHAID	The Dead Band Half Angle In Degrees
DEN(i)	The DENsity of chemical C(i) in lbs/ft^3
IDWHB	Means Do We Have a Bipropellant large thruster. Depending upon the value of IDWHB, the computer will decide whéther there is a biprop or not
IDWPET(i)	Is a code that identifies which chemicals are expelled under pressure and which ones are not (Do We Pressurize Each Tank)
IDWSEP(i)	Is a code which identifies which chemicals are stored in a tank and which ones are not (Do We Store Each Propellant in a tank)
IDWWP	This is a code which tells the computer Do We Want a Pressurization system
INOP	The Number Of different Propellant, C(i), in the system
INOSTR	The Number Of Systems To Be Run or calculated. A system refers to a particular large-small thruster combination
IS(i)	A code which tells the computer which thruster (large or small) is used for mission function i
ISCBC	A code which tells the computer the geometry of the centerbody. (Satellite Center Body Code)
LL(i)	The number of systems which perform common mission functions
MM	A code which tells the computer whether to add inert weights or not
OPPRE	The initial storage Pressurant PREssure in psi

TABLE XIX. COMPUTER INPUT VARIABLES (Continued)

PTDEN	The density of the tank material used for storing a pressurant in $lbs/in.^3$ (Pressurant Tank DENsity)
PTSIG	The yield stress of the tank material used for storing a pressurant in psi (Pressurant Tank SIGma)
PWMIN	The minimum pulse width of the small thruster in seconds (Pulse Width MINimum)
SCBDEN	The Satellite CenterBody bulk DENsity in lbs/ft^3
SCBLOD	The Satellite CenterBody Length Over Diameter if it is a cylinder and the Z/Y ratio if it is a rectangle
SCBZTX	The Satellite CenterBody Z To X ratio if it is a rectangle
SDV(3)	The Satellite Delta Velocity required for injection error in ft/sec
SIAM	The Satellite Initial Angular Momentum in ft-lb-sec
SIG(i)	The yield stress (SIGma) for the storage tank material for chemical C(i) in psi
SISP(i)	Are the System ISP's for a given propellant system for the 10 steps or functions required in the mission in sec
SIT(2)	The total impulse required for tipoff rate in lb_f-sec (Satellite Impulse Total)
SLIFE	The Satellite LIFE in years
SPHTL	The Solar Panel Height To Length ratio
SPISW	The Solar Panel Ideal Specific Weight in lbs/kw
SPPCLD	The Solar Panel PerCent Life Degradation
SPSSA	Solar Panel Specific Surface Area in ft^2/kw
SREPRA	The Satellite REPositioning RAte in degrees/day

TABLE XIX. COMPUTER INPUT VARIABLES (Continued)

SUB(i)	The propellant (SUBstance) or propellant combination used in a thruster
SWGT	Is the Satellite WeiGhT (initial gross weight) in pounds
TAMA(i)	The name of the storage TAnk MATerial for chemical C(i)
TAPR(i)	Is the storage TAnk PRessure for chemical C(i) in psi
THEDMI	The minimum achievable angular rate of the satellite for limit cycling in degrees/sec (THEta Dot MInimum)
THRMIN	The small THRuster MINimum thrust in lbs_f
TMDEN(i)	The storage Tank Material DENsity for chemical C(i) in $lbs/in.^3$
TMMT(i)	The minimum workable thickness for storage tank material TAMA(i) in inches (Tank MinimuM Thickness)
WGTI(i)	The inert weight of the propulsion system - includes, pipes, valves and thrusters in pounds (WGT Inert

INPUT DATA CARD FORMATS

Card No.	
1	Contol and Setup (31I2)
2	Large and Small Thruster Names [3 (3A6)]
3	Propellant Name and Propellant Density [3 (2A6), 3F10.3]
4	Propulsion Function and System Specification (10I2, 9X, I1, 9X, I1, 9X, I1, 10X, F6.3)
5	Propulsion Function Isp's (10F8.3)
6	General Satellite Specifications (5F10.4, 9X, I1, 2F10.4)
7	Solar Panel Specifications (4F10.4)
8	Thruster Specifications (F10.4, 3 F10.6, 2F10.4)
9	Propellant Storage Tank Materials [3 (2A6)]
10	Storage Tank Material Properties (3F10.3, 3F10.2, 3F6.4)
11	Pressurant Storage Tank Material Properties and Operating Pressures (2F10.3, F10.2, 3F10.3, 1X, I1, 1X, I1, 1X, I1, 5X, I1, 1X, I1, 1X, I1)
12	Thruster, Piping and Plumbing Weights (4F10.3, 1X, I1)

CARD NO. 1 (31I2)

CONTROL AND SETUP

Variable	Columns	Remarks
INØSTR	1-2	Place the total number of distinct system cases to be investigated in these two columns. The number must be right oriented. (Limited to 99)
LL (1)	3-4	Place the number of system cases that perform common mission functions here. The number must be right oriented.*
LL (2)	5-6	Place the number of systems cases in the second group which perform like mission functions here. The number must be right oriented.*
.	.	
.	.	
.	.	
.	.	
LL (30)	61-62	

*At the end of the computer output, the computer ranks all system cases with common parameters (i.e., initial gross weight, life, etc.) or mission functions (i.e., north-south stationkeeping, repositioning, etc.) in order of ascending total propulsion system weight. These variables (LL (I)) tell the computer how many system cases are in each common grouping. If LL(1) = 5 and LL(2) = 8, then the first 5 cases in the input cards will be ranked together and the next 8 input cases will be ranked together. There can be up to 30 such groupings.

CARD NO. 2 [3 (3A6)]

LARGE AND SMALL THRUSTER NAMES

This card can be filled out four different ways. Match the system to be investigated with either CASE A, B, C or D and input accordingly.

Variable	Columns	Remarks
CASE A -		The large thruster is a monopropellant. The small thruster is a monopropellant. The chemical used in the large thruster is not the same as that used in the small thruster.
SUB(1)	1-18	Place a descriptor for the large thruster here. Example: CATALYTIC N2H4
SUB(2)	19-36	Place a descriptor for the small thruster here. Example: DART (NH3)
CASE B -		The large thruster is a monopropellant. The small thruster is a monopropellant. The chemical used in each thruster is the same.
SUB(1)	1-18	Place a descriptor for the large thruster here. Example: CATALYTIC N2H4
SUB(2)	19-36	Place a descriptor for the small thruster here. Example: ELECTROLYTIC N2H4
CASE C -		The large thruster is a bipropellant. The small thruster is a monopropellant. The chemical in the monopropellant IS the same as the fuel in the bipropellant.
SUB(1)	1-18	Place a descriptor for the bipropellant large thruster here. Example: NTO/HYDRAZINE
SUB(2)	19-36	Place a descriptor for the monopropellant small thruster here. Example: CATALYTIC N2H4
CASE D -		The large thruster is a bipropellant. The small thruster is a monopropellant. The chemical in the monopropellant is NOT the same as the fuel in the bipropellant.
SUB(1)	1-18	Place a descriptor for the bipropellant large thruster here. Example: NTO/HYDRAZINE
	19-36	NOT USED
SUB(3)	37-54	Place a descriptor for the monopropellant small thruster here. Example: DART (NH3)

CARD NO. 3 [3 (2A6), 3F10.3]

PROPELLANT NAME AND PROPELLANT DENSITY

Fill out this card according to the instructions matching the case chosen for CARD 2.

Variable	Columns	Decimal Location	Remarks
CASE A			
C(1)	1-12	None	Place the chemical symbol here for the chemical used in the large thruster.
C(2)	13-24	None	Place the chemical symbol here for the chemical used in the small thruster.
	25-36		NOT USED
DENS(1)	37-46	COL. 43	The density of chemical C(1) in lb/ft^3
DENS(2)	47-56	COL. 53	The density of Chemical C(2) in lb/ft^3
CASE B			
C(1)	1-12	None	Place the chemical symbol here for the chemical used in both the large and small thruster.
	13-36		NOT USED
DENS(1)	37-46	COL. 43	The density of chemical C(1) is lb/ft^3
CASE C			
C(1)	1-12	None	Place the chemical symbol here for the oxidizer in the large thruster bipropellant.
C(2)	13-24	None	Place the chemical symbol here for the fuel in the large thruster bipropellant
	25-36		NOT USED
DENS(1)	37-46	COL. 43	The density of the biprop oxidizer in lb/ft^3
DENS(2)	47-56	COL. 53	The density of the biprop fuel in lb/ft^3
CASE D			
C(1)	1-12	None	Place the chemical symbol here for the biprop oxidizer.
C(2)	13-24	None	Place the chemical symbol here for the biprop fuel.
C(3)	25-36	None	Place the chemical symbol here for the chemical in the monoprop small thruster.
DENS(1)	37-46	COL. 43	The density of the biprop oxidizer in lb/ft^3
DENS(2)	47-56	COL. 53	The density of the biprop fuel in lb/ft^3
DENS(3)	57-66	COL. 63	The density of the monoprop chemical in lb/ft^3

Note: The decimal is assumed to be in column shown unless a decimal point is explicitly inserted in input.

