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A SUMMARY OF THE MECHANICAL DESIGN, TESTING AND PERFORMANCE OF THE IMP-H AND J ATTITUDE CONTROL SYSTEMS

JAMES R. METZGER

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ABSTRACT

This document treats three main aspects of the Attitude Control System used on both the IMP-H and J spacecraft. First, it completely describes the mechanical configuration and provides detailed information on all the specific components comprising the flight system. Secondly, it summarizes all the acceptance and qualification testing of both individual components and the installed system. Finally, it provides all the functional information regarding the operation and performance in relation to the orbiting spacecraft and its mission. Other related topics are also included such as the safety requirements, servicing procedures, anomalous behavior and pyrotechnic devices.

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A SUMMARY OF THE MECHANICAL DESIGN, TESTING AND PERFORMANCE OF THE IMP-H AND J ATTITUDE CONTROL SYSTEMS

INTRODUCTION

The purpose of this document is to supply useful and pertinent information regarding the mechanical portion of the Attitude Control Systems (ACS) for the IMP-H and J spacecraft. It is not an attempt to present a complete history of the design and operation, but is intended rather as a summary of significant engineering analysis, qualification testing and system performance, including selected component specifications, safety and spacecraft requirements. In addition, an effort is made to provide some insight into the criterion which was used in establishing many of the basic decision policies and in arriving at solutions to some of the more perplexing problems which arose throughout the program.

The similarity between the two spacecraft, particularly the structure and mission, permitted the control systems to be virtually identical and thus it is possible to treat both in a single document. However, the basic design and hardware development were performed as part of the IMP-I program and consequently there is much commonality with that system as well. Incidentally, the IMP-I preceded the IMP-H by approximately 19 months and was launched on March 13, 1971 as Explorer 43. The IMP-H was launched on September 22, 1972 as Explorer 47 and the IMP-J was launched on October 25, 1973 as Explorer 50. It might also be pointed out that the IMP-I was entirely an in-house project while both IMP-H and J were built by EMR Aerospace Sciences. However, in all cases GSFC retained responsibility for the design, construction, testing, installation, servicing and operation of the ACS.

Part I of this document deals with those aspects of the ACS which were derived from the IMP-I effort and are common to all three systems, including major hardware components, safety and certain performance equations. The fact that a sufficient quantity of primary components for three flight spacecraft was purchased in a single procurement for IMP-I, allowed for one series of acceptance tests, with qualified spare components carrying over to the IMP-H spacecraft as flight hardware without further testing. Similarly, spare IMP-H hardware became IMP-J flight hardware. In addition, leak testing and servicing procedures were developed for the IMP-I with various improvements and minor changes incorporated for the later spacecraft. Another item common among the spacecraft was the Freon-14 gas propellant, and its particular properties have been examined and tabulated in a form directly applicable to this ACS. Finally, it was necessary to develop general performance equations from which to determine propellant consumption and spacecraft maneuverability.

Part II deals with those aspects of the system which were changed or developed specifically for the IMP-H spacecraft. These include such things as new components, weights, dimensions and mass properties. In addition, it was necessary to insert the particular spacecraft characteristics into the dynamic equations in order to obtain specific performance parameters for the IMP-H, with the ultimate purpose being to arrive at the propellant allocation and total quantity required. Finally, the problem of the characteristic delay in the motion of the spacecraft at higher spin rates was investigated and proper corrective measures were determined.

Part III, then, deals with those aspects of the system which apply specifically to the IMP-J spacecraft, including the particular performance parameters. The major differences resulted primarily from the installation of long, deployable wire antennas and their effect on the spacecraft motion and mass properties. One additional topic was also investigated and describes the change in spin rate associated with the consumption of ACS propellant.

It is useful to mention that both spacecraft have similar and complementary missions which began with a launch into a low inclination transfer orbit. A fourth stage kick motor was fired to circularize the orbits at approximately 32 earth radii perigee and 39 earth radii apogee, with the two spacecraft nominally 180 degrees apart. The orbital periods are approximately 12.3 days. The spin rate of IMP-H has been adjusted to just under 46 rpm and the spin rate of IMP-J has been adjusted to just over 23 rpm, and both spacecraft have been maneuvered perpendicular to the ecliptic plane in fulfillment of the scientific and solar power requirements. The IMP-J Electric Field Measurement antennas have also been deployed to an acceptable length. At this point, all scheduled ACS maneuvers have been completed and it can be stated that, with a record of no serious malfunctions or failures, the ACS has successfully performed a useful and necessary function.

Appendix A contains specific information concerning the selection, lot qualification testing and functional characteristics of the pyrotechnic devices used to initiate the ACS and Experiment boom deployments.

PART I: SYSTEM DEVELOPMENT AS DERIVED FROM THE IMP-I

Section A — System Description

The Attitude Control System (ACS) for these spacecraft is a cold gas system utilizing Freon-14 as a propellant and incorporates much of the technology developed for the AIMP-E system. These are spin stabilized spacecraft and all operations are commanded from the ground with an automatic shut-off.

A 10% partial pressure of helium was added as a tracer gas to aid in the leak detection procedures during assembly and check out of the system prior to launch. A maximum total leak rate of 10^{-3} scc/sec (standard cubic centimeters per second) of the propellant has been established as acceptable, which amounts to 0.25 lb of Freon-14 per year.

The ACS is capable of performing three main functions during the spacecraft mission; spin-up, reorientation and despin. These all serve to maintain the spin axis orientation perpendicular to the ecliptic plane, directed toward the North ecliptic pole, and also provide spin rate adjustment throughout the required one year minimum life time of the spacecraft. In the case of IMP-J, a large portion of the propellant is used for spin-up prior to the Electric Field Measurement (EFM) antenna deployment operation and, if the need arises, there is sufficient contingency propellant to completely retract the antenna as well.

Redundancy is achieved by a series-parallel arrangement of the four solenoid valves for each function, and the complete failure of any one valve will not fail the entire system either by eliminating one function or by depleting the propellant supply. Each function has a degraded mode in which the spacecraft response is reduced by one half due to the failure of one of the four valves to open. Actuation, duration and pulsing of the valves is controlled electronically and is synchronized with the spin period.

Temperatures are controlled by a combination of surface coatings, aluminized tape and multilayered thermal blankets, and are expected to be maintained between -5°C and +40°C for various components. One special feature of the system is a rotating joint which eliminates the need for flexible tubing in the area of the boom hinge.

The total weight of the pneumatic portion of the ACS, excluding the propellant, is approximately 30 lb. The flight propellent quantity is determined from the final mass property measurements and mission requirements. To aid in installation, the system is divided into five major modules; two tanks diametrically opposed to each other to maintain balance; a shelf assembly containing a majority of the components which can be leak checked before installation; and two Valve-Nozzle assemblies mounted on booms to give a 6.60 ft thrust moment arm when deployed. Experimental data indicated a specific impulse of 45 lb-sec per lb for the propellant in this system.

This is a medium pressure system with a maximum allowable working pressure of 1800 psig at 23°C and a safety factor of 4. When filled with 19 lb of Freon-14, this provides a maximum of 860 lb-sec of total impulse with 90% Freon-14 and 10% helium. The pressure is regulated to 40 psig before passing through the swivel joint, solenoid valves and nozzles. Both supply and regulated pressures are monitored by means of pressure transducers, and the temperature is monitored by means of a thermistor located in a probe in one of the tanks. The system is filled through a check valve, and the propellant is filtered before entering the regulator. Excess downstream pressure is vented through a relief valve on the regulator. A thermistor is also located near the outlet of one of the solenoid valves.

During ground check out of the ACS, the performance and operation of the solenoid valves are monitored through a test connector on the diode electronics pack on the end of each boom, and by a set of low pressure transducers installed as Ground Support Equipment (GSE) between the solenoid valves and the nozzles. Thus a current trace and pressure profile are obtained for each solenoid valve and for each function of the ACS. All normal servicing details are described in "IMP-H and J ACS Fill Procedure H, JFP-001, Revision B".

A schematic diagram of the pneumatic portion of the ACS is shown in Figure 1, and the overall ACS electronics interface and electrical schematic diagram are shown in Figure 2. Although the latter illustration is a description of the IMP-I system, the IMP-H and J arrangements were essentially the same, with only minor changes in some pin assignments, component nomenclature and facet locations.

In addition, an identification code system was established in order to monitor and control the location and test history of all the major components comprising the entire spacecraft. The ACS was included in this system as an Instrumentation item with the sub-heading of Control, and the major ACS components are listed below:

IC 1 ACS Electronics

IC 2 ACS Tank

IC 3 ACS Diode Pack

IC 4 ACS Valve-Nozzle Assembly

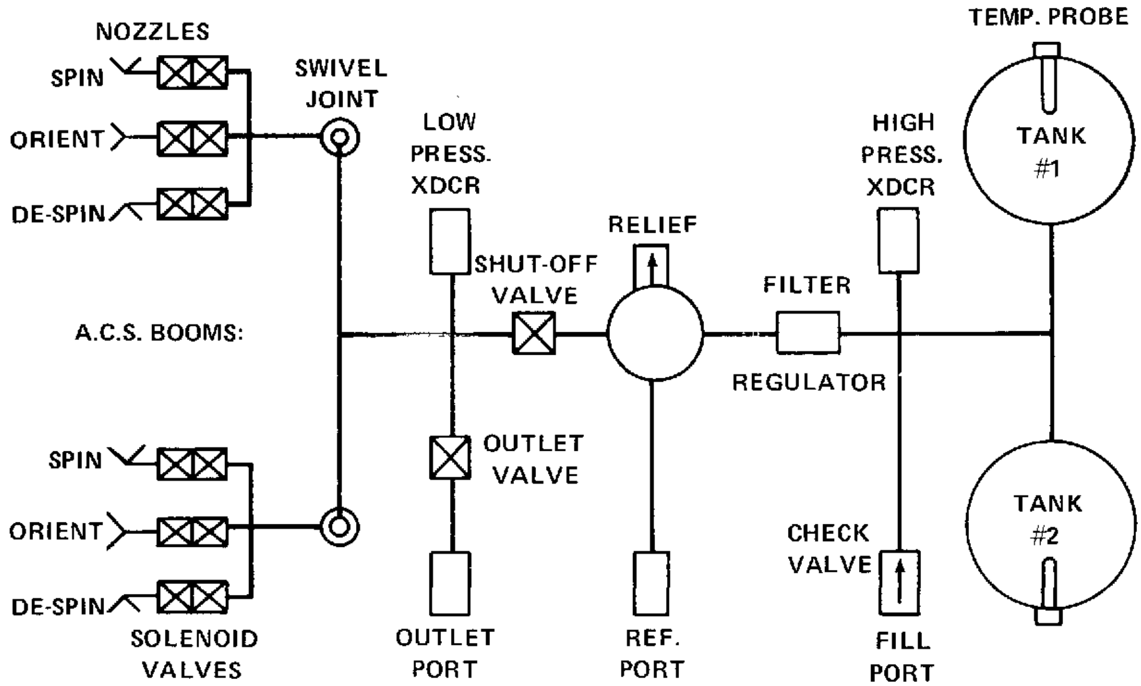


Figure 1. ACS Schematic

IC	5	ACS Shelf Assembly
IC	6	ACS Boom Line
IC	7	ACS Swivel Joint
IC	8	ACS Temperature Probe
IC	9	ACS High Pressure Line
IC	10	ACS Low Pressure Line

Identical components were distinguished from each other by means of a serial number (S/N) suffix attached to the above identification numbers.

Section B — Basic Safety Requirements

As a pressurized system, both the design and operation of the ACS were subject to specific safety requirements, including primarily those listed in AFETRM 127-1 relating to activity at the Eastern Test Range. The applicable paragraphs and selected definitions are presented below.

7. Pressurized Systems.

7.1 Space vehicle propellent tanks and high pressure vessels will conform to the following for all temperatures at which the tanks are pressurized.

7.1.1 Proof Pressure = (operating pressure) x (1.50).

7.1.2 Burst Pressure = (operating pressure) x (2.00).

7.2 Spare vehicle components (tubing, fittings, etc.) will have a burst pressure rating of four times the operating pressure.

7.3 Each complete system must be leak-checked to at least the maximum operating pressure. Any elements, components or joints removed or disconnected must be revalidated and affected parts leak-checked.

7.4 Ground support equipment and facilities installed equipment will conform to ASME standards and/or TO-000-25-223.

7.5 Personnel must be evacuated for the first system pressurization at CKAFS, or the initial pressurization after modification or repair, and thereafter when initial pressurization levels are exceeded. In addition, personnel will be evacuated whenever the pressure exceeds operating pressure or 50% of burst pressure whichever is lower.

7.6 Procedures for pressurizing systems will be developed by the Launch Agency in cooperation with ETDM to determine evacuation distances, personnel controls, etc. Procedures developed will be submitted to ETDM for final approval. Pressure systems will be allowed to stabilize before access is granted by the Pad Safety supervisor.

7.7 Air Force Technical Orders 00-25-223, 00-25-224, and 00-25-229, in addition to Military Specification MIL-P-5518C, will be applied as required to all pressure systems used on the AFETR.

7.8 The following information will be submitted to ETDM for all pressure vessels:

7.8.1 Materials of fabrication.

7.8.2 Size/volume.

7.8.3 Wall thickness.

7.8.4 Operating and design burst pressure.

7.8.5 Proof pressure, including set-up for proof pressure test.

7.8.6 Location of relief valves and burst discs.

FOLDOUT FRAME 1

FOLDOUT FRAME 2

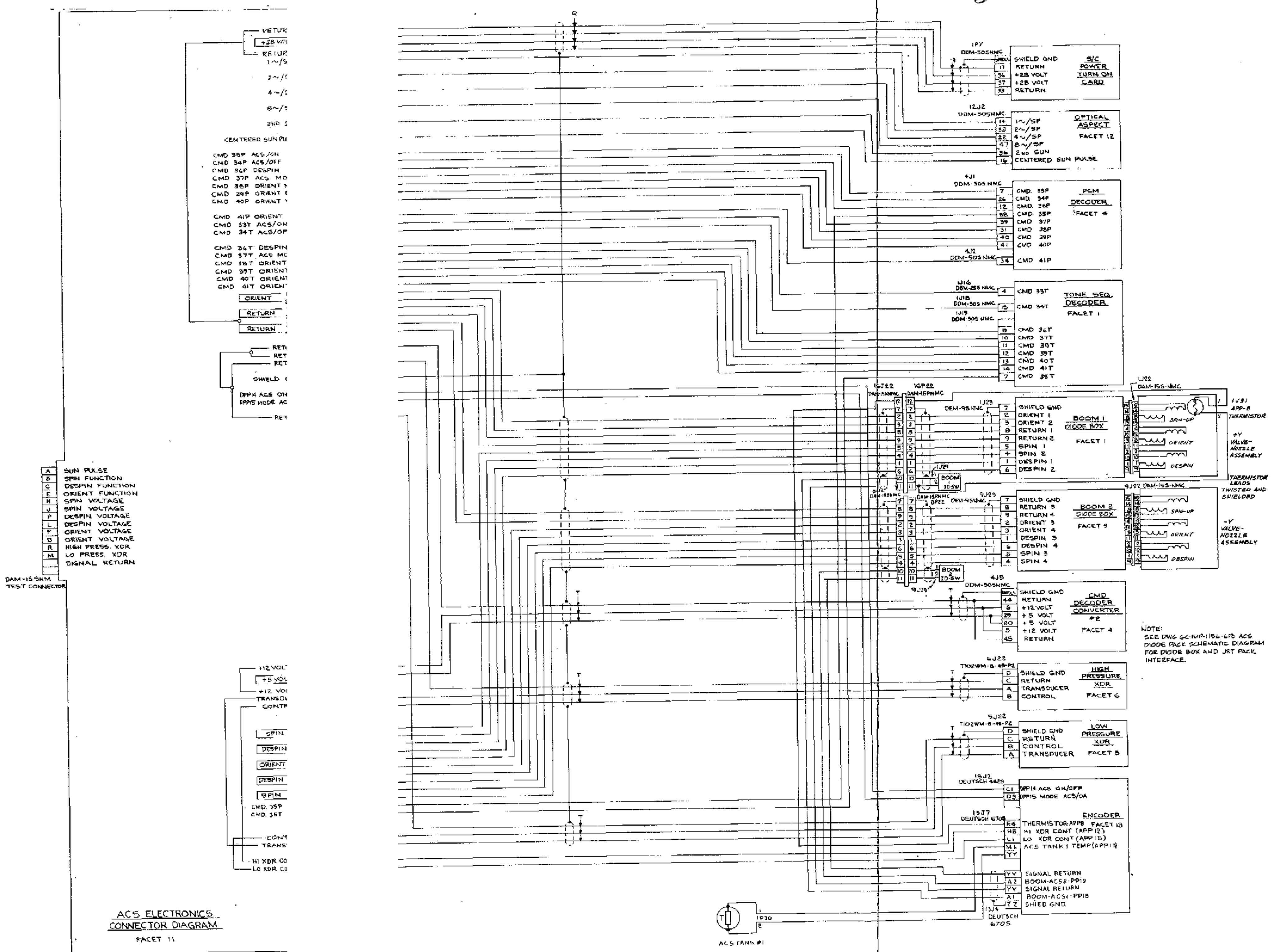


Figure 2. ACS Electronics Inner-Connecting

7.8.7 Type fluid to be used in tank.

7.8.8 Compatibility of tank materials with fluid to be used or fluids used for testing.

7.8.9 Schematics for pressurization and depressurization.

7.8.10 Remote pressurization scheme for initial CKAFS pressurization.

7.8.11 When tanks will be pressurized to operating levels.

7.8.12 Cycle limits if fatigue is a factor in tank life.

8. Propellants and Propulsion Systems.

8.1 Propulsion System Requirements. The Launch Agency/Range User will submit three copies of the following information to ETDM:

8.1.1 A general description of the system and its operation.

8.1.2 Schematic drawings of the system with identification of components in such a manner as to be usable with operating procedures.

8.1.3 Mechanical drawings showing the physical position of all components of the system.

8.1.4 Compatibility studies of the propellants or test fluids versus the materials in the system.

8.1.5 Detailed procedures for all hazardous operations to be performed.

Prelaunch Safety Procedures. Procedures involving all safety functions from the receipt of missiles, space vehicles, and components at the Range until launch.

Pressure, Design Burst. As defined in Mil Spec P-5518-B, no part of a pneumatic system shall rupture when subjected to applicable burst pressure.

Pressure, Maximum Allowable Working Pressure. The maximum operating pressure permissible for a vessel at the operating temperature specified for that pressure.

Pressure, Nominal Working Pressure. The maximum pressure to which the component or system is subjected under steady state conditions.

Pressure, Operating. Operating pressure is that system pressure which is at or below the maximum allowable working pressure.

Pressure, Proof. The test pressure applied to a pressure vessel and system without permanent set or deformation adversely affecting performance of safety.

Pressure System. A pressure system is defined as any system above 0 psig and are classified as follows:

Low Pressure	0 to 500 psi
Medium Pressure	501 to 3000 psi
High Pressure	3001 to 10,000 psi
Ultrahigh Pressure	Above 10,000 psi

It must be remembered, however, that the degree of hazard in pressure systems is proportional to the amount of energy stored, not the amount of pressure present. Therefore, low pressure, high volume systems can be as hazardous to personnel as high pressure systems.

Pressure, Working. Maximum pressure to which the component is subjected steady state operating condition/or the effect of launch or catapult loads, whichever is more severe.

Additional requirements are listed in the Dalta Spacecraft Design Restraints manual and may be summarized as follows.

4.4.1 MDAC (McDonnell Douglas Astronautics Company) personnel safety requirements which are, in some respects, more restrictive than the Range requirements, do not permit MDAC personnel to be exposed to leak, functional, or operational testing of pressure vessels/systems at safety factors, i.e., ratio of burst-to-operating pressure, of less than 4 to 1, except on the gantry and in the spin facility where a safety factor of 2 to 1 is acceptable for vessels. The Delta Project requires, therefore, that for spacecraft operations (except in the noted facilities) where MDAC personnel are required to be present, the 4 to 1 safety factor shall apply. The design and operations requirements governing activities involving MDAC participation are as follows.

4.4.1.1 Systems with 4 to 1 Safety Factor

Vessels designed with a minimum calculated burst pressure of four times maximum allowable operating pressure, and after a proof test of 1.5 times the maximum allowable operating pressure, shall be permitted to have functional or leak tests performed in all areas with the following provisions.

a. Maximum allowable operating pressure shall not be exceeded.

b. A posted and controlled area shall be provided.

c. Only assigned and properly instructed personnel shall be permitted to perform the required tests.

d. Testing will be controlled by written operating instructions.

e. Systems shall incorporate properly designed fill mechanisms equipped with pressure regulators and pressure relief devices.

f. Mechanical work may be done only on depressurized systems.

4.4.1.2 Systems with Less than 4 to 1 Safety Factor

For vessels with a minimum calculated burst pressure design of less than four times maximum allowable operating pressure and/or with proof test requirements of less than 1.5 times maximum allowable operating pressure, functional or leak tests may be performed, if the following requirements are observed.

a. Test pressure shall not exceed one-fourth of the minimum calculated design burst pressure.

b. A proof test of the system shall have been performed in an approved shelter or with other adequate personnel protection at 1.5 times the operating pressure.

c. Testing shall be conducted in a posted and controlled area.

d. Only assigned and properly instructed personnel shall be permitted to perform the required tests.

e. Testing shall be controlled by written operating instructions.

f. Systems shall incorporate properly designed fill mechanisms equipped with pressure regulators and pressure relief devices.

g. Mechanical work shall be done only on depressurized systems.

h. System pressure shall be not greater than one-fourth rated burst pressure during handling and transport to the gantry.

4.4.1.3 Operations in the Spin Facility and on the Gantry

Spacecraft operations (in these specific controlled facilities) which require exposure of personnel to pressure vessels (or systems) not designed to ASME or Department of Transportation (DOT) codes, and which provide less than 4 to 1 safety margin based on minimum calculated burst pressure, the following is required.

a. The minimum acceptable safety margin shall be 2 to 1 based on minimum calculated burst to maximum operating pressure.

b. Pressurization of the system shall be accomplished remotely whenever possible. When remote operation is impractical, approved personnel protection shall be provided.

c. Certification of a proof test performed to at least one and one-half (1-1/2) times the operating pressure is required.

d. The first pressurization cycle of the vessel or system to operating pressure and depressurization shall be performed without personnel exposure. All subsequent pressurizations to operating pressure require a stabilization time of five minutes prior to personnel exposure.

e. Exposure of personnel shall be held to an absolute minimum as to frequency, total time, and number of personnel exposed. Also only personnel approved by the facility operations engineer, test conductor, or safety engineer shall be permitted in the controlled area.

f. A complete log of the pressurization hold time and number of pressurization cycles shall be maintained.

g. Operating and emergency backout procedures approved by Delta shall be provided by the Spacecraft Agency for all pressure operations.

4.4.1.4 Documentation

a. As early as possible, but not less than 78 weeks prior to launch, the following information shall be provided to the Delta Project:

1. General description of the pressurized system including schematic, diagram, method of support, subsystem operating pressures, pressurant fluid characteristics, physical dimensions, etc.

2. Design and test data on working, proof, and burst pressures for pressure vessels, piping and system componentry.

3. Proposed operating procedures and safety precautions.

b. For all spacecraft and AGE (Aerospace Ground Equipment) pressurized systems, the following information shall be provided to the Delta Project as early as practical but not less than four months prior to launch:

1. Final system design description with detailed schematic, component part descriptions, subsystems physical characteristics and operating pressures, type of pressurant fluid, etc.

2. Test data on pressure vessels and subsystem parts, including certification of proof and burst tests.

3. Detailed description of fill equipment and other related support equipment.

4. Detailed operating procedures including backout procedures, schedules, personnel requirements and assignments, facility requirements, shipping and handling and safety precautions.

c. For systems with a safety factor of less than 4 to 1, the following additional data shall be provided to the Delta Project as soon as possible.

1. Stress analysis certified by a registered professional engineer.

2. Inspection Data: Total inspection and Quality Assurance Records which shall include proof of 100 percent radiographic inspection of all welds and dye penetrant testing of all welds. A summary statement of the acceptability of inspection data (dimensional, X-ray, hardness, etc.) for each unit fabricated with an explanation covering pertinent deviations. Raw material inspection data should be included if applicable.

3. Test Results: A summary description of qualification and acceptance test programs (e.g., proof, burst, yield, life, cycle) and test results. Include pertinent information concerning any failures experienced and a description of any hardware modifications made as a result of testing or since completion of testing.

4. Flight Unit Data: Specific test results and facsimilies of inspection records for all flight units.

5. Documented justification substantiating the reasons for not complying with 4 to 1 safety regulations.

4.4.1.5 Waivers

a. Where compliance with pressure vessel safety requirements is not feasible but equivalent safety can be provided, waivers will be required from Delta.

b. Where compliance with State, Federal, Military, or other regulatory agencies is not feasible, but the degree of safety is approved by Safety, waivers shall be required from the appropriate regulatory agency.

c. Pressure vessel waiver requests shall be prepared by the responsible agency and submitted to Delta for approval.

d. All applications and negotiations for waivers shall be accomplished by or processed through the Delta Project Office.

Finally, more detailed safety precautions are described in Section E — System Servicing, and copies of selected safety documentation are presented in both Parts II and III.

Section C — Component Specifications

Tanks —

GSFC drawing no.	GD 1063682
Material	6 AL-4V Titanium
Pressure range	0-1800 psig
Proof pressure (to be tested with gas)	2700 psig
Burst pressure (after 12 cycles 0-2700 psig)	7200 psig
Contained volume	445 in^3 min. at 70°F
Operating media	N_2, He, CF_4 (Freon-14)
Temperature range	-65°F to 165°F

Vibration	0.60 da 5 cps to 20 cps 21 g max. 20 cps to 2000 cps
Acceleration	20 g any direction
Shock	60 g 2 milliseconds duration
Pressure (vacuum)	10^{-10} to 760 mm Hg
Sand, salt spray, etc.	per MIL-E-5272
Magnetic materials	avoid where possible
Weight	6.2 lb max.
Leakage	none allowed within integral tank up to 7200 psig
Manufacturer	Sargent Industries, Arite Div. 1700 E. Grand Ave. El Segundo, California 90245
Part number	6853
Construction	welded Titanium sphere
Diameter	9.760 inches
Actual volume	447 in^3
Ports (2)	MS33649-4
Wall thickness	0.110 inches nominal
Quantity purchased	10
Cost (total)	$33,215.00
Contract no.	NAS 5-15790

Gas storage tanks per GSFC Dwg 1063682 Rev. D dated Sept. 24, 1968 and subject to Airite spec. no. 72-0001 "Inspection and Test Procedures" dated March 13, 1961 as written for part no. 6355 which includes Airite specifications:

No. 59-00016 Titanium alloy closed die forgings 6AL-4V heat treated, rev. B;

No. 71-00050 Welding Titanium 6AL-4V Pressure Vessels (Girth);

No. 71-00051 Cleaning 6AL-4V Titanium Pressure Vessels;

No. 71-00052 Heat Treatment of Forged Titanium 6AL-4V Pressure Vessels.

Prior to delivery, each unit must demonstrate performance in accordance to the above specifications and be supplied with documentation to that effect, except that burst testing of one unit shall be subject to review by GSFC.

The tank material shall not be exposed to, under any circumstances, any alcohol other than Isopropyl.

Pressure Regulator —

GSFC drawing no.	GD 1063687
Operating pressure	0-1800 psig at 25°C max.
Proof pressure	2700 psig
Burst pressure	7200 psig
Regulated pressure (300-1800 psia inlet)	40 ±2 psig
Lockup pressure	46 ±2 psig
Relief (crack)	54 ±2 psig
Relief valve reseat pressure	50 ±2 psig
Reference pressure	ambient
Filter (CRES mesh)	inlet 3.5 μ (microns) nom., 13 μ absolute; relief 5 μ nominal; ambient press. vent 20 μ screen
Operating media	N_2, He, CF_4 (Freon-14)
Primary flow (300-1800 psia inlet)	6.0 lb/hr (Freon-14)
Relief flow	0.2 lb/hr
Internal leak rate	10^{-4} scc/sec (Freon-14)
External leak rate	6×10^{-5} scc/sec (helium)
Response Time	100 milliseconds max.
Stability	regulated pressure shall not oscillate in excess of 0.5 psi peak to peak
Temperature range	-10°C to +50°C
Vibration	0.60 da 5 cps to 20 cps 21 g max. 20 cps to 2000 cps

Acceleration	20 g any direction without loss of regulation
Shock	60 g 2 milliseconds duration
Sand, salt spray, etc	per MIL-E-5272
Materials	Unless approved, suitability must have been proven by prior space flight use. Magnetic materials are to be avoided where possible. Seat and o-ring materials subject to GSFC approval.
Test gases	Must contain less than 3 PPM (parts per million) moisture and be passed through 10 μ nominal filter prior to use.
Cleaning	Each unit is to be cleaned in accordance with the manufacturer's cleaning process specification CPS 401 rev. C.
Manufacturer	Carleton Controls Corp. Jamison Rd. East Aurora, N.Y. 14052
Part number	1-59-00-5
Ports (3)	MS-33514E4
Seat material	Vespel SP-1
Relief seat material	4404 Silicone
O-ring material	Neoprene
Actual weight	0.45 lb
Quantity purchased	5
Cost (total)	$18,777.00
Contract no.	NAS 5-15819

All specifications apply after exposure to proof pressure. Prior to delivery, each unit must demonstrate performance in accordance with the above specifications and be accompanied by documentation to that effect. Assembly drawings procedures and special tool requirements are requested in order that each unit may be disassembled, cleaned, lubricated, and reassembled by GSFC prior to service operation. At such time, a qualified vendor representative shall be present to monitor methods and procedures. The pressure regulator is shown in Figure 3.

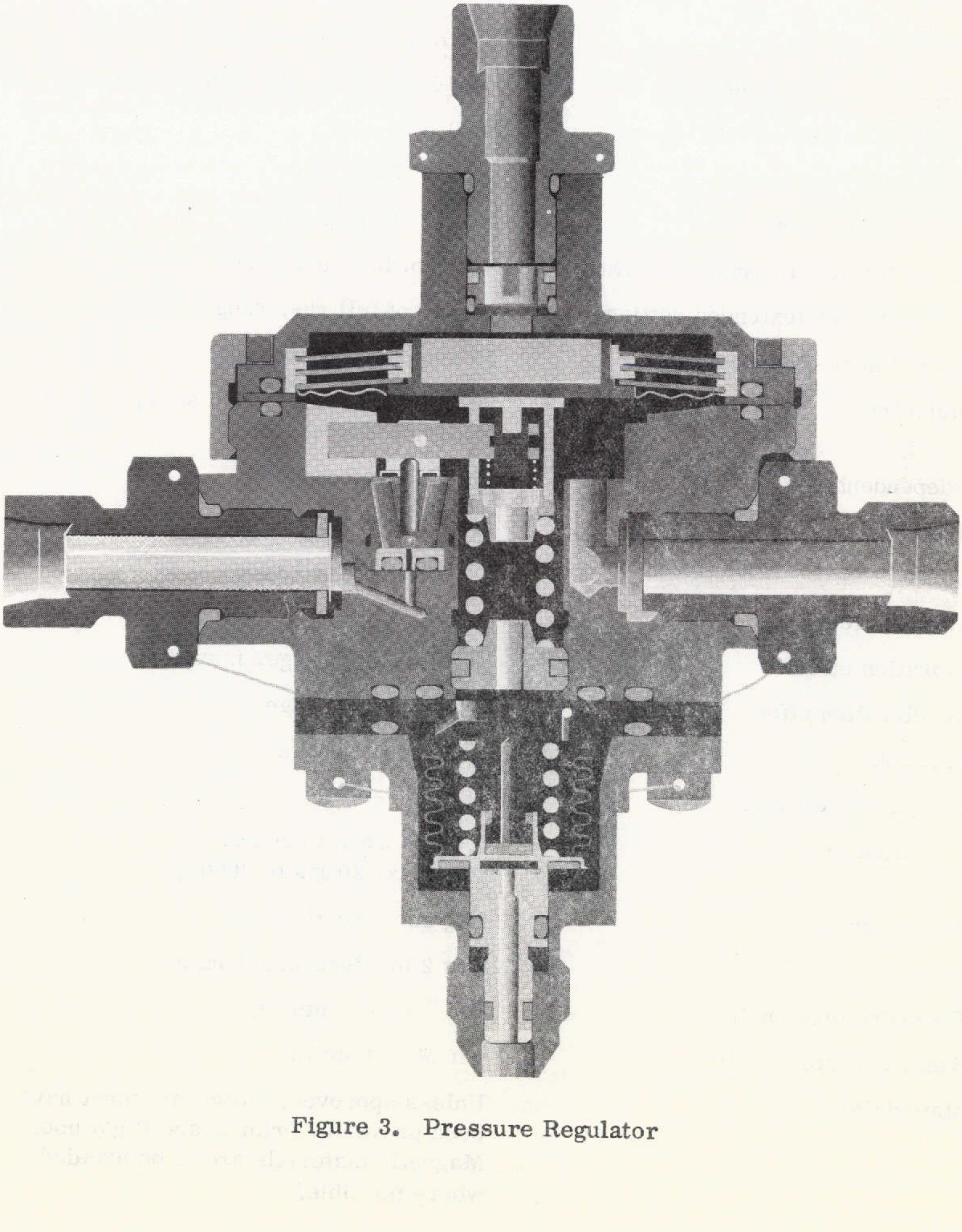


Figure 3. Pressure Regulator

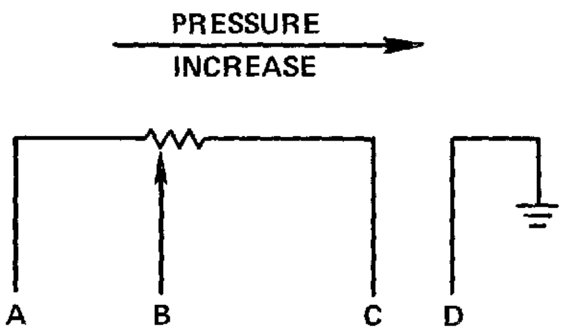
Pressure Transducers (general) —

Type	potentiometer
Operating media	N_2, He, CF_4 (Freon-14)
Leakage (case and element)	6×10^{-5} scc/sec He at max. press.
Standard resistance (full range)	5000 ±250 ohms
Resolution	0.3% of full range
Maximum current	10 ma. DC or AC rms
Zero pressure (retracted setting)	3 ±2% of full res. range
Full pressure (extended setting)	97 ±2% of full res. range
Insulation resistance	50 megohms at 500 VDC
Dielectric	600 VAC 60 cycles for 5 sec., leakage shall not exceed 1 ma.
Independent linearity	±1.0% of full range
Hysteresis	1.0% of full range at 25°C
Life	25000 cycles full range at 25°C
Temp. effect, max.	0.02% of full range per °C
Vibration effect	±1.0% of full range, max.
Acceleration effect	±1.0% of full range
Friction	1.0% of full range
Temperature range	-10°C to +50°C
Vibration	0.60 da 5 cps to 20 cps 21 g max. 20 cps to 2000 cps
Acceleration	20 g any direction
Shock	60 g 2 milliseconds duration
Pressure (external)	10^{-10} to 760 mm Hg
Sand, salt spray, etc.	per MIL-E-5272
Materials	Unless approved, suitability must have been proven by prior space flight use. Magnetic materials are to be avoided where possible.

Fitting end	MS 33656-2, style E
Mating connector	T 102 WM-8-4P-F2 (or equiv.)

Connector shell shall be gold plated 0.005 thick over copper per MIL-G-45204; pins shall be gold plated 0.00003 thick per MIL-G-45204 over silver, 0.0003 thick per QQ-S-365.

Schematic



Prior to delivery each unit must demonstrate performance in accordance with the above specification and be supplied with documentation to that effect, including calibration information. Two mating electrical connectors shall also be supplied with each unit and shall be subject to the conditions specified in note number three of the referenced drawing.

High Pressure Transducer —

GSFC drawing no.	GD 1063685
Pressure range or travel	0–2000 psia
Proof pressure (element)	3000 psia
Maximum pressure (element)	4000 psia
Case burst pressure	8000 psia, min.
Weight	0.25 lb max.
Response (minimum)	25 milliseconds to 63% of applied step
Manufacturer	Conrac Corp., Instrument Controls Div. 1600 South Mountain Ave. Duarte, California 91010
Part number	461319
Quantity purchased	6
Unit cost	$290.00 each

Low Pressure Transducer —

GSFC drawing no.	GD 1063686
Pressure range or travel	0-75 psia
Proof pressure (element)	110 psia
Maximum pressure (element)	150 psia
Case burst pressure	240 psia, min.
Weight	0.13 lb max.
Response (minimum)	15 milliseconds to 63% of applied step
Manufacturer	Bourns, Inc., Instrument Div. 6135 Magnolia Ave. Riverside, California 92506
Part number	443
Quantity purchased	16
Unit cost	$243.00 each

High Pressure Line —

Material	304 SS 1/8 H. seamless MIL-T-6845
Size	1/4 O.D. x 0.035 inch wall

Low Pressure Line —

Material	AL ALY WW-T-700/6 6061-T4
Size	1/4 O.D. x 0.028 inch wall

Temperature Probe —

GSFC drawing no.	GD 1074085
Material	303 SS cond. B. QQ-S-763
Thermistor manufacturer	YSI Components Div. Yellow Springs, Ohio
Part number	44006

Connector installed per GSFC drawing no. GD 1074377

Fill Port Check Valve —

Manufacturer	Nupro Co. 15635 Saranac Rd. Cleveland, Ohio 44110
Part number	SS-4C-25
Cracking pressure	25 psid
Seat material	Buna 'N' o-ring

Filter —

Manufacturer	Nupro Co.
Part number	SS-4F-7
Particle size	7 microns (μ)

Tube Fittings —

Swagelok, 400 series, aluminum and 316 stainless steel.

Manufacturer	Crawford Fitting Co. 29500 Solon Rd. Cleveland, Ohio 44139

O-Rings —

Pressure transducers	3-902, C147-7 neoprene
Tank ports	3-904, C147-7 neoprene
Regulator inlet and outlet	3-903, C147-7 neoprene
Regulator reference port	3-902, C147-7 neoprene
Swivel joint	2-011, C147-7 neoprene
Valve-Nozzle assembly inlet	3-904, C147-7 neoprene
Solenoid valve inlet and outlet	2-012, L608-6 fluorosilicone
Nozzles	3-904, C147-7 neoprene
Test port plug	3-902, C147-7 neoprene
Manufacturer	Parker Seal Co. 10567 Jefferson Blvd. Culver City, California 90230

Boom Material —

Structure	Continuous, filament wound, resin bonded glass fiber tubing
Ultimate strength:	
flexural	40,000 psi (min.)
tensil, axial	70,000 psi (min.)
compressive	40,000 psi (min.)
torsional, shear	30,000 psi (min.)
Modulus:	
flexural	4.5 to 5.0 x 10^6 psi
tensil, axial	4 to 6 x 10^6 psi
compressive	0.7 to 0.9 x 10^6 psi
Density	0.072 lb/in^3
Temperature range	-65° to +350°F
Size	1.250 O.D. x 0.062 wall
Installation:	
IMP-H	GJ 1074231
IMP-J	GJ 1074421

Swivel Joint —

The swivel joint was manufactured per GSFC drawing no. GD 1063874. This item would be more correctly referred to as a rotating joint since it allows only a single degree of freedom of motion about one axis. It was developed to permit the installation of the ACS thruster nozzles as far from the spacecraft spin axis as possible, which required the use of hinged appendages or booms. These booms actually served a dual purpose in that they provided an increase in the moment of inertia (MOI) of the spacecraft as well as the larger thrust moment arm. Earlier attempts to combine pressurized lines with folding booms involved the use of flexible tubing and encountered two major problems which were eliminated by the use of the swivel joint. First of all was the problem of geometry, or the length of flexible line and volume of free space required to accommodate the motions during the folding and deployment sequences. The swivel joint provided a small, compact means of bridging the hinge area. The second problem involved the method of achieving a leak tight seal between the non-metallic flexible line and the metallic fixed portion, which would withstand the stresses induced by the folding motion and the vibration of the unsecured length of flexible line during launch. The advantage of the swivel joint was that it was rigidly attached to both the stationary and rotating portions of the hinge and was also constructed of the same material as the adjoining tubing which permitted the use of standard tube fittings to carry the pressure. Some other problems overcome by the swivel joint were related to the cycle lifetime in which the reliability of the flexible line and its attachments decreased significantly with the number of flexing cycles, and the tendency for nonmetallic tubing to deteriorate under prolonged exposure to the cold and ultraviolet radiation in space. However, the use of the swivel joint required certain precautions to assure cleanliness of the seals to avoid leakage, and a very precise alignment to prevent binding during rotation. Its successful operation on three flight spacecraft can be attributed mainly to its inherent simplicity. A diagram of the swivel joint is shown in Figure 4.

Solenoid Valves –

The solenoid valve specifications are presented in Part II, Section A and Part III, Section A.

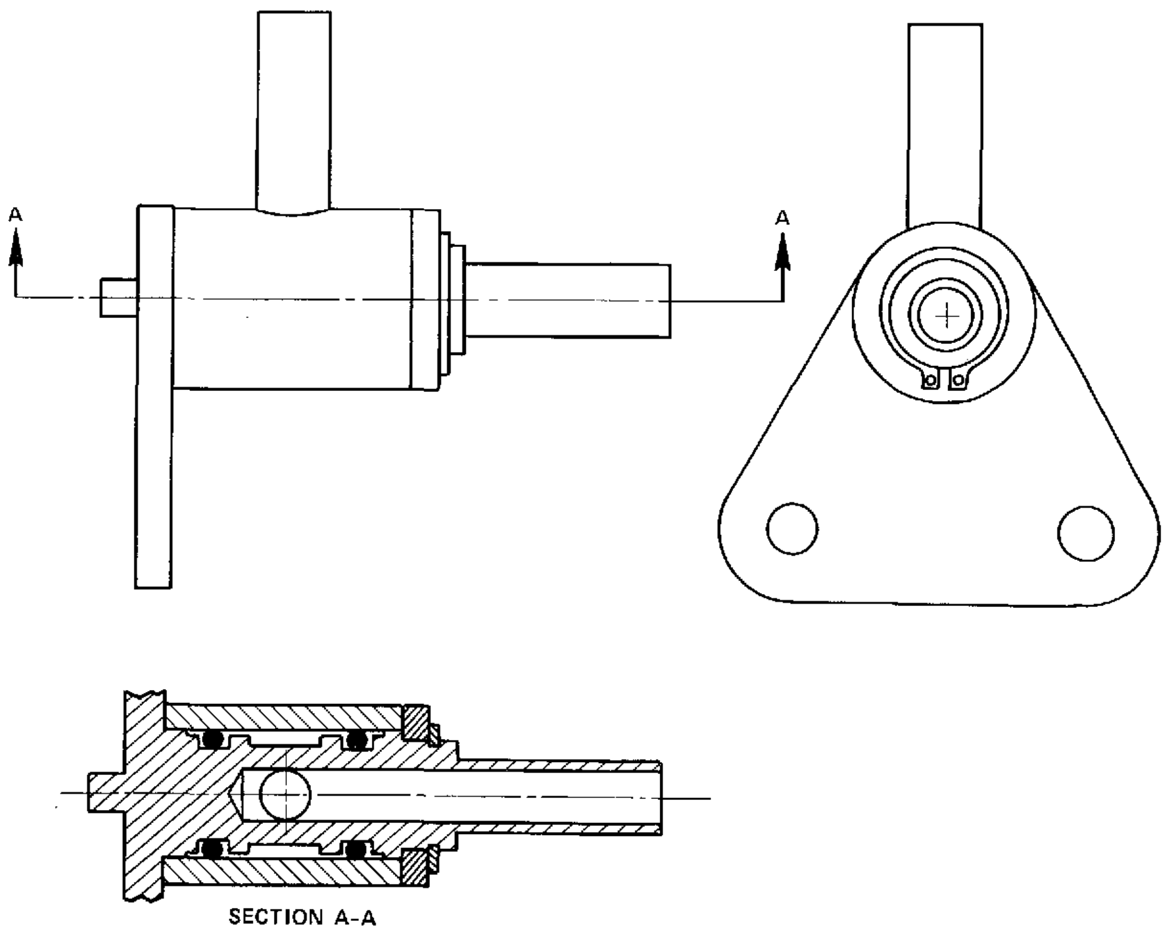


Figure 4. Swivel Joint

Freon-14 Propellant —

Specific information on the Freon-14 propellant is presented in Part I, Section G and Part III, Section A.

Nozzles —

GSFC drawing no.	GC 1074340
Type	conical
Inlet half angle	45 degrees
Outlet half angle	10 degrees
Throat diameter	0.0370 inches
Area ratio	50:1 (100:1 for IMP-I)
Interface	MS 33514 E4 (external)

Manual Valves —

Manufacturer	Hoke Manufacturing Co. 1 Tenakill Park Cresskill, N.J. 07626
Part number	D 3251 G4A
Material (body)	Aluminum
Seat material	KEL-F
Packing	Buna 'N' o-ring
Temperature range	-20° to +250°F
Operating pressure	3000 psig max.
Burst pressure	12,000 psig min.
Orifice size	0.170 inches
Flow coefficient	0.35
Interface fittings	Gyrolok, for 1/4 inch tube

ACS Electronics —

The attitude control system electronics provide the timing and control functions required in the three operating attitude control modes. The control modes are selected by commands to the spacecraft; each command is redundant, being available from PCM decoder or the tone sequential decoder. Orient operating mode has selectable maneuvering quadrants designated North, East, South, and West. The quadrants are generated from the OA spin sync clock functions and from an ACS mode quadrant generator operating at a fixed 23.6 rpm rate for IMP-H and 46 rpm for IMP-J. The selection of functions to be used is by command with the OA functions selected by off commands, and the ACS Mode selecte by direct command. Quadrant selection by command and system on command completes the sequence required for orient mode operation. The on command applies 28 volt solenoid power to the drive electronics and provides gating and synchronization for the first orient pulse. A three stage binary counter allows 8 quadrant pulses to drive orient solenoids then inhibits further orient operation. The sequence of commands must be repeated for additional or continued operation. Transmission of the off command disables 28-volt solenoid power, resets all orient quadrants, returns ACS electronics to OA function control, and inhibits orient pulse gating.

Thermal Coatings —

In general, the thermal coating specification for the ACS requires that all components external to the main cylindrical body of the spacecraft and directly exposed to sunlight, be polished to a high luster silvery finish. Iriditing and painting were avoided except as noted below. Also, these surfaces were maintained free of contamination, discoloration and finger prints. In addition, both the lower hemisphere of the ACS tanks and the pressure regulator were covered with thermal blankets constructed generally as follows.

> Aluminized Mylar or Capton, five layers minimum, with nylon mesh between each layer, and a 2 mil Capton outer layer.

However, the upper hemisphere of the tanks and the various mounting brackets, together with the side edge surfaces of the Valve-Nozzle assemblies were painted flat black. Similarly, the top planar surface of these assemblies were equipped with an area of white paint for thermal control. All critical surfaces were protected with a Strip Coat layer which was removed prior to launch.

Cleanliness —

The environmental cleanliness requirements for the assembled and installed ACS were identical to those for the spacecraft and are, in general, as follows.

Cleanliness	Class 100,000 or better; applies to spacecraft with detector covers removed.
	Class 300,000 or better; applies to spacecraft with detector covers on.

Relative humidity	30 to 50%
Temperature	70° ±5°F
Chemical	Environment shall be free of harmful chemical vapors or fumes. Only approved solvents, paint, adhesives, and cleaning agents shall be used in the vicinity of the spacecraft.
Pressure	Slightly positive in the area surrounding the spacecraft.

However, prior to assembly, all except the more complex ACS components were disassembled and cleaned according to the "Particulate Decontamination Procedures for Spacecraft Hardware Used for Critical Subsystems" issued by GSFC. The actual allowable contaminating particle size specification for each component varied according to the amount of surface area exposed to the propellant, its material of construction, and its functional position in the system. In general, no particles, either organic or metallic, larger than 50 microns were allowed per 100 ml of cleaning fluid.

Section D — Summary of Hardware Testing

Tanks —

Each tank, S/N 0001 through 0010, was inspected, tested and documented by the manufacturer according to the Inspection Test Procedure for Gas Storage Bottles No. 72-00082, including:

a. Material: Mill test report and certification for material, heat number, grain size and chemical analysis. Tensil properties measured before and after heat treating for each specimen.

b. Process: All welds inspected radiographically (X-ray) and with penetrant by manufacturer. All cleaning, aging and finishing performed according to manufacturer's specifications.

c. Acceptance tests: Examined for conformance to GSFC specifications concerning physical dimensions, weight and leakage (with helium at 300 psig). Volume was measured before and after exposure to proof pressure of 2700 psig for 3 minutes.

d. Qualification test: In addition to the above testing, tank S/N 0007 was subjected to a design qualification test consisting of examination of product, cycle life test (100 cycles 0 to 1800 psig), vibration, acceleration, shock and burst test. Documentation supplied by the manufacturer reported a burst pressure of 9100 psig at 70°F. All of the above testing was completed by 3/21/69.

The flight tanks were subsequently inspected, cleaned and thermal painted by GSFC prior to installation on the spacecraft.

Temperature Probes —

Temperature probe bodies, S/N 1 through 4 and 11 through 15, were hydrostatically proof tested to 4000 psig, and S/N 5 and 16 were tested to 10,000 psig without evidence of failure. These tests were performed by GSFC on 9/30/69, request no. 1340-33, and prior to thermistor installation. Thermistors are bonded in place per GSFC Dwg. GD1074085. Additional tests were performed to demonstrate the feasibility of placing a temperature probe inside the tank. These tests were completed, with staisfactory results, by GSFC on 5/2/69, request no. 1340-16.

Subsequently, temperature probe bodies S/N 21 through 26 were similarly hydrostatically proof tested through 2 cycles 0 to 5000 psig each, without evidence of failure. This work was completed on 4/21/71. Prior to assembly, all temperature probe bodies were examined for adequate wall thickness by means of X-ray photographs taken in two directions. Following thermistor installation, S/N 14, 15, 16, 21, 22, 23, 25 and 26 were calibrated between -50°C and +100°C. Probe S/N 24 was destroyed when a pin broke loose during assembly. The above testing was performed by GSFC per request no. 1350-7 and completed on 7/1/71.

In addition, a test thermistor was calibrated in order to obtain a representative baseline curve for temperature determination. The calibration set-up, together with the final curve and selected point values are presented in Table 1.

Tubing and Fittings (high pressure) —

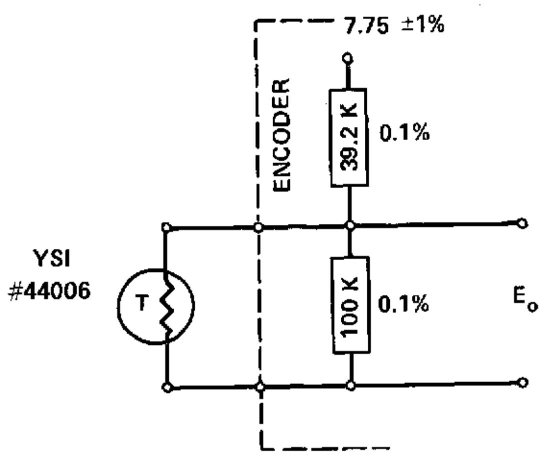
All stainless steel tubing (type 304 CRES) and fittings (Swagelok 316 CRES) used on the ACS are standard items and rated by the manufacturer for a maximum allowable working pressure of 4000 psig and a burst pressure in excess of 12000 psig. No testing was performed by GSFC on these items; however, all such hardware was inspected and cleaned prior to installation on the spacecraft.

Pressure Transducers —

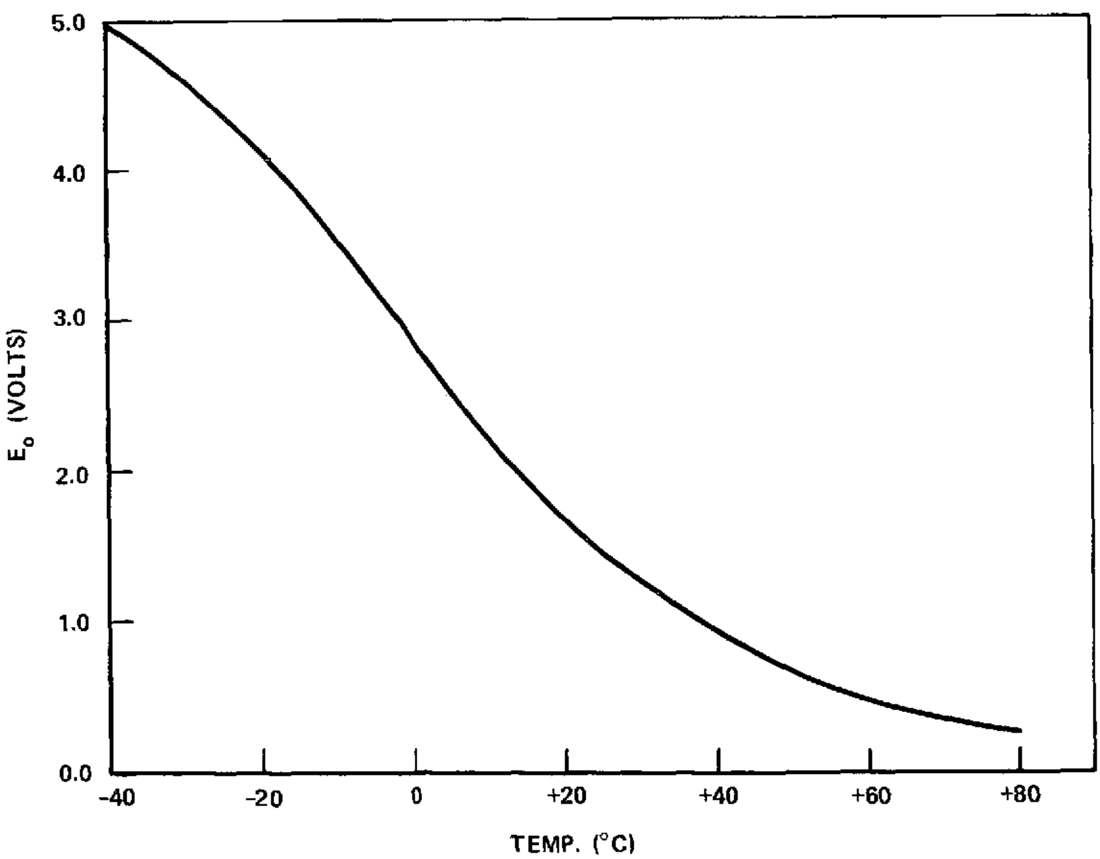
The high pressure transducer is a standard item designed with a case burst pressure greater than 8000 psig. The low pressure transducer is also a standard

Table 1

IMP-I Thermistor Calibration



TEMP. (°C)	E_o CALCULATED OUTPUT VOLTS
80	0.2741
70	0.3675
60	0.4969
50	0.6762
40	0.9224
30	1.2549
20	1.6887
10	2.2282
0	2.8479
-10	3.4964
-20	4.1032
-30	4.6078
-40	4.9824



item designed with a case burst pressure greater than 240 psig. No further testing was performed by GSFC; however, all units were inspected, cleaned and calibrated by GSFC.

Check Valve and Filter —

Both the check valve and filter are standard items and rated by the manufacturer for a maximum allowable working pressure of 3000 psig. Check valves S/N 05 and 06 and filters S/N 05 and 06 were tested together for leakage and flow rates by GSFC, request no. 1340-12 completed 2/6/69. The units were tested at ambient temperature and at -10°C with helium, and in all cases the leak rate was less than 10^{-6} scc/sec and the flow rate much greater than that required by the regulator. A minimum burst pressure verification test was also performed by GSFC, request no. 1340-51 completed 12/9/70, from which it was determined that the assembled configuration of check valve, filter and connecting manifold had a burst pressure greater than 8000 psig at ambient temperature. Items used in this test were check valve S/N 06 and filter S/N 06. The flight components have been inspected and cleaned prior to installation on the spacecraft.

Pressure Regulator —

The regulator is a standard design modified by the manufacturer to conform to GSFC specification. The MS style inlet and outlet ports were replaced by GSFC with tube outlet fittings in order to meet special interface requirements. Acceptance tests on all units were performed by GSFC, request no. 1340-23, to verify operating and environmental specifications concerning regulated pressure, relief pressure and flow rate, at temperatures of +60°C, ambient and -10°C, and inlet pressures ranging from 200 to 1400 psig. Regulator S/N 2 was also tested at -45°C. The above tests were performed in a vacuum chamber with no appreciable external leakage detected from the regulator.

Upon receipt of regulators S/N 1 and 2, it was discovered they contained silicone o-rings which are not recommended for use with Freon-14. These two units were returned to the manufacturer to have neoprene o-rings installed. The remaining three units were received with o-rings of the proper material.

Pressure regulator S/N 5 was subsequently installed in the IMP-J shelf assembly, but was found to have unacceptable leakage emanating from the relief valve reference hole. It was sent back to the manufacturer for rework, and upon completion of repairs was returned to GSFC and retested according to the original procedure specified in request no. 1340-23. It was found that this regulator again conformed to the leakage specification between -45°C and +60°C in tests that were completed on 3/27/72.

Some applicable testing was also performed for the AIMP-E program, and involved expansion cooling through the same basic regulator. By determining the temperature drop due to the expansion of the Freon-14 gas in the regulator it was possible to determine the maximum allowable moisture content for the propellant. The regulator was connected to a representative solenoid valve which was pulsed 65 times with a 180 milliseconds pulse width. A 500 psia Freon-14 supply was attached to the regulator inlet and the tests were run at ambient temperature and at -40°C. At ambient, 25°C, the total drop in temperature was 1.21°C, and at -40°C the total drop was 3.60°C. At the latter temperature, it was calculated that a moisture content of 84 PPM by volume would be required to produce condensation inside the regulator. Analysis of a sample of the Freon-14, having been passed through the GSE, revealed a moisture content of only 15 PPM.

However, the solenoid valves used on IMP-I, H and J were somewhat larger and were often operated with a pulse width in excess of 60 sec. With the significantly higher flow rate, a much larger temperature drop was expected. In fact, during periods of extensive ACS operation, an external layer of frost was formed downstream of the regulator, indicating a temperature of less than 0°C, but no serious discrepancies in the flow or leakage characteristics were ever detected, and it was assumed that internal condensation and freezing did not occur. Similarly, condensation of the Freon-14 propellant was avoided because its critical temperature and pressure were not attained.

Manual Valves —

The manual valves are standard items rated by the manufacturer for a working pressure of 3000 psig, and a burst pressure greater than 12,000 psig. Valves S/N 09 and 10 were helium leak tested by GSFC, request no. 1340-14 completed 3/18/69. The leak rate across the seat and through the valve packing was found to be less than 10^{-6} scc/sec for all tests. The flight valves were inspected, cleaned and the o-rings lubricated prior to installation in the ACS.

Eight additional valves of an identical design but with a stainless steel body were purchased for the IMP-J, but no specific tests were performed with these units.

Other manual valves tested included a ball valve, Whitey P/N 43S4, which was used in the GSE. It was tested per request no. 1340-10, completed 10/4/68, and found to have a leak rate less than 10^{-9} scc/sec in all configurations.

Similarly, a Nupro valve, P/N SS-4L, was leak tested with helium at 60 psig, and at -10°C and ambient temperatures per request no. 1350-3, completed 5/11/71. In general the results indicated an unacceptable leak rate, both across the seat and through the packing, and this valve was not selected as flight hardware.

Swivel Joints —

The swivel joints were designed by GSFC, and are normally cleaned, assembled and leak tested just prior to installation. S/N 01 and 02 have been helium leak tested to 40 psig at +50°C, ambient and -40°C; cycled 100 times; and proof pressure tested to 60 psig by GSFC, request no. 1340-17 completed 4/24/69. The leak rate was found to be less than 2 x 10^{-6} scc/sec for all tests.

Tubing and Fittings (low pressure) —

The aluminum (6061-T4) tubing and fittings (Swagelok) used on the low pressure portion of the ACS are standard items and rated by the manufacturer to have a burst pressure greater than 1000 psig. No testing was performed by GSFC on these items; however, all hardware was inspected and cleaned prior to installation on the spacecraft. In addition, all tubing and fittings to be exposed to sunlight in orbit were polished to a high luster finish as a thermal coating.

O-Rings —

All o-rings used in the ACS were Parker C147-7 Neoprene or Parker L608-6 or L677-7 fluorosilicone material and standard sizes. Each o-ring was inspected, cleaned and lubricated with Dow Corning (silicone) High Vacuum grease before assembly. No testing was performed on these items. In the event it became necessary to disassemble any component, the o-rings were replaced at the time of reassembly. Also it was necessary to fabricate special thimbles for use in the installation of the o-rings and to exercise caution in order to avoid twisting, tearing, scratching, chipping or contamination during assembly.

Boom Material —

Two representative samples of the glass fiber boom material were structurally tested per request no. 1350-10, completed 7/22/71. One sample failed under a bending moment of 326 ft-lb, and the other failed at 330 ft-lb.

All the original material segments were weighed and marked with S/N 101 through 107, and the pair of flight segments was chosen according to nearest matching weights. The test samples consisted of excess material removed from one end of the oversize segments when they were cut to flight length.

Upon fabrication of a set of ETU booms, a series of drop tests was conducted between heights of 2 and 15 inches. Successful completion of the tests on 8/19/69 per request no. 1340-28, indicated sufficient structural capability for the composite boom and hinge design to withstand the deployment loads.

Solenoid Valves —

The solenoid valves were a standard design modified by the manufacturer to conform to GSFC specifications. Although each valve was subjected to acceptance testing by GSFC, the basic design qualification testing was conducted by the manufacturer during the IMP-I program and applies to the valves used on all three spacecraft by virtue of their similarity.

The qualification tests required one valve, labeled "TEST", to demonstrate performance as follows: Proof test to 90 psig; pull-in and drop-out voltage measurement; internal leakage determined to be less than 10^{-7} scc/sec (CF_4); insulation resistance measurement; vibration; low temperature functioning at -40°F; high temperature operation at +125°F; and endurance cycling to 2.5 million cycles. The results of these tests indicated that the required valve specification could be met.

Upon delivery, each valve was also tested by GSFC for certain specific performance characteristics. Although, for IMP-I, 13 out of 39 valves were found to be unacceptable, mostly due to excessive leakage, and were returned to the manufacturer for rework, only the valves with the best test results were chosen for flight and flight spare hardware. Low leak rate at cold temperatures was the primary criteria for this choice.

Upon completion of the assembly of the first set of IMP-I Valve-Nozzle assemblies, a magnetic properties measurement was made, completed on 1/9/70, using a representative arrangement of ACS valves in which various power configurations and separation distances were simulated. The results indicated a substantial magnetic field contribution with the valves energized, but little permanent residual accumulation after successive actuations. The conclusion was that the selected ACS design was compatible with other spacecraft components, including the magnetometer experiment.

Finally, a discussion concerning the ACS solenoid valves during the IMP-I design review resulted in the recommendation that the valves be actuated only when pressurized. It was feared that "dry firing" without the benefit of damping by the pressurant would cause damage to the internal parts, especially the valve seat. Although no evidence of such damage was ever observed, dry firing was kept to a minimum, primarily to take advantage of the flushing action afforded by the flowing gas whenever the valves were actuated.

Further discussion of solenoid valve specifications and testing can be found in Parts II and III of this document.

Nozzles —

A series of tests was performed by GSFC, request no. 1340-9, in order to determine the optimum nozzle design for the ACS. Various nozzle angles, area ratios and chamber pressures were examined, at ambient temperature, using both Freon-14 and nitrogen; and specific impulse measurements were made for each case. Some of these results are presented in Table 2. The IMP-I nozzle configuration was further tested by GSFC, request no. 1340-21, and found to deliver a specific impulse of 44.6 sec, with Freon-14 at 25°C and 40 psia, and a thrust of 33 millipounds.

The nozzles used on IMP-H and J were basically the same as those used on IMP-I except that the throat diameter was enlarged to 0.037 inches, giving an area ratio of 50:1. This was also one of the configurations tested per request no. 1340-9, and at 40 psia and ambient temperature the specific impulse was measured at 46.9 sec. Additional tests were conducted per request no. 1350-8, completed 7/27/71, in which a sample flight type nozzle was tested at both 0°C and ambient temperature with various inlet pressures between 20 and 50 psia using Freon-14. At 40 psia, the thrust force was 0.066 lb at 0°C and 0.065 lb at ambient temperature.

All nozzles were inspected, polished and cleaned prior to installation in the ACS.

Freon-14 Propellant —

Each container of Freon-14 was tested by the manufacturer for purity and a moisture content of less than 2 PPM prior to shipment, and a sample was tested and verified by GSFC after delivery. A portion of this Freon-14 was transferred to four GSFC containers at a higher pressure, and these were tested on 7/16/70 for moisture content and found to have a dew point less than -100°F. The pressure-temperature relationship for Freon-14, both for 100% Freon-14 and for a mixture with a 10% partial pressure of helium, was investigated experimentally by GSFC, request no. 1340-41, and found to compare satisfactorily, within 5% of the theoretical values obtained from the Martin-Hou Equation for Freon-14. At the time of the above test, an accurate measurement of the ACS tank, S/N 0006, volume, with temperature probe and fittings installed, was made and found to be 7328 ml (447 in^3).

Subsequently, it was decided to purchase the ACS propellant in pre-mixed quantities and thus improve the reliability of obtaining a consistent helium percentage during each filling of the system. The specifications called for 10% ±1/2% partial pressure of helium and the manufacturer's analysis indicated that 10.2% had been achieved. Tests performed by GSFC, by means of gas chromatography, produced values between 10.0% and 10.3% helium.