CARD NO. 4 (10I2, 9X, I1, 9X, I1, 9X, I1, 10X, F6.3)

PROPULSION FUNCTION AND SYSTEM SPECIFICATION

Variable	Columns	Decimal Location	Remarks
IS(1)	1-2	None	Despin code*
IS(2)	3-4	None	Tipoff rate code*
IS(3)	5-6	None	Injection error code*
IS(4)	7-8	None	E-W stationkeeping code*
IS(5)	9-10	None	N-S stationkeeping code*
IS(6)	11-12	None	Stationkeeping contingency code*
IS(7)	13-14	None	Solar pressure code*
IS(8)	15-16	None	Limit cycle code*
IS(9)	17-18	None	Attitude maintenance contingency code*
IS(10)	19-20	None	Repositioning code*
	21-29		NOT USED
IDWHB	30	None	Bipropellant large thruster code**
	31-39		NOT USED
IDWWP	40	None	Pressurization code***
	41-49		NOT USED
INØP	50	None	Number of chemicals code****
	51-60		NOT USED
WGTR	61-66	COL 63	The mixture ration for the bipropellant large thruster. It must be written as the ratio of C(1)/C(2)

CARD 4 (cont)

* These ten codes tell the computer which thruster (large or small) is used for each of the ten mission functions. If a function requires the large thruster, then IS(i) = 1. If a function requires the small thruster, then IS(i) = 2 or 3 depending on whether SUB(2) or SUB(3) was used on Card 2. If it is desired to eliminate one of the ten functions from the system, then IS(i) = 0 for that particular function. More than one propulsion function can be eliminated at once. All numbers must be right oriented in the fields.

** = 0 if the large thruster is a monopropellant

= 1 if the large thruster is a bipropellant

*** = 0 if all of the system is a blowdown

= 1 if any part or all of the system is to be pressurized from a gas bottle

**** The total number of chemicals placed on Card 3

CARD NO. 5 (10F8.3)

PROPULSION FUNCTION Isp's

Variable	Columns	Decimal Location	Remarks
SISP(1)	1-8	COL 5	Despin Isp
SISP(2)	9-16	COL 13	Tipoff rate Isp
SISP(3)	17-24	COL 21	Injection error Isp
SISP(4)	25-32	COL 29	E-W stationkeeping Isp
SISP(5)	33-40	COL 37	N-S stationkeeping Isp
SISP(6)	41-48	COL 45	Stationkeeping contingency Isp
SISP(7)	49-56	COL 53	Solar pressure Isp
SISP(8)	57-64	COL 61	Limit cycle Isp
SISP(9)	65-72	COL 69	Attitude maintenance contingency Isp
SISP(10)	73-80	COL 77	Repositioning Isp

These are the 10 Isp values in seconds which are obtainable from the particular propellant(s) and the duty cycle for the 10 mission functions.

CARD NO. 6 (5F10.4, 9X, I1, 2F10.4)

General Satellite Specifications

Variable	Columns	Decimal Location	Remarks
SWGT	1-10	Col 6	The initial gross weight of the satellite in pounds.
SCBDEN	11-20	Col 16	The bulk density of the satellite centerbody is lb/ft^3
SCBLØD	21-30	Col 26	If the centerbody of the satellite is a cylinder, then this is the L/D ratio. If the centerbody is a rectangle, then this ratio is the ratio of the dimensions of the end of the rectangle which faces the earth.
SCBZTX	31-40	Col 36	This is used only if the centerbody is a rectangle. It is the ratio of one side of the end of the rectangle to the length or height of the rectangle.
SLIFE	41-50	Col 46	The life of the satellite in years.
	51-59		Not used.
ISCBC	60	None	Centerbody shape code*
SIAM	61-70	Col 66	The satellite initial angular momentum in FT - LB - SEC
SREPRA	71-80	Col 76	The satellite repositioning rate in degrees per day.

* 1 if centerbody is a rectangle
2 if centerbody is a sphere
3 if centerbody is a cylinder

CARD NO. 7 (4F10.4)

Solar Panel Specifications

Variable	Columns	Decimal Location	Remarks
SPISW	1-10	Col 6	The solar panel ideal specific weight in LB/KW
SPPCLD	11-20	Col 16	The solar panel percent life degradation at the end of the satellite life.
SPSSA	21-30	Col 26	The solar panel specific surface area in FT^2/KW.
SPHTL	31-40	Col 36	The ratio of the height of the solar panels (the side adjacent to the centerbody) to the length of the solar panel (the side perpendicular to the centerbody)

CARD NO. 8 (F10.4, 3F10.6, 2F10.4)

Thruster Specifications

Variable	Columns	Decimal Location	Remarks
THRMIN	1-10	Col 6	The minimum thrust of the thruster used for limit cycling in LB_F.
PWMIN	11-20	Col 14	The minimum pulse width obtainable with the valving for the thruster used in limit cycling in seconds.
DBHAID	21-30	Col 24	The dead band half-angle for limit cycling in degrees.
THEDMI	31-40	Col 34	The minimum achievable average angular rate in limit cycling in degrees per second.
SIT (2)	41-50	Col 46	The total impulse in LB-SEC required for tip-off rate.
SDV (3)	51-60	Col 56	The delta V in FT/SEC required for injection error.

CARD NO. 9 | 3 (2A6) |

Propellant Storage Tank Materials

Variable	Columns	Remarks
TAMA (1)	1-12	A descriptor for the tank material for storing C (1). Example: TITANIUM
TAMA (2)	13-24	A descriptor for the tank material for storing C (2).
TAMA (3)	25-36	A descriptor for the tank material for storing C (3).

CARD NO. 10 (3F10.3, 3F10.2, 3F6.4)

Storage Tank Material Properties

Variable	Columns	Decimal Location	Remarks
TMDEN (1)	1-10	Col 7	The density of tank material TAMA (1) in LB/IN^3
TMDEN (2)	11-20	Col 17	The density of tank material TAMA (2) in LB/IN^3
TMDEN (3)	21-30	Col 27	The density of tank material TAMA (3) in LB/IN^3
SIG (1)	31-40	Col 38	The yield stress for tank material TAMA (1) in PSI
SIG (2)	41-50	Col 48	The yield stress for tank material TAMA (2) in PSI
SIG (3)	51-60	Col 58	The yield stress for tank material TAMA (3) in PSI
TMMT (1)	61-66	Col 62	The minimum workable thickness for tank material TAMA (1) in INCHES
TMMT (2)	67-72	Col 68	The minimum workable thickness for tank material TAMA (2) in INCHES
TMMT (3)	73-78	Col 74	The minimum workable thickness for tank material TAMA (3) in INCHES

CARD NO. 11 |2F10.3, F10.2, 3F10.3, 3(1x, I1), 4x, 3(1x, I1)|

Pressurant Storage Tank Material Properties and Operating Pressures

Variable	Columns	Decimal Location	Remarks
ØPPRE	1-10	Col 7	The initial storage pressure of the pressurant (N_2) in PSIA.
PTDEN	11-20	Col 17	The density of 6AL-4V Titanium used as the tank material for the pressurant - This has a value of 0.161 LB/IN^3
PTSIG	21-30	Col 28	The yield stress of the 6AL-4V Titanium used as the tank material for the pressurant - This has a value of 176,000 PSIA
TAPR (1)	31-40	Col 37	The storage pressure of chemical C (1) in PSIA
TAPR (2)	41-50	Col 47	The storage pressure of chemical C (2) in PSIA
TAPR (3)	51-60	Col 57	The storage pressure of chemical C (3) in PSIA
	61		Not used
IDWPET (1)	62	None	Pressurization code for chemical C (1)*
	63		Not used
IDWPET (2)	64	None	Pressurization code for Chemical C (2)*
	65		Not used

Variable	Columns	Decimal Location	Remarks
IDWPET (3)	66	None	Pressurization code for chemical C (3)*
	67-71		Not used
IDWSEP (1)	72	None	Storage tank code for Chemical C (1)**
	73		Not used
IDWSEP (2)	74	None	Storage tank code for chemical C (2)**
	75		Not used
IDWSEP (3)	76	None	Storage tank code for chemical C (3)**

* 0 if chemical C(i) is pressurized from gas bottle
1 if chemical C(i) is blown down

** = 0 if chemical C(i) is stored in a tank
1 if chemical C(i) is not stored in a tank

CARD NO. 12 (4F10.3, 1X, I1)

Thruster, Piping and Plumbing Weights

Variable	Columns	Decimal Location	Remarks
WGTI (1)	1-10	Col 7	The inert weight (piping, valves, thrusters, etc.) of the system for one propellant tank per propellant
WGTI (2)	11-20	Col 17	Same as above for two tanks per propellant
WGTI (3)	21-30	Col 27	Same as above for three tanks per propellant
WGTI (4)	31-40	Col 37	Same as above for four tanks per propellant
	41		Not used
MM	42	None	Inert weight code*

* = 0 if computer is to add these inert weights to propellant and tank weights
= 1 if computer is not to add these inert weights

Some input variables have recommended values to be used. These variables and the values are listed below.