Table 2

Specific Impulse for Freon-14

Nozzle Cone 1/2 Angle	Area Ratio A_e/A_t	Inlet Pressure (psia)	Ambient Press. P_A (mm H_G)	Flow Rate (lb/sec x 10^{-4})	Thrust Force (milli-lb)	Specific Impulse (sec)		
						Calc. at $P_A = 0$	Calc. at P_A	Measured
10°	100	20	1	5.2	23.2	49.7	47.3	44.6
		30	1	7.75	35.0	49.9	48.2	45.2
		40	2	10.1	46.3	49.8	47.4	45.8
		50	2	12.8	59.2	49.8	47.8	46.3
		50	5	12.8	58.2	49.8	44.8	45.5
10°	50	20	1	5.1	23.4	48.6	47.3	45.9
		30	2	7.75	35.0	48.6	46.9	45.2
		40	2	10.0	46.9	48.6	47.4	46.9
		50	3	12.5	59.6	48.6	47.1	47.7
		50	10	12.8	57.4	48.6	43.6	45.8
10°	20	20	1	5.0	21.6	46.6	46.1	43.2
		30	1	7.65	34.2	46.7	46.4	44.7
		40	1	9.9	45.9	46.7	46.4	46.4
		50	3	12.5	57.8	46.7	46.1	46.2
		50	20	12.5	55.8	46.7	42.7	44.6
20°	100	20	2	5.1	19.6	48.6	43.8	38.4
		30	2	7.75	30.1	48.6	45.5	38.8
		40	3	9.9	41.4	48.6	45.1	41.8
		50	2	12.5	52.7	48.7	46.7	42.2
		50	5	12.5	51.7	48.7	43.8	41.4
20°	50	20	1	5.25	21.2	47.5	46.2	40.4
		30	2	7.75	32.7	47.5	45.9	42.2
		40	2	10.0	43.9	47.5	46.3	43.9
		50	4	12.5	54.6	47.5	45.5	43.7
		50	21	12.5	52.1	47.5	37.3	41.7
20°	20	20	1	5.1	21.6	45.7	45.1	42.4
		30	2	7.65	32.3	45.7	45.0	42.2
		40	3	9.9	43.4	45.6	44.9	43.8
		50	3	12.4	55.0	45.6	45.0	44.4
		50	21	12.4	52.5	45.6	41.4	42.3

Further discussion of the Freon-14 propellant can be found in Part I, Section G and Part II, Section A.

Air Bearing Test —

An interesting test was conducted using the IMP-I spare ACS in a nearly friction-free environment. The Shelf assembly and both Valve-Nozzle assemblies were installed on the air bearing facility to undergo a performance and system calibration test under simulated orbital conditions of vacuum, moment of inertia, spin rate, two degrees of freedom of motion, sun pulse and telemetry. The only compromising features were a gravity torque created by a slight unbalance and the apparent precession caused by the rotation of the earth. Although the test was prematurely terminated on 12/2/70 due to support equipment failure, the small amount of data which was obtained, indicated good correlation with the calculated performance.

A similar test performed, previously, with the AIMP-E system, thoroughly investigated the full range of precession control and produced results which compared remarkably well with the calculated values.

Section E — System Servicing

The system is designed with three pneumatic servicing ports in facet 6 and two manual control valves in facet 5, all of which were accessible from the periphery of the spacecraft. In addition, various electrical test connectors located in facets 10 and 12, and at the ends of the ACS booms, were used in the check out of the system several times before launch. Details of all normal servicing operations are outlined in the IMP-H and J ACS Fill Procedure H, JFP-001 Rev. A, and it is this procedure which was followed for all pressurizations of the system.

The Fill Procedure for the ACS provides a controlled method for filling the system with Freon-14 propellant, 90% by pressure, and helium gas, 10% by pressure. Provisions are included for initial filling, proof testing, venting, topping off and leak testing, with the helium added to the system solely for the purpose of leak detection prior to launch. When each step has been completed and signed off, a copy of the Fill Procedure document becomes an official record of the particular operation. Alternate procedures are also included to allow for the use of a pre-mixed propellant, as well as the use of nitrogen for proof testing. A leak test sequence and the ACS checkout procedure are included in the appendixes of the Fill Procedure.

Generally, during the initial fill operation, the ACS is evacuated to remove moisture and gaseous impurities. It is then filled with Freon-14 to 10%, but not less than 100 psi, of the maximum pressure expected during the fill operation. Another

10%, but not less than 100 psi, in helium pressure is then added and a leak test performed. This constitutes the initial fill portion of the procedure. Finally, the ACS is filled with Freon-14 to the desired total pressure where another leak test is conducted. When using pre-mixed propellant, the initial fill consists of evacuation, filling to approximately 500 psi, and a leak test. In all cases, the tank temperature is monitored through the test connector in facet 10, and the tank pressure is monitored either through telemetry or a GSE cable attached to the high pressure transducer.

For proof testing, the area is cleared of personnel following the initial fill, and the ACS is filled with Freon-14 to 2700 psig and held at that pressure for at least ten minutes. This subjects the ACS to 1.5 times the maximum allowable working pressure and constitutes the proof test for the system. It may be necessary to add some helium, prior to the proof test, in order to raise the helium partial pressure to 270 psia in order to ensure a 10% partial pressure after venting.

After ten minutes at 2700 psig, the system is vented to approximately 1800 psig, where a leak test is performed. A proof test is required only once for each assembled system. However, spare components must also have been proof tested individually. The proof test requirements may also be satisfied by substituting clean dry nitrogen gas for the Freon-14 in the proof test procedure when the Freon-14 supply must be conserved. When proof testing in this manner, system evacuation is not required at first, and the initial fill procedure consists of filling the ACS with nitrogen to 270 psia, adding helium to 540 psia, and performing a leak test. The proof test is accomplished by filling the ACS with nitrogen to 2700 psi, holding for ten minutes and then venting all the gas. This is an optional method and requires deviation from the written procedures. Subsequent charging of the ACS consists of performing the initial fill procedure as originally described.

Topping off and refill operations are done in such a manner so as to achieve the desired working pressure together with the 10% helium pressure. However, when the additional gas required is 100 psi or less, topping off can be done entirely with Freon-14. The final flight pressure is determined from the latest mass property information and mission requirements, but for the purpose of spacecraft testing, 1800 psig at 23°C constitutes working pressure.

In order to calculate the amount of propellant onboard, it is important to accurately determine the actual helium percentage when the ACS is filled. To accomplish this, it is necessary to record the pressure before and after helium addition only when the temperatures have stabilized at the same values. The use of the pre-mixed propellant simplifies not only the helium percentage determination, but also all of the other fill operations as well. Since a temperature rise normally occurs during any fill operation, a tabulation of acceptable final pressure-temperature combinations is made, based on a constant weight of propellant required for the mission. Venting or dumping of propellant is done either through the check valve by means of the special vent tool or through the outlet port by means of the outlet valve.

Any changes or revisions to the procedure are noted on a marked up copy of the document, and updated copies are made available to all appropriate personnel. In the course of performing any of the fill operations, certain deviations from the written procedures are permissible, and must be reviewed and approved by the cognizant engineer and noted at the appropriate step. When performing any of the fill procedures at a facility other than GSFC, all changes and deviations from the written procedures must be reviewed and approved by the appropriate safety personnel for that facility prior to performing the operation. At ETR, approval must be obtained from KSC-ULO and Air Force Safety.

The performance of any of the fill procedures requires the presence of at least one mechanical technician and a cognizant engineer. In some instances, another technician, either mechanical or electrical, is required to assist with some specific operations. These personnel must be familiar with the equipment used in this particular operation. A pad safety supervisor must be present for the initial filling and for each pressurization above a pressure previously attained at the launch facility. Appropriate spacecraft personnel must also be present to assist with spacecraft handling.

The fill operations may be performed only in a suitable facility consisting of the following: (e.g., at KSC in Hangar S)

a. sufficient room for the spacecraft with its support and handling equipment

b. an area, somewhat removed from the spacecraft, for the fill operations equipment and personnel

c. a protective barrier arrangement to shield personnel (for hazardous operations only)

d. isolation from other areas containing personnel and unrelated activities

e. restricted and controlled access by personnel

f. a monitored and controlled atmosphere in accordance with spacecraft requirements for cleanliness

g. emergency exits and warning devices, including a telephone

h. standard electrical power outlets

i. communication link to receive spacecraft telemetry data when required.

The ACS Fill Procedure equipment setup is shown in Figure 5.

As a prerequisite, the ACS must be assembled on the spacecraft at least up to the boom interface area before the ACS fill procedures can be performed. If any pneumatic components are missing, the interface must be capped or plugged. As these components are installed, their connections must be leak tested separately. In performing a leak test on the spacecraft, access to all of the pressurized fittings is required, and it may therefore be necessary to remove several of the solar cell panels from the spacecraft for this purpose. Also, due to the sensitivity of the leak test equipment, access to the vicinity of the spacecraft must be limited solely to the operator of the test equipment. Air currents in the vicinity of the items being examined will increase the difficulty of the leak detection process, and must therefore be kept to a minimum.

In the interest of safety, only the required personnel are to be present during any of the fill operations. Special observers must be kept to a minimum and must obtain prior approval from the cognizant engineer; or, when operations are performed at a facility other than GSFC, prior approval must be obtained from the appropriate safety officer. For personnel safety, the following warnings must be observed:

a. filling the ACS to proof pressure must be performed from a distance of at least 50 feet or with all personnel behind protective barriers

b. use extreme care when working with the charged ACS, as damage to the system could cause abrupt outgassing and injury to personnel

c. vent lines before breaking any pressurized connection

d. care must be taken when handling electrical equipment to avoid electircal shock

e. safety goggles must be worn while working around pressurized equipment; at ETR, a full length face shield is required

f. when purging fill lines prior to attachment, firmly secure outlet end to prevent whipping when gas is permitted to flow

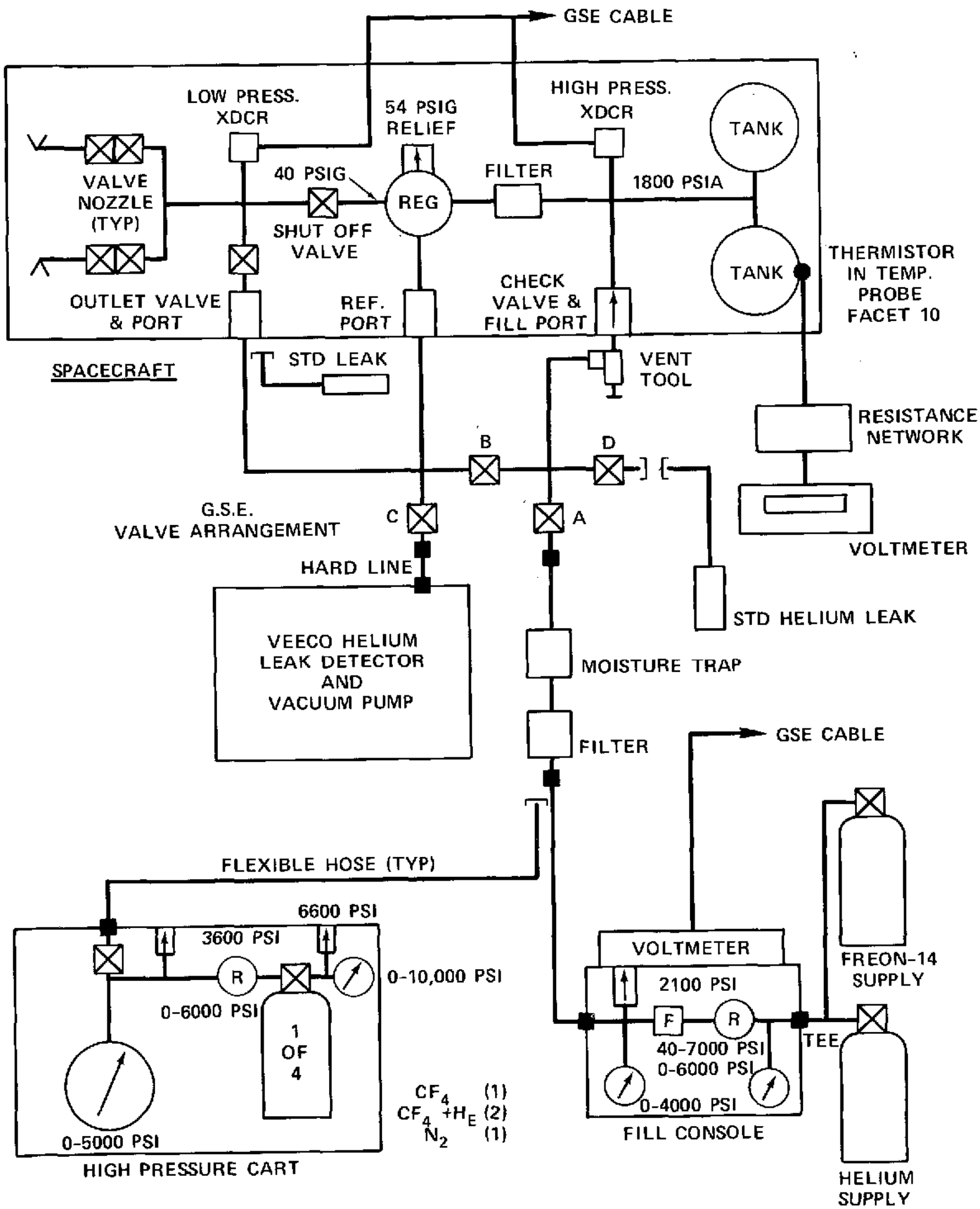


Figure 5. ACS Fill Procedure Equipment Setup

g. note the locations of fire exits, and become familiar with emergency reporting procedures before performing any hazardous operations

h. when initial pressure is applied to new components, the area must be cleared of personnel.

In order to prevent damage to equipment, these precautions must also be observed:

a. do not fill the ACS at greater than 100 psi/min, as indicated on the high pressure transducer readout, nor allow the tank temperature to exceed 40°C at any time during filling

b. do not vent the ACS at greater than 100 psi/min, as indicated on the high pressure transducer readout, nor allow the regulator temperature to drop below -10°C at any time when venting through the outlet port

c. any flexible line with 150 psi or over, with the exception of flight hardware, must be secured at each end, across each union, and at 6-foot intervals, with lead shot bags or other restraining devices to hold it in place in the event of rupture; however, securing flex lines to flight structure is exempt.

d. perform the proof test in an area free of windows, glass partitions, and other breakable items where practicable

e. the particular regulator design used in this ACS has shown susceptibility to damage when operated with 100% helium; therefore, at no time should the gas mixture used in this system exceed a 50% partial pressure of helium (helium must never be added to the ACS first)

f. to prevent contamination of the ACS, all lines and fittings used between the fill console or high pressure cart and the spacecraft must be cleaned prior to use, and capped, plugged, or bagged when not in use

g. all fill lines must be purged with a trickle of gas at approximately 1 psig for 10 seconds, prior to allowing any gas to enter the spacecraft

h. in order to maintain the cleanliness of the ACS, the minimum initial fill pressure is 200 psig; during periods of testing the pressure must not be permitted to go below 200 psig at room temperature

i. clean cotton laboratory coats, hats and gloves must be worn when working on or near the spacecraft; specific spacecraft requirements apply at all times

j. all equipment, including the spacecraft, must be attached to a common electrical ground before any connections are made

k. only appropriate and approved tools may be used in accordance with spacecraft requirements

l. the pressure on the reference port of the regulator must always be less than or equal to the internal downstream pressure of the regulator; in order to prevent damage to the relief valve bellows, lock-up pressure must be maintained on the downstream side of the regulator during evacuation.

The initial fill or first filling and, in particular, the proof test are considered hazardous operations, and as such, must be performed remotely. A hazard exists when the ACS is exposed to pressures not previously experienced as an assembly. Although the leak test and topping off operations are not themselves hazardous, they are performed in the presence of pressurized containers and caution must be observed. Any step that is particularly hazardous is so noted in the operational procedure; and at ETR, pad safety concurrence is required before proceeding.

If an emergency arises due to a significant mechanical failure, such as the rupture of a pressurized container, during any of the fill operations, the pressure must be shut off immediately at the supply if possible. If a pressurized line breaks and is whipping about, all personnel should evacuate the area immediately, and remain out of the area, until such time that all motion has dissipated. In the event of an electrical failure, all filling operations must be discontinued; all lines must be vented, and all gas supplies must be secured.

All personnel present during the performance of any of the fill operations must be familiar with the procedures for summoning emergency assistance in the event of fire or personal injury. For example, at GSFC dial '0' (operator) on the telephone, or use the nearest standard fire alarm box.

During periods of time when the system remains in a pressurized condition, it is recommended that the pressure and temperature readings be monitored on a daily basis. For the purpose of shipping, the ACS pressure must be vented to approximately 800 psig at room temperature, and both the outlet valve and shut off valve must be closed. However, in order to reduce wear on the o-ring seal, the shut off valve may remain open during the entire period of environmental testing of the flight spacecraft. It must also be open for flight and during launch.

In addition, it was recommended that the moisture content of the Freon-14 supply be monitored periodically during the test program to ensure a dew point of less than -94°F prior to its use for any fill operations. A similar test was recommended for the residual propellant in the ACS tanks prior to the final topping off procedure, and for the filled flight system at some convenient time before launch. The purpose of this sampling was to verify the precautions taken to ensure propellant purity and cleanliness within the system, and to provide assurance that condensation and freezing would not occur during prolonged operation in the cold temperature of space.

It should be noted that a Cleanliness Control Plan was established, to be used throughout the integration and environmental testing of the spacecraft. It specified that the area surrounding any spacecraft activity have a particle count consistent with, or better than, the Class 100,000 requirements. In addition, the atmospheric pressure was maintained slightly positive, with a temperature of 70° ±5°F and a relative humidity of between 30 and 50%. Although most facilities complied with these requirements, a portable downflow unit was used in marginal cases and for redundancy to ensure a clean environment.

If the equipment and facilities are available, some of the ACS fill procedures may be performed with the spacecraft located on a set of weighing scales or some other equivalent weight measuring device. This provides an opportunity to compare the calculated amount of ACS charge with the actual weight of propellant added to or removed from the spacecraft. In general, any filling follows the topping off procedure, and any venting consists of dumping propellant through the outlet port, and recording the pressure and temperature both before and after the operation. Since a predetermined amount of propellant must be transferred, weight readings must be monitored closely throughout the operation in order to obtain an accurate end result.

Prior to shipment of the spacecraft to the launch site, the Project Office and the appropriate launch site authority were officially informed, in writing, of the status of the ACS. The written notice contained certification that the ACS had been successfully proof tested and indicated that the installed system was qualified for flight.

In general, the normal operations performed at the launch site prior to launch included an ACS checkout, a leak test, topping off to flight pressure, and a final leak test, all as described in the Fill Procedures document. Equipment was also available to perform a proof test if it became necessary. Although no ACS fill operations were performed after the spacecraft was moved to the service gantry, a small excess of propellant was available and expelled during the final functional test of the spacecraft prior to fairing installation.

Subsequent to pneumatic servicing, the ACS must be thoroughly and periodically examined electrically. The purpose of this checkout operation is to verify the electrical integrity and functional capability of some specific and critical components in the ACS. Appropriate records must be obtained which are useful in the analysis and evaluation of particular system parameters and characteristics. This data also provides a means of comparison among identical components and serves as an aid in detecting time or environment related changes in performance. Ultimately, it is intended to reveal any anomalistic behavior which may be detrimental to the system or the spacecraft. Finally, since the ACS is a vitally important system, its proper operation is a mandatory prerequisite to launch, and must be demonstrated during the prelaunch operations. The checkout is performed in addition to the operations included as part of the normal integration and environmental tests.

The ACS checkout requires obtaining a current trace for each of the twelve solenoid valves within the system. This provides an analog record of current drawn versus time, and reveals the valve opening characteristics, including response time. Normally, the four valves which control one specific function (i.e., spin, despin, or reorient) are actuated and examined simultaneously with the information recorded on a strip chart. Valve actuation is controlled either through the normal spacecraft power system or by means of externally applied power; and the information is obtained through a special test connector incorporated into the ACS Diode Pack.

Another item which is investigated during the ACS checkout is the nozzle thrust chamber pressure profile. This is another analog record which is related to the dynamic forces applied to the spacecraft by means of the ACS. Since one coordinate is time, it is possible to determine any inherent delay in the system and predict the characteristic error in the motion of the spacecraft. Information is obtained by means of a GSE pressure transducer placed in the special port of each thruster nozzle. The data is recorded on the same strip chart as the valve current information. A typical current trace and pressure profile recording is shown in Figure 6.

It is also possible to coordinate the above information with the centered sun pulse, and then determine the precise rotation angle at which the ACS thrusters fire in each quadrant. A test connector on the ACS electronics card in facet 12 is provided for this purpose.

In general, the ACS checkout is performed, with appropriate modifications, at some convenient time following the first pressurization, during thermal vacuum testing at various temperatures, during the final prelaunch operations at the launch site, and at any other time determined to be desirable.

It should be noted that prior to integration into the ACS, the solenoid valves in the Valve-Nozzle assembly are tested for proper solenoid polarity when actuated.

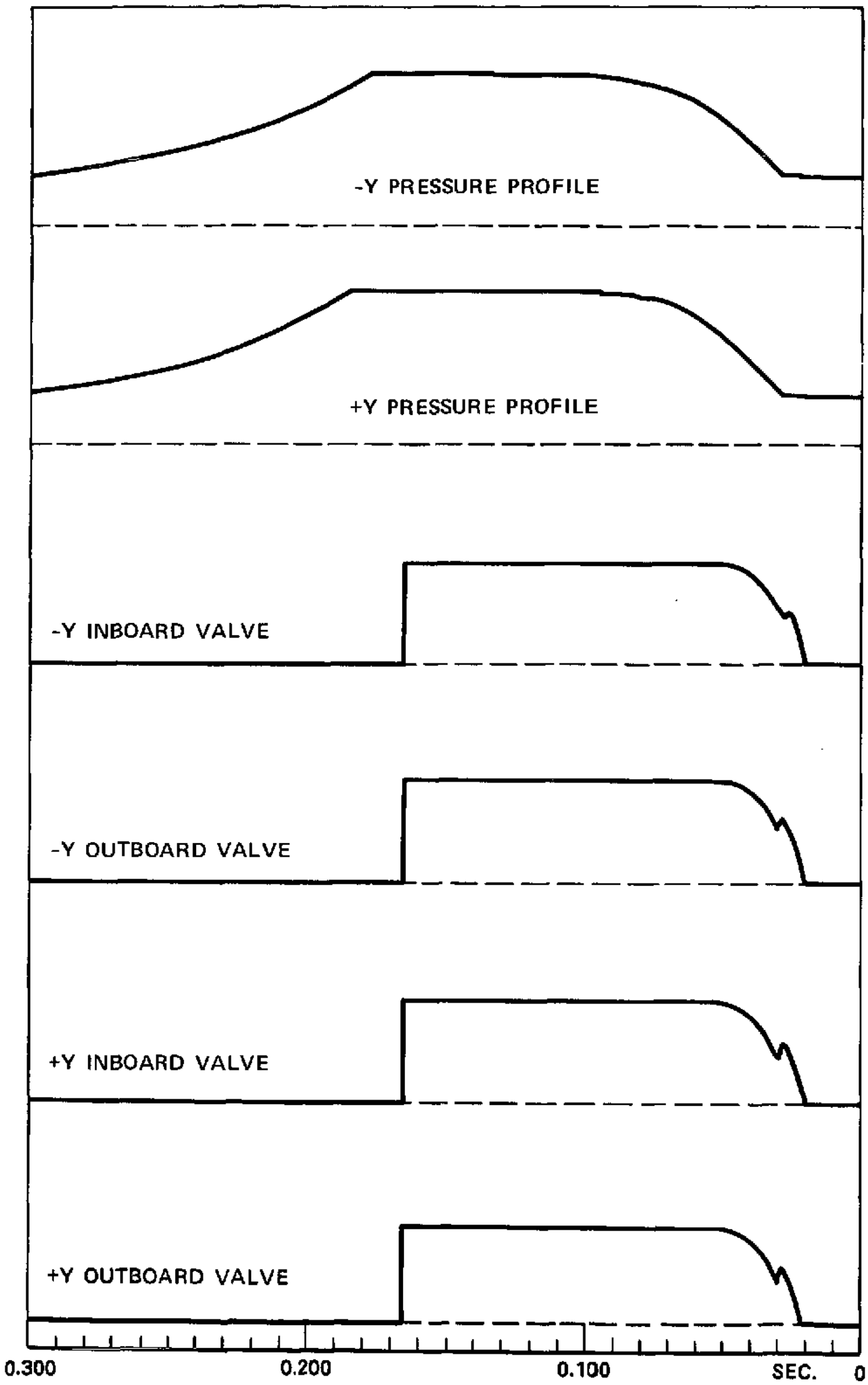


Figure 6. Typical Current Trace and Pressure Profile

This is accomplished by placing a small magnetic compass in proximity to each valve when it is energized and by observing the compass needle orientation. For correct polarity, the needle should indicate opposite orientation for each series pair of valves.

Another item investigated is the polarity of the high and low pressure transducers. This is accomplished by releasing gas and observing the indicated pressure changes. Polarity is correct if both pressure readouts show a decrease as gas is expended.

In order to conduct the ACS checkout, one electronic technician, one mechanical technician, and a cognizant engineer are required. In addition, appropriate spacecraft personnel are required to perform specific duties in preparation of the spacecraft.

In preparation for the ACS checkout, the spacecraft configuration must be such that the entire ACS is installed with the tanks pressurized to greater than 200 psig. The booms may be either folded or deployed so long as access is provided in the area of the Valve-Nozzle assemblies. The strip chart recorder and power supply must be in an appropriate location so as to allow access to standard electrical power and attachment to the spacecraft by means of the special GSE cables. For thermal vacuum testing, the cables utilize the standard feedthrough in the vacuum chamber wall. All equipment must also be properly grounded.

The blue plugs in the Valve-Nozzle assemblies must be removed and replaced by the GSE transducers, distinctly marked for each specific location. Similarly, the cables must be attached according to the markings on the connectors. On the diode packs, the dummy connectors must be removed and replaced by the test connector and cable. If external power is used, the boom cables must be disconnected, and the appropriate GSE cable attached. For centered sun pulse information, a special cable is attached to the test connector in the ACS electronics card. The ACS shut-off valve must be open on the spacecraft, and the nozzle protective covers must be removed.

It is most desirable to record the first valve actuation following an extended dormant period, and it is recommended that the valves not be actuated during a dry run nor when they are not pressurized with a gas. Normally for a manually controlled checkout operation, two pulses of approximately 2 seconds duration each are recorded. Otherwise, the pulses are controlled automatically by the spacecraft and ACS electronics. When testing in a vacuum chamber, the spin-up and despin pulses may be cut to 10 seconds or less in order to avoid flooding the chamber.

Upon completion of the checkout, the GSE cables and transducers are removed and the spacecraft is returned to its original pre-ACS checkout configuration. Although the features are available, no lock wire is used on the blue plugs when they are reinstalled on the Valve-Nozzle assemblies. Subsequently, the ACS strip chart record is analyzed for any ACS difficulties or discrepancies, and for the amount of characteristic delay. Finally, a certification signature is required at the completion of the checkout procedure.

In summary, the normal schedule of ACS and related operations during integration and qualification are as follows.

1. Initial filling and leak test to verify the integrity of the newly assembled system.

2. Proof test to demonstrate compliance with safety requirements.

3. Filling and leak test as prerequisite to ACS Electronics integration procedure.

4. ACS check out to obtain current trace and pressure profile.

5. Total spacecraft magnetic measurement.

6. Sun spin test to calibrate installed sun aspect sensor.

7. Spacecraft mass properties measurements.

8. Functional test of entire spacecraft including leak test.

9. Vibration test in launch configuration.

10. Deployment test series of both the ACS and Experiment booms.

11. Second functional test and leak check.

12. Thermal vacuum environment simulation with total leak rate measurement together with functional tests of all subsystems.

13. Refill of ACS to intended flight quantity.

14. Final spacecraft mass property measurement, random vibration, magnetic measurement and functional test.

15. ACS venting in preparation for shipping to launch site.

In addition, the following operations are also performed at the launch facility prior to launch.

1. Preliminary leak check to detect any leaks developed during shipment to the launch site.

2. ACS checkout to determine final valve characteristics such as current trace and pressure profile.

3. Topping off to flight propellant quantity; performed, preferably, on a set of scales in order to obtain an accurate weight measurement.

4. Final leak test immediately following topping off operation.

5. Final inspection to verify proper assembly and configuration, including removal of strip coat from thermally coated surfaces.

6. Gantry check utilizing telemetry to demonstrate total system functional capability in an abbreviated form.

Finally, it is recommended that a short calibration maneuver, similar to the gantry check, be performed as soon after launch as is practical in order to verify complete survival through the launch phase.

Section F — Leak Testing

Another periodic examination of the ACS is the leak test. In general, the leak detection philosophy for this system is a compromise between simplicity and accuracy of measurement. Since it was more important to be able to locate a specific leak rather than to measure its actual magnitude, it was decided to utilize a mass spectrometer type helium leak detector. This instrument, a Veeco MS-9, is equipped with a probe which is used to sniff for helium at any specific location and is capable of detecting a leak as small as 10^{-5} scc/sec. Since there are approximately 100 pressurized fittings or areas of potential leakage, the maximum total undetectable leak rate is 10^{-3} scc/sec, which is the leak specification limit for this system. Some of the major difficulties in using this method are the fact that air currents tend to prevent the leaking helium from entering the probe and that testing in a vacuum chamber or at other than ambient temperature is all but impossible. Also it is necessary to fly heavier tanks to accommodate the extra pressure contributed by the helium, and to convert the helium leak rate into a Freon-14 leak rate by multiplying by 0.213. On the other hand, the ability to locate a leak by direct means, reduces the amount of time and effort required to repair the system. In addition, the Veeco is reasonably portable and a leak test can be performed in nearly any facility compatible with the spacecraft. However, in the course of spacecraft environmental testing, there are several opportunities in which to obtain a cross check on the overall total leak rate of the system. When the spacecraft is placed in a vacuum chamber, such as during thermal vacuum tests, the steady state chamber pressure is compared to that for the same chamber when empty, and thus the partial pressure contributed by the spacecraft and subsystems is determined. Simultaneously, the residual atmosphere in the chamber is analyzed by means of a mass spectrometer in order to obtain the concentration of Freon-14, and by comparison with a calibration curve, the actual total leak rate is determined. Although the leak rate is not expected to change significantly in a vacuum, this method does have the obvious advantage of being able to detect temperature related leaks. In general, the probe and sniff method combined with vacuum chamber measurements has proven to be a workable leak test scheme for cold gas systems, and involves a minimum of sophistication and down time for the spacecraft.

It is interesting to compare some of the results obtained from previous vacuum chamber tests. During the IMP-H Solar Environment Simulation, the ACS total leak rate at approximately +25°C was measured at 2.3×10^{-3} scc/sec (CF_4); but during a 2-1/2 hour simulated shadow at -40°C, the leak rate increased to 1.5×10^{-2} scc/sec (CF_4). Upon warming to +20°C, the leak rate returned to the original value. Although the leakage at the warmer temperatures was slightly higher than the specification, it was comparable to the rate measured for the IMP-I and considered acceptable. Later, the specification was raised to 5×10^{-3} scc/sec based on the IMP-I experience. However, the eight fold increase at -40°C was also acceptable since full recovery occurred after a relatively short shadow duration and a reasonably small propellant loss, with a leak rate at least an order of magnitude smaller than that measured for IMP-I in the same type test. These leak rates for IMP-H were accepted because the measurements were somewhat compromised by the outgassing from the spacecraft and the higher residual concentration of Freon-14 produced by previous actuations of the system during functional testing. Other leak detection methods could not locate any predominant individual leaks and subsequent thermal vacuum measurements recorded leakage on the order of 1×10^{-3} scc/sec (CF_4) at ambient temperatures.

At various times during the qualification testing of the spacecraft, such as before and after a vibration test and during certain fill operations, a separate sniff leak test is normally performed.

To aid in the leak check of the ACS while using the Veeco machine, provisions have been made for the installation of a standard leak on the outlet port of the spacecraft. This is a temporary installation (not flight hardware) and consists of a standard helium leak, rated at 9.8×10^{-3} scc/sec. The probe on the Veeco machine is used to periodically sniff this leak in order to verify the sensitivity of the leak detector. Also, monitoring the pressure drop in the ACS over a period of several days with this leak installed provides an indication of the expected rate of pressure drop from a known leak.

The leak test is performed using the Veeco to sniff for helium at each connection of the ACS, and at the standard leak. Appendix A of the Fill Procedure contains the specific details and locations of the connections. A leak rate of less than 10^{-6} scc/sec is acceptable for each connection. If any leaks are detected in the high pressure portion of the ACS, the locations are marked and the system depressurized, either through the check valve or the outlet port. When leaks are detected in the low pressure portion of the ACS, the locations are marked and only the shut-off valve is closed on the spacecraft so as to allow venting of the low pressure portion either through the solenoid valves or the outlet port. After tightening the connections as required, the shut-off valve is opened and, if necessary, the ACS is refilled according to the topping off procedure. If tightening of the connections fails to correct all the leaks and it is necessary to replace the defective components, care must be taken to prevent contamination during disassembly and only properly cleaned parts must be used as replacements. Upon reassembly of the system, pressurization follows the initial fill procedure.

In certain cases, tightening of the standard tube fittings is permitted, in an effort to reduce leakage, while pressurized up to the maximum working pressure so long as the manufacturer's torque specifications are not exceeded. This practice is not permitted at ETR.

Finally, a certification signature is required upon completion of the leak test procedure.

Section G — Freon-14 Properties

Some basic data on Freon-14 can be found in the Specialty Gases and Equipment catalog published by Air Products and Chemicals Inc. In general, Freon-14 is an inert, colorless, odorless, nontoxic, noncorrosive and nonflammable gas under ambient conditions. Other characteristics are as follows:

Chemical formula	CF_4 (Tetra-Fluoromethane)
Molecular weight	88.011
Boiling point	-198.32°F
Melting point	-299°F
Density, gas at 70°F, 1 atm	0.228 lb/ft^3
Density, liquid at boiling point	122.36 lb/ft^3

Specific gravity of gas at 70°F, 1 atm	3.03
Critical temperature	-50.2°F (-45.7°C)
Critical pressure	543.2 psia
Critical density	39.06 lb/ft^3
Critical volume	0.0256 ft^3/lb
Solubility in water at 50°F, 1 atm	0.0015% by weight
Heat of vaporization	5160 BTU/lb-mole
Specific heat, 70°F, 1 atm	Cp = 14.6 BTU/lb-mole -°F

The purity specification of the product is as follows:

Purity, exclusive of air	99.80% by volume, min.
Moisture content	2 PPM by weight, max.
Carbon monoxide content	0.20% by volume, max. at room temperature.
Combined air and carbon monoxide	1.0% by volume, max. at room temperature
Combined organic impurities and carbon monoxide	0.20% by volume, max.
Free acidity, as hydrochloric acid	0.100 PPM by weight, max.

The Freon Products Division of E.I. Dupont De Nemours and Co., Inc. Wilmington, Delaware 19898, has supplied additional information regarding the properties of Freon-14. Table 3 contains some experimental values for specific heats, including Cp, Cv, K and R, which may be used to calculate a theoretical specific impulse;

$$I_{SP} = \left[\frac{2KRJTn}{g(K-1)}\right]^{1/2} = \left[\frac{2CpJTn}{g}\right]^{1/2}$$

where n is the nozzle efficiency, T is the absolute temperature in °R, J is the conversion factor 778 ft-lb/BTU, and g is the acceleration of gravity, 32.16 ft/sec^2. Some experimental results of the determination of thrust and specific impulse are also presented in Table 2. These values were used to design the flight nozzles for all three spacecraft.

In addition, the University of Michigan has developed the Martin-Hou equation of state for Freon-14. It was this equation which was used to determine the

Table 3

Specific Heats for Freon-14

Pressure psia	Temp. °F	Spec. Vol. ft^3/lb	Cp BTU/lb-°F	Cv BTU/lb-°F	K Cp/Cv	R Cp-Cv
14.696	-50	3.3679	0.1438	0.1204	1.1948	0.0234
	0	3.7056	0.1534	0.1301	1.1788	0.0233
	50	4.2103	0.1627	0.1396	1.1657	0.0231
	100	4.6298	0.1716	0.1486	1.1549	0.0230
40	50	1.5376	0.1638	0.1396	1.1734	0.0242
100	0	0.5358	0.1582	0.1303	1.2137	0.0279
	50	0.6027	0.1663	0.1396	1.1909	0.0267
	100	0.6684	0.1745	0.1487	1.1739	0.0258
200	0	0.2548	0.1654	0.1305	1.2673	0.0349
	100	0.3273	0.1783	0.1487	1.1989	0.0296
500	-10	0.0792	0.2182	0.1295	1.6854	0.0887
	70	0.1121	0.1926	0.1436	1.3411	0.0490
540	0	0.0753	0.2206	0.1313	1.6796	0.0893
	100	0.1125	0.1951	0.1489	1.3105	0.0462
543.16	-50.19	0.0256	-24200	0.1241	-195062	-24200
1000	0	0.0258	0.3882	0.1324	2.9319	0.2558
	20	0.0329	0.3361	0.1357	2.4768	0.2004
	40	0.0393	0.2841	0.1390	2.0437	0.1451
	60	0.0451	0.2541	0.1424	1.7851	0.1117
	80	0.0502	0.2375	0.1458	1.6296	0.0917
	100	0.0548	0.2279	0.1492	1.5280	0.0787
2000	0	0.0175	0.2767	0.1321	2.0946	0.1446
	100	0.0249	0.2485	0.1494	1.6632	0.0991
5000	160	0.0186	0.2093	0.1593	1.3133	0.0500

pressure-temperature-volume relationship for the ACS. However, due to the extensive number and complexity of the calculations required, the equation was adapted to the Olivetti Programma 101 desk top computer. Although a great number of intermediate calculations were made, the general relationship is presented, in a condensed form, in Table 4.

The Martin-Hou equation may be written as:

$$P = \frac{F_1}{(V-b)^1} + \frac{F_2}{(V-b)^2} + \frac{F_3}{(V-b)^3} + \frac{F_4}{(V-b)^4} + \frac{F_5}{(V-b)^5}$$

where b = 0.005710497; and P is the Freon-14 pressure in psia, and V is the specific volume in ft^3/lb. The F values are a function of temperature and are calculated as follows:

$$G_1 = K_1 F_1 = RT = 0.121935(T)$$
$$K_1 = 1$$

$$G_2 = K_2 F_2 = A_2 + B_2 T + C_2 \left[e^{\frac{-kT}{2Tc}} \right]^2$$
$$K_2 = 1$$
$$A_2 = -3.1553788$$
$$B_2 = 0.0032480704$$
$$C_2 = -2.1911976$$

$$G_3 = K_3 F_3 = A_3 + B_3 T + C_3 \left[e^{\frac{-kT}{2Tc}} \right]^2$$
$$K_3 = 10^3$$
$$A_3 = 56.830627$$
$$B_3 = -0.056586787$$
$$C_3 = 52.630252$$

$$G_4 = K_4 F_4 = A_4 = -0.00031575738$$
$$K_4 = 1$$

$$G_5 = K_5 F_5 = A_5 + B_5 T + C_5 \left[e^{\frac{-kT}{2Tc}} \right]^2$$
$$K_5 = 10^6$$
$$A_5 = -1.5210836$$
$$B_5 = 0.0066533754$$
$$C_5 = -3.5786565$$

Table 4

Freon-14 Pressure (psia) in 0.515 ft^3

V (ft^3/lb)	Weight (lb)									
	1	2	3	4	5	6	7	8	9	10
°R(°C)	.515	.260	.170	.128	.103	.086	.0735	.0645	.0570	.0515
450 (-23.2)	104	191	277	351	415	473	526	572	615	651
455 (-20.4)	106	194	281	357	423	483	538	586	631	669
460 (-17.6)	107	197	286	363	431	492	550	599	647	687
465 (-14.8)	108	199	290	369	438	502	562	613	664	706
470 (-12.1)	109	202	294	375	446	512	573	627	679	724
475 (-9.3)	111	205	298	381	454	521	585	641	695	743
480 (-6.5)	112	207	303	386	461	531	597	655	711	761
485 (-3.7)	113	210	307	392	469	541	608	668	727	779
490 (-0.9)	115	212	311	398	477	550	620	682	743	798
495 (1.8)	116	215	315	404	485	560	632	696	759	816
500 (4.6)	117	218	319	410	492	569	643	710	775	834
505 (7.4)	119	220	323	416	500	579	655	724	791	853
510 (10.2)	120	223	327	422	508	589	667	737	807	871
515 (12.9)	121	226	331	428	515	598	678	751	823	889
520 (15.7)	122	228	335	434	523	608	690	765	839	908
525 (18.5)	124	231	339	440	531	617	702	779	855	926
530 (21.3)	125	234	343	446	538	627	713	792	871	944
535 (24.1)	126	236	347	452	546	637	725	806	887	963
540 (26.8)	128	239	351	458	554	646	737	820	903	981
545 (29.6)	129	241	356	464	561	656	748	834	919	999
550 (32.4)	130	244	360	469	569	665	760	847	935	1018
555 (35.2)	132	247	364	475	577	675	772	861	951	1036
560 (37.9)	133	249	368	481	585	685	783	875	967	1054
565 (40.7)	134	252	373	487	592	694	795	889	983	1073
570 (43.5)	135	255	377	493	600	704	807	902	999	1091

Table 4 (cont'd.)

V (ft^3/lb) / °R(°C)	Weight (lb)									
	11	12	13	14	15	16	17	18	19	20
	.0468	.0430	.0396	.0368	.0343	.0322	.0303	.0286	.0271	.0258
450 (-23.2)	684	713	741	767	791	814	838	863	888	915
455 (-20.4)	705	736	767	795	822	848	875	902	931	961
460 (-17.6)	725	759	793	823	853	882	911	941	973	1006
465 (-14.8)	746	783	819	851	884	915	947	981	1016	1052
470 (-12.1)	767	806	844	880	915	949	984	1020	1058	1098
475 (-9.3)	788	829	870	908	946	983	1020	1060	1101	1144
480 (-6.5)	809	852	895	936	977	1016	1057	1099	1144	1190
485 (-3.7)	829	875	921	964	1008	1050	1093	1138	1186	1236
490 (-0.9)	850	898	947	993	1038	1083	1130	1178	1229	1282
495 (1.8)	871	921	973	1021	1069	1117	1166	1217	1271	1328
500 (4.6)	892	944	998	1049	1100	1150	1202	1257	1314	1373
505 (7.4)	912	968	1024	1077	1132	1184	1239	1296	1356	1419
510 (10.2)	933	991	1050	1106	1162	1218	1275	1335	1399	1465
515 (12.9)	954	1014	1076	1134	1193	1251	1311	1375	1441	1511
520 (15.7)	974	1037	1101	1162	1223	1285	1348	1414	1484	1557
525 (18.5)	995	1060	1127	1190	1254	1318	1384	1454	1526	1603
530 (21.3)	1016	1083	1153	1218	1285	1352	1421	1493	1569	1649
535 (24.1)	1037	1106	1178	1247	1316	1385	1457	1532	1612	1694
540 (26.8)	1057	1129	1204	1275	1347	1419	1493	1572	1654	1740
545 (29.6)	1078	1152	1230	1303	1377	1452	1530	1611	1697	1786
550 (32.4)	1099	1175	1255	1331	1408	1486	1566	1650	1739	1832
555 (35.2)	1119	1199	1281	1359	1439	1519	1602	1690	1782	1878
560 (37.9)	1140	1222	1306	1388	1470	1553	1639	1729	1824	1924
565 (40.7)	1161	1245	1332	1416	1501	1586	1675	1768	1867	1970
570 (43.5)	1182	1268	1358	1444	1532	1620	1711	1808	1909	2015

Also, $k = 5$, $T_c = 409.5°R$, and T is the absolute temperature in °R.

The K factors have been introduced solely to facilitate the maximum significant digit capacity of the particular computer used in these calculations, and the F values are easily derived from the G values by shifting the decimal point the appropriate amount. In practice, for this ACS, the system volume is fixed at $0.515\,ft^3$ and the amount, or weight, of Freon-14 is readily calculated by,

$$W = \frac{0.515}{V}$$

However, the only measured quantities available from the spacecraft are the pressure and temperature, and it is necessary to obtain the specific volume, V, from a tabulation covering the range of all expected temperatures and pressures. With a fine enough interval for these quantities, fairly accurate results are obtained, even when interpolation is used. Figure 7 is a family of curves depicting the Freon-14 properties.

With the addition of 10% helium, the Freon-14 pressure is taken to be simply 90% of the total measured pressure, and the weight is obtained by referring to the above mentioned tabulation for the measured temperature. Under these conditions, the helium is treated as a perfect gas and its weight contribution is neglected since it is on the order of 0.1% of the total. Using this procedure, the weight determination has consistently been accurate to ±5% of the actual value. The largest portion of the error is undoubtedly due to the fact that Freon-14 deviates considerably from an ideal gas and exhibits a high degree of compressibility around 1400 psia at ambient temperature. The addition of helium also complicates the weight calculation by virtue of the fact that the pressure-temperature relationship for the mixture is not well defined. Further discussion of this subject can be found in Part III.

Finally, the fact that the Freon-14 supply was obtained in standard cylinders at a pressure of 2100 psig, made it advantageous to transfer the gas, at a higher pressure, to a special portable storage facility from which all the ACS servicing functions were performed. This transfer operation utilized a pneumatic pump to compress the gas, which in effect actually combined two cylinders into the volume of one, and provided Freon-14 at pressures up to 5000 psig for proof testing as well as filling the ACS to flight pressure. In the case of the IMP-J proof test, nitrogen was used and handled in the same manner. This special facility, referred to as the high pressure cart, was periodically tested and certified in order to comply with certain safety standards and to ensure safe operating conditions throughout the program.

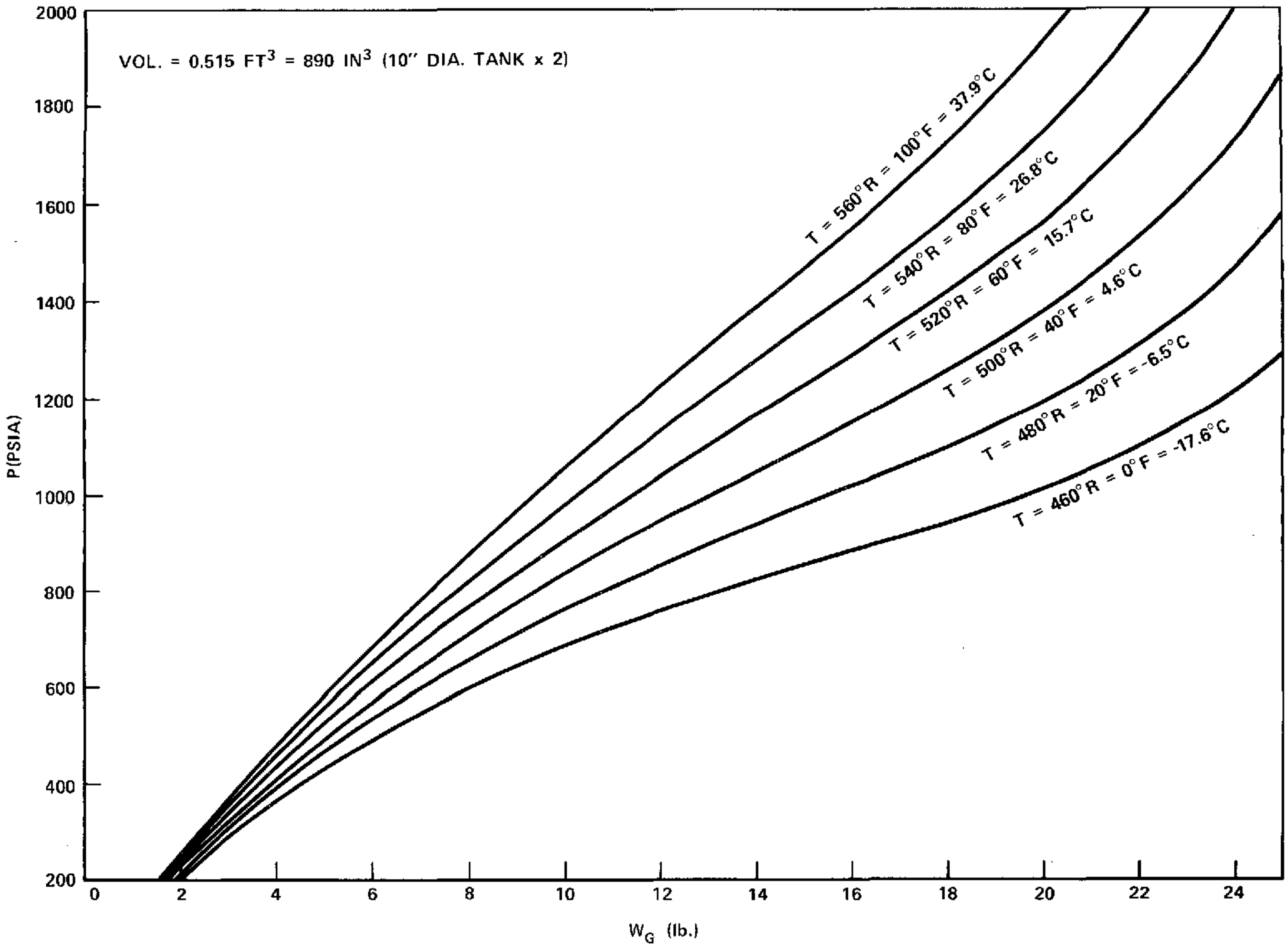


Figure 7. Freon-14

Section H — Basic Performance Equations

The ACS provides control of both the spin rate and the spacecraft orientation in space. The spin control function is accomplished by applying either a positive or negative torque, T, parallel to the spacecraft angular momentum vector, H, and the orientation control is accomplished by applying a momentary, synchronous torque perpendicular to the spin axis. These maneuvers are depicted in Figure 8. The desired orientation is then achieved by precessing the spin axis in any successive combination of the four cardinal directions, North, East, South or West, depending upon the particular angular change required. These directions are all measured relative to a celestial sphere centered on the spacecraft with the sum at the north pole and the spin axis nominally located in the equatorial plane when the sun aspect angle is 90 degrees. A North maneuver decreases the spin axis-sun angle; a South maneuver increases the angle; and East and West maneuvers move the spin axis right or left, respectively, while maintaining the spin axis-sun angle at a constant value. Response to North and South commands is observed in real time by means of the Optical Aspect sensor, whereas response to East and West commands must be estimated from an attitude determination process. Thus East and West commands are referred to as "blind maneuvers" and the actual motion must be calculated from solution of geometric equations involving the relative positions of the Sun, Earth and satellite.

The changes in satellite motion are produced by control torques which are derived from the thrust force of expelling compressed gas, the Freon-14 propellant, through nozzles located at some moment arm distance from the spacecraft center of mass. The effect of these torques on the spin rate and orientation of the spacecraft are described by some simplified forms of the general dynamic equations. The use of these somewhat idealized equations is justified by the reduction in complex calculations and the fact that accumulated errors are easily corrected by appropriate operation of the ACS.

Basically, the mechanics of the spin-up and despin maneuvers are identical in that a change in spin rate, $\Delta\omega$ (omega), is accomplished. This change is either positive or negative. With

F_T = thrust force (lb)

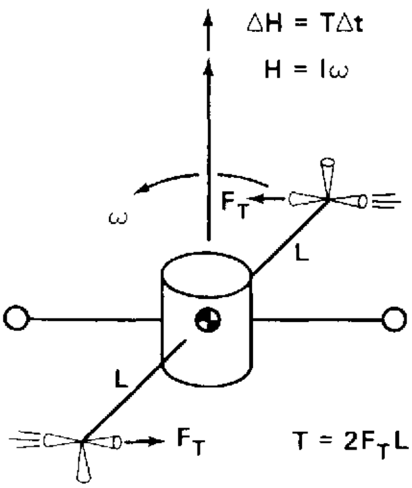
L = moment arm (ft)

I = spin axis moment of inertia (sl-ft^2)

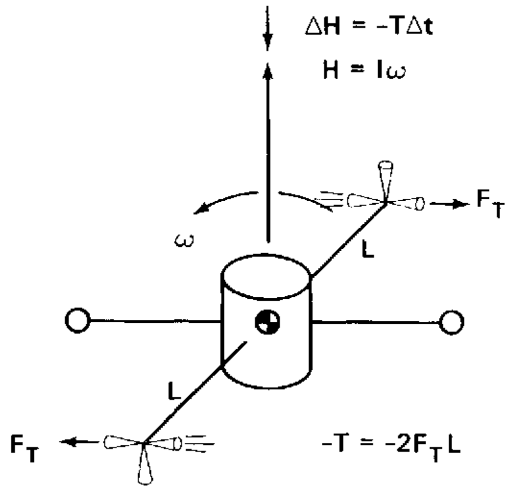
ω = spin rate (rad/sec)

a = angular acceleration (rad/sec^2)

torque, $T = Ia = F_T L$ and $a = F_T L/I$ = constant, from which $a\Delta t = \Delta\omega = (F_T L/I)\Delta t$.



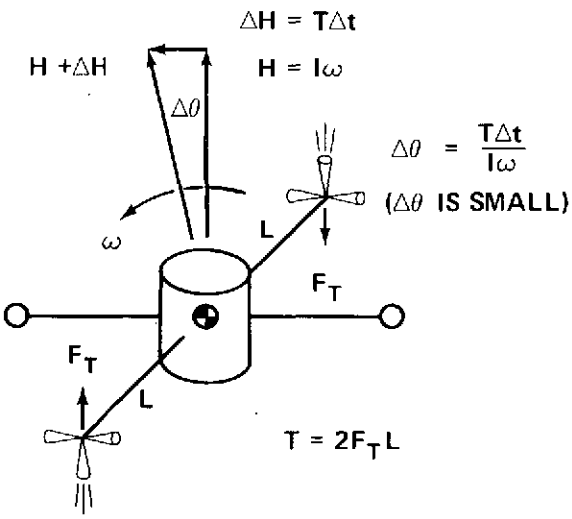
SPIN-UP



DESPIN

NOTE:
ONE PULSE OCCURS
EACH REVOLUTION
SO THAT

$$\Delta t = \frac{2\pi}{16\omega}$$



ATTITUDE CONTROL

Figure 8. ACS Maneuvers

For ω in terms of rpm:

$$\Delta\omega = \left(\frac{60}{2\pi}\right)\left(\frac{F_T L}{I}\right)\Delta t$$

or $\Delta\omega = A(\Delta t)$ where $A = \left(\frac{60}{2\pi}\right)\left(\frac{F_T L}{I}\right)$

Since F_T, L and I are essentially constant for all practical purposes, the change in spin rate is solely dependent upon the length of time that gas is permitted to flow through the nozzles. In this regard, the ACS is designed such that any time interval may be selected either by successive commands or by manually truncating a single command to only a few seconds duration. Also, the spin control function is redundant in that the loss of thrust from any one nozzle will result in one half of the normal change in spin rate and can be made up by additional commands.

The reorientation maneuver is a bit more complicated in that the amount of angular change is dependent upon the spin rate in the form of the angular momentum. In addition, the torque is applied as a periodic pulse, once, and at the same point during each revolution, and has as short a duration as practical in order to concentrate the accumulated precession in the selected direction. Theoretically, precession in any desired direction is possible but the command sequence and amount of electronics is significantly reduced by allowing only the four cardinal directions and by maneuvering in incremental steps. Two nozzles are available for changing the attitude angle and each is located on a boom 180 degrees from the other. They are actuated simultaneously and arranged such that each contributes one half of the precession torque, even when operated with the booms in the folded configuration where the moment arm is slightly reduced. The duration of each actuation or pulse is controlled by the ACS electronics which divides the spin period into 128 sectors and allows current to flow to the valves for 8 sectors or 1/16 of each revolution until a total of 8 pulses have accumulated. The beginning of each pulse is preset to occur after 24, 56, 88 or 120 sectors following the centered sun pulse according to the particular direction selected, i.e., East, North, West or South, respectively. With this ACS, the torques and pulse durations are sufficiently small so that small angle approximations are permissible, i.e., $\sin\theta = \theta$ (theta).

With $\Delta\theta$ = incremental precession angle (rad)

T = torque causing precession (ft-lb)

$\dot{\theta}$ = precession rate (rad/sec)

then $\Delta\theta = \frac{T\Delta t}{I\omega} = \left(\frac{F_T L}{I\omega}\right)\Delta t$

and $\dot{\theta} = \frac{\Delta\theta}{\Delta t} = \frac{T}{I\omega} = \frac{F_T L}{I\omega}$;

for ω in rpm and θ in degrees:

$$\Delta\theta = \left(\frac{180}{\pi}\right)\left(\frac{60}{2\pi}\right)\left(\frac{F_T L}{I\omega}\right)\Delta t,$$

or $\Delta\theta = B(\Delta t)$ where $B = \left(\frac{180}{\pi}\right)\left(\frac{60}{2\pi}\right)\left(\frac{F_T L}{I\omega}\right)$.

In practice, B is constant for any given spin rate, and Δt is the total accumulated 'on' time since θ changes only when gas is flowing through the nozzles. It is therefore apparent that the maneuverability, or rate of precession, increases at lower spin rates, not only due to the inverse effect of angular momentum but also due to the increase in the amount of 'on' time during each revolution. Consequently it is advantageous to perform large reorientation maneuvers at the lowest acceptable spin rate. Here again redundancy is achieved in that the loss of thrust from one nozzle simply reduces the precession by one half.

Another important performance parameter is the rate of propellant consumption for any given type of maneuver. Once again the analysis has been reduced to the simplest form in order to accommodate accuracies which are consistent with the input values as well as the desired results. The characteristic governing consumption is the Specific Impulse which can be described as the delivered thrust force divided by the propellant flow rate. Note that the flow rate is the weight of propellant consumed per unit of time, and is approximated to be constant during the 'on' time.

With $I_{SP} = F_T/\dot{W}$

where $\dot{W} = \Delta W/\Delta t = \text{constant}$,

then $F_T \Delta t = I_{SP}\Delta W$

By substituting this relationship into the equation for ΔW:

$$\Delta\omega = \left(\frac{60}{2\pi}\right)\left(\frac{I_{SP} L}{I}\right)\Delta W = C(\Delta W)$$

from which

$$\Delta W = \left(\frac{2\pi}{60}\right)\left(\frac{I}{I_{SP} L}\right)\Delta\omega = D(\Delta\omega),$$

where ΔW is the change in propellant quantity or the amount consumed to produce a change in spin rate of $\Delta\omega$. Actually this represents a change in angular momentum, but with the moment of inertia remaining essentially constant, the change is manifested simply as a change in spin rate.

A similar substitution is made into the equation for $\Delta\theta$:

$$\Delta\theta = \left(\frac{180}{\pi}\right)\left(\frac{60}{2\pi}\right)\left(\frac{I_{SP} L}{I\omega}\right) \Delta W = E(\Delta W)$$

from which

$$\Delta W = \left(\frac{\pi}{180}\right)\left(\frac{2\pi}{60}\right)\left(\frac{I\omega}{I_{SP} L}\right) \Delta\theta = F(\Delta\theta) .$$

Here, the value of the angular momentum remains constant while its vector is simply rotated in space by an amount, $\Delta\theta$.

The coefficients A thru F in the above equations are characteristics of the particular spacecraft in its various configurations and can be evaluated from the specific information presented in Parts II and III of this document.

One other characteristic affecting the spacecraft response to ACS operations is the dynamic stability. If the structure is not perfectly rigid, or if there is a nutation damper, energy may be dissipated in a spinning spacecraft and it will always tend to rotate about the axis of maximum moment of inertia. With Z assigned as the eventual spin axis, both X and Y are transverse axes, and positive stability is achieved when the moment of inertia ratio, R_I, is somewhat greater than one. This ratio is calculated as follows.

$$R_I = 1 + \sqrt{\frac{(I_Z - I_X)(I_Z - I_Y)}{I_X I_Y}}$$

Certainly, with spin about a transverse axis, the ACS functions are entirely ineffective.

Subsequently, it is the purpose of the nutation dampers to reduce the cone angle by dissipating energy at a known rate. In this manner the spin axis is maintained in the proper orientation with respect to the spacecraft reference axes, provided the value of R_I is favorable.

Finally, one other basic physical relationship which is used extensively in spin rate calculations and expresses the conservation of angular momentum is on the following page.

$$\omega_2 = \left(\frac{I_1}{I_2}\right) \omega_1 \qquad \text{or} \qquad I_1 \omega_1 = I_2 \omega_2$$

Primarily, this equation is used to calculate the spin rate change resulting from the deployment of booms or antennas, and the subscripts refer to initial and final conditions for any specific event.

PART II: SYSTEM SPECIFICATIONS PECULIAR TO THE IMP-H

Section A — Component Changes for IMP-H

Elastomeric Seals —

Throughout the environmental testing of the IMP-I spacecraft, low temperature leakage in the ACS was a significant source of difficulty. During thermal vacuum testing, this leakage was controlled by attaching temporary heaters to the Valve-Nozzle assemblies and maintaining the temperature of the solenoid valves above -20° C where leakage usually began to increase rapidly. Several months after launch, on 10/14/71, the IMP-I passed through a 5 hour apogee shadow during which the valve temperatures reached an estimated -70° C and 68% of the ACS propellant onboard at the time was lost due to leakage. Up to this point, the valve temperatures were fairly warm between +13° and +25° C, and the total leak rate was calculated to be 0.006 lb/day at most. Fortunately, the ACS had all but completed its required operations much earlier in the mission and this sudden propellant loss was not detrimental. Although some perturbations to the spacecraft were attributed to the leakage during shadow, corrections and a final trim maneuver were accomplished shortly thereafter with the remaining propellant. Subsequently, a second apogee shadow on 10/8/72 completely depleted the propellant supply without significant perturbation to the spacecraft, and rendered the ACS permanently ineffective.

Although the exact location of the leak could not be determined, the thermal vacuum experience indicated it was in the Valve-Nozzle assemblies. Since all the o-rings, as well as the solenoid valve seats, were made of neoprene, a material which Parker Seal Company rates as an acceptable seal only to as low as -55° C, it was concluded that these items were the primary source of leakage at cold temperature. Although the vast majority of the seals in the ACS were of the MS style where the o-rings experience a high degree of compression and therefore retain their sealability to a lower temperature, it was the valve inlet o-ring with its face seal application which was suspected of premature shrinkage and loss of sealability. Furthermore, with the inlet o-rings comprising a much larger percentage of the sealing surface area than the valve seats, it was decided to definitely change these o-rings for IMP-H and then investigate modifications to the seat.

The most obvious and simplest solution, with the limited time available, was to change both the o-ring and seat materials and keep the basic design intact. However, the only other standard material available with a significantly lower temperature rating was fluorosilicone and the little information concerning this material indicated that it was not especially compatible with Freon-14. Some possible disadvantages to the use of fluorosilicone were: (a) a suspicion that it would swell in the presence of Freon-14 at ambient temperature and thus be unacceptable as a valve seat material, (b) its permeability to both helium and Freon-14 was excessive, being at least an order of magnitude greater than that of neoprene, and (c) its coefficient of thermal expansion was about 40% greater than that of neoprene and an order of magnitude greater than the mating materials of aluminum and stainless steel. However, a service temperature rating of -63°C warranted at least a series of investigative tests.

In the first test series per requests no. 1350-4 and 1350-12, a solenoid valve, taken from the original IMP-I lot but equipped with an L449-6 fluorosilicone seat, was tested for leakage at approximately -70°C with 100% helium. In several tests, the leak rate across the seat was on the order of 10^{-7} scc/sec, which is considerably better than neoprene at that temperature. This same valve, P/N 15457-4 S/N 12, was then placed in a simulated flight configuration which consisted of exposure to gaseous Freon-14, with a 10% helium tracer, at 40 psia and ambient temperature. The valve was pulsed several times and initial leak rate and flow rate measurements were made. At each three day interval, flow rate measurements were made, and at twenty-one days the final leak rate and flow rate measurements were made. In all cases the flow rate was 1.2×10^{-3} lb/sec and the leak rate was on the order of 10^{-7} scc/sec. Examination under a 10X microscope revealed a slight impression in the seat material and no evidence of swelling or abrasion, which is considered a normal and desirable condition.

The second test involved placing two L449-6 fluorosilicone seat material pellets from the intended IMP-H lot and a representative neoprene o-ring in a chamber filled with Freon-14 at 200 psig and ambient temperature. After 10 days of exposure, there were no detectable changes in the linear dimensions of the samples. For comparison, a third pellet was placed in liquid Freon (PCA) for six days and considerable swelling was noted. However, within several hours after its removal from the liquid, it had nearly returned to its original dimensions.

A third test was conducted per request no. 1350-13 to verify that the L608-6 fluorosilicone o-rings would also perform satisfactorily. Leakage was checked in thermal vacuum at -45°C and found to be as good as what was obtained with neoprene. Equipment limitations prevented testing at lower temperatures.

All of the above testing was completed by 12/8/71, and it was concluded that the fluorosilicones as used in this application, for the valve seat and o-rings, in the presence of gaseous Freon-14, have acceptable compatibility characteristics both at ambient and low temperatures. It was realized that this material was a compromise in time and expense, and offered a simple but marginal improvement over the IMP-I situation. Subsequently, acceptance testing of the new solenoid valves and environmental testing of the spacecraft revealed that significant improvement in the leak rate characteristics of the ACS had been accomplished using fluorosilicone seals in the Valve-Nozzle assemblies.

Characteristics of fluorosilicone, in general, are:

Density	0.051 lb/in^3
Specific gravity	1.4
Coefficient of thermal expansion	45×10^{-5} in/in/°F
Permeability (helium at 1 atm)	14.36×10^{-7} cm^3/sec/cm^2/cm (25° C) 46.1×10^{-7} cm^3/sec/cm^2/cm (80° C) 97.3×10^{-7} cm^3/sec/cm^2/cm (150° C)
Low temp. stiffening	begins at -70° F
Low temp. brittle point	-85° F
Good characteristics	sunlight aging, oxidation, oxone cracking
Fair characteristics	in exposure to radiation, water, steam, and alcohols with molecular weight under 80
Poor characteristics	resilience, impact strength, tear resistance, abrasion resistance, exposure to ketones.