Card No.	Variable	Value
6	SCBDEN	20.0 lb/ft^3
	SIAM	300.0 lb-ft-sec
	SREPRA	15.0 deg/day
7	SPISW	88.0 lb/kW
	SPPCLD	80.0 percent
	SPSSA	100.0 ft^2/kW
8	DBHAID	0.125 deg (Coarse Mode)
		0.100 deg (Fine Mode)
	THEDMI	0.0002 deg/sec
	SIT (2)	23.0 lb/sec
	SDV (3)	50.0 ft/sec
11	PTDEN	0.161 lb/in^3
	PTSIG	176,000.0 lbf/in^2

It should be noted however, that it is not mandatory that any of the above values be used. These are only recommended as being representative values for a post-1975 SYNCSAT satellite.

This completes the input cards required to investigate one thruster combination. If a second system is desired, repeat cards 2 through 12 for system 2, and stack them immediately behind card 12 for system 1. Card 1 is not repeated, but the value of INOSTR just updated. The diagram on the next page demonstrates the stacking procedure required to calculate more than one propellant system and the control cards required by the IBM 7040 computer.

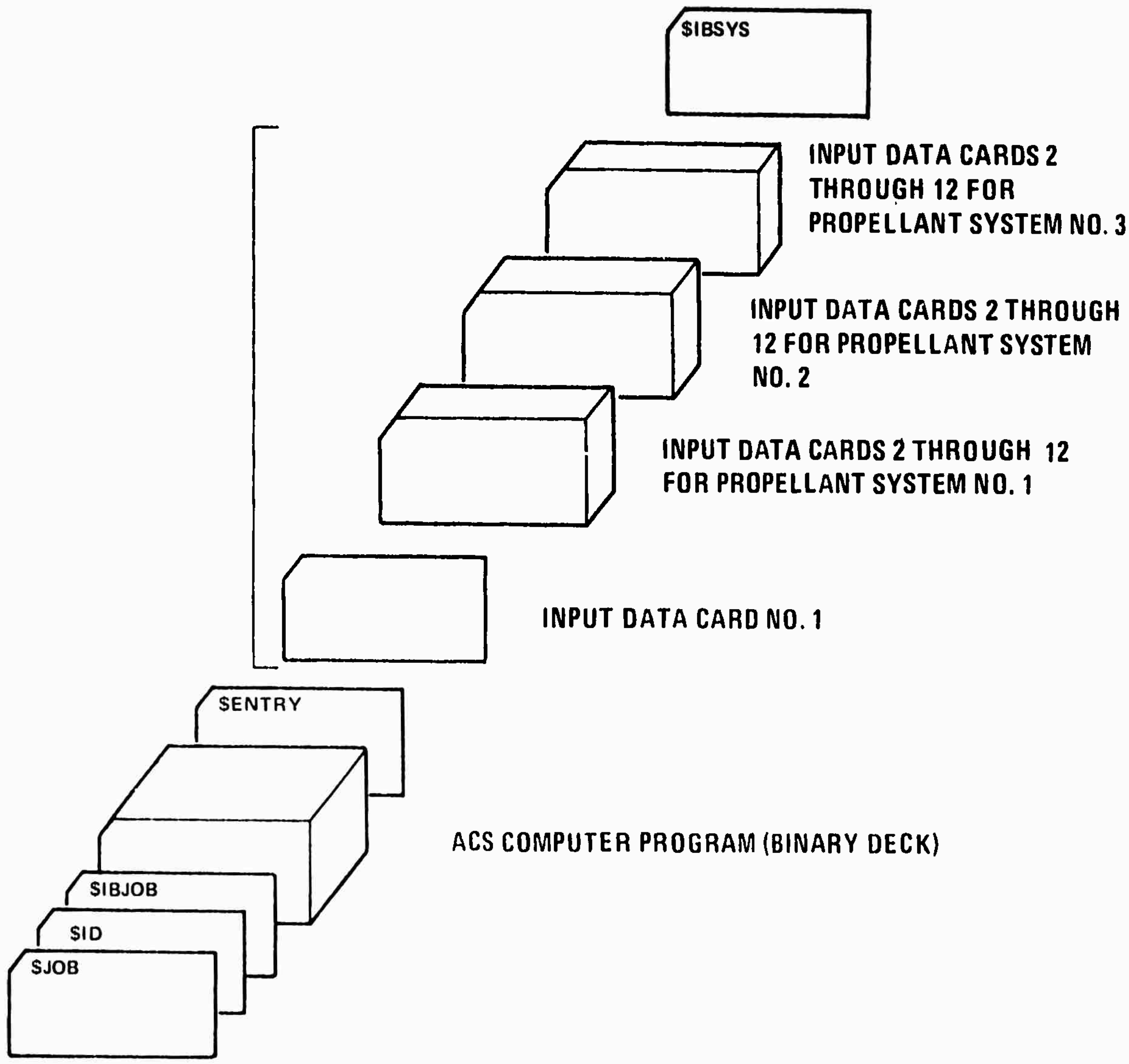


Figure 34. ACS Computer Program and Input Data Card Arrangement

The next page shows a sample propellant case. The large thruster is a bipropellant using ClF_5 and N_2H_4 with a mixture ratio of 2.0. The small thruster used for solar pressure corrections, limit cycling and attitude maintenance contingency is a N_2H_4 gas generator plenum. The satellite initial gross weight is 3000 pounds and has a cylindrical center-body and square solar panels. The ClF_5 is stored in a tank made of 301 cryostretched stainless steel, while the N_2H_4 is stored in 6Al-4V titanium. Both are stored at 150 psi and the pressurant (N_2) is stored at 3000 psi. The different values for Isp for the same propellant and thruster for different propulsion functions is a result of the duty cycles for the functions being different.

SAMPLE CASE INPUT CARDS

FORTRAN CODING RECORD

PROGRAM	CODED BY	DECK NUMBER	DATE PAGE OF PAGES

```
STMT  |C|                                                                  | SERIAL
NUMBER|O|                  FORTRAN STATEMENT                               | NUMBER
      |N|                                                                  |
      |T|                                                                  |
 1
C LF 5/ N2H4            N 2H 4  GG  PLENUM
CL F 5         N2H4                            110.0      62.4
    1 1  1  1  1  2  2  2  1        1           1           2          2.0
 290.0    215.0    290.0    275.0    290.0    275.0    110.0    110.0    110.0    290.0
 3000.0          20.0          2.0                    10.0                 3  300.0  15.0
   88.0          80.0      100.0          1.0
    0.05     0.01          0.125       0.0002        23.0        50.0
301 CRYO SS 6AL-4V TITAN
     0.29        0.161                  300000.0  176000.0               0.017  0.030
  3000.0          0.161  176000.0       150.0     150.0
     21.15       24.25       27.35       30.45
```

AFFTC FORM 100 SEP 67 PREVIOUS EDITION OF THIS FORM WILL BE USED UNTIL STOCK IS EXHAUSTED

A sample output from this program will be of the form as shown on the next three pages. The words shown on these pages are a part of the output also.

```
THIS SYSTEM IS COMPOSED OF THE FOLLOWING PROPELLANT(S)
    LARGE THRUSTER       CLF5/N2H4
    SMALL THRUSTER       N2H4 GG PLENUM

THE SATELLITE WEIGHT IS   3000.000 LBS

THE SATELLITE LIFE IS   10.00 YEARS

THE ON BOARD POWER IS    3.350 KW

THE SOLAR PANELS WEIGH   368.500 POUNDS

THE SOLAR PANEL DIMENSIONS ARE
    HEIGHT   12.942 FEET      LENGTH   12.942 FEET

THE SOLAR PANEL SPECIFIC WEIGHT IS  110.000 LBS/KW

THE SOLAR PANEL SPECIFIC SURFACE AREA IS   100.00 FT2/KW

THE CENTER BODY IS A CYLINDER

THE SATELLITE CENTER BODY WEIGHS   2631.500 POUNDS

THE SATELLITE CENTER BODY BULK DENSITY IS   20.00 LBS/FT3

ITS DIMENSIONS ARE
    DIAMETER    4.375 FEET         LENGTH    8.751 FEET

MAXIMUM PROJECTED AREA IS    373.288 SQUARE FEET

THE MINIMUM IMPULSE BIT FOR LIMIT CYCLING IS  0.0005000 LB-SEC

THE SATELLITE MOMENTS OF INERTIA IN SLUGS-FT2 ARE
       I(XX)       I(YY)       I(ZZ)
       889.300     779.033    1796.791

THE MIXTURE RATIO FOR THE BIPROP IS   2.000
```