Solenoid Valves —

In addition to changing the valve seat material, several other improvements were sought which made it necessary to place an entirely new order for solenoid valves for the IMP-H. Among these improvements were the elimination of plated surfaces and the added requirement that the manufacturer test and clean the valves before delivery. Thus GSFC was spared the tedious task of disassembly, cleaning and reassembly of each valve prior to performing a thorough acceptance test. With the IMP-I valves, leakage and contamination of the valve seats were repeatedly traced to tiny particles of plating material which had been dislodged from the parent surface, and it was necessary to completely clean each individual piece before testing. It was also possible that this procedure altered some of the performance characteristics due to disturbance of the precise shimming built into the valve at the time of original assembly. In as much as the manufacturer stated that the surfaces were plated in the interest of prolonging the valve service lifetime by providing a very hard sliding surface, it was determined that the actual expected cycle lifetime for the IMP-H (and IMP-J) was sufficiently low to easily permit the use of unplated surfaces. Thus with the primary source of contamination eliminated, the cleaning specifications were relaxed and the manufacturer was capable of performing the task without a large investment in new equipment and with only a modest increase in cost to cover the additional service. Finally upon delivery to GSFC, the valve testing, per request no. 1350-14, was reduced to a current trace, flow rate measurement and leak testing at both ambient and at a cold temperature of -50°C, with one good valve selected at random to be given a more thorough testing at +40° C as well. Although this new policy saved a considerable amount of time, it had little affect on the rejection rate, and 11 out of 36 valves did not pass the acceptance test. The rejected valves, usually with excessive leak rates caused by metallic particles embedded in the soft seat, were sent back to the manufacturer for rework, and upon their return to GSFC, were usually assigned as the spare units.

One interesting comparison between the IMP-I valves and those for IMP-H is that, although the neoprene seats had a slightly lower leak rate at ambient temperature than the fluorosilicone seats, the leak rate increased much more rapidly as the temperature was lowered so that at -40°C the neoprene leak rate was several orders of magnitude greater, while the fluorosilicone was still within the specification. The difference at ambient temperature was attributed to the higher permeability of the fluorosilicone, whereas at the lower temperature, the neoprene contracts and hardens, producing leakage.

A pictorial representation of the solenoid valve and its various sealing methods is shown in Figure 19; and its procurement specifications are as follows.

GSFC drawing no.	GD 1074084
Operating inlet pressure	0-60 psig
Proof pressure, inlet	90 psig
Case burst pressure	240 psig min.
Weight	0.25 lb
Operating media	air, N_2, He, CF_4 (Freon-14)
Filter (CRES mesh)	50μ nominal inlet and outlet
Voltage:	
Operating (continuous)	28 VDC
Pull-in (at 40 psig inlet)	20 VDC max.
Drop-out (at 40 psig inlet)	5 VDC min.
Power	2 watts max. at 26 VDC and 76° F

Insulation resistance	50 megohms at 500 VDC
Dielectric	600 VAC, 60 cycles
Response (at 40 psig inlet)	15 milliseconds max. opening and closing
Leak rate (at all environmental temperatures):	
Internal	10^{-6} scc/sec max., He at 60 psid
External	10^{-6} scc/sec max., He at 60 psid
Flow rate (at 40 psig inlet)	2 x 10^{-3} lb/sec min. (CF_4)
Pressure drop at rated flow	3 psid max. at 76° F
Life	5 years intermittent with 2000 hours powered operation
Temperature (environment):	
Ambient (static)	-85° F to +125° F
Ambient (operating)	-50° F to +125° F
Fluid	-50° F to +125° F
Vibration	0.60 da 5 cps to 20 cps 21 g max., 20 cps to 2000 cps
Acceleration	20 g any direction
Shock	60 g 2 milliseconds duration
Materials	Unless approved, suitability must have been proven by prior space flight use. Magnetic materials are to be avoided where possible. Seat, poppet and o-ring materials are subject to GSFC approval and must be certified by the vendor. All plated surfaces must be free of blisters and nodules.
Interface o-ring	Parker size 2-012
Material	L 608-6 fluorosilicone
Groove depth	0.055 ±0.002 inches
Compression	0.015 inches

Lead wires are to be #22 Ray Chem Aerospace spec. 44; insulation length 72 inches minimum and marked with polarity reference plus (+) or minus (-), or color coded. All specifications apply after exposure to proof pressure.

Test gases must have a moisture content less than 3 PPM and be passed through a 3.5μ (nom) filter prior to use.

All sliding and sealing surfaces must be free of burrs, pits and scratches larger than 5 microns (0.0002 in.).

Outlet filter is to be installed after all acceptance tests at GSFC.

The internal surfaces are to be cleaned to the extend that there are no more than 100 contaminating particles, 5-25 microns in size; no more than 10 contaminating particles, 26-50 microns in size; and no contaminating particles larger than 50 microns in size per 100 ml of cleaning fluid.

The contractor's quality control system, as a minimum, must comply with the following paragraphs of NPC 200-3, concerning inspection system provisions for suppliers of space materials, parts, components and services:

Paragraph No.	Title
3.6	Inspections and tests
3.7	Process controls
3.9	Controls of inspection, measuring, and test equipment

Individual units are to be packaged in double, heat sealed polyethylene bags (or equivalent). Bagged units are to be wrapped in shock absorbing material prior to being boxed. Prior to delivery each unit must be tested to demonstrate performance in accordance with the above drawing and be accompanied by documentation to the effect that specifically included are proof test, voltage, power, vibration, response time, leak rate, flow rate, and temperature requirements for each valve.

Each unit is to be delivered with inlet filter screens installed, but outlet filter screens not installed. Assembly drawings and a list of materials are also to be supplied by the vendor.

Manufacturer	Wright Components, Inc. Clifton Springs, N.Y. 14432
Part number	15607
Equivalent orifice size	0.069 inches

Seat material	L449-6 fluorosilicone
Unit cost	$525.00 each
Contract number	NAS 5-11429
Quantity purchased	36
Approximate internal surface area	2.0 in^2

Nozzles —

Structural differences between the IMP-I and IMP-H resulted in a shorter ACS boom length and, consequently, a smaller thrust moment arm for IMP-H. This fact, together with the absence of the long, deployable EFM antennas carried on the IMP-I, which dictated a maximum torque limit of 1/2 ft-lb, made it desireable to increase the nozzle thrust force by a factor of two. With the resulting net increase in torque, the time required to perform the various maneuvers was reduced, and some compensation for the decrease in torque associated with performing ACS maneuvers with the booms in the folded configuration, was provided. The new nozzles were identical to those for the IMP-I except that the throat diameter was increased to 0.037 inches and the resulting thrust was measured at 0.065 lb in vacuum at ambient temperature.

Thermal Shields —

Difficulties in working with the IMP-I Valve-Nozzle assemblies were significantly reduced for IMP-H by redesigning the thermal shields for the valves. The new shields totally revamped the assembly procedure and greatly improved the valve alignment and thermal coating processes by virtue of the fact that they were the final items installed and were completely external and independent of the main structural items. Also, replacement did not require any major disassembly.

Temperature Probe —

For the IMP-H and J, the extra temperature probe located in the ACS tank in facet 10 was equipped with a permanent connector which made GSE attachment much easier during any of the ACS servicing operations. This connector was accessible from the periphery of the spacecraft and greatly reduced the amount of mechanical preparation required for obtaining temperature measurements.

Micro Switch —

Several minutes after the IMP-I was inserted into orbit, the boom deployment sequence was initiated. Mission failure was feared when only one to the ACS booms indicated deployment and the position of the second was shown as still folded. Subsequent analysis of prelaunch testing and inflight data suggested that both booms had fully deployed and that one of the two micro switches had failed to indicate such. The records also revealed that the operation of the particular switch in question had not been thoroughly checked prior to launch. For the IMP-H, special attention was paid to preventing a recurrence of this problem and an entirely new micro switch arrangement was incorporated. The main feature of the new design was a failsafe condition in which the spring force of the micro switch actuator acted in the same direction as the detent pin spring in the hinge and thus did not hinder the boom deployment. For this arrangement, a Columbus T574 switch was used and proved successful during the IMP-H boom deployment sequence in flight.

Fourth Stage —

A fourth stage or kick motor was added to both the IMP-H and J in order to place these spacecraft in circular orbits. Although not a part of the ACS, the changes in the center of gravity and moments of inertia resulting from the fourth stage burn, certainly affected the ACS operation and performance. The actual calculated performance parameters, reflecting these effects, are described later in this document, whereas certain applicable kick motor information is presented in Table 5.

Select Component Serial Numbers —

Panel Assembly, IC 5-04:

Pressure Regulator S/N 4
High Pressure Transducer S/N 584-1
Low Pressure Transducer S/N 139717

Valve-Nozzle Assembly, IC 4-07:

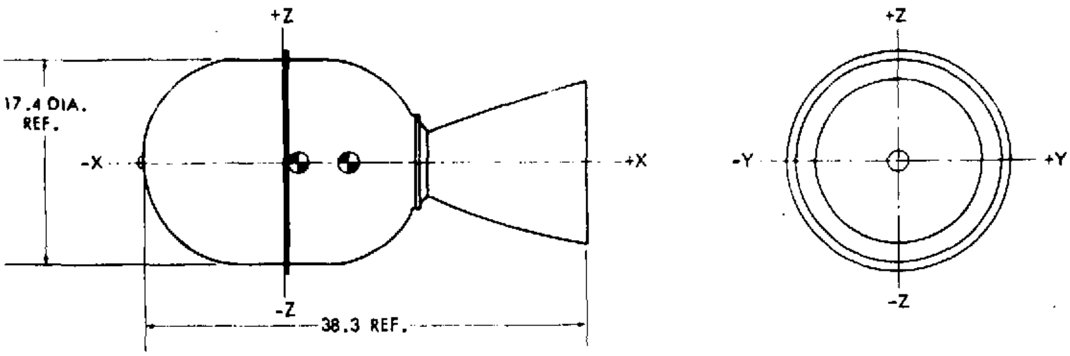
Thermistor S/N 91

	Solenoid Valve S/N		
	spin-up	reorient	despin
outboard	10	9	12
inboard	13	15	16

Table 5

Fourth Stage Data

TE-M-521 ROCKET MOTOR



MOTOR CONDITION	WEIGHT lbm.	LONG. C.G. in.	LATERAL C.G. in.	VERT. C.G. in.	Ixo lbm. in.^{2}	Iyo lbm. in.^{2}	Izo lbm. in.^{2}
LOADED	273.24	+0.13	0	0	2.07 SL.FT.^{2}	3.36 SL.FT.^{2}	3.36 SL.FT.^{2}
FIRED	24.14	+6.37	0	0	0.23 SL.FT.^{2}	0.59 SL.FT.^{2}	0.59 SL.FT.^{2}

MOTOR PERFORMANCE*

Burn Time/Action Time (t_b/t_a), sec	18.13/19.13
Ignition Delay Time (t_d), sec	0.070
Burn Time Avg. Cham. Press. ($\bar{P}_b$), psia	735
Action Time Avg. Cham. Press ($\bar{P}_a$), psia	710
Maximum Chamber Pressure (P_{max}), psia	850
Total Impulse (I_T), lbf-sec	71,500
Burn Time Impulse (I_b), lbf-sec	69,800
Motor Specific Impulse (I_{mo}), lbf-sec/lbm	262
Propellant Specific Impulse (I_{sp}), lbf-sec/lbm	289
Burn Time Average Thrust ($\bar{F}_b$), lbf	3,850
Action Time Average Thrust ($\bar{F}_a$), lbf	3,720
Maximum Thrust (F_{max}), lbf	4,470
Measured Thrust Coefficient (C_f)	1.88
Theoretical Thrust Coefficient (C_f)	1.96
Discharge Coefficient (C_d)	0.96

*60°F, Vacuum.

NOZZLE

Body Material	Vitreous Silica Phenolic
Throat Insert Material	Graph-I-Tite G-90
Initial Throat Area, in.^{2}	2.563
Exit Are, in.^{2}	148.4
Expansion Ratio	57.9
Expansion Cone Half Angle, degrees	Contoured
Type	Fixed
Number of Nozzles	1

IGNITER

Thiokol Model Designation	TE-P-386
Type	Pyrogen
Minimum Firing Current, amperes	4.0 ±0.5
Circuit Resistance, ohms	1.0 +0.2
No. of Squibs	1

WEIGHTS, lbm

Total Loaded	273.25
Propellant	247.0
Case Assembly	11.61
Nozzle Assembly	9.16
Igniter Assembly	0.82
Internal Insulation	3.95
External Insulation	0
Liner	0.44
Miscellaneous	0.27
Total Inert	26.25
Burnout	24.15
Propellant Mass Fraction	0.904

TEMPERATURE LIMITS

Operation	0°F to 110°F
Storage	0°F to 110°F

PROPELLANT

Propellant Designation	TP-H-3062

PROPELLANT CHARACTERISTICS

Burn Rate @ 1000 psia (r_b), in./sec	0.32
Burn Rate Exponent (n)	0.29
Density, lbm/in.^{3}	0.0627
Temperature Coefficient of Pressure (π_k), %/°F	0.10
Characteristic Exhaust Velocity (C*), ft/sec	4,955
Adiabatic Flame Temperature, °F	5,662
Effective Ratio of Specific Heats (Chamber)	1.145
(Nozzle Exit)	1.16

Valve-Nozzle Assembly, IC 4-08:

	Solenoid Valve S/N		
	spin-up	reorient	despin
outboard	3	4	8
inboard	1	5	6

Note: Solenoid Valve Part No. 15607

Section B — Mass Properties and Dimensions

The basic arrangement of the IMP-H spacecraft is as shown in Figures 9, 10 and 11, and the various flight configurations can be described as follows.

1. Launch Configuration

Booms	all folded, except inertia booms which deploy at fairing separation
Fourth stage	unfired
Spin axis MOI	66.22 sl-ft^2
Nominal spin rate	46 rpm after third stage separation
Weight	861.05 lb
Center of gravity	24.43 inches above separation plane
MOI ratio	1.048
Spin control moment arm	2.12 ft
Attitude control moment arm	3.40 ft

2. Intermediate Configuration

Booms	all folded, except inertia booms
Fourth stage	burned out
Spin axis MOI	64.33 sl-ft^2
Expected spin rate	48 rpm
Weight	611.03 lb

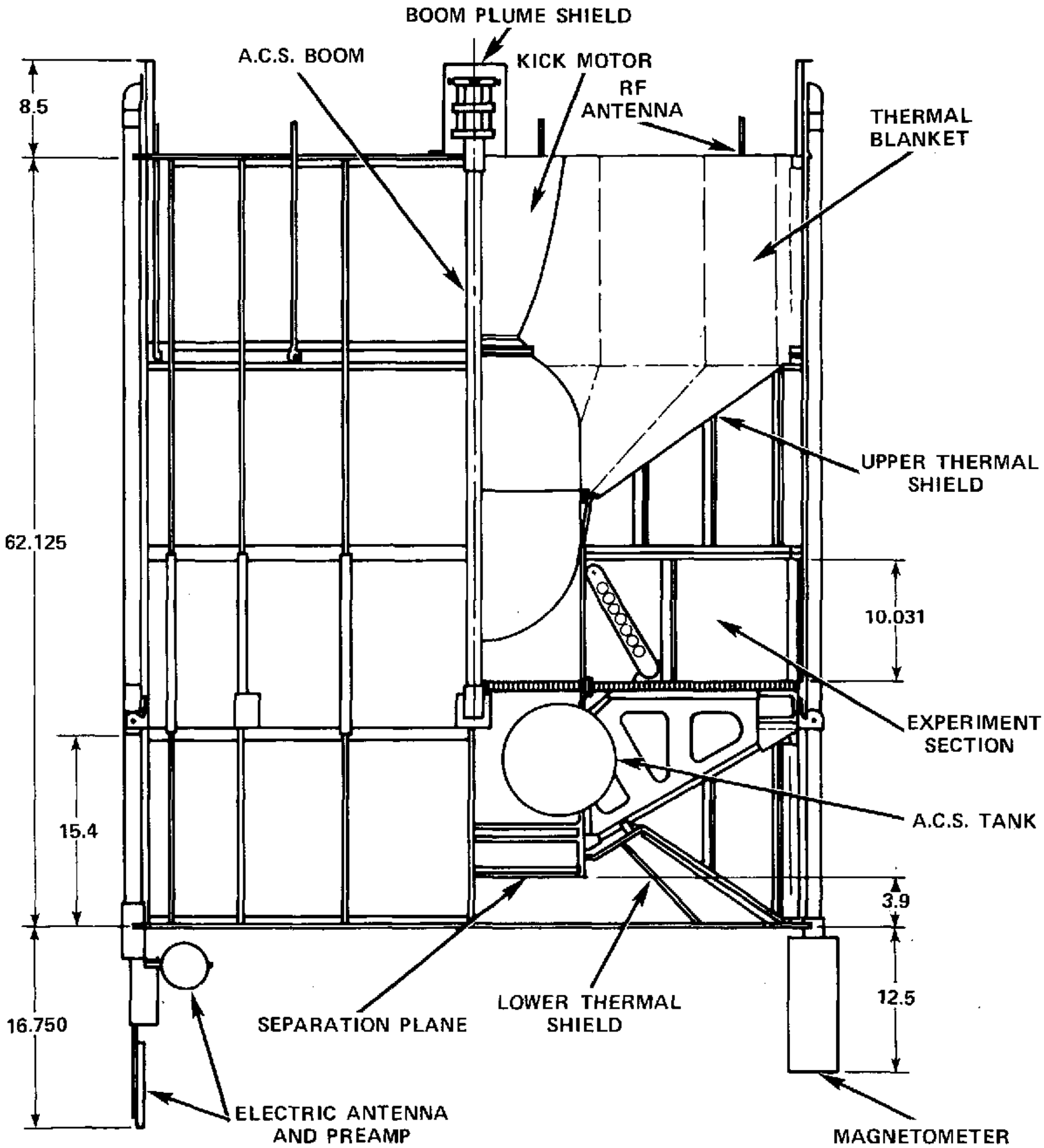


Figure 9. IMP-H General Layout

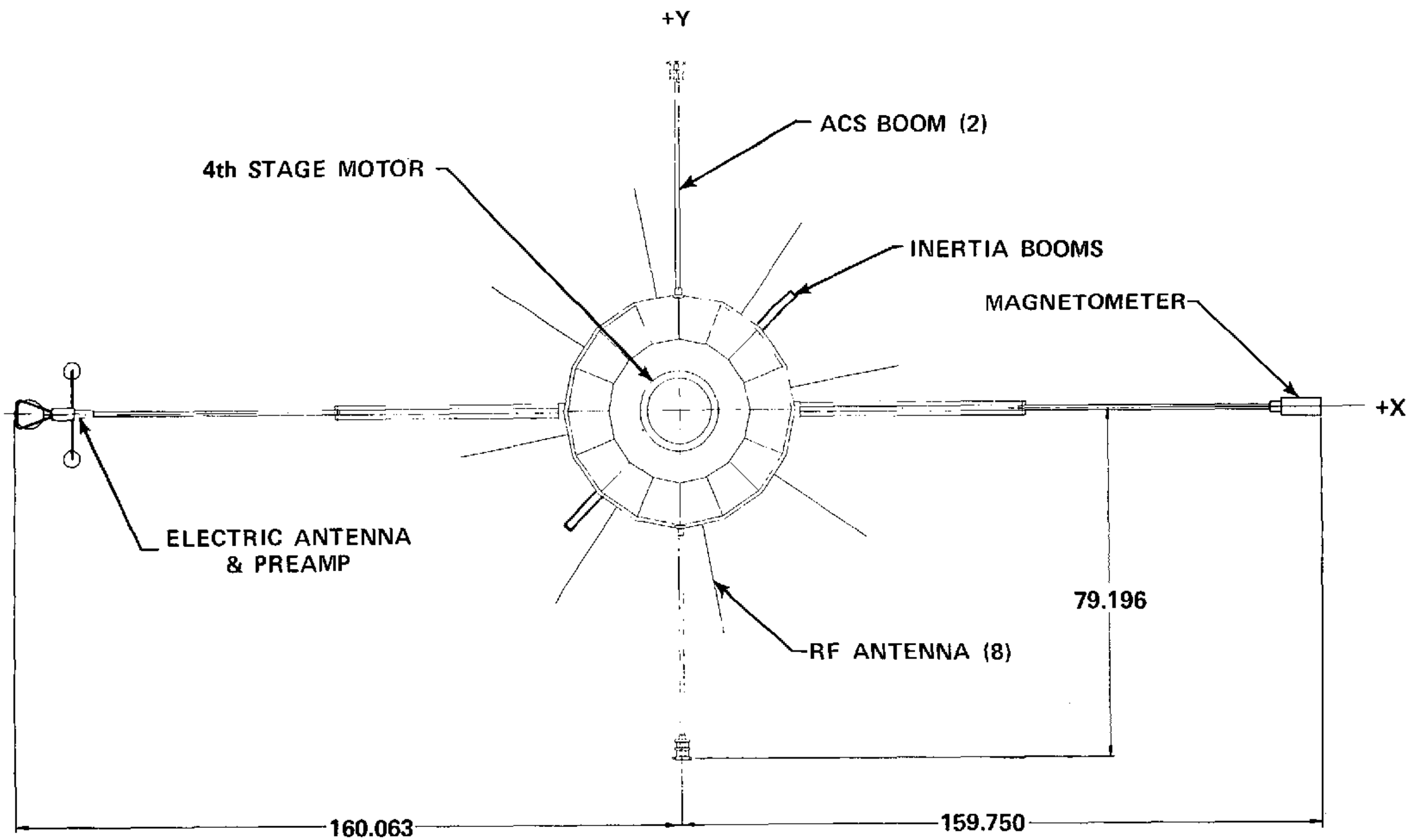


Figure 10. IMP-H Orbit Configuration

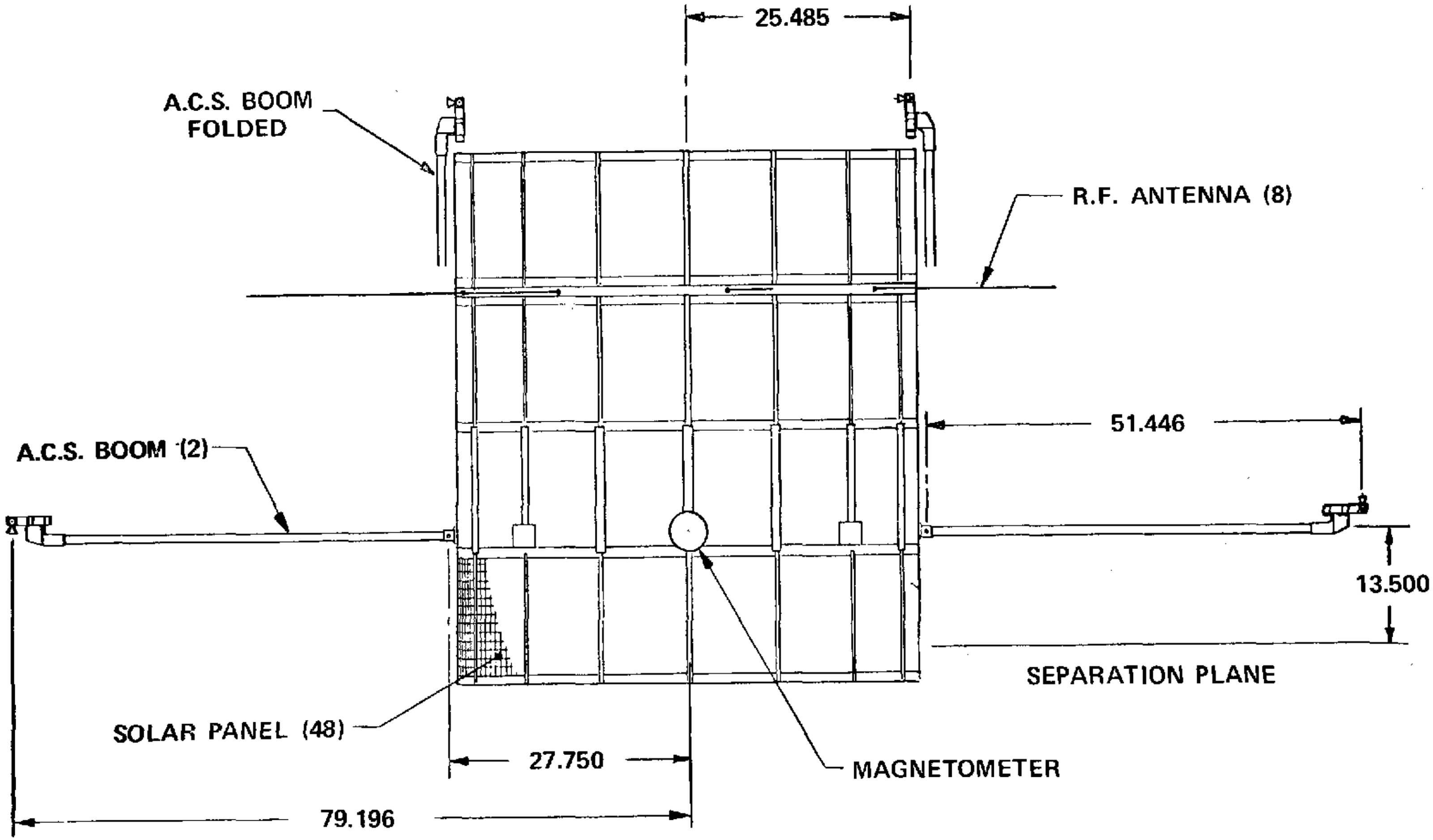


Figure 11. IMP-H ACS Boom Positions

Center of gravity	21.79 inches above separation plane
Spin control moment arm	2.12 ft
Attitude control moment arm	3.60 ft

3. Slow Spin Configuration

Booms	all deployed
Fourth stage	burned out
Spin axis MOI	108.70 sl-ft^2
Expected spin rate	11.8 rpm due to boom deployment
Weight	611.03 lb
Center of gravity	20.52 inches above separation plane
Spin control moment arm	6.60 ft
Attitude control moment arm	6.60 ft

4. Orbit Configuration

Booms	all deployed
Fourth stage	burned out
Spin axis MOI	108.70 sl-ft^2
Nominal spin rate	46 rpm
Weight	611.03 lb
Center of gravity	20.52 inches above separation plane
MOI ratio	1.203
Spin control moment arm	6.60 ft
Attitude control moment arm	6.60 ft

The above numbers represent the most recent prelaunch calculated values and may have differed slightly from the actual post launch refined information. In any event, they are sufficiently accurate to describe the mission and were used to determine the various ACS performance parameters.

A weight breakdown of all the individual ACS components, including certain support and structural hardware, is presented in Table 6. Drawing numbers,

Table 6
IMP-H ACS Weights

Components and Assemblies

Item (Ident No.)	Dwg or Part No.	Qty	lb Ea	lb Total
Tank (IC 2-03, IC 2-05)	GD 1063682	2	6.20	12.40
Temperature Probe (IC 8-22)	GD 1074085	1	0.06	0.06
Thermistor (IC 8-23)	GD 1074377	1	0.09	0.09
AN Union	400-6-4AN-316	2	0.07	0.14
Tube (IC 9-12)	GD 1064241	1	0.20	0.20
Tube (IC 9-13)	GD 1064242	1	0.24	0.24
Panel Assembly (IC 5-04)	GJ 1064116	1	3.32	3.32
Tube (IC 10-11)	GD 1064243	1	0.07	0.07
Tube (IC 10-12)	GD 1064244	1	0.09	0.09
Tube	GC 1064257	2	0.01	0.02
Union Elbow	A 400-9	4	0.03	0.12
Swivel Joint (IC 7-09, IC 7-10)	GD 1063874	2	0.03	0.06
Bulkhead Union	A 400-61	2	0.04	0.08
Tube (IC 6-11, IC 6-12)	GD 1074274	2	0.12	0.24
Valve-Nozzle Assy (IC 4-07)	GE 1074240-1	1	2.30	2.30
Valve-Nozzle Assy (IC 4-08)	GE 1074240-2	1	2.30	2.30
Diode Pack (IC 3-05, IC 3-07)	GD 1063822	2	0.21	0.42
	Total			22.15

Note: ACS Electronics Card, IC 1-10, not included in ACS weight.

Table 6 (cont'd.)

Support and Structural Hardware

Item	Dwg No.	Qty	lb Ea	lb Total
Tank Support Bracket	GE 1063863	4	0.47	1.88
Tank Clamp	GC 1063783	4	0.03	0.12
Tank Retainer	GD 1064166	2	0.03	0.06
Tube Support Bracket	GC 1063832	8	0.015	0.12
Tube Clamp	GC 1063834	9	0.004	0.04
Tube Saddle	GC 1063833	9	0.006	0.05
Tank Thermal Blanket		2	0.03	0.06
Regulator Thermal Blanket		1	0.02	0.02
ACS Boom Assembly	GJ 1074231	2	2.25	4.50
Connector Bracket	GC 1063928	2	0.01	0.02
Tube Clamp	GC 1064169	8	0.01	0.08
Dummy Connector		2	0.03	0.06
Micro Switch Assembly		2	0.03	0.06
Boom Standoff	GD 1074331	2	0.05	0.10
Boom Cable Segment		2	0.15	0.30
Mounting Bolts	No. 6, 8, 10	108	0.004	0.40
	Total			7.87

Components and Assemblies	22.15
Support and Structural Hardware	7.87
ACS Propellant for IMP-H Mission	18.00
ACS Installation Total Weight	48.02 lb

part numbers and Identification Control System numbers are also included for reference information. The IMP-H ACS installation is shown by GSFC drawing no. GJ 1074232.

Section C — Flow Rates

The ACS performance is directly related to the propellant flow rate through certain critical components. Measurements made with the pressure regulator indicate that it is capable of flowing Freon-14 at the rate of 16 lb/hr, far in excess of its specified minimum. This amounts to 0.267 lb/min or 0.00444 lb/sec. Similarly, the solenoid valves are rated for 0.002 lb/sec, each, which amounts to 0.120 lb/min or 7.2 lb/hr. Finally, the nozzles have a calculated flow rate, based on specific impulse and measured thrust, of 0.00144 lb/sec, which amounts to 0.086 lb/min or 5.18 lb/hr. Clearly, the nozzles, having the lowest flow rate, are the limiting elements in the line of flow, as would be desired. Since all maneuvers are accomplished using a pair of nozzles, the total system flow rate is 0.00288 lb/sec, or 0.172 lb/min, or 10.36 lb/hr, and it is this number which has been used in the calculations for the ACS performance parameters. It should be noted that the total flow rate is extremely difficult to measure, especially under simulated orbit conditions, and that it is influenced by many factors and variables. Among these are the actual line pressure and temperature, both of which tend to decrease shortly after flow commencement. Similarly, the ambient conditions also cause variations; especially the surrounding pressure which, at one atmosphere, greatly reduces the flow rate and efficiency of the nozzles. In addition, there are small differences between each individual nozzle, and some small nominal tolerance must be applied to the overall system flow rate. Finally, as the propellant is consumed and the supply pressure decreases, the small orifice within the regulator becomes increasingly more effective in restricting the flow rate; and when the inlet pressure drops below 300 psia, the condition is such that the downstream pressure can no longer be maintained within the specified range. This is not particularly detrimental because the situation occurs quite late in the schedule of events and also because there is sufficient volume downstream of the regulator to provide a plenum or reservoir in which to accumulate propellant for a subsequent maneuver.

Section D — Commands

The following is a list of commands related to the remote operation of the ACS, and is applicable to both IMP-H and J.

Title	Code	Command Number				Manual Mode	
		IMP-H		IMP-J		Check Code	CMD Code
		Tone	PCM	Tone	PCM		
ACS/O.A. Mode	245	35 T	35 P	735	935	362	104
Spin-Up	325	33 T	33 P	733	933	746	100
Despin	454	34 T	34 P	734	934	052	102
Orient N	535	36 T	36 P	736	936	476	106
Orient E	546	37 T	37 P	737	937	502	110
Orient W	446	38 T	38 P	738	938	216	112
Orient S	346	39 T	39 P	739	939	126	114
ACS On	436	31 T	31 P	731	931	472	074
ACS Off/Reset	326	32 T	32 P	732	932	366	076
ACS Boom Deploy	455	19 T	19 P	719	919	326	044

In addition, the following ACS information is received from the spacecraft by means of telemetry.

Digital Parameters (DP)

- 2-19 ACS on/off
- 2-20 ACS mode ACS/OA
- 3-5 ACS boom 1 deploy/fold
- 3-6 ACS boom 2 deploy/fold

Analog Parameters (AP)

- 20 Temperature, ACS boom 1
- 21 Temperature, ACS tank 1
- 23 Buss current
- 32 ACS high pressure
- 38 ACS low pressure

Also; OA spin rate (rpm)
OA spin time (sec)
Alpha angle (deg)
Spacecraft clock (day, hr, min)

The normal procedure for operating the ACS is to first select the mode. The OA mode is primary and semi-automatic, with the ACS mode acting as a manual backup. Next, an ACS off/reset command is sent, followed by the desired motion command. Finally, the ACS ON command permits current and thus propellant to flow; and the resulting motion of the spacecraft is observed by means of the various parameters returned via telemetry. The system is designed with an automatic off feature, but in practice, an off/reset command is usually sent between successive sequences of commands to assure proper operation. When sending a large number of identical sequences, a command tape is used to automatically load and send each command, and thus the time spacing between each command is reduced to a minimum value. Actual performance of the ACS is determined by correlating the various commands executed with the observed changes in the spacecraft spin rate or orientation. In general, the Optical Aspect (OA) sensor is the primary source of attitude information, and is capable of resolving an alpha angle to ±0.25 degrees. This same instrument also records the sun pulse from which the spin rate and spin period are determined.