THE AMOUNTS OF PROPELLANT, IMPULSE AND DELV FOR THE MISSION ARE

FUNCTION	PROPELLANT	IMPULSE, SEC	LBS PROP	DELV, FT/SEC
TIPOFF RATE	CLF5/N2H4	23.000	0.107	0.247
INJECTION ERROR	CLF5/N2H4	4645.779	16.020	50.000
EAST-WEST S.K.	CLF5/N2H4	6143.465	22.340	71.500
NORTH-SOUTH S.K.	CLF5/N2H4	123593.968	426.186	1500.000
CONTINGENCY S.K.	CLF5/N2H4	3892.123	14.153	53.410
SOLAR PRESSURE	N2H4 GG PLENUM	7721.468	70.195	98.840
LIMIT CYCLE	N2H4 GG PLENUM	7510.052	68.273	97.483
CONTINGENCY	N2H4 GG PLENUM	7615.760	69.234	100.253
REPOSITIONING	CLF5/N2H4	22599.724	77.930	279.944

THE TOTAL IMPULSE REQUIRED FOR THE MISSION IS 183745.332 LB-SEC

THE TOTAL DELTA V REQUIRED FOR THE MISSION IS 2251.678 FT/SEC

TOTAL AMOUNTS OF PROPELLANT REQUIRED

PROPELLANT	WEIGHT, LBS
CLF5	376.774
N2H4	399.232

PROPELLANT TANK MATERIALS AND WEIGHTS IN POUNDS

PROPELLANT	TANK MATL	1 TANK	2 TANKS	3 TANKS	4 TANKS
CLF5	301 CRYO SS	8.97	11.30	12.94	14.24
N2H4	6AL-4V TITAN	13.33	16.80	19.23	21.16

PROPELLANT TANK DIAMETERS IN FEET

PROPELLANT	1 TANK	2 TANKS	3 TANKS	4 TANKS
CLF5	1.3702	1.4844	1.2967	1.1782
N2H4	2.3033	1.8281	1.5970	1.4510

PRESSURANT IS N2
IT IS STORED AT 3000.00 PSI AND REQUIRES 7.870 LBS OF N2
THE TANK MATERIAL IS 6AL-4V TITANIUM
THE TANK WEIGHT IS 6.17 LBS AND TANK DIAMETER IS 1.0121 FEET

TOTAL SYSTEM WEIGHT AS FUNCTION OF NUMBER OF PROPELLANT TANKS

ONE TANK, LBS	TWO TANKS, LBS	THREE TANKS, LBS	FOUR TANKS, LBS
812.345	818.142	822.208	825.445

THE INERT WEIGHTS AS A FUNCTION OF NUMBER OF PROPELLANT TANKS

ONE TANK, LBS	TWO TANKS, LBS	THREE TANKS, LBS	FOUR TANKS, LBS
21.150	24.250	27.350	30.450

THE TOTAL PROPULSION SYSTEM WEIGHT INCLUDING INERT WEIGHTS AS A FUNCTION OF THE NUMBER OF STORAGE TANKS PER PROPELLANT ARE