Normally, both the spin-up and despin commands are pre-set to be ON for a duration of 64 sec each. With a flow rate of 0.00288 lb/sec, this amounts to 0.184 lb/command. However, a command may be manually truncated to a shorter duration, with a corresponding decrease in propellant consumption, by simply sending an ACS OFF command at the desired time.

The reorientation commands are a bit more complicated in that the timing mechanism allows, nominally, for 8 pulses, which will vary in time duration according to the spin rate. The spin period is electronically divided into 128 sectors, with the reorientation pulse occupying one particular group of 8 adjacent sectors on each of eight successive revolutions. Thus, propellant is flowing during 22.5 degrees of each spacecraft rotation, and at 46 rpm, this results in a pulse duration of 0.081 sec, with a consumption rate of 0.00023 lb/pulse. Since each reorientation command consists of 8 pulses, the flow rate becomes 0.00184 lb/command at 46 rpm.

It should be noted that all commands involve the simultaneous actuation of four solenoid valves and a nominal buss current increase of 0.284 amps.

A more thorough tabulation of the calculated ACS flow rates and performance parameters is presented in Section E.

Section E — ACS Performance

The ACS performance calculations for the IMP-H were based upon the equations developed in Part I; namely:

$$\Delta W = \left(\frac{2\pi}{60}\right)\left(\frac{I}{I_{SP}L}\right)\Delta\omega = D(\Delta\omega)$$

and

$$\Delta W = \left(\frac{2\pi}{60}\right)\left(\frac{\pi}{180}\right)\left(\frac{I\omega}{I_{SP}L}\right)\Delta\theta = F(\Delta\theta),$$

together with the flow rates determined in the previous two sections. In all cases, the specific impulse, I_{SP}, is 45 sec.

The various parameters are tabulated for spin-up and despin in Table 7, and for reorientation in Table 8. In addition, the propellant consumption rates are shown graphically in Figures 12 and 13.

Section F — Propellant Allocation

In order to accomplish its purpose, the ACS must maneuver the spacecraft in a specified manner with a fixed quantity of propellant. Figure 14 shows the IMP-H mission profile with all significant spacecraft events and their relative time sequence. Also, listed below are the scheduled ACS maneuvers required to achieve the final orbit configuration.

1. Reorientation following separation of the spacecraft from the burned out third stage. This maneuver was necessary to place the spacecraft in a position so as to permit accurate attitude determination, maintain acceptable temperatures, and provide a reasonable antenna pattern throughout the 2-1/2 days coast in the transfer orbit and prior to the fourth stage burn. The spacecraft was in the launch configuration, spinning at approximately 46 rpm with all booms folded, and as much as 90 degrees of attitude change was permitted. The amount of propellant allocated for this purpose was 3.28 lb.

2. Reorientation of the spacecraft in preparation for the fourth stage burn. Upon reaching apogee in the transfer orbit, the plan was to place the spacecraft in a circular orbit by means of the fourth stage motor, and it was, therefore, necessary that its thrust vector be properly aligned by means of the ACS prior to burning. This maneuver was also performed with the spacecraft in the launch configuration, at approximately

Table 7

IMP-H Spin-Up and Despin

Parameter	Configuration		
	1 Launch	2 Intermediate	3 & 4 Slow Spin & Orbit
I (sl-ft^2)	66.22	64.33	108.70
Moment Arm (ft)	2.12	2.12	6.60
D Factor (lb/rpm)	0.0727	0.0706	0.0383
Duration (sec)	64	64	64
Torque (ft-lb)	0.276	0.276	0.858
Flow (lb/CMD)	0.184	0.184	0.184
Change (rpm/CMD)	2.53	2.61	4.84
Change (rpm/sec)	0.040	0.041	0.075
Change (rpm/lb)	13.73	14.14	26.09
(CMD/rpm)	0.395	0.384	0.208
(sec/rpm)	25.3	24.6	13.2
Change ($\Delta I\omega$/CMD)	167.60	167.66	521.85
Change ($\Delta I\omega$/sec)	2.62	2.62	8.15
Change ($\Delta I\omega$/lb)	909.3	909.6	2836.1

Constants: $\left(\frac{2\pi}{60}\right) = 0.10472$

$$\left(\frac{2\pi}{60}\right)\left(\frac{\pi}{180}\right) = 0.0018277$$

Table 8

IMP-H Reorientation

Parameter	Configuration			
	1 Launch	2 Intermediate	3 Slow Spin	4 Orbit
I (sl-ft^2)	66.22	64.33	108.70	108.70
ω (rpm)	46	48	11.8	46
Moment Arm (ft)	3.40	3.60	6.60	6.60
F Factor (lb/deg)	0.0364	0.0348	0.0079	0.0308
Spin Period (sec)	1.304	1.250	5.085	1.304
Pulse Length (sec)	0.081	0.078	0.318	0.081
Flow (lb/pulse)	0.00023	0.00022	0.00092	0.00023
Change (rad/pulse)	0.00011	0.00011	0.00203	0.00013
Change (rad/CMD)	0.00088	0.00088	0.01627	0.00104
Change (rad/lb)	0.480	0.501	2.211	0.567
Ave Rate (rad/sec)	0.00008	0.00009	0.00040	0.00010
Change (deg/pulse)	0.0063	0.0063	0.1163	0.0075
Change (deg/CMD)	0.0504	0.0505	0.9305	0.0598
Change (deg/lb)	27.50	28.70	126.7	32.46
Ave Rate (deg/sec)	0.0046	0.0050	0.0229	0.0057
(pulses/rad)	9091	9066	493	7692
(CMD/rad)	1136	1133	62	962
(lb/rad)	2.08	2.00	0.45	1.76
Total Time (sec/rad)	12500	11351	2505	10000
Total Time (sec/deg)	217	198	43.7	175
(pulses/deg)	159	159	8.6	133
(CMD/deg)	19.8	19.8	1.1	16.7
(lb/CMD)	0.00184	0.00176	0.00736	0.00184
Torque (ft-lb)	0.44	0.47	0.86	0.86
Iω (sl-ft^2-rpm)	3046.12	3087.84	1286.60	5000.20

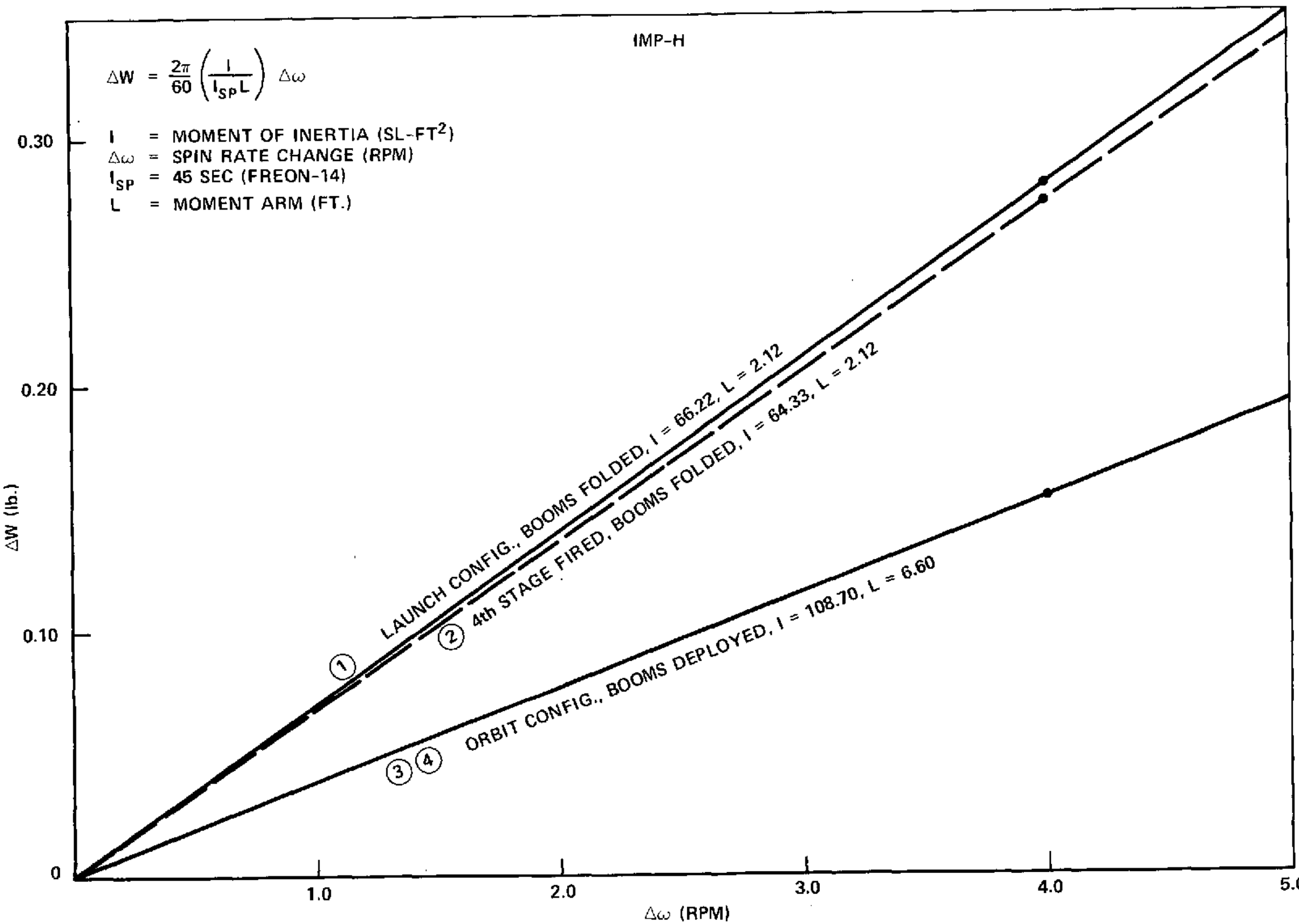


Figure 12. Propellant Required for Spin Rate Change

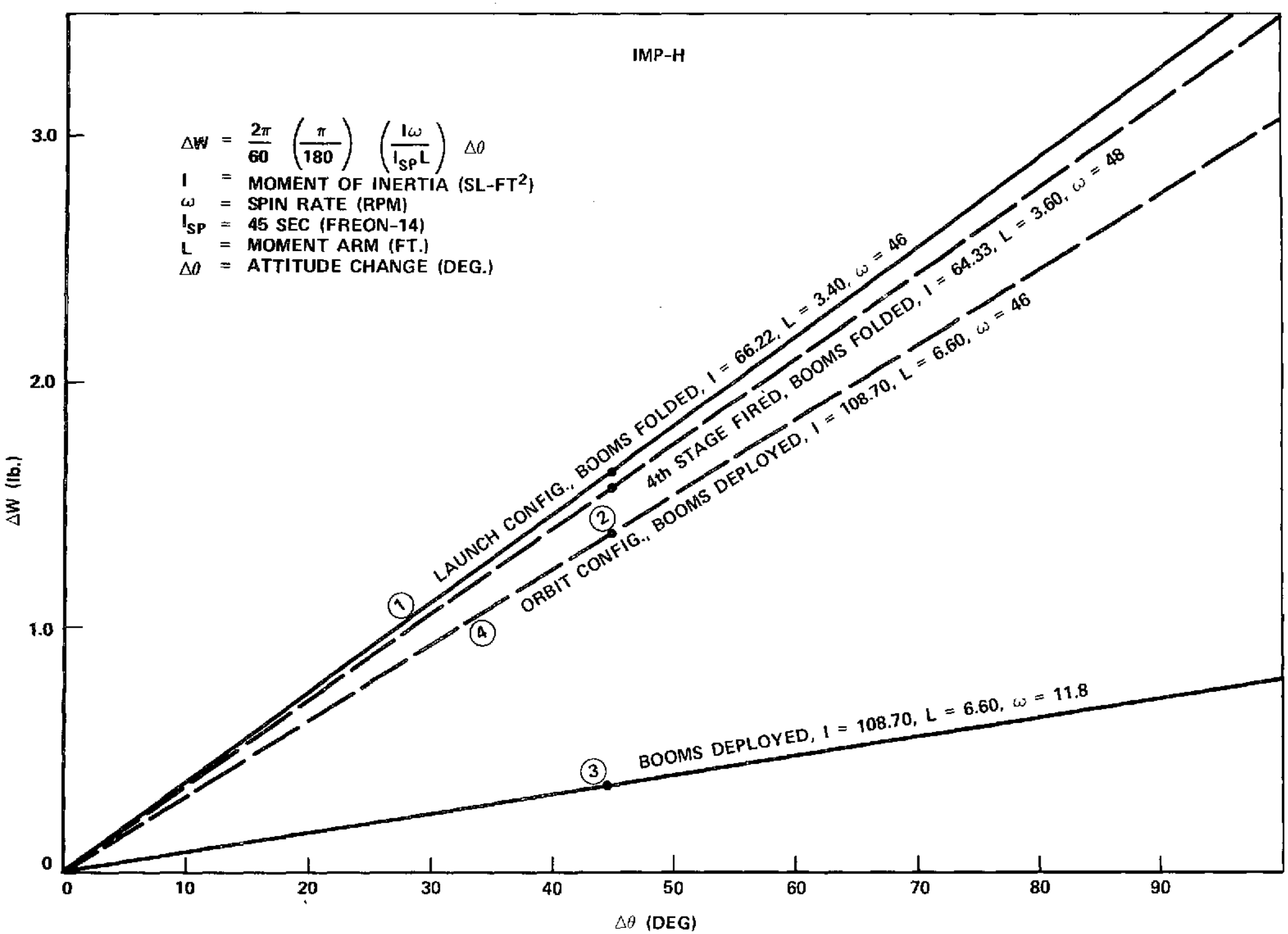


Figure 13. Propellant Required for Attitude Change

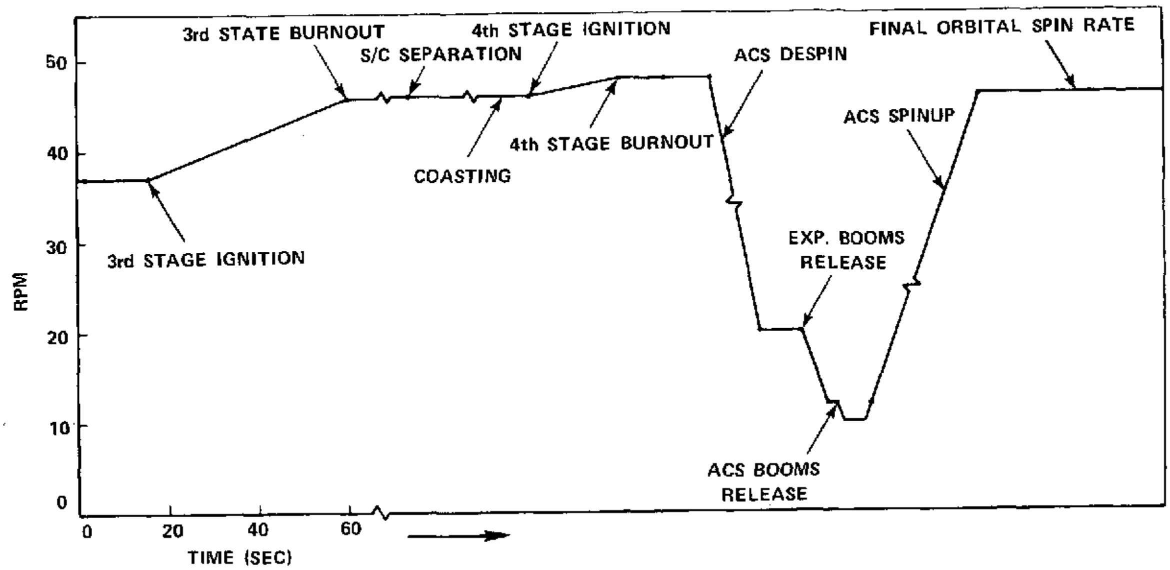


Figure 14. IMP-H Mission Profile

46 rpm, with all booms folded. Again, as much as 90 degrees of attitude change was permitted and the amount of propellant allocated for this purpose was also 3.28 lb.

3. Despin in preparation for boom deployment. Throughout the transfer orbit and fourth stage burn, a high spin rate was maintained in order to improve the stability and reduce the cone angle. However, both the ACS and Experiment booms were designed for deployment at a nominal 20 rpm, and the spacecraft had to be despun to this spin rate by the ACS before the deployment sequence could begin. Since a small random increase in spin rate was expected due to the fourth stage burn, it was estimated that the amount of ACS despin would be as much as 30 rpm and would require 2.12 lb of propellant.

4. Reorientation to final attitude. Due to the conservation of angular momentum, the boom deployment process reduced the spin rate from 20 to 11.8 rpm, and it was this lower spin rate together with the increased moment arm which made this particular reorientation maneuver very efficient from a propellant consumption standpoint. With the spacecraft in this configuration, with all booms deployed, as much as 90 degrees of attitude change was permitted, and the amount of propellant allocated for this purpose was 0.72 lb.

5. Spin-up to mission spin rate. Both the scientific experiments and the data handling equipment onboard the spacecraft were designed to operate

most effectively at a minimum of 46 rpm. The ACS was capable of producing the required changes in spin rate, including a means of using partial commands to obtain fine adjustment, in order to meet the above requirements. As much as 36 rpm change was expected, with a propellant allocation of 1.38 lb.

These maneuvers were based upon nominal conditions, and the operations described are conservative and represent the largest changes which were expected in a normal sequence. In practice, the attitude changes in particular, were actually somewhat smaller than those listed, but the exact numbers were not able to be determined until after launch and orbit injection.

In addition to the above maneuvers which comprise a total propellant budget of 10.78 lb, a contingency allotment of 50% was included in the total amount of ACS propellant. This extra quantity was carried to cover a wide assortment of possible situations or occurrences which are described below.

a. After the vast majority of the ACS propellant had been consumed, the last remaining 2 lb or so was considered essentially unusable due to its low pressure and the resulting low flow rate. Although it is true some maneuvering could actually be accomplished with this propellant, it provided a conservative but convenient cut off point in planning ACS operations.

b. Another large portion included as contingency was intended for failure mode recovery. Due to the large variety of possible failure modes, it was extremely difficult to budget a specific quantity for this purpose, and it was anticipated that whatever propellant was available at the time of failure would be allocated for recovery. It was a decision which could only be made after the fact, and the total propellant budget was based on the policy that no particular failures were expected.

c. Since very few spacecraft follow the script exactly as written, it was very likely that some unscheduled maneuvers would be necessary. Such maneuvers were distinguished from failure mode recovery in that they were used to correct or improve a situation which was not necessarily detrimental to the mission, or were of an experimental nature. Again, no specific quantity could be assigned.

d. It is very common for spacecraft to receive a significant amount of spin-up due to the burning of the third stage motor, and it was impossible to predict exactly what the final spin rate would be. Often the increase in spin rate is greater than expected and the ACS was intended to provide a means for removing the excess angular momentum by reducing the spin rate. Usually this requires only a small amount of propellant.

e. The ACS performance parameters were calculated for specific values of spin axis moment of inertia. This is one mass property which was quite difficult to measure accurately and it was necessary to compute the values for the various different spacecraft configurations, especially for the case of all booms deployed. As a result, the propellant consumption rates could possibly be slightly greater than calculated, allowing only for the worst case situation, with the excess requirements included as part of the contingency supply.

f. Similarly, flow rates and torques for the installed ACS were very difficult to measure accurately, especially under thermal vacuum conditions, and an allowance for the tolerances on these calculations was also included as part of the contingency.

g. With a rotating spacecraft, the thrust pulse for orientation commands was spread over 22.5 degrees of arc and some cosine errors were therefore accumulated. In addition, all pulses were comprised of a finite rise time and an extended tail off. These distortions of the ideal pulse shape caused some inefficiency in the actual performance of the system, and slightly increased the amount of propellant required for any given maneuver.

h. Similarly, any thrust misalignment causes an accumulation of error over a period of extended operation, in the form of small changes in either spin rate or attitude. In addition, some despin was to be expected as a result of the consumption of the ACS propellant which, in the process of flowing, must move from the tanks located near the spin axis, to the nozzles at some considerable distance from the spin axis. The decrease in spin rate is caused by the conservation of angular momentum. All of these errors were to be corrected by means of ACS operations using the propellant carried as contingency.

Although many more items could certainly be included, the above list describes the most likely possibilities and is based upon the general experience of previous spacecraft with similar systems. Contingency policies can seldom be very specific and are often arrived at by an emotional decision as to what seems or feels like a comfortable safety margin. However, one facet of the policy which is quite certain is the fact that the summation of all possible error sources must be made with the allowable tolerances stacking up to produce the worst case situation. Although the 50% number was chosen arbitrarily and for practicality, it is an established fact that the reliability of the mission was directly related to the number of uncertainties covered by the contingency policy, and that the more propellant carried, the more chance there was for a successful mission. There was, of course, a physical limit, and the continued addition of propellant was subject to the affect of diminishing returns.

In arriving at the total propellant quantity, two other allocations were included, separately. The first was leakage. The IMP-I experience showed that a considerable amount of propellant could be lost during any shadows which were encountered, and in addition, the long term overall leak rate was essentially unknown, especially with a new seal material in the valves. Leakage differed from the items listed under contingency in that it was ever-present and was not directly associated with the actual operation of the system where the propellant was consumed by the deliberate actuation of the valves. Further motivation for a separate leakage assignment was provided by the fact that a system leak rate specification existed and that the total leak rate was capable of being measured and analyzed. The final allocation was for system checkout at times when the propellant supply could not be replenished. This situation occurred when the ACS was exercised through a short series of spin-up, despin and reorientation commands as part of the gantry operations just prior to the final fairing installation. Similarly, another checkout was performed shortly after third stage separation in orbit and verified that the system had survived the launch environment.

Finally, the total propellant quantity is summarized as follows:

Scheduled ACS maneuvers	10.78 lb
Contingency at 50%	5.39 lb
Leakage and checkout	1.83 lb
Total	18.00 lb

This amount of propellant, with a specific volume of 0.0286 ft^3/lb, represents a total impulse of 810 lb-sec, and was contained in the ACS tanks at the pressures and temperatures tabulated below.

Temp °R	Temp °C	Temp °F	Pressure (psia)	
			Total	Freon-14 (90%)
450	-23.16	-9.7	958.4	862.6
460	-17.61	0.3	1046.0	941.4

Temp °R	Temp °C	Temp °F	Pressure (psia)	
			Total	Freon-14 (90%)
470	-12.05	10.3	1133.6	1020.2
480	-6.50	20.3	1221.1	1099.0
490	-0.94	30.3	1308.7	1177.8
500	4.61	40.3	1396.2	1256.6
510	10.17	50.3	1483.8	1335.4
520	15.72	60.3	1571.2	1414.1
530	21.28	70.3	1658.8	1492.9
540	26.83	80.3	1746.2	1571.6
550	32.39	90.3	1833.7	1650.3
560	37.94	100.3	1921.2	1729.1
570	43.50	110.3	2008.7	1807.8

However, the final filling operation at ETR produced the following results for the ACS.

High pressure	1770 psia
Tank 1 temperature	24.9°C
Calculated propellant weight	18.4 lb

The IMP-H was successfully launched on September 22, 1972 and the following ACS information was obtained.

High pressure	1698 psia
Low pressure	47 psia
Tank 1 temperature	20.0°C

Boom 1 temperature	13.5°C
Alpha angle (θ)	109.25 degrees
Spin rate	50.639 rpm
Calculated propellant weight	18.50 lb
Calculated Freon-14 percentage	89%

The third stage burn had produced a slightly higher than nominal spin rate, and with the spacecraft in configuration 1, one despin command was executed with the following results.

$$\Delta\omega = -2.70 \text{ rpm}$$

$$\Delta W = -0.30 \text{ lb}$$

It should be noted that prelaunch data indicated that the spin-up and despin commands actually had a duration of 69 sec each, so that the flow rate for the above command was calculated at 0.00435 lb/sec. A calibration and checkout was then performed with $\Delta W = -0.10$ lb. The following information was obtained prior to the first scheduled reorientation maneuver.

High pressure	1572 psia
Low pressure	43 psia
Tank 1 temperature	14.5°C
Boom 1 temperature	7.6°C
Alpha angle (θ)	116.75 degrees
Spin rate	47.92 rpm
Calculated propellant weight	18.05 lb

Although a great many North and West commands were sent, neither the exact number received by the spacecraft nor the actual West response could be immediately determined. However, the North response was as follows.

$$\Delta\theta = -7.5 \text{ degrees}$$

$$\Delta W = -0.35 \text{ lb}$$

This yields 21.429 deg/lb; and for the West maneuver $\Delta W = -0.55$ lb. With the spacecraft in the coast phase of the transfer orbit, another reorientation maneuver was required in preparation for the fourth stage burn. The ACS information prior to this operation was as follows.

High pressure	1468 psia
Low pressure	43 psia
Tank 1 temperature	12.1°C
Boom 1 temperature	10.8°C
Alpha angle (θ)	110.25 degrees
Spin rate	47.89 rpm
Calculated propellant weight	17.15 lb

The following North response was obtained.

$$\Delta\theta = -8.5 \text{ degrees}$$

$$\Delta W = -0.35 \text{ lb}$$

This yields 24.286 deg/lb. Again, many West commands were also sent and the response could not easily be determined except that $\Delta W = -0.55$ lb. The burning of the fourth stage produced a spin rate increase of 0.16 rpm, and the spacecraft was despun, by the ACS, in preparation for boom deployment with the following initial information obtained.

High pressure	1364 psia
Low pressure	42 psia
Tank 1 temperature	8.8°C
Boom 1 temperature	16.1°C
Alpha angle (θ)	104.75 degrees
Spin rate	48.03 rpm
Calculated propellant weight	16.25 lb

With the spacecraft in configuration 2, ten despin commands were sent with the following results.

$$\Delta\omega = -27.86 \text{ rpm or } -2.786 \text{ rpm/CMD}$$

$$\Delta W = -2.25 \text{ lb}$$

The calculated flow rate was 0.00326 lb/sec. At this point, both the ACS and Experiment booms were deployed and the spin rate was reduced by 8.19 rpm. The next maneuver was the final reorientation, and the following initial information was obtained.

High pressure	1187 psia
Low pressure	49 psia
Tank 1 temperature	5.3° C
Boom 1 temperature	15.3°C
Alpha angle (θ)	104.75 degrees
Spin rate	11.98 rpm
Calculated propellant weight	14.00 lb

With the spacecraft in configuration 3, several North commands were sent with the following results.

$$\Delta\theta = -14.0 \text{ degrees}$$

$$\Delta W = -0.25 \text{ lb}$$

This yields 56 deg/lb. In addition, several East commands were sent, but the response could not be immediately determined, except that $\Delta W = -0.40$ lb. The spacecraft was placed in configuration 4 by means of a spin-up maneuver for which the following initial information was obtained.

High pressure	1114 psia
Low pressure	43 psia
Tank 1 temperature	1.9°C
Boom 1 temperature	7.2°C
Alpha angle (θ)	88.75 degrees
Spin rate	11.94 rpm
Calculated propellant weight	13.35 lb

Six spin-up commands were sent with the following results.

$$\Delta\omega = +31.99 \text{ rpm or } +5.33 \text{ rpm/CMD}$$

Subsequently, a partial spin-up command with a duration of 25 sec was also sent, and produced the following change.

$$\Delta\omega = +1.93 \text{ rpm}$$

For the entire spin-up operation, $\Delta W = -1.40$ lb, and the flow rate was 0.00338 lb/sec. After several days, an attempt was made to trim both the orientation and spin rate, beginning with the following information.

High pressure	999 psia
Low pressure	42 psia
Tank 1 temperature	-1.4°C
Boom 1 temperature	10.0°C
Alpha angle (θ)	86.75 degrees
Spin rate	45.86 rpm
Calculated propellant weight	11.85 lb

A large number of both West and South commands were sent with the following results.

$$\Delta\theta = +3.5 \text{ degrees}$$

$$\Delta\omega = -0.20 \text{ lb}$$

In order to achieve the required small change in spin rate, a 10 sec spin-up command was sent, followed by a 6 sec despin command, with the following net result.

$$\Delta\omega = +0.25 \text{ rpm}$$

$$\Delta W = -0.20 \text{ lb}$$

Several weeks later, another orientation trim maneuver was performed, and the spacecraft was placed in the following final condition.

High pressure	1000 psia
Low pressure	46 psia
Tank 1 temperature	2.4°C
Boom 1 temperature	7.8°C
Alpha angle (θ)	90.25 degrees
Spin rate	45.905 rpm
Calculated propellant weight	11.30 lb

After 16 months of operation, the following ACS information was obtained prior to entering a 2-1/2 hour shadow.

High pressure	969 psia
Low pressure	45 psia
Tank 1 temperature	3.7°C

Boom 1 temperature	14.3°C
Alpha angle (θ)	89.25 degrees
Spin rate	45.192 rpm
Calculated propellant weight	10.60 lb

The above data indicate that possibly 0.70 lb of propellant was lost due to long term leakage at a rate of approximately 2×10^{-3} scc/sec for the entire system. Upon exposure to the shadow, the ACS solenoid valves on the ends of the booms reached a temperature of -24.4°C and the tank temperature dropped to as low as -16.7°C. Full recovery was achieved several hours after return to sunlight and the following ACS data was recorded on 3/27/74.

High pressure	948 psia
Low pressure	45 psia
Tank 1 temperature	3.3°C
Boom 1 temperature	14.3°C
Alpha angle (θ)	89.25 degrees
Spin rate	44.797 rpm
Calculated propellant weight	10.30 lb

This indicates that another 0.30 lb of propellant was lost by leakage during the shadow, possibly through one of the despin valves since the spin rate also shows a proportional decrease. However, the transfer of such a quantity of propellant from the tanks to a leak near the valves would also account for approximately one half of the amount of the measured change in spin rate. Subsequently, with an abundance of ACS propellant remaining, a spin trim maneuver was considered which would restore the IMP-H spin rate to the value originally desired by the experimenters, but this operation was postponed indefinitely so as to investigate the data characteristics over a period of time at the lower spin rate.

In the final analysis, the overall IMP-H ACS performance was reasonably close to the predicted values. The largest percentage of error was undoubtedly due to the difficulty in accurately determining the quantity of propellant present in the ACS tanks, based on the telemetry data. These difficulties arose not only from the small errors in the pressure and temperature measurements, and the previously described uncertainties in the Freon-14 plus helium mixture curve, but also from the fact that the measurements were taken during a period of transition, when the thermodynamic properties of the system were not stabilized. Although the pressure measurements were essentially real time, the processed data readout provided a resolution of only 10 psi increments. In the case of temperature, the resolution was approximately 0.4° C, but a considerable time lag was experienced before stabilization. In light of the above, a significant tolerance must be applied to the calculations of the propellant quantity consumed during each of the various IMP-H maneuvers. It should be noted that the propellant quantity determined shortly after launch was only about 2% higher than the amount calculated at the time of the final prelaunch filling. Also at the time of filling, the Freon-14 percentage was calculated to be 89% based on the ratio of the partial pressures of helium and Freon-14 added to the system.

The actual performance of the ACS during the reorientation maneuvers was clouded by the fact that the East and West response could not be determined in real time, and by the lack of knowing the precise number of commands received and executed by the spacecraft. This was basically a procedural problem which was later corrected for IMP-J. However, the meager data available did show some resemblance, in order of magnitude, to the predicted valves, with most of the error attributed primarily to the inaccuracies in propellant quantity determination for each maneuver.

The spin-up and despin maneuvers were much more amenable to analysis. When the 8% increase in command duration time was considered, the spacecraft response to spin rate changes was very close to the predicted values. This fact, together with the spin rate change during boom deployment, indicated that the spacecraft moment of inertia measurements were fairly accurate. The calculated post deployment spin rate was 11.94 rpm, based on the initial spin rate of 20.17 rpm, whereas the actual value was 11.98 rpm. However, the calculated propellant flow rates were significantly larger than expected, and the error, again, was attributed primarily to propellant quantity determination. There was, of course, the possibility that the actual delivered specific impulse was slightly less than the value used, so that more propellant was expended, in the same length of time, to produce the same thrust, but this discrepancy was never actually resolved. Fortunately there was little need for contingency plans, and the total amount of propellant consumed was actually less than the budgeted amount, leaving a substantial reserve. Similarly, no significant losses due to leakage were ever indicated, even during one brief shadow.

Further analysis of the spacecraft data revealed two other more subtle characteristics in the response and performance of the ACS. The first of these was a tendency for the spacecraft to despin slightly as the ACS propellant was consumed. This effect, referred to as gas motion despin, was most noticeable during large reorientation maneuvers and is covered in more detail in Part III. The other effect was the characteristic delay in the spacecraft response to reorientation maneuvers. In this case, the precession of the spin axis was actually displaced slightly, counterclockwise, from the intended direction, with the amount of displacement being dependent upon the spin rate. This is the topic of the next section in this document.

Section G — Characteristic Delay

The IMP-H spacecraft, with a spin rate of 46 rpm, experienced a counterclockwise error or delay in all precession maneuvers. The error, in degrees, was approximately equal to 1/4 of the rpm, and was attributed to the displacement of the centroid of the thrust pulse from the nozzles with respect to the center of the signal from the ACS electronics which occurs coincident with the sun passage of the X or Y axis of the spacecraft, depending on the quadrant selected. In detail, there was a 15 millisecond delay associated with the physical opening of the solenoid valves. Following this, approximately 60 milliseconds was required for thrust build up to reach the maximum steady state level. Similarly, approximately 20 milliseconds was required for valve closing once the signal was terminated, followed by approximately 60 milliseconds for thrust tail off to zero. These delays were nearly fixed time values and were significant in the region of 48 rpm (chosen for simplicity of calculation) where the signal duration was only 80 milliseconds and corresponded to a spacecraft rotation of 22-1/2 degrees. However, the effect was considerably reduced when the same amount of time delay was compared to a 312 millisecond signal duration at 12 rpm. At this spin rate, the thrust pulse began to approach a square wave coincident with the signal pulse. Needless to say, the spin-up and despin functions were not affected by this characteristic due to the absence of the need for synchronization and the relatively long signal duration of 64 seconds, which usually encompassed several complete revolutions of the spacecraft.

Inasmuch as the amount of error was determined graphically rather than measured, and was also subject to the peculiar characteristics of each individual solenoid valve which vary somewhat in time with the slower ones predominating, the results and predictions were, at best, a rough estimate but, nevertheless, simply adjusted for. For example, at 48 rpm the expected error was 12 degrees, and for each 4.8 degrees of reorientation required in a cardinal direction (North, East, South or West), the spacecraft would be commanded 4.7 degrees in that direction and also given a 1 degree correction in the next clockwise direction. The correction, of course, would be done at the end of the primary maneuver, when the precise total amount of error could be determined. Although these corrections are also subject to the characteristic delay, these second order effects were neglected in all but very large attitude changes. Maneuvers in other that the cardinal directions must be done in steps and arranged so as to take into account the effect of the expected error.

It should be noted that this type of problem was not new or unusual, and had been experienced by the AIMP-E spacecraft, which had a spin rate of 24 rpm. Similarly, the IMP-I used the same type ACS, but at 5.4 rpm, the error was less than 1-1/2 degrees and considered negligible except during very large orientation changes.

This problem can be practically eliminated, for example, by simply setting the Optical Aspect angle according to the expected spin rate which in effect would shift the timing of the sun pulse signal and place the thrust pulse centroid coincident with the boom axis sun passage. Such an adjustment would have to be made at some time before launch and would be permanent. There are, of course, other solutions which will not be covered at this time.

Figure 15 shows the location of the Optical Aspect sensor and the timing of the sun and signal pulses in terms of spacecraft rotation angle. It should be pointed out that the signal pulses shown represent the location and spacing arrangement for all four of the cardinal directions, and that in practice the signal pulses for each particular reorientation command, or direction, would always occur on the same axis, with a separation of 360 degrees until a total of 8 pulses had accumulated. Since the pulse spacing and durations are fixed angular values, the actual times are related to the spacecraft angular velocity and can be easily determined by measuring the spin period and converting the angles to time.

A more precise determination of the actual precession direction can be made by plotting the thrust chamber pressure pulse in a polar coordinate system in the plane of rotation of the spacecraft. As long as the torque levels are relatively small, the changes in angular momentum will occur in a direction 90 degrees from the centroid of the area of the pressure pulse. Since this procedure is quite time consuming, it is therefore useful primarily as a calibration exercise prior to launch. However, a simplified analysis of this valve related anomaly is shown in Figure 16, and serves to illustrate the basis of the characteristic delay. Also, the effect of the error angle is shown in Figure 17 and a variety of related information is tabulated in Table 9.

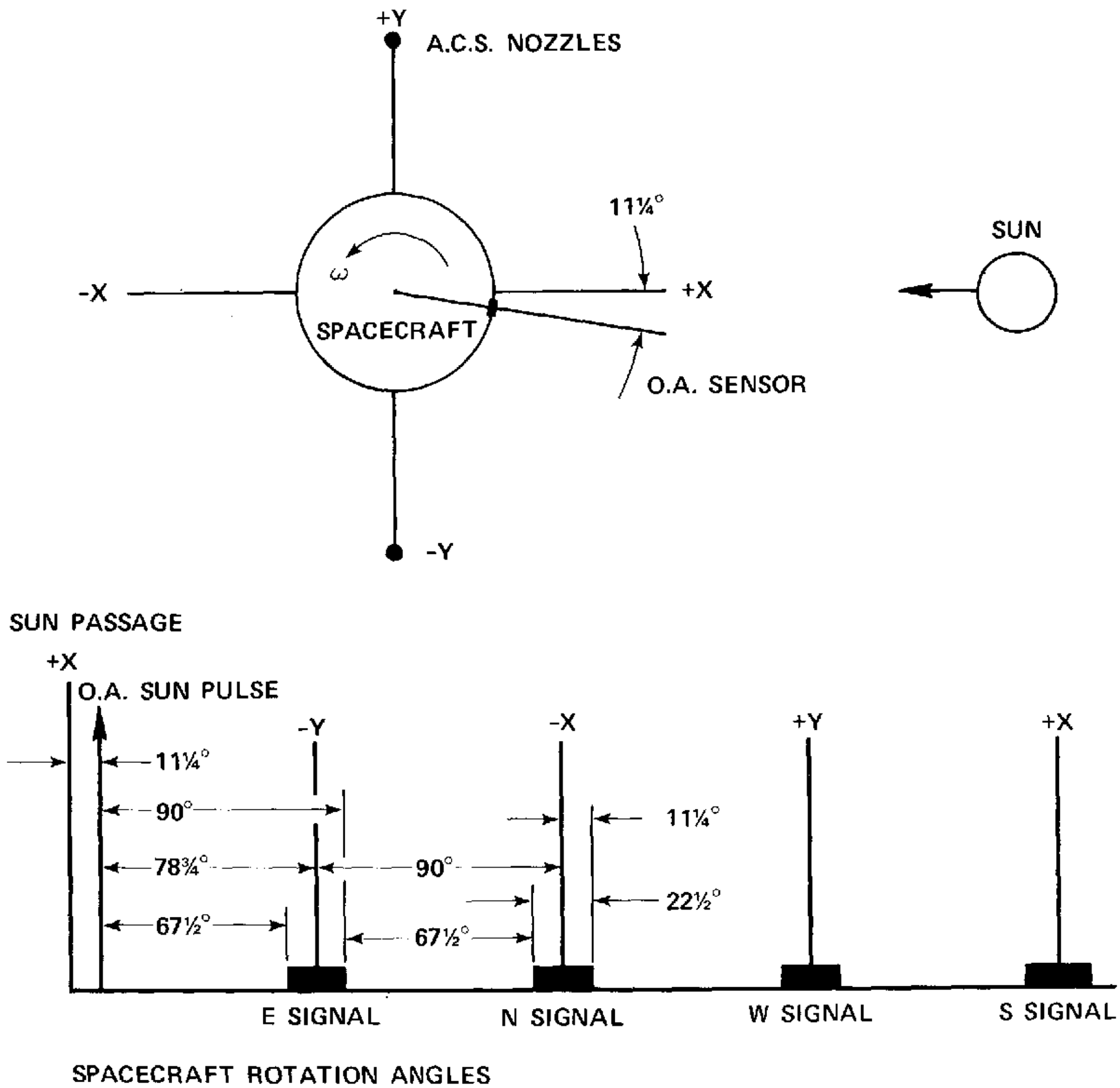
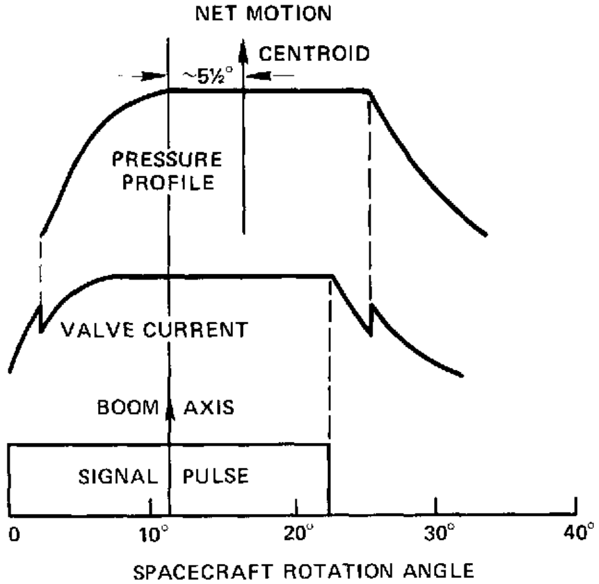


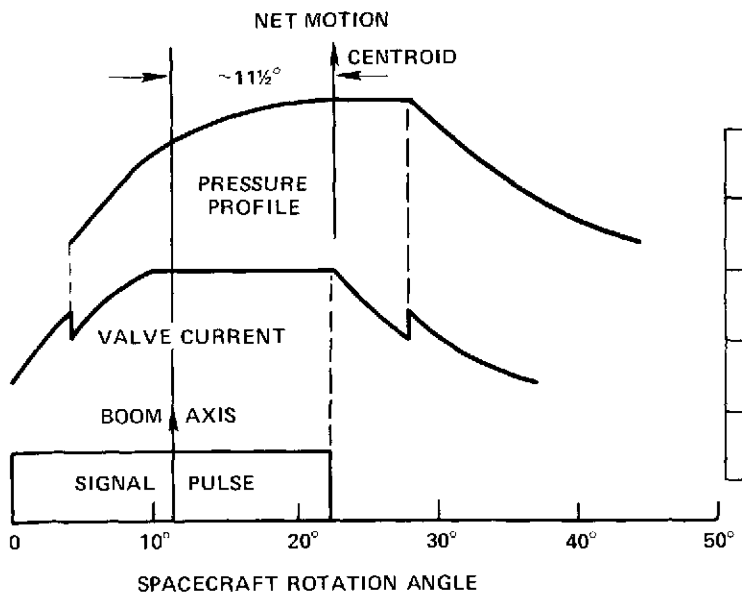
Figure 15. ACS Pulse Timing

23 RPM 0.138°/MILLISEC



TIME	ROTATION ANGLE
VALVE OPENING 15 MILLISEC	2.07°
PRESSURE RISE 60 MILLSEC	8.28°
VALVE CLOSING 20 MILLISEC	2.76°
PRESSURE TAIL OFF 60 MILLISEC	8.28°

46 RPM 0.276°/MILLISEC



TIME	ROTATION ANGLE
VALVE OPENING 15 MILLISEC	4.14°
PRESSURE RISE 60 MILLISEC	16.56°
VALVE CLOSING 20 MILLISEC	5.52°
PRESSURE TAIL OFF 60 MILLISEC	16.56°

Figure 16. Characteristic Delay

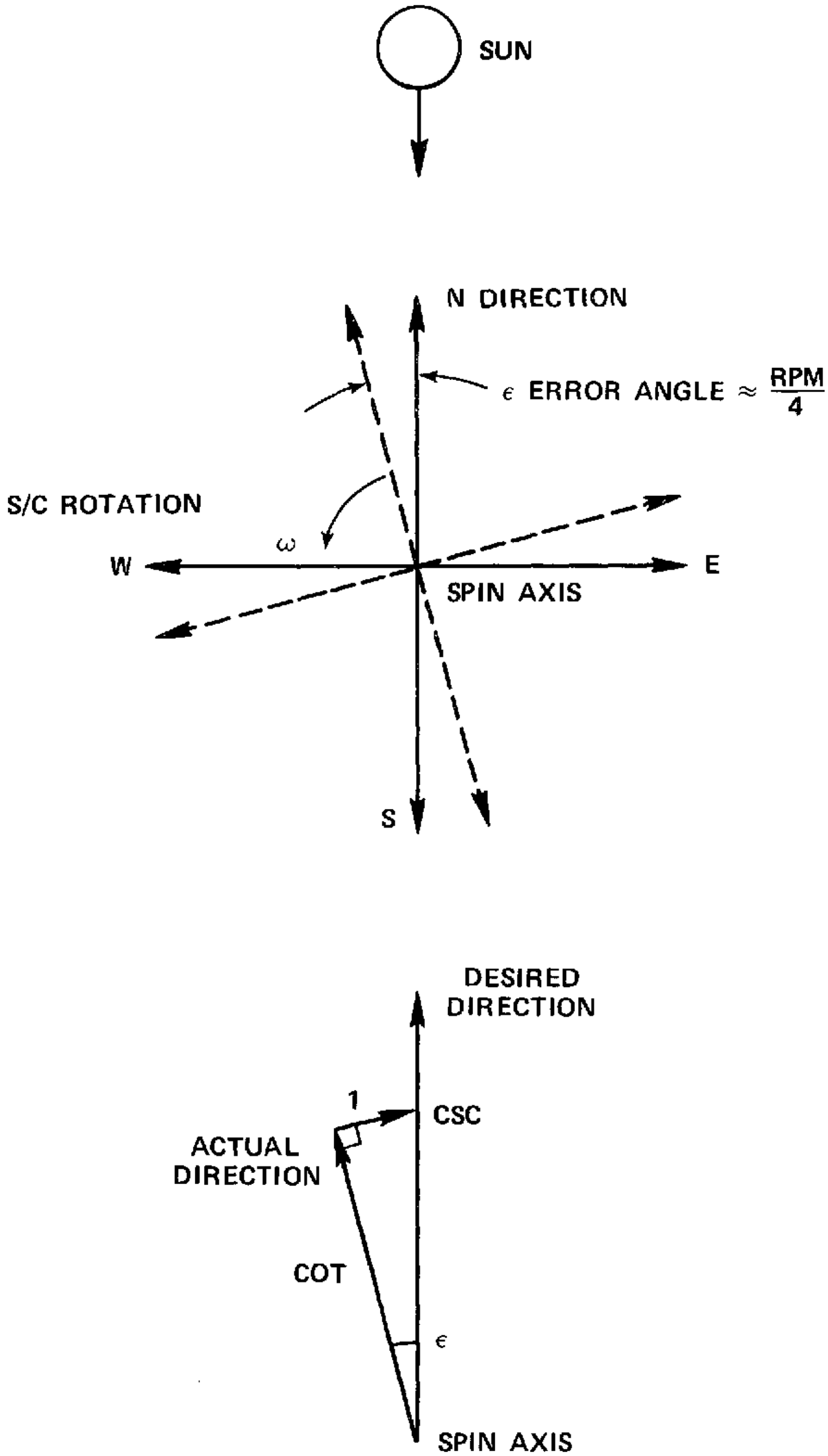


Figure 17. Error Angle

Table 9

Error Angle Tabulation

rpm	Period (sec)	ϵ (deg)	tan ϵ	cot ϵ	csc ϵ	Rotation Angle (deg)		
						0.015 sec	0.020 sec	0.060 sec
4	15.00	1	0.01746	57.29	57.3	0.36	0.48	1.44
6	10.00	1-1/2	0.02619	38.19	38.2	0.54	0.72	2.16
8	7.50	2	0.03492	28.64	28.7	0.72	0.96	2.88
10	6.00	2-1/2	0.04366	22.90	22.9	0.90	1.20	3.60
12	5.00	3	0.05241	19.08	19.1	1.08	1.44	4.32
14	4.29	3-1/2	0.06116	16.35	16.4	1.26	1.68	5.04
16	3.75	4	0.06993	14.30	14.3	1.44	1.92	5.76
18	3.33	4-1/2	0.07870	12.71	12.7	1.62	2.16	6.48
20	3.00	5	0.08749	11.43	11.5	1.80	2.40	7.20
22	2.73	5-1/2	0.09629	10.39	10.4	1.98	2.64	7.92
24	2.50	6	0.10510	9.51	9.6	2.16	2.88	8.64
26	2.31	6-1/2	0.11394	8.78	8.8	2.34	3.12	9.36
28	2.14	7	0.12278	8.14	8.2	2.52	3.36	10.08
30	2.00	7-1/2	0.13165	7.60	7.7	2.70	3.60	10.80
32	1.88	8	0.14054	7.12	7.2	2.88	3.84	11.52
34	1.76	8-1/2	0.14945	6.69	6.8	3.06	4.08	12.24
36	1.67	9	0.15838	6.31	6.4	3.24	4.32	12.96
38	1.58	9-1/2	0.16734	5.98	6.1	3.42	4.56	13.68
40	1.50	10	0.17633	5.67	5.8	3.60	4.80	14.40
42	1.43	10-1/2	0.18534	5.40	5.5	3.78	5.04	15.12
44	1.36	11	0.19438	5.14	5.2	3.96	5.28	15.84
46	1.30	11-1/2	0.20345	4.92	5.0	4.14	5.52	16.56
48	1.25	12	0.21256	4.70	4.8	4.32	5.76	17.28
50	1.20	12-1/2	0.22169	4.51	4.6	4.50	6.00	18.00

Section H — Safety Documentation

In order to fulfill the safety documentation requirements for proof test certification, the following information was transmitted to the Delta Project Office on April 19, 1972.

The flight unit Attitude Control System consisting of tanks, IMP-H identification code system no. IC 2-03 and IC 2-05, and Shelf Assembly IC 5-04, completely assembled on the flight spacecraft, was successfully tested to a proof pressure of 2700 psig on September 9, 1971 at EMR. This represents 1.5 times the maximum allowable working pressure of 1800 psig for this system which is designed with a four (4) to one (1) safety factor. Actual tests performed by the manufacturer confirmed a burst pressure in excess of 7200 psig for the tank design used in this system.

Components of the flight spare system, consisting of tanks IC 2-04 and IC 2-08, and Shelf Assembly IC 5-03, have also been individually proof tested to a pressure of 2700 psig.

With the installation of the flight Valve-Nozzle Assemblies, IC 4-07 and IC 4-08, on the spacecraft on February 4, 1972, the ACS is completely assembled in its flight configuration; and with the successful completion of the final thermal vacuum test on April 14, 1972, the pneumatic portion of the ACS is considered qualified for flight.

PART III: SYSTEM SPECIFICATIONS PECULIAR TO THE IMP-J

Section A — Component Changes for IMP-J

Propellant —

Some difficulties in determining the precise final spacecraft weight for both the IMP-I and H were attributed partly to the uncertainty in calculating the amount of propellant contained in the ACS tanks. The use of a theoretical thermodynamic relationship together with errors in instrumentation and measurements of actual pressure, temperature, and volume were cited as contributing factors. However, the largest source of error was traced to uncertainty in the amount of helium mixed with the Freon-14. In the original procedure for filling the ACS, a predetermined change in pressure was attempted by the addition of pure helium to the system in a separate operation, followed by the addition of pure Freon-14, and then comparing the actual recorded pressure changes to the final total pressure in order to arrive at the helium partial pressure percentage. However, the accuracy of this method suffered from temperature changes during the procedure and from the fact that the helium percentage did not remain constant over the range of pressures involved. Recall that Freon-14 deviates significantly from an ideal gas, whereas helium retains fairly linear properties. Subsequently, it was decided to purchase the ACS propellant in a premixed condition in an effort to not only improve the weight determination accuracy, but also simplify the filling procedures as well.

The procurement requirements for this material are presented below, and it should be mentioned that the purity specifications are identical to those for the original Freon-14.

Cylinders are to contain 52 pounds ±2 pounds of TETRA-Fluoromethane (Freon-14) with 10% ±1/2% partial pressure of helium gas. The composition of the gas within each container is to be certified, in writing, in regards to total pressure and percentage of major constituents. The gas mixture is to be delivered with a purity as described in the following specifications.

The cylinders are to be standard ICC 3AA2265 or equivalent and contain a minimum gas pressure of 2100 psi total.

Purity Specification:

1. The minimum purity of the mixture, exclusive of air, shall be 99.80% by volume.

2. The moisture content of the mixture shall not exceed 2 PPM by weight.

3. The carbon monoxide content of a sample taken at room temperature shall not exceed 0.20% by volume.

4. The combined contents of air and carbon monoxide in a sample taken at room temperature shall not exceed 1.0% by volume.

5. Its combined contents of organic impurities (other halocarbons) and carbon monoxide shall not exceed 0.20% by volume.

6. Its free acidity, expressed as hydrochloric acid, shall not exceed 0.100 PPM by weight.

Supplier	Matheson Gas Products P. O. Box 85 East Rutherford, N. J. 07073
Cost per cylinder	\$705.60
Deposit per cylinder (refundable)	\$75.00
Measured helium percentage	10.2%

Calculations for the variable helium pressure were based on the equation of state,

$$P = \frac{RT}{v}$$

or for constant volume,

$$P = \frac{WRT}{V}$$

where

$$v = \frac{V}{W}$$

and for helium specifically,

$$P_H = \frac{W_H R_H T}{V}.$$

With the premixed gas, the weight ratio of helium and Freon-14 remained constant with both at the same temperature, and may be described as follows.

$$r = \frac{W_H}{W_F}$$

with

$$W_H = \frac{P_H V}{R_H T}, \quad W_F = \frac{P_F V}{R_F T}$$

and

$$R_H = \frac{\bar{R}}{M_H}, \quad R_F = \frac{\bar{R}}{M_F},$$

then

$$r = \frac{P_H M_H}{P_F M_F}$$

The subscript H refers to helium and F refers to Freon-14. Since the specifications called for a 10% helium pressure, this number was used in the original calculations. Assuming, arbitrarily, a total pressure of 100 psia, the helium pressure is 10 psia and the Freon-14 pressure is 90 psia. Also, the molecular weight, M_H, of helium is 4.003 and the molecular weight, M_F, of Freon-14 is 88.01. With this information, r is calculated to be 0.005054; and W_H can be found, in terms of pounds, by multiplying by the weight of Freon-14, W_F, present at any given temperature and pressure. With the appropriate conversion factor, the equation of state then becomes,

$$P_H = (rW_F) \frac{R_H T}{144V}.$$

The universal gas constant, $\bar{R}$, is used to obtain R_H:

$$R_H = \frac{1545.4}{4.003} = 386.06 \frac{\text{ft-lb}}{\text{lb-}^\circ\text{R}}.$$

Also, the contained volume, V, is 0.515 ft^3. Finally the equation becomes,

$$P_H = 0.02631 \, (W_F T).$$

The Freon-14 properties have been tabulated in detail, and W_F is obtained from this chart for any given temperature. The pressure is also given in the chart, and when this value is added to the calculated helium pressure, the total supply pressure is obtained.

$$P_T = P_H + P_F$$

In addition, the specific helium percentage, %, is also obtained by,

$$\% = \frac{P_H}{P_F} \times 100 .$$

A condensed tabulation of the values used for IMP-J is presented in Table 10. In practice, the total pressure reading is supplied by the high pressure transducer, and the propellant temperature is obtained from a thermistor located in a temperature probe inside one of the ACS tanks. With this information, the chart is consulted, and by means of interpolation, the weight of propellant onboard is calculated. As in all previous cases, the weight of the helium is neglected from the total. Although the accuracy of this method is still compromised by certain simplifying assumptions, the overall accuracy of the ACS propellant weight determination has been improved by approximately 40%.

Past experience has indicated that the ACS tank temperature, in orbit is usually on the order of 0°C, and the pressure versus weight relationship at this temperature is shown in Figure 18.

Metallic Seals —

The leakage problems experienced with the IMP-I system inspired further investigation into methods of applying the latest sealing techniques to the Valve-Nozzle assemblies. As previously mentioned in regards to IMP-H, the short lead time available allowed only the simplest material changes to be made for that spacecraft. In the case of IMP-J, the fluorosilicone o-rings and seat material were also incorporated into the solenoid valves, since these items eventually proved to be satisfactory. However, more lead time was available for IMP-J and it was decided to take advantage of the new metallic V-Seals developed by the Parker Seal Company, as a replacement for the valve inlet o-rings only. The seal chosen for this particular application had the following specifications.

Seal design series	Mark II (8900)
Part number	8910-2101-0062
Cross section free height	0.051 inches

Table 10

Pre-Mixed Propellant Properties

Temp. °R (°C)	Press. Total %He	Total Pressure (psia) and Helium Pressure (%)									
		Propellant Weight, W_F (lb); V = 0.515 ft^3									
		1	2	3	4	5	6	7	8	9	10
450	PT	116	215	313	398	474	544	609	666	722	768
(-23.2)	%	10.5	10.9	11.4	12.0	12.5	13.0	13.6	14.2	14.8	15.4
460	PT	119	221	323	411	491	565	635	696	757	807
(-17.6)	%	10.4	10.9	11.4	11.8	12.3	12.8	13.4	13.9	14.4	15.0
470	PT	122	226	332	424	508	586	660	726	791	847
(-12.1)	%	10.4	10.8	11.3	11.7	12.2	12.6	13.1	13.6	14.1	14.6
480	PT	125	232	341	437	524	607	685	755	826	886
(-6.5)	%	10.4	10.8	11.2	11.6	12.0	12.5	12.9	13.3	13.8	14.2
490	PT	128	238	351	450	541	627	710	785	861	925
(-0.9)	%	10.4	10.7	11.1	11.5	11.9	12.3	12.7	13.1	13.5	13.9
500	PT	131	244	360	463	558	648	736	815	895	964
(4.6)	%	10.4	10.7	11.1	11.4	11.8	12.2	12.5	12.9	13.3	13.6
510	PT	134	249	369	476	575	669	761	844	930	1004
(10.2)	%	10.3	10.7	11.0	11.3	11.7	12.0	12.4	12.7	13.0	13.3
520	PT	137	255	379	489	591	690	786	874	965	1043
(15.7)	%	10.3	10.6	10.9	11.3	11.6	11.9	12.2	12.5	12.8	13.1
530	PT	139	261	388	502	608	710	811	904	999	1082
(21.3)	%	10.3	10.6	10.9	11.2	11.5	11.8	12.0	12.3	12.6	12.9
540	PT	142	267	397	515	625	731	836	933	1034	1121
(26.8)	%	10.3	10.5	10.8	11.1	11.4	11.6	11.9	12.2	12.4	12.6
550	PT	145	273	407	528	641	752	861	963	1068	1161
(32.4)	%	10.3	10.5	10.8	11.0	11.3	11.5	11.8	12.0	12.2	12.4
560	PT	148	278	416	541	658	773	887	992	1103	1200
(37.9)	%	10.2	10.5	10.7	11.0	11.2	11.4	11.6	11.9	12.1	12.3
570	PT	151	284	425	554	675	793	912	1022	1137	1239
(43.5)	%	10.2	10.4	10.7	10.9	11.1	11.3	11.5	11.7	11.9	12.1

Table 10 (cont'd.)

Temp. °R (°C)	Press. Total %He	Total Pressure (psia) and Helium Pressure (%)										
		Propellant Weight, W_F (lb); V = 0.515 ft^3										
		11	12	13	14	15	16	17	18	19	20	21
450	PT	814	855	895	932	969	1004	1039	1076	1113	1151	1197
(-23.2)	%	16.0	16.6	17.2	17.8	18.3	18.9	19.4	19.8	20.2	20.5	20.8
460	PT	859	904	950	992	1035	1075	1117	1159	1203	1248	1302
(-17.6)	%	15.5	16.0	16.6	17.1	17.6	18.0	18.4	18.8	19.1	19.4	19.5
470	PT	903	954	1005	1053	1101	1147	1194	1243	1293	1345	1407
(-12.1)	%	15.1	15.5	16.0	16.4	16.9	17.2	17.6	17.9	18.2	18.4	18.5
480	PT	947	1003	1060	1113	1167	1218	1271	1326	1383	1442	1513
(-6.5)	%	14.7	15.1	15.5	15.9	16.3	16.6	16.9	17.1	17.3	17.5	17.5
490	PT	992	1053	1115	1173	1232	1289	1349	1410	1474	1539	1618
(0.9)	%	14.3	14.7	15.0	15.4	15.7	16.0	16.2	16.5	16.6	16.7	16.7
500	PT	1036	1102	1169	1233	1298	1361	1426	1493	1564	1636	1724
(4.6)	%	14.0	14.3	14.6	14.9	15.2	15.5	15.7	15.9	16.0	16.1	16.0
510	PT	1081	1151	1224	1293	1364	1432	1503	1577	1654	1733	1829
(10.2)	%	13.7	14.0	14.3	14.5	14.8	15.0	15.2	15.3	15.4	15.5	15.4
520	PT	1125	1201	1279	1353	1430	1503	1580	1660	1744	1830	1935
(15.7)	%	13.4	13.6	13.9	14.1	14.4	14.6	14.7	14.8	14.9	14.9	14.9
530	PT	1169	1250	1334	1414	1495	1575	1658	1744	1834	1927	2040
(21.3)	%	13.1	13.4	13.6	13.8	14.0	14.2	14.3	14.4	14.4	14.4	14.4
540	PT	1214	1299	1389	1474	1561	1646	1735	1827	1924	2024	2146
(26.8)	%	12.9	13.1	13.3	13.5	13.7	13.8	13.9	14.0	14.0	14.0	13.9
550	PT	1258	1349	1443	1534	1627	1717	1812	1911	2014	2121	2251
(32.4)	%	12.7	12.8	13.0	13.2	13.4	13.5	13.6	13.6	13.7	13.6	13.5
560	PT	1302	1398	1498	1594	1693	1789	1889	1994	2104	2218	2357
(37.9)	%	12.4	12.6	12.8	12.9	13.1	13.2	13.3	13.3	13.3	13.3	13.1
570	PT	1347	1447	1553	1654	1758	1860	1966	2078	2194	2315	2462
(43.5)	%	12.3	12.4	12.6	12.7	12.8	12.9	13.0	13.0	13.0	12.9	12.8

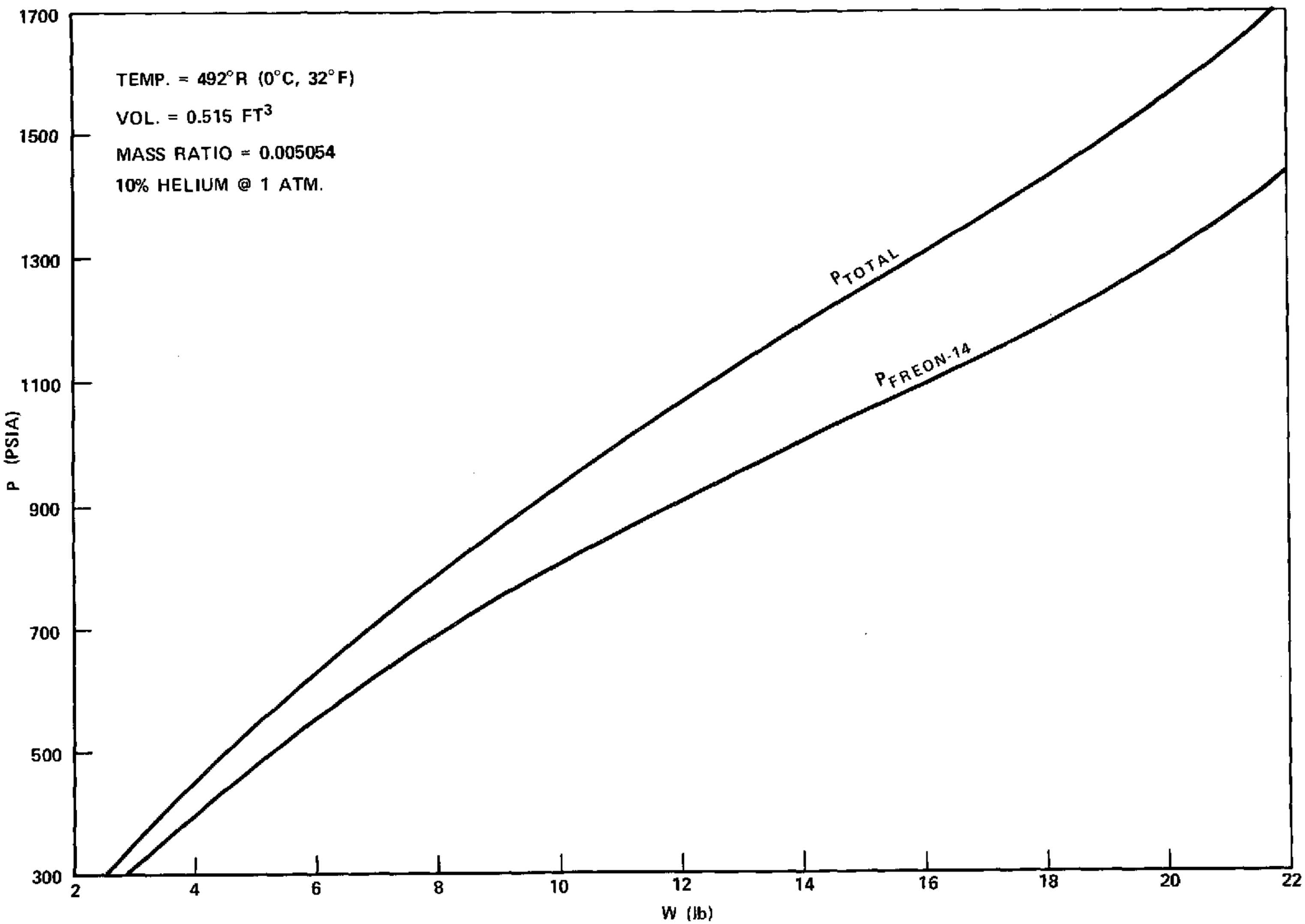


Figure 18. IMP-J ACS Pressure-Weight Curve

Base material	Nickel alloy 718
Plating material	Silver
Nominal diameter	0.625 inches
Temperature range (base)	-423°F to 1400°F
Temperature range (plating)	-325°F to 1300°F
Comments (base)	Excellent physical properties over broad temperature range
Comments (plating)	All purpose plating, least expensive
Seating load	300 lb/in of circumference
Recovery (spring back)	0.002 inches
Pressure capability (internal)	50,000 psi
Mating surface finish	8c recommended
Reusability	2 to 4 times to maintain vacuum and helium leak rate of 10^{-9} scc/sec
Quantity purchased	50

Upon receipt of the V-Seals, it was discovered that approximately 90% displayed a defective surface finish, and these were returned to the manufacturer in exchange for replacement units. The new seals were then individually cleaned by immersing them in a bath of alcohol contained in a sealable plastic bag, and subjecting them to the ultrasonic cleaning process. Following this, a number of the seals were acceptance tested simultaneously with the new IMP-J solenoid valves. The seals proved to be very effective in meeting the low temperature leak specifications and were reused 2 or 3 times before having to be discarded. Although the soft surface plating warranted extremely delicate handling, the failure rate was quite low, with most of the failed units being rejected due to apparent flaws discovered during the visual inspection of the surface finish prior to use. In addition, the build up of the Valve-Nozzle assemblies proved to be a tedious task owing to the fact that additional screws were required to obtain proper compression of the V-Seals, with each screw being alternately tightened to ensure even seating. In spite of these initial difficulties, the V-Seals have performed flawlessly throughout both the spacecraft qualification testing and the orbital spaceflight environment.