ONE TANK, LBS	TWO TANKS, LBS	THREE TANKS, LBS	FOUR TANKS, LBS
833.495	842.392	849.558	855.895

The following is a listing of the computer program.

```
$JOB           WL-200   10  LAUKHUF               LK               RZ
$IBF           WL-200
$IBFTC
C      THIS PROGRAM CALCULATES THE TOTAL PROPELLANT REQUIRED, THE TOTAL
C      IMPULSE, THE TOTAL DELTA V FOR A THREE AXIS STABILIZED SATELLITE.
C      THE AMOUNT OF PROPELLANT, IMPULSE AND DELTA V FOR EACH OF TEN
C      MISSION FUNCTIONS ARE ALSO CALCULATED.  PROPELLANT STORAGE TANK
C      SIZES AND WEIGHTS ARE CALCULATED BASED ON THE PROPELLANT REQUIRED.
C      THE INPUT DATA     IS    AS FOLLOWS
C      CARD 1   TYPES OF PROPULSION SYSTEMS TO BE INVESTIGATED
C      CARD 2   PROPELLANT COMBINATIONS
C      CARD 3   PROPELLANTS AND THEIR DENSITIES
C      CARD 4   PROPELLANT COMBINATION CODE FOR THE 10 MISSION FUNCTIONS
C               BIPROP CODE 1=BIPROP PRESENT    C=ALL MONOPROP
C               PRESSURANT CODE 1=USE PRESSURANT  0=BLOW DOWN SYST.
C               NUMBER OF PROPELLANTS
C               MIXTURE RATIO IF USE BIPROP
C      CARD 5   ISP FOR EACH OF 10 MISSION FUNCTIONS
C      CARD 6   SATELLITE CENTER BODY DATA - SATELLITE WEIGHT, CENTER BODY
C               BULK DENSITY, CENTER BODY DIMENSIONS, SATELLITE LIFE,
C               CENTER BODY CODE (1=RECTANGLE, 2=SPHERE, 3=CYLINDER),
C               INITIAL ANGULAR MOMENTUM, REPOSITIONING RATE
C      CARD 7   SOLAR SAIL DATA - IDEAL SPECIFIC WEIGHT, PERCENT LIFE
C               DEGRADATION, SPECIFIC SURFACE AREA, DIMENSIONS
C      CARD 8   THRUSTER DATA - MIN THRUST, MIN PULSE WIDTH, DEAD BAND
C               HALF ANGLE, THETA DOT MIN, IMPULSE FOR TIPOFF, DELTA V FOR
C               INJECTION ERROR
C      CARD 9   STORAGE TANK MATERIALS
C      CARD10   TANK MATERIAL DENSITY, YIELD STRESS AND MIN WORKING THICK
C      CARD11   PRESSURANT STORAGE PRESS, PRESSURANT TANK MATERIAL AND
C               YIELD STRESS, AND PROPELLANT STORAGE PRESSURES
C      CARD12   INERT WEIGHTS AS A FUNTION OF NUMBER OF STORAGE TANKS
C               PER PROPELLANT  -  INERT WEIGHTS INCLUDE PIPES, VALVES,
C               THRUSTERS - ANY PLUMBING WEIGHTS WHICH ARE NOT TANKAG
      DIMENSION ICP(3,3),C(3,2),DEN(3),IS(10),SISP(10),SIT(10),SDV(10)
      DIMENSION TANA(3,2),TMDEN(3),SIG(3),TAPR(3),WP(10),SUM(3)
      DIMENSION TWGT(3,4),TDIA(3,4),TOTSUM(4),STW(4),VOL(3)
      DIMENSION TMAT(3),IDWPET(3),IDWSEP(3)
      DIMENSION WITI(4),ATSUM(4)
      DIMENSION TLVANE(100,3),TSRAM (100,3),WT(100),STDV(100),STIMP(100)
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      DIMENSION XXXX(3)
      DIMENSION LL(30)
      DIMENSION SLGTLL(100),SLIFLL(100),ISCLL(100),ISLL(100,10)
    1 FORMAT(3I12)
    2 FORMAT(3A6,3A6,3A6)
    3 FORMAT(2A6,2A6,2A6,3F10.3)
    4 FORMAT(10I2,8X,I2,8X,I2,8X,I2,9X,F6.3)
    5 FORMAT(10F8.3)
    6 FORMAT(5F10.4,8X,I2,2F10.4)
    7 FORMAT(4F10.4)
    8 FORMAT(6F10.4)
    9 FORMAT(2A6,2A6,2A6)
   10 FORMAT(6F10.3,3F6.3)
   11 FORMAT(6F10.3,3I2,4X,3I2)
   12 FORMAT(1H1,5X,54HTHIS SYSTEM IS COMPOSED OF THE FOLLOWING PROPELLA
     1NT(S))
   13 FORMAT(10X,14HLARGE THRUSTER,6X,3A6)
   14 FORMAT(10X,14HSMALL THRUSTER,6X,3A6)
   15 FORMAT(/,5X,23HTHE SATELLITE WEIGHT IS,1X,F10.3,1X,3HLBS)
   16 FORMAT(1H1,5X,63HTHE AMOUNTS OF PROPELLANT, IMPULSE AND DELV FOR T
     1HE MISSION ARE)
   17 FORMAT(/,5X,8HFUNCTION,7X,10HPROPELLANT,7X,35HIMPULSE, SEC LB. PR
     1P  DELV, FT/SEC)
   18 FORMAT(/,5X,6HDESPIN,11X,3A6,1X,F10.3,2X,F8.3,3X,F9.3)
   19 FORMAT(5X,11HTIPOFF RATE,6X,3A6,1X,F10.3,2X,F8.3,3X,F9.3)
   20 FORMAT(5X,15HINJECTION ERROR,2X,3A6,1X,F10.3,2X,F8.3,3X,F9.3)
   21 FORMAT(5X,14HEAST-WEST S.K.,3X,3A6,1X,F10.3,2X,F8.3,3X,F9.3)
   22 FORMAT(5X,16HNORTH-SOUTH S.K.,1X,3A6,1X,F10.3,2X,F8.3,3X,F9.3)
   23 FORMAT(5X,16HCONTINGENCY S.K.,1X,3A6,1X,F10.3,2X,F8.3,3X,F9.3)
   24 FORMAT(5X,14HSOLAR PRESSURE,3X,3A6,1X,F10.3,2X,F8.3,3X,F9.3)
   25 FORMAT(5X,11HLIMIT CYCLE,6X,3A6,1X,F10.3,2X,F8.3,3X,F9.3)
   26 FORMAT(5X,11HCONTINGENCY,6X,3A6,1X,F10.3,2X,F8.3,3X,F9.3)
   27 FORMAT(5X,13HREPOSITIONING,4X,3A6,1X,F10.3,2X,F8.3,3X,F9.3)
   28 FORMAT(/,5X,45HTHE TOTAL IMPULSE REQUIRED FOR THE MISSION IS,1X,F1
     11.3,1X,6HLB-SEC)
   29 FORMAT(/,5X,45HTHE TOTAL DELTA V REQUIRED FOR THE MISSION IS,1X,F1
     11.3,1X,6HFT/SEC)
   30 FORMAT(/,5X,36HTOTAL AMOUNTS OF PROPELLANT REQUIRED)
   31 FORMAT(/,5X,10HPROPELLANT,5X,11HWEIGHT, LBS)
   32 FORMAT(5X,2A6,3X,F8.3)
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33 FORMAT(/,5X,47HPROPELLANT TANK MATERIALS AND WEIGHTS IN POUNDS)
34 FORMAT(/,5X,10HPROPELLANT,5X,9HTANK MATL,5X,6H1 TANK,3X,7H2 TANKS,
  13X,7H3 TANKS,3X,7H4 TANK )
35 FORMAT(6X,2A6,1X,F7.2,2X,F7.2,2X,F7.2,3X,F7.2,3X,F7.2)
36 FORMAT(1H ,5X,38HPROPELLANT TANK DIAMETERS IN FEET)
37 FORMAT(/,5X,10HPROPELLANT,5X,6H1 TANK,2X,7H2 TANKS,2X,7H3 TANKS,2X
  1,7H4 TANKS)
38 FORMAT(6X,2A6,1X,F7.4,2X,F7.4,2X,F7.4,2X,F7.4)
39 FORMAT(/,5X,14HPRESSURANT IS  2)
40 FORMAT(5X,15HIT IS STORED AT,1X,F8.2,1X,15HPSI AND REQUIRES,1X,F7.
  13,1X,9HLBS OF N2)
41 FORMAT(5X,36HTHE TANK MATERIAL IS 6AL-4V TITANIUM)
42 FORMAT(5X,18HTHE TANK WEIGHT IS,2X,F7.2,1X,24HLBS AND TANK DIAMETE
  1R IS,1X,F7.4,1X,4HFEET)
43 FORMAT(/,5X,45HTHE SYSTEM DOES NOT HAVE A PRESSURIZATION SYSTEM)
44 FORMAT(/,5X,71HTOTAL SYSTEM WEIGHT AS FUNCTION OF NUMBER OF PROPEL
  1LANT TANKS)
45 FORMAT(/,5X,61HONE TANK, LBS TWO TANKS, LBS THREE TANKS, LBS FOUR
  1TANKS, LBS)
46 FORMAT(/,7X,F9.3,5X,F9.3,7X,F9.3,8X,F9.3)
50 FORMAT(/,5X,21HTHE SATELLITE LIFE IS,1X,F7.2,1X,5HYEARS)
501 FORMAT(/,5X,21HTHE ON BOARD POWER IS,1X,F5.3,1X,2HKW)
502 FORMAT(/,5X,26HTHE SOLAR PANELS WEIGH,2X,F8.3,1X,6HPOUNDS)
503 FORMAT(/,5X,30HTHE  SOLAR PANEL DIMENSIONS ARE)
504 FORMAT(10X,6HHEIGHT,1X,F8.3,1X,4HFEET,5X,6HLENGTH,1X,F8.3,1X,4HFEE
  1T)
505 FORMAT(/,5X,34HTHE  SOLAR PANEL SPECIFIC WEIGHT IS,1X,F8.3,1X,6HLBS
  1/KW)
506 FORMAT(/,5X,42HTHE  SOLAR PANEL SPECIFIC SURFACE AREA IS,1X,F8.2,1X
  1,6HFT2/KW)
510 FORMAT(/,5X,30HTHE CENTER BODY IS A RECTANGLE)
511 FORMAT(/,5X,27HTHE CENTER BODY IS A SPHERE)
512 FORMAT(/,5X,29HTHE CENTER BODY IS A CYLINDER)
514 FORMAT(/,5X,32HTHE SATELLITE CENTER BODY WEIGHS,2X,F9.3,1X,6HPOUND
  1S)
515 FORMAT(/,5X,41HTHE SATELLITE CENTER BODY BULK DENSITY IS,1X,F7.2,1
  1X,7HLBS/FT3)
516 FORMAT(/,5X,18HITS DIMENSIONS ARE)
520 FORMAT(10X,5HWIDTH,2X,F8.3,1X,4HFEET,3X,7HTO EARTH,2X,F8.3,1X,4HFEE
  1T,3X,6HLENGTH,2X,F8.3,1X,4HFEET)
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521 FORMAT(10X,8HDIAMETER,1X,F8.3,1X,4HFEET)
522 FORMAT(10X,8HDIAMETER,1X,F8.3,1X,4HFEET,5X,6HLENGTH,1X,F8.3,1X,4HF
   1EET)
524 FORMAT(/,5X,25HMAXIMUM PROJECTED AREA IS,1X,F10.3,1X,11HSQUARE FEE
   1T)
525 FORMAT(/,5X,44HTHE MINIMUM IMPULSE BIT FOR LIMIT CYCLING IS,1X,F10
   1.7,1X,6HLB-SEC)
526 FORMAT(/,5X,49HTHE SATELLITE MOMENTS OF INERTIA IN SLUGS-FT2 ARE)
527 FORMAT(13X,5HI(XX),6X,5HI(YY),6X,5HI(ZZ))
528 FORMAT(10X,F10.3,1X,F10.3,1X,F10.3)
529 FORMAT(/,5X,35HTHE MIXTURE RATIO FOR THE BIPROP IS,1X,F7.3)
800 FORMAT(4F10.3,I2)
903 FORMAT(/,5X,61HTHE INERT WEIGHTS AS A FUNCTION OF NUMBER OF PROPEL
   1LANT TANKS)
908 FORMAT(//,5X,41HTHE TOTAL PROPULSION SYSTEM WEIGHT INCLUDING INERT
   1 WEIGHTS IS,/,5X,50HA FUNCTION OF THE NUMBER OF STORAGE TANKS PER
   2PROPELLANT ARE)
903 FORMAT(1H1,7X,68HLARGE THRUSTER       SMALL THRUSTER      WEIGHT
   1IMPULSE      DELTA V,/)
907 FORMAT(5X,3A6,2X,3A6,1X,F9.3,1X,F11.3,1X,F11.3)
981 FORMAT(1H1,5X,54HTHE FOLLOWING SYSTEMS HAVE COMMON PARAMETERS WHIC
   1H ARE)
982 FORMAT(/,5X,35HTHE MISSION FUNCTIONS PERFORMED ARE)
985 FORMAT(/,5X,6HDESPIN)
992 FORMAT(/,5X,11HTIPOFF RATE)
995 FORMAT(/,5X,15HINJECTION ERROR)
998 FORMAT(/,5X,14HEAST-WEST S.K.)
1001 FORMAT(/,5X,16HNORTH-SOUTH S.K.)
1004 FORMAT(/,5X,16HCONTINGENCY S.K.)
1007 FORMAT(/,5X,14HSOLAR PRESSURE)
1010 FORMAT(/,5X,11HLIMIT CYCLE)
1013 FORMAT(/,5X,11HCONTINGENCY)
1016 FORMAT(/,5X,13HREPOSITIONING)
     READ(5,1)     INCSTR,(LL(I),I=1,30)
C    INCSTR IS NUMBER OF SYSTEMS TO BE CALCULATED
     L=1
  47 READ(5,2)     (SUB(1,J),J=1,3),(SUB(2,J),J=1,3),(SUB(3,J),J=1,3)
     READ(5,3)     (C(1,J),J=1,2),(C(2,J),J=1,2),(C(3,J),J=1,2),(DEN(I),
    1I=1,3)
     READ(5,4)     (IS(I),I=1,10),IAWHB,IDWAP,INERP,AGTR
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C     IDWFB=1 HAVE BIPROP    =0 DO NOT HAVE BIPROP
C     IDWWP=1 WANT PRESSURANT   =0 DO NOT WANT PRESSURANT
C     INCP = NUMBER OF PROPELLANTS ON BOARD
C     IS(I) = PROPELLANT IDENTIFICATION FOR FUNCTION STORES
      READ(5,3)      (ISP(I),I=1,10)
      READ (5,6)     SWGT,SCBDEN,SCBLD,SCBZTX,SLIFE,ISCBC,STAN,SPPRA
C     ISCBC = 1 HAVE RECTANGULAR CENTER BODY
C           = 2 HAVE SPHERICAL CENTER BODY
C           = 3 HAVE CYLINDRICAL CENTER BODY
      READ(5,7)      SPIS,SPPCLD,PCSA,SPLTL
      READ(5,8)      ...,IL,THL,...,SIT(2),SIV(3)
      READ(5,9)      (TAMA(1,J),J=1,2),(TAMA(2,J),J=1,2),(TAMA(3,J),J=1,2)
      READ(5,10)     (TA...(I),I-1,3),(SIG(I),I=1,3),(TMMT(I),I=1,3)
      READ(5,11)     UPPR,PTTEN,PTSIG,(TAPP(I),I=1,3),(IDWPET(I),I=1,3),(
     1IDWSTP(I),I=1,3)
C     IDWPET(I) = 0 PRESSURIZE TANK I
C               = 1 DO NOT PRESSURIZE TANK I
C     IDWSTP(I) = 0 STORE CHEMICAL I IN TANK
C               = 1 DO NOT STORE CHEMICAL I IN TANK
      READ(5,800)    (WGTI(I),I=1,4),MM
C     MM IS A COUNTER WHICH TELLS WHETHER INERT WEIGHTS ARE TO BE ADDED
C     MM = 0 ADD INERT WEIGHTS INTO TOTAL WEIGHT
C        =   DO NOT ADD INERT WEIGHTS INTO TOTAL WEIGHT
      DO 980 I=1,10
  980 ISLL(L,I)=IS(I)
      ISCLL(L)=ISCBC
      SLIFLL(L)=SLIF
      SWGTLL(L)=SWGT
C     SIZE AND WEIGHT SOLAR PANELS
      PCB=(-400.+1.25*SWGT)/1000.
      SPSW=SPISW/(SPPCLD/100.)
      SPWGT=SPSW*PCB
      ADEP=PCB*SPSSA/2.
      SPX=(ADEP*SPLTL)** .5
      SPY=SPX/SPLTL
C     WEIGH AND SIZE CENTER BODY
      SCBWGT=SWGT-SPWGT
      SCBVCL=SCBWGT/SCBDEN
      IF(ISCBC-2)531,532,533
  531 SCBZ=(SCBLD*SCBZTX*SCBVOL)**(1./3.)
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```
      SCBX=SCBZ/SCBZTX
      SCBY=SCBZ/SCBLOD
      GO TO 534
  532 SCBDIA=(SCBVOL*6./3.14159)**(1./3.)
      GO TO 534
  533 SCBDIA=(4.*SCBVOL/(SCBLOD*3.14159))**(1./3.)
      SCBLEN=SCBLOD*SCBDIA
C     OBTAIN MOMENTS OF INERTIA
  534 IF(ISCBC-2)535,536,537
  535 SMIXX=(SCBWGT/(12.*32.2))*((SCBZ**2.)+(SCBY**2.))+SPWGT*(SPY**2.)/
     1(3.*32.2)+SPWGT*((SCBY/2.)**2.)/32.2
      SMIYY=(SCBWGT/(12.*32.2))*((SCBX**2.)+(SCBZ**2.))+SPWGT*(SPX**2.)/
     1(3.*32.2)-SPWGT*((SPX/2.)**2.)/32.2
      SMIZZ=(SCBWGT/(12.*32.2))*((SCBX**2.)+(SCBY**2.))+(SPWGT/(12.*32.2
     1))*((SPY**2.)+(SPX**2.))+SPWGT*((SCBY/2.+SPY/2.)**2.)/32.2
      GO TO 538
  536 SMIXX=(2.*SCBWGT/(5.*32.2))*((SCBDIA/2.)**2.)+SPWGT*(SPY**2.)/(3.*
     132.2)+SPWGT*((SCBDIA/2.)**2.)/32.2
      SMIYY=(2.*SCBWGT/(5.*32.2))*((SCBDIA/2.)**2.)+SPWGT*(SPX**2.)/(3.*
     132.2)-SPWGT*((SPX/2.)**2.)/32.2
      SMIZZ=(2.*SCBWGT/(5.*32.2))*((SCBDIA/2.)**2.)+SPWGT*((SPX**2.)+(SP
     1Y**2.))/(12.*32.2)+(SPWGT/32.2)*((SCBDIA/2.+SPY/2.)**2.)
      GO TO 538
  537 SMIXX=(SCBWGT/(2.*32.2))*((SCBDIA/2.)**2.)+SPWGT*(SPY**2.)/(3.*32.
     12)+SPWGT*((SCBDIA/2.)**2.)/32.2
      SMIYY=(SCBWGT/(4.*32.2))*((SCBDIA/2.)**2.+(SCBLEN**2.)/3.)+SPWGT*(
     1SPX**2.)/(3.*32.2)-SPWGT*((SPX/2.)**2.)/32.2
      SMIZZ=(SCBWGT/(4.*32.2))*((SCBDIA/2.)**2.+(SCBLEN**2.)/3.)+SPWGT*(
     1SPY**2.+SPX**2.)/(12.*32.2)+SPWGT*((SCBDIA/2.+SPY/2.)**2.)/32.2
C     GET MAXIMUM PROJECTED AREA
  538 IF(ISCBC-2)539,540,541
  539 PARMAX=SCBY*SCBX+2.*ADEP
      GO TO 542
  540 PARMAX=3.14159*(SCBDIA**2.)/4.+2.*ADEP
      GO TO 542
  541 PARMAX=SCBDIA*SCBLEN+2.*ADEP
C     CALCULATE IMPULSE FOR SOLAR PRESSURE, LIMIT CYCLE, ATTITUDE
C     MAINTENANCE CONTINGENCY AND DESPIN
C     CALCULATE DELTA V FOR E-W STATION KEEPING, N-S STATION KEEPING
C     AND REPOSITIONING
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543 IF(IS(7))700,700,544
700 SIT(7)=0.0
    GO TO 546
544 SIT(7)=5.91*SLIFF*0.35*PMAX
546 IF(ISCBC-2)547,548,549
547 RX=SCBZ
    RY=SCBX
    RZ=(SCBX**2.+SCBY**2.+SCBZ**2.)**0.5
    GO TO 550
548 RX=SCBDIA
    RY=RX
    RZ=RX
    GO TO 550
549 RX=SCBDIA
    RY=SCBLEN
    RZ=(SCBDIA**2.+SCBLEN**2.)**0.5
550 SCLMID=THRMID*PWMID
    IF(IS(8))701,701,702
701 SIT(8)=0.0
    GO TO 545
702 ABC=(SCLMID**2.)*SLIFF*(RZ/(SMIXX+SMIYY)+RY/(SMIXX+SMIZZ)+RX/(SMIY
   1Y+SMIZZ))/(DBHAID*0.01745)
    DEF=4.*(THLMI**2.)*SLIFF*((SMIYY+SMIZZ)/RX+(SMIXX+SMIZZ)/RY+(SMIX
   1X+SMIYY)/RZ)*0.01745/DBHAID
    IF(ABC-DEF)551,552,552
551 SIT(8)=DEF*365.*24.*3600.
    GO TO 545
552 SIT(8)=ABC*365.*24.*3600.
545 IF(IS(9))703,703,554
703 SIT(9)=0.0
    GO TO 553
554 SIT(9)=0.5*(SIT(7)+SIT(8))
553 IF(IS(1))704,704,556
704 SIT(1)=0.0
    GO TO 555
556 IF(ISCBC-2)557,558,558
557 IF(SCBY-SCBZ)559,560,560
559 SIT(1)=SIAM*2./SCBZ
    GO TO 555
560 SIT(1)=SIAM*2./SCBY
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```
      GO TO 555
  558 SIT(1)=SIAM*2./SCBDIA
  555 IF(IS(4))705,705,562
  705 SDV(4)=0.0
      GO TO 561
  562 SDV(4)=7.15*SLIFE
  561 IF(IS(5))706,706,564
  706 SDV(5)=0.0
      GO TO 563
  564 SDV(5)=150.*SLIFE
  563 IF(IS(10))707,707,566
  707 SDV(10)=0.0
      GO TO 565
  566 SDV(10)=2.*10078.*SREPRA/(3.*360.)
  565 CONTINUE
C     NOW CALCULATE IMPULSES, DELTA VS AND PROPELLANT WEIGHTS FOR THE
C     TEN MISSION FUNCTIONS
      DO 270 I=1,10
      IF(SISP(I))271,271,270
  271 SISP(I)=1.0
  270 CONTINUE
      WRINJ=EXP(SDV(3)/(32.2*SISP(3)))
      WRHEW=EXP(SDV(4)/(32.2*2.*SISP(4)))
      WRHNS=EXP(SDV(5)/(32.2*2.*SISP(5)))
      WRREP=EXP(SDV(10)/(32.2*SISP(10)))
      WP(1)=SIT(1)/SISP(1)
      WP(2)=SIT(2)/SISP(2)
      WP(7)=SIT(7)/SISP(7)
      WP(8)=SIT(8)/SISP(8)
      WP(9)=SIT(9)/SISP(9)
      WP13=0.5*(WP(7)+WP(8)+WP(9))
      WE1=SWGT-WP(1)
      WE2=WE1-WP(2)
      WE3=WE2/WRINJ
      WP(3)=WE2-WE3
      WE4=WE3/WRHEW
      WP11=WE3-WE4
      WE5=WE4/WRHNS
      WP12=WE4-WE5
      WE6=WE5-WP13
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      WE7=WE5/WREP
      WP(10)=WE6-WE7
      W  =W 7/W
      WP14=W 7-W
      W 9=W /W  S
      WP15=W 8-W 9
      W 10=W 9-W 13
      WP(4)=WP11+WP14
      WP( )=WP12+WP15
      SIT(4)=WP(4)*SISP(4)
      SIT( )=WP( )*SISP( )
      SIT(6)=0.  *(SIT(4)+SIT( ))
      WP(6)=SIT(6)/SISP(6)
      SIT(3)=WP(3)*SISP(3)
      SIT(10)=WP(10)*SISP(10)
      SUMIT= .
      DO 4  I=1,10
 4    SUMIT=SUMIT+SIT(I)
      STIMP(L)=SUMIT
      SDV(1)=32.2*SISP(1)*ALOG(SWGT/WE1)
      SDV(2)=32.2*SISP(2)*ALOG(WE1/WE2)
      SDV(6)=32.2*SISP(6)*ALOG(WE10/(WE10-WP(6)))
      SDV(7)=32.2*SISP(7)*ALOG(WE5/(WE5-(WP(7)/2.)))+32.2*SISP(7)*ALOG(W
     1E9/(WE9-(WP(7)/2.)))
      SDV(8)=32.2*SISP(8)*ALOG((WE5-(WP(7)/2.))/(WE5-(WP(7)/2.)-(WP(8)/2
     1.)))+32.2*SISP(8)*ALOG((WE9-(WP(7)/2.))/(WE9-(WP(7)/2.)-(WP(8)/2.)
     2))
      SDV(9)=32.2*SISP(9)*ALOG((WE5-(WP(7)/2.)-(WP(8)/2.))/(WE5-(WP(7)/2
     1.)-(WP(8)/2.)-(WP(9)/2.)))+32.2*SISP(9)*ALOG((WE9-(WP(7)/2.)-(WP(8
     2)/2.))/(WE9-(WP(7)/2.)-(WP(8)/2.)-(WP(9)/2.)))
      SUMDV=0.0
      DO 49 I=1,10
 49   SUMDV=SUMDV+SDV(I)
      STDV(L)=SUMDV
      DO 50 I=1,
 50   SUM(I)=0.0
      IF(INUP-2)52,53,54
 52   DO 55 I=1,10
 55   SUM(1)=SUM(1)+WP(I)
      SUM(1)=SUM(1)+1.1  *(SUM(1)/76.)
```

```
      VOL(1)=SUM(1)/DEN(1)
      GO TO 56
   53 DO 57 I=1,10
      IF(IS(I)-2)58,59,59
   58 SUM(1)=SUM(1)+WP(I)
      GO TO 57
   59 SUM(2)=SUM(2)+WP(I)
   57 CONTINUE
      IF(IEXHR-1)60,61,61
   60 SUM(1)=SUM(1)+1.15*(SUM(1)/76.)
      SUM(2)=SUM(2)+1.15*(SUM(2)/76.)
      VOL(1)=SUM(1)/DEN(1)
      VOL(2)=SUM(2)/DEN(2)
      GO TO 56
   61 A=SUM(1)*WSTR/(1.+WSTR)
      B=SUM(1)-A
      SUM(1)=A
      SUM(2)=SUM(2)+B
      SUM(1)=SUM(1)+1.15*(SUM(1)/76.)
      SUM(2)=SUM(2)+1.15*(SUM(2)/76.)
      VOL(1)=SUM(1)/DEN(1)
      VOL(2)=SUM(2)/DEN(2)
      GO TO 56
   54 DO 62 I=1,10
      IF(IS(I)-2)63,63,64
   63 SUM(1)=SUM(1)+WP(I)
      GO TO 62
   64 SUM(3)=SUM(3)+WP(I)
   62 CONTINUE
      SUM(2)=(1./(1.+WSTR))*SUM(1)
      SUM(1)=SUM(1)-SUM(2)
      DO 65 I=1,3
   65 SUM(I)=SUM(I)+1.15*(SUM(I)/76.)
      DO 66 I=1,3
   66 VOL(I)=SUM(I)/DEN(I)
   56 CONTINUE
C     NOW SIZE TANKAGE
      IF(IACP-2)67,68,69
   67 N=1
      GO TO 70
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      N=2
      GO TO 70
      N=1
70    DO 71 I=1,4
      IF(IDASET(I)-1)2[illegible],251,2[illegible]
251   DO 252 K=1,4
      TDIA(I,K)=0.0
252   TWGT(I,K)=0.0
      GO TO 71
      TDIA(I,1)=(VOL(I)*6./3.14159)**(1./3.)
      TWGT(I,1)=(2.*3.14159*((6.*TDIA(I,1))**3.)*TAPR(I)*TMDEN(I)*1.25)/
     1(.9*SIG(I))
      T1=TWGT(I,1)/(TMDEN(I)*3.14159*((TDIA(I,1)*12.)**2.))
      T2=TAPR(I)*TDIA(I,1)*6.*1.25/(2.*SIG(I))
      IF(T2-T1)200,200,201
200   IF(T1-TMAT(I))202,72,72
202   T=TMAT(I)
      GO TO 203
201   IF(T2-TMAT(I))202,73,73
72    TWGT(I,1)=1.15*TWGT(I,1)
      TDIA(I,2)=(VOL(I)*6./(2.*3.14159))**(1./3.)
      TWGT(I,2)=(2.*3.14159*((6.*TDIA(I,2))**3.)*TAPR(I)*TMDEN(I)*1.25*2
     1.*1.15)/(.9*SIG(I))
      TDIA(I,3)=(VOL(I)*6./(3.*3.14159))**(1./3.)
      TWGT(I,3)=(2.*3.14159*((6.*TDIA(I,3))**3.)*TAPR(I)*TMDEN(I)*1.25*3
     1.*1.15)/(.9*SIG(I))
      TDIA(I,4)=(VOL(I)*6./(4.*3.14159))**(1./3.)
      TWGT(I,4)=(2.*3.14159*((6.*TDIA(I,4))**3.)*TAPR(I)*TMDEN(I)*1.25*4
     1.*1.15)/(.9*SIG(I))
      GO TO 71
73    T=1.25*T2
203   TWGT(I,1)=3.14159*((12.*TDIA(I,1))**2.)*T*TMDEN(I)*1.15
      TDIA(I,2)=(VOL(I)*6./(2.*3.14159))**(1./3.)
      TWGT(I,2)=3.14159*((12.*TDIA(I,2))**2.)*T*TMDEN(I)*1.15*2.
      TDIA(I,3)=(VOL(I)*6./(3.*3.14159))**(1./3.)
      TWGT(I,3)=3.14159*((12.*TDIA(I,3))**2.)*T*TMDEN(I)*1.15*3.
      TDIA(I,4)=(VOL(I)*6./(4.*3.14159))**(1./3.)
      TWGT(I,4)=3.14159*((12.*TDIA(I,4))**2.)*T*TMDEN(I)*1.15*4.
71    CONTINUE
      DO 74 I=1,4
```

```
   74 STW(I)=0.0
      DO 75 I=1,N
      STW(1)=STW(1)+TWGT(I,1)
      STW(2)=STW(2)+TWGT(I,2)
      STW(3)=STW(3)+TWGT(I,3)
   75 STW(4)=STW(4)+TWGT(I,4)
C     SIZE PRESSURIZATION SYSTEM AND WEIGH IT
      DO 260 I=1,INOP
      IF(ICWPET(I)-1)260,261,261
  261 TAPR(I)=0.0
  260 CONTINUE
      IF(ICWWP-1)76,77,77
   77 IF(INCP-2)79,80,81
   79 V=TAPR(1)*VOL(1)/(OPPRE-TAPR(1))
      V=1.05*V
      GO TO 82
   80 V=(TAPR(1)*VOL(1)/(OPPRE-TAPR(1)))+(TAPR(2)*VOL(2)/(OPPRE-TAPR(2))
     1)
      V=1.05*V
      GO TO 82
   81 V=(TAPR(1)*VOL(1)/(OPPRE-TAPR(1)))+(TAPR(2)*VOL(2)/(OPPRE-TAPR(2))
     1)+(TAPR(3)*VOL(3)/(OPPRE-TAPR(3)))
      V=1.05*V
   82 PTDIA=(V*6./3.14159)**(1./3.)
      PTWGT=(2.*3.14159*((6.*PTDIA)**3.)*OPPRE*PTDEN*1.25*1.15)/(.9*PTSI
     1G)
      WN2=OPPRE*V*28./5734.2
C     GET SYSTEM TOTAL WEIGHT
   76 DO 83 I=1,4
   83 TOTSUM(I)=0.0
      A=0.0
      DO 84 I=1,N
   84 A=A+SUM(I)
      DO 85 I=1,4
   85 TOTSUM(I)=A+STW(I)
      IF(ICWWP-1)86,87,87
   87 DO 86 I=1,4
      TOTSUM(I)=TOTSUM(I)+WN2+PTWGT
   86 CONTINUE
      WRITE(6,12)
```

```
      WRITE(6,13)   (SUB(1,J),J=1,3)
      DO 900 J=1,3
  900 TLSNAME(L,J)=SUB(1,J)
      IF(INCP-2)88,88,89
   88 WRITE(6,14)   (SUB(2,J),J=1,3)
      DO 901 J=1,3
  901 TSNAME(L,J)=SUB(2,J)
      GO TO 90
   89 WRITE(6,14)   (SUB(3,J),J=1,3)
      DO 902 J=1,3
  902 TSNAME(L,J)=SUB(3,J)
   90 WRITE(6,15)  SWGT
      WRITE(6,500) SLIF
      WRITE(6,501) POB
      WRITE(6,502) SPWCT
      WRITE(6,503)
      WRITE(6,504) SPX,SPY
      WRITE(6,505) SPSW
      WRITE(6,506) SPSSA
      IF(ISCBC-2)507,508,509
  507 WRITE(6,510)
      GO TO 513
  508 WRITE(6,511)
      GO TO 513
  509 WRITE(6,512)
  513 WRITE(6,514) SCBWGT
      WRITE(6,515) SCBDE
      WRITE(6,516)
      IF(ISCBC-2)517,518,519
  517 WRITE(6,520) SCBY,SCBZ,SCBX
      GO TO 523
  518 WRITE(6,521) SCBDIA
      GO TO 523
  519 WRITE(6,522) SCBDIA,SCBLEN
  523 WRITE(6,524) PARAX
      WRITE(6,525) SCLMIB
      WRITE(6,526)
      WRITE(6,527)
      WRITE(6,528) SMIXX,SMIYY,SMIZZ
      IF(ICWHP)630,630,631
```

```
431 WRITE(6,529) WGTR
430 CONTINUE
    WRITE(6,16)
    WRITE(6,17)
    DO 91 I=1,IC
    N=IS(I)
    IF(N)91,91,114
114 GO TO (92,93,95,96,98,99,101,102,104,105),I
 92 WRITE(6,18)  (SUB(N,J),J=1,3),SIT(I),WP(I),SDV(I)
    GO TO 91
 93 WRITE(6,19)  (SUB(N,J),J=1,3),SIT(I),WP(I),SDV(I)
    GO TO 91
 95 WRITE(6,20)  (SUB(N,J),J=1,3),SIT(I),WP(I),SDV(I)
    GO TO 91
 96 WRITE(6,21)  (SUB(N,J),J=1,3),SIT(I),WP(I),SDV(I)
    GO TO 91
 98 WRITE(6,22)  (SUB(N,J),J=1,3),SIT(I),WP(I),SDV(I)
    GO TO 91
 99 WRITE(6,23)  (SUB(N,J),J=1,3),SIT(I),WP(I),SDV(I)
    GO TO 91
101 WRITE(6,24)  (SUB(N,J),J=1,3),SIT(I),WP(I),SDV(I)
    GO TO 91
102 WRITE(6,25)  (SUB(N,J),J=1,3),SIT(I),WP(I),SDV(I)
    GO TO 91
104 WRITE(6,26)  (SUB(N,J),J=1,3),SIT(I),WP(I),SDV(I)
    GO TO 91
105 WRITE(6,27)  (SUB(N,J),J=1,3),SIT(I),WP(I),SDV(I)
 91 CONTINUE
    WRITE(6,28)  SUMIT
    WRITE(6,29)  SUMDV
    WRITE(6,30)
    WRITE(6,31)
    N=NCP
    DO 106 I=1,N
106 WRITE(6,32)  (C(I,J),J=1,2),SUM(I)
    WRITE(6,33)
    WRITE(6,34)
    DO 107 I=1,N
107 WRITE(6,35)  (C(I,J),J=1,2),(GAMA(I,J),J=1,2),(TWST(I,J),J=1,4)
    WRITE(6,36)
```

```
      WRITE(6,37)
      DO 108 I=1,M
  108 WRITE(6,38)  (C(I,J),J=1,2),(TDIA(I,J),J=1,4)
      IF(IDAMP-1)109,110,110
  110 WRITE(6,39)
      WRITE(6,40)  OPPRM,WN2
      WRITE(6,41)
      WRITE(6,42)  PTWGT,PTDIA
      GO TO 111
  109 WRITE(6,43)
  111 WRITE(6,44)
      WRITE(6,45)
      WRITE(6,46)  (TOTSUM(I),I=1,4)
      IF(MM)805,805,806
  805 DO 801 I=1,4
  801 ATSUM(I)=0.0
      DO 802 I=1,4
  802 ATSUM(I)=WGTI(I)+TOTSUM(I)
      WRITE(6,803)
      WRITE(6,45)
      WRITE(6,46)  (WGTI(I),I=1,4)
      WRITE(6,804)
      WRITE(6,45)
      WRITE(6,46)  (ATSUM(I),I=1,4)
  806 CONTINUE
      IF(MM)820,820,821
  821 WT(L)=0.0
      GO TO 822
  820 WT(L)=ATSUM(1)
  822 CONTINUE
      IF(L-INCSTR)112,113,113
  112 L=L+1
      GO TO 47
  113 CONTINUE
      IF(LL(1))960,960,961
  960 LL(1)=INCSTR
  961 N=1
      M=1
  963 KKKK=M+LL(N)-1
      KK=M+LL(N)-2
```

```
      WRITE(6,981)
      WRITE(6,500) SLIFLL(M)
      WRITE(6,15)  SWSTLL(M)
      IF(ISCLL(M)-2)988,987,988
  988 WRITE(6,510)
      GO TO 989
  987 WRITE(6,511)
      GO TO 989
  988 WRITE(6,512)
  989 WRITE(6,982)
      IF(ISLL(M,1))983,983,984
  984 WRITE(6,985)
  983 IF(ISLL(M,2))990,990,991
  991 WRITE(6,992)
  990 IF(ISLL(M,3))993,993,994
  994 WRITE(6,995)
  993 IF(ISLL(M,4))996,996,997
  997 WRITE(6,998)
  996 IF(ISLL(M,5))999,999,1000
 1000 WRITE(6,1001)
  999 IF(ISLL(M,6))1002,1002,1003
 1003 WRITE(6,1004)
 1002 IF(ISLL(M,7))1005,1005,1006
 1006 WRITE(6,1007)
 1005 IF(ISLL(M,8))1008,1008,1009
 1009 WRITE(6,1010)
 1008 IF(ISLL(M,9))1011,1011,1012
 1012 WRITE(6,1013)
 1011 IF(ISLL(M,10))1014,1014,1015
 1015 WRITE(6,1016)
 1014 CONTINUE
      IF(LL(M)-1)964,964,965
  965 DO 950 I=N,KK
      KKK=I+1
      DO 950 J=KKK,KKKK
      IF(WT(I)-WT(J))950,950,951
  951 XXX=WT(I)
      WT(I)=WT(J)
      WT(J)=XXX
      XXX=STOV(I)
```

```
      STDV(I)=STDV(J)
      STDV(J)=XXX
      XXX=STIMP(I)
      STIMP(I)=STIMP(J)
      STIMP(J)=XXX
      DO 952 L=1,3
  952 XXXX(L)=TLNAME(I,L)
      DO 953 L=1,3
  953 TLNAME(I,L)=TLNAME(J,L)
      DO 954 L=1,3
  954 TLNAME(J,L)=XXXX(L)
      DO 955 L=1,3
  955 XXXX(L)=TSNAME(I,L)
      DO 956 L=1,3
  956 TSNAME(I,L)=TSNAME(J,L)
      DO 957 L=1,3
  957 TSNAME(J,L)=XXXX(L)
  950 CONTINUE
  964 WRITE(6,903)
      IF(LL(M)-33)904,904,905
  904 DO 906 I=M,KKKK
  906 WRITE(6,907) (TLNAME(I,J),J=1,3),(TSNAME(I,J),J=1,3),WT(I),STIMP(I
     1),STDV(I)
      GO TO 914
  905 NN=M+32
      DO 908 I=M,NN
  908 WRITE(6,907) (TLNAME(I,J),J=1,3),(TSNAME(I,J),J=1,3),WT(I),STIMP(I
     1),STDV(I)
      WRITE(6,903)
      NNN=M+33
      IF(LL(M)-66)909,909,910
  909 DO 911 I=NNN,KKKK
  911 WRITE(6,907) (TLNAME(I,J),J=1,3),(TSNAME(I,J),J=1,3),WT(I),STIMP(I
     1),STDV(I)
      GO TO 914
  910 NNNN=M+65
      DO 912 I=NNN,NNNN
  912 WRITE(6,907) (TLNAME(I,J),J=1,3),(TSNAME(I,J),J=1,3),WT(I),STIMP(I
     1),STDV(I)
      WRITE(6,903)
```

```
      NNNNN=M+66
      DO 913 I=NNNNN,KKKK
  913 WRITE(6,907) (TLNAME(I,J),J=1,3),(TSNAME(I,J),J=1,3),WT(I),STIMP(I
     1),STDV(I)
  914 CONTINUE
      M=M+LL(N)
      N=N+1
      IF(LL(N))962,962,963
  962 CONTINUE
      CALL EXIT
      END
$ENTRY          ACS
$IBSYS
```

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