Since these seals required such high compression forces, other changes were made to accommodate the situation. The mating manifolds were redesigned to be made from stainless steel instead of aluminum, and to include the seal gland with the necessary surface finish. Additional threaded holes were added to accept the increased number of mounting screws, and special efforts were made to minimize the increase in weight. Finally, the solenoid valve specifications were appropriately modified and a new batch of valves was ordered.

Solenoid Valves —

The IMP-J solenoid valves, manufactured by Wright Components, Inc., were essentially identical to those for IMP-H except that the specifications were revised to the following extent.

The GSFC drawing was updated to apply to both valves, so that the IMP-H valve became GD1074084-1 and the IMP-J valve became GD1074084-2. In order to accommodate the V-Seal interface, the o-ring groove was removed from the inlet side of the valve, and a 16 surface finish requirement was added to that surface. The outlet o-ring material was changed to L677-7 fluorosilicone solely due to availability. In addition, the -2 valve was equipped with both an elastomeric and redundant metal internal seal. This was also a V-Seal, part number 8910-2101-0050, and was installed by the manufacturer. Subsequently, the manufacturer's valve part number was also changed, to 15607-1, and reflected no increase in unit cost with a purchase of 18 units. Finally, the vibration requirement was reduced to 0.50 da 5 cps to 20 cps in order to provide compatibility with the test instrumentation.

Acceptance testing required a new fixture to accommodate the V-Seal, and was performed, per request No. 1350-19 completed 2/13/73, for all valves at ambient temperature in a vacuum chamber. Helium at 60 psia was applied to the inlet of each valve, and after several pulse cycles, the seat leak rate, case leak rate and flow rate measurements and a current trace were made. The temperature was then lowered to -45° ±5°C and again the seat and case leak rates were measured. Finally, one good valve was selected at random and tested for operation and leakage at +45° ±5°C. In all cases, the outlet filter screens were installed before testing. Of the 18 valves tested, 4 had a leak rate greater than 10^{-6} scc/sec and were rejected. These were subsequently repaired by the manufacturer and returned to GSFC. The leak rates for the acceptable valves ranged from 7.4×10^{-8} scc/sec to less than 5×10^{-10} scc/sec over the entire temperature range of testing for either the valve seat or the case.

This small quantity of valves allowed the build up of only one set of flight Valve-Nozzle assemblies, and the IMP-H spare units were assigned as the IMP-J spares as well. However, the new assemblies were approximately 1/2 lb heavier and necessitated the requirement that the assemblies be exchanged only in pairs, and that new moments of inertia be calculated, if for some reason the spare units were to be installed and flown.

A cutaway diagram of the solenoid valve and V-Seal interface is shown in Figure 19.

Manual Valves —

Difficulties in obtaining a good leak tight connection to the manual valves prompted a material change from aluminum to stainless steel for the valve bodies. The problem was attributed to the fact that some of the mating tubing was stainless steel and the aluminum tube fittings could not properly deform the harder material in order to produce a leak tight seal. The new valves were identical to the older ones, except for the body material, and were manufactured by Hoke, Inc., part number D3251G4Y, also with Gyrolok fittings.

Micro Switch —

Although the IMP-H micro switch design arrangement solved most of the problems encountered with IMP-I and performed successfully in flight, it was not without its own peculiar characteristics which caused some difficulties to be experienced during spacecraft integration. The major problem was the large side force generated by the highly deflected micro switch tang when the detent pin was in the fully retracted position. In some instances the side force was sufficient to overcome the detent spring force and hold the pin against the casing and thus prevent boom lockup during deployment. Another problem was the large amount of slop in the attachment of the tang to the switch body. Not only was it possible for the tang to catch on technician's clothing or cause injury by scratching, but it was also possible for the tang to slip over the edge of the actuator and render the switch ineffective.

Several modifications were made for the IMP-J in order to eliminate the above problems. Since it was desirable to retain the same micro switch, the actuator and detent pin were redesigned so as to minimize the side forces and to enclose the tang over the center of the pin. These changes proved to be successful and were essentially troublefree throughout the IMP-J program.

Select Component Serial Numbers —

Panel Assembly, IC 5-05:

Pressure Regulator S/N 5
High Pressure Transducer S/N 584-6
Low Pressure Transducer S/N 139703

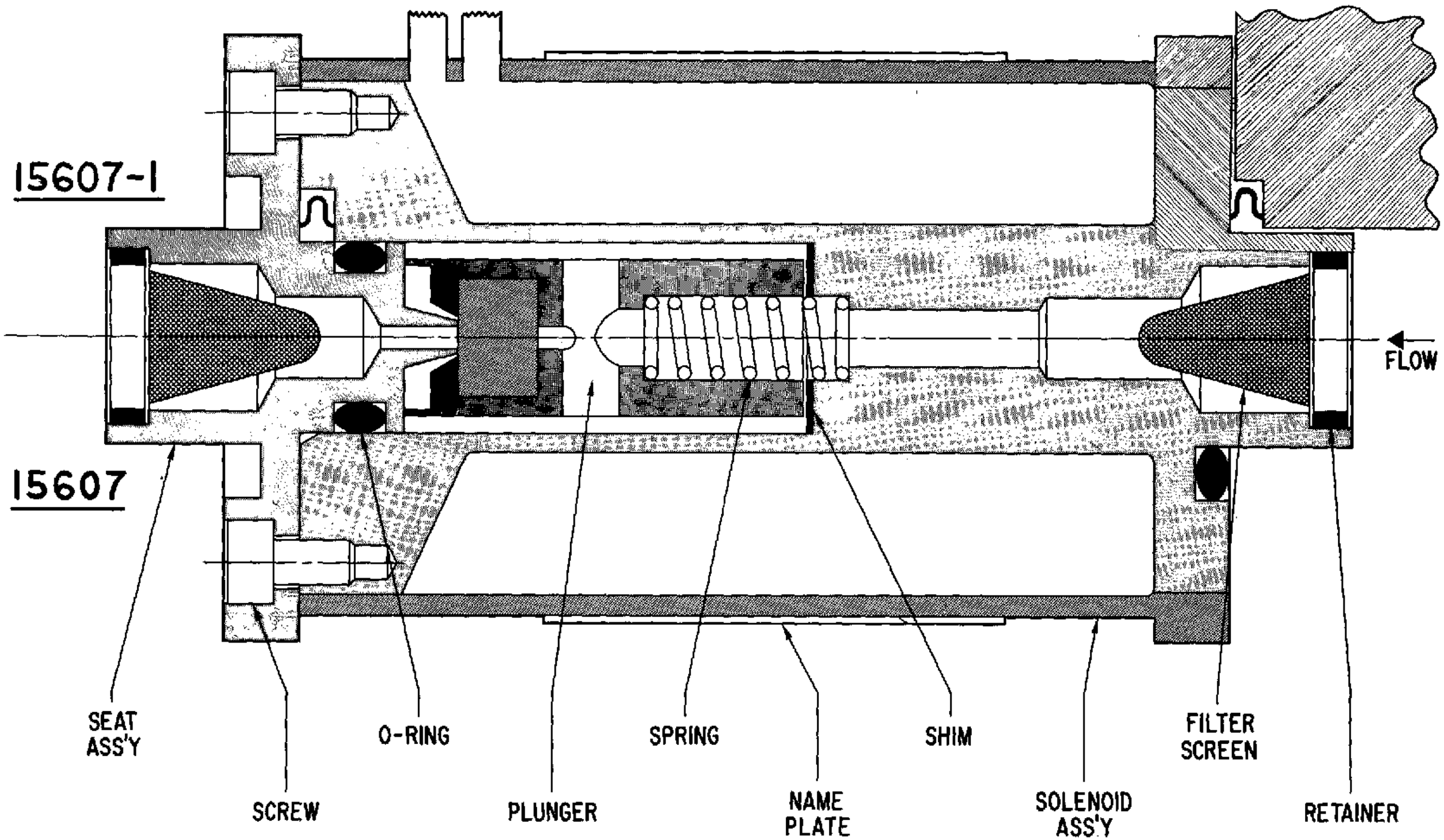


Figure 19. Axial Solenoid Valve

Valve-Nozzle Assembly, IC 4-11:

Thermistor S/N 89

	Solenoid Valve S/N		
	spin-up	reorient	despin
outboard	2	7	9
inboard	3	8	6

Valve-Nozzle Assembly, IC 4-12:

	Solenoid Valve S/N		
	spin-up	reorient	despin
outboard	12	13	17
inboard	11	16	18

Note: Solenoid Valve Part No. 15607-1.

Section B — Mass Properties and Dimensions

The basic layout of the IMP-J spacecraft was essentially identical to that of IMP-H and is shown in Figures 20 and 21. Also, some reference dimensions are shown in Figure 22, and the primary configurations can be summarized as follows.

1. Launch Configuration

Booms	all folded, except inertia booms which deploy at fairing separation
Fourth stage	unfired
Spin axis MOI	67.77 sl-ft^2
Nominal spin rate	46 rpm after third stage separation
Weight	876.5 lb
Center of gravity	24.28 inches above separation plane

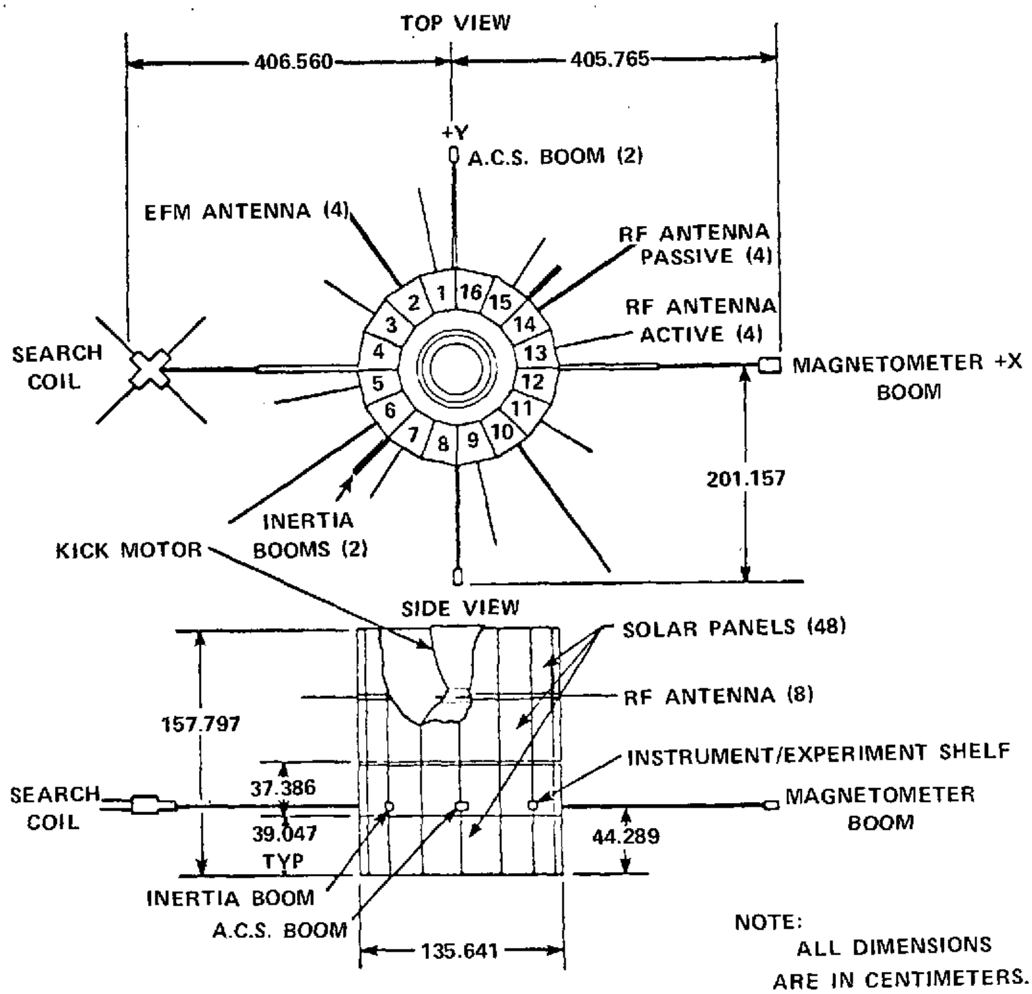


Figure 20. IMP-J Spacecraft

MOI ratio	1.041
Spin control moment arm	2.12 ft
Attitude control moment arm	3.39 ft

2. Intermediate Configuration

Booms	all folded, except inertia booms
Fourth stage	burned out
Spin axis MOI	65.88 sl-ft^2
Expected spin rate	48 rpm

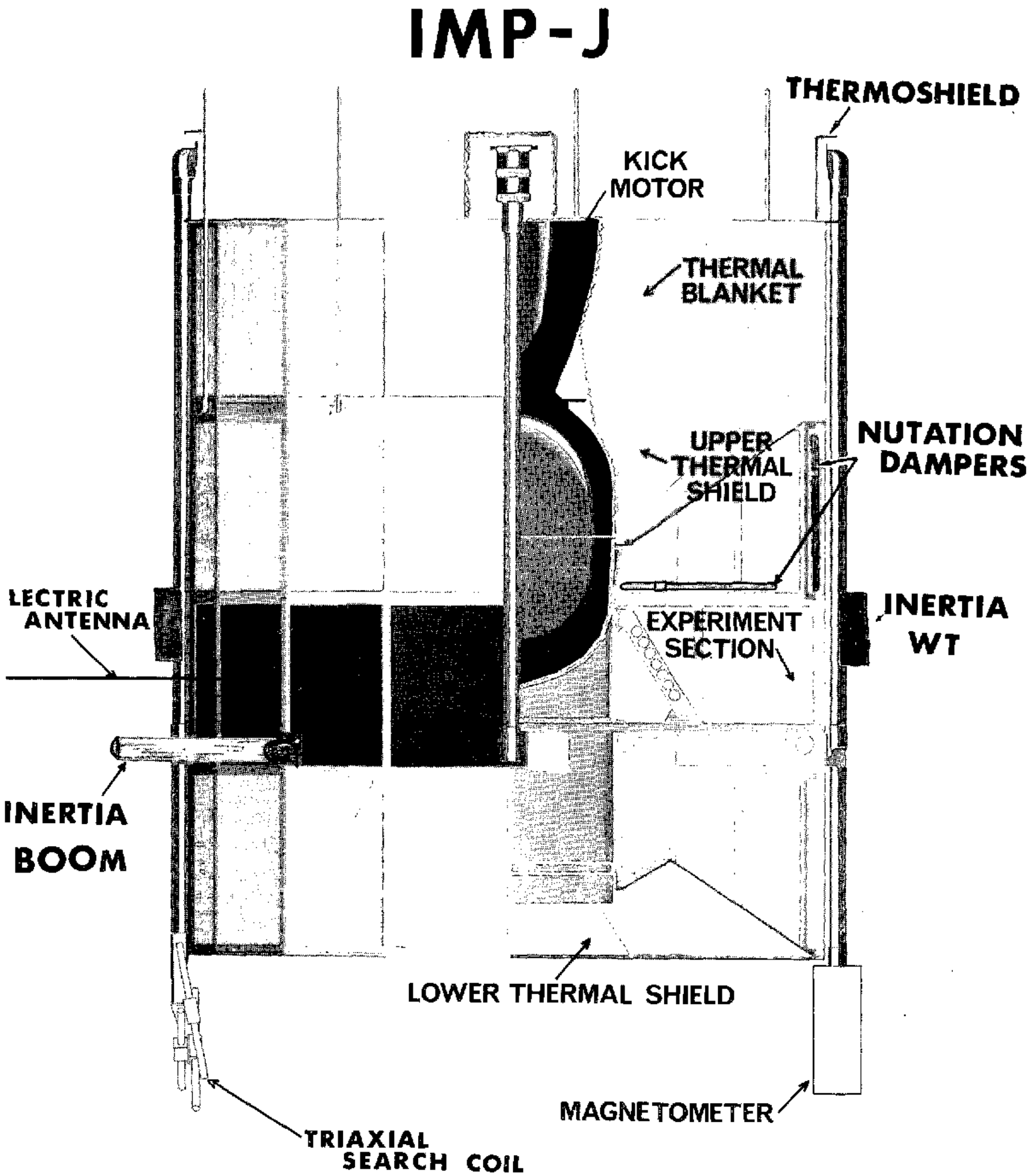


Figure 21. IMP-J Structure

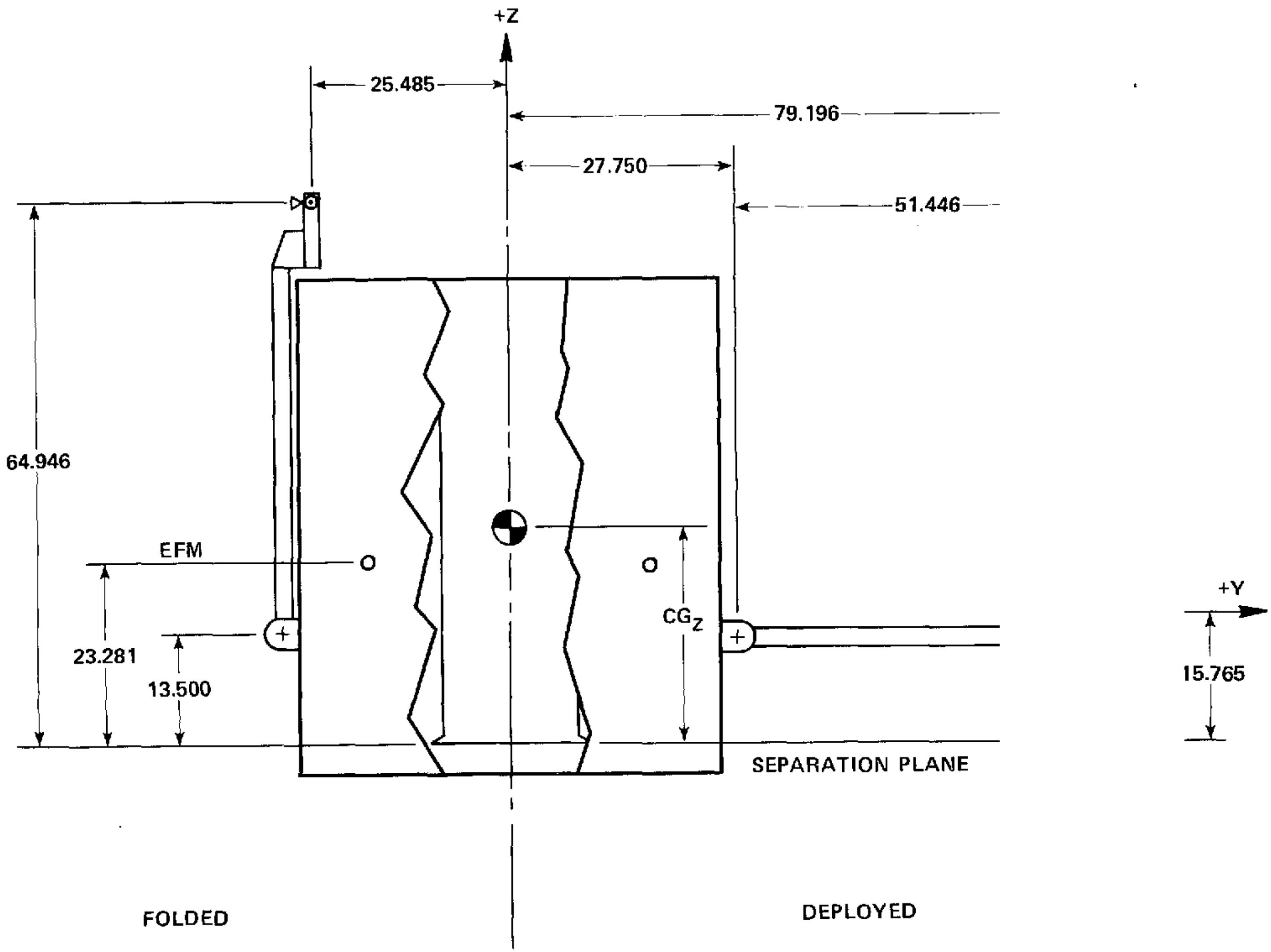


Figure 22. IMP-J ACS Reference Dimensions

Weight	625.5 lb
Center of gravity	21.44 inches above separation plane
Spin control moment arm	2.12 ft
Attitude control moment arm	3.63 ft

3. Preliminary Orbit Configuration

Booms	all deployed
Fourth stage	burned out
Spin axis MOI	126.53 sl-ft^2
Spin rate range	9.37 rpm to 68 rpm
Weight	625.1 lb
Center of Gravity	20.18 inches above separation plane
MOI ratio	1.216
Spin control moment arm	6.60 ft
Attitude control moment arm	6.60 ft

4. Final Orbit Configuration

Booms	all deployed
EFM antennas	extended to 200 ft
Spin axis MOI	521.01 sl-ft^2
Spin rate	23 rpm
Weight	625.1 lb
Center of gravity	20.18 inches above separation plane
Spin control moment arm	6.60 ft
Attitude control moment arm	6.60 ft

The above numbers represent the most recent prelaunch calculated values and may differ slightly from the actual post launch refined information. In any event, they are sufficiently accurate to describe the mission and were used to determine the various ACS performance parameters.

A weight breakdown of all the individual ACS components, including certain support and structural hardware, is presented in Table 11. Drawing numbers, part

Table 11

IMP-J ACS Weights

Components and Assemblies

Item (Ident No.)	Dwg or Part No.	Qty	lb Ea	lb Total
Tank (IC 2-04, IC 2-08)	GD 1063682	2	6.20	12.40
Temperature Probe (IC 8-26)	GD 1074085	1	0.06	0.06
Thermistor (IC 8-25)	GD 1074377	1	0.09	0.09
AN Union	400-6-4AN-316	2	0.07	0.14
Tube (IC 9-08)	GD 1064241	1	0.20	0.20
Tube (IC 9-07)	GD 1064242	1	0.24	0.24
Panel Assembly (IC 5-05)	GJ 1074455	1	3.52	3.52
Tube (IC 10-07)	GD 1064243	1	0.07	0.07
Tube (IC 10-08)	GD 1064244	1	0.09	0.09
Tube	GC 1064257	2	0.01	0.02
Union Elbow	A 400-9	4	0.03	0.12
Swivel Joint (IC 7-11, IC 7-12)	GD 1063874	2	0.03	0.06
Bulkhead Union	A 400-61	2	0.04	0.08
Tube (IC 6-13, IC 6-14)	GD 1074274	2	0.12	0.24
Valve-Nozzle Assy (IC 4-11)	GE 1074420-1	1	2.75	2.75
Valve-Nozzle Assy (IC 4-12)	GE 1074420-2	1	2.74	2.74
Diode Pack (IC 3-04, IC 3-11)	GD 1063822	2	0.21	0.42
	Total			23.24

Note: ACS Electronics Card, IC 1-12, not included in ACS weight.

Table 11 (cont'd.)

Support and Structural Hardware

Item	Dwg No.	Qty	lb Ea.	lb Total
Tank Support Bracket	GE 1063863	4	0.47	1.88
Tank Clamp	GC 1063783	4	0.03	0.12
Tank Retainer	GD 1064166	2	0.03	0.06
Tube Support Bracket	GC 1063832	8	0.015	0.12
Tube Clamp	GC 1063834	9	0.004	0.04
Tube Saddle	GC 1063833	9	0.006	0.05
Tank Thermal Blanket		2	0.03	0.06
Regulator Thermal Blanket		1	0.02	0.02
ACS Boom Assembly	GJ 1074421-1	1	1.90	1.90
ACS Boom Assembly	GJ 1074421-2	1	1.85	1.85
Connector Bracket	GC 1063928	2	0.01	0.02
Tube Clamp	GC 1064169	8	0.01	0.08
Dummy Connector		2	0.03	0.06
Micro Switch Assembly		2	0.03	0.06
Boom Standoff	GD 1074331	2	0.05	0.10
Boom Cable Segment,	+Y	1	0.17	0.17
Boom Cable Segment,	-Y	1	0.12	0.12
Mounting Bolts,	No. 6, 8, 10	108	0.004	0.40
Total				7.11
Components and Assemblies				23.24
ACS Propellant for IMP-J Mission				20.00
ACS Installation Total Weight				50.35 lb

numbers and Identification Control System numbers are also included for reference information. In addition, the center of gravity and moment of inertia calculations for the various ACS boom configurations are tabulated in Table 12.

However, this table does not take into account the 1.25 lb inertia weights added to each ACS boom following the spacecraft mass property measurements. Finally, the complete IMP-J ACS installation is documented on GSFC drawing No. GJ1074454.

In regards to balance, an analysis was made of the effect of a 4°C temperature differential between the two ACS tanks caused by the proximity of a high power dissipating device in a facet just above one of the tanks. With assuming that the pressure remained equal in both tanks and corresponded to the average temperature of 10°C, it was calculated that the cooler tank would contain as much as 1/2 lb more propellant than the warmer tank, with the system fully loaded. The dynamic unbalance resulting from this situation for IMP-J would produce a total cone angle of approximately 1-1/4 degrees and was determined from the relationship shown in Figure 23.

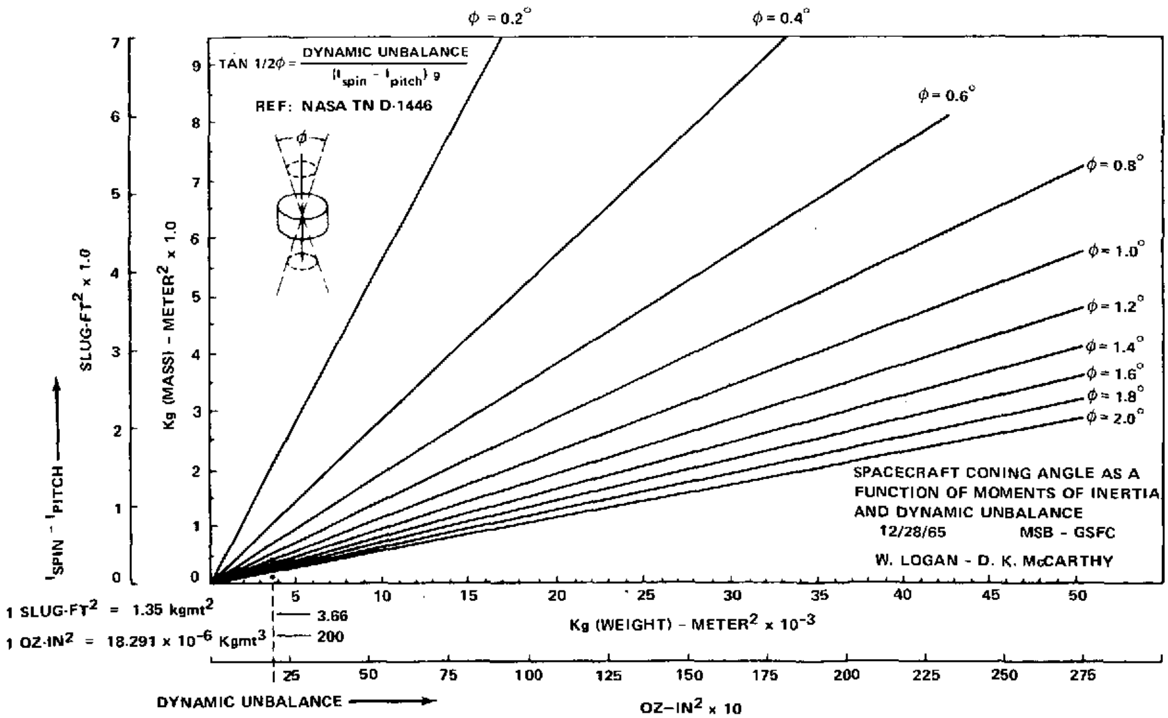


Figure 23. Cone Angle

Table 12

IMP-J ACS Boom Mass Properties

A) ACS Boom C.G. Data: (Notes 3 and 4)									
			Weight (lb.)	CG_X (in.)		CG_Y (in.)		CG_Z (in.)	
				1	2	1	2	1	2
DEPLOYED	(+Y) BOOM #1	Flight Boom	5.42	0.041	0.041	62.68	34.93	-5.536	1.064
		Spare Boom	4.97	0.045	0.045	61.49	33.74	-5.636	0.964
		Boom w/o valves	2.67	0.067	0.067	48.22	20.47	-6.718	-0.118
		Flight valves	2.75	0.015	0.015	76.72	48.97	-4.388	2.212
		Spare valves	2.30	0.020	0.020	76.90	49.15	-4.380	2.220
	(-Y) BOOM #2	Flight Boom	5.31	-0.043	-0.043	-62.15	-34.40	-5.490	1.110
		Spare Boom	4.86	-0.052	-0.052	-60.89	-33.14	-5.590	1.010
		Boom w/o valves	2.57	-0.078	-0.078	-46.61	-18.86	-6.644	-0.044
		Flight valves	2.74	-0.010	-0.010	-76.73	-48.98	-4.408	2.192
		Spare valves	2.29	-0.023	-0.023	-76.91	-49.16	-4.407	2.193
FOLDED	(+Y) BOOM #1	Flight Boom	5.42	0.050	0.050	26.57	-1.176	24.12	34.82
		Spare Boom	4.97	0.056	0.056	26.66	-1.086	23.08	33.78
		Boom w/o valves	2.67	0.087	0.087	27.64	-0.109	9.84	20.54
		Flight valves	2.75	0.015	0.015	25.54	-2.212	38.27	48.97
		Spare valves	2.30	0.020	0.020	25.53	-2.220	38.45	49.15
	(-Y) BOOM #2	Flight Boom	5.31	-0.043	-0.043	-26.53	1.222	23.35	34.05
		Spare Boom	4.86	-0.052	-0.052	-26.62	1.133	23.14	33.84
		Boom w/o valves	2.57	-0.078	-0.078	-27.56	0.189	9.49	20.19
		Flight valves	2.74	-0.010	-0.010	-25.56	2.192	38.28	48.98
		Spare valves	2.29	-0.023	-0.023	-25.56	2.193	38.46	49.16

Notes: All axes are parallel to respective S/C axes,

1) with respect to S/C spin axis and C.G.
2) with respect to ACS boom centerline and hinge axis.
3) Booms folded: in launch config. with full 4th stage.
4) Data is for booms without balance weights.

Table 12 (cont'd.)

B) ACS Boom MOI Data: (Notes 3 and 4)

g = 32.16 ft/sec^2			Mass (sl)	I_{XX} (sl-ft^2)		I_{YY} (sl-ft^2)		I_{ZZ} (sl-ft^2)	
				1	2	1	2	1	2
DEPLOYED	(+Y) BOOM #1	Flight Boom	0.1685	5.107	0.474	0.0392	0.0033	5.069	0.472
		Spare Boom	0.1545	4.546	0.455	0.0371	0.0030	4.511	0.454
		Boom w/o valves	0.0830	1.599	0.233	0.0267	0.0007	1.573	0.233
		Flight valves	0.0855	3.508	0.0014	0.0124	0.0010	3.497	0.0019
		Spare valves	0.0715	2.947	0.0012	0.0103	0.0008	2.937	0.0016
	(-Y) BOOM #2	Flight Boom	0.1651	4.935	0.472	0.0379	0.0033	4.898	0.469
		Spare Boom	0.1511	4.375	0.452	0.0358	0.0030	4.339	0.449
		Boom w/o valves	0.0799	1.439	0.209	0.0254	0.0009	1.413	0.208
		Flight valves	0.0852	3.496	0.0014	0.0125	0.0010	3.485	0.0019
		Spare valves	0.0712	2.936	0.0012	0.0104	0.0008	2.926	0.0016
FOLDED	(+Y) BOOM #1	Flight Boom	0.1685	1.977	0.470	1.150	0.469	0.830	0.0033
		Spare Boom	0.1545	1.785	0.451	1.022	0.450	0.766	0.0030
		Boom w/o valves	0.0830	0.726	0.230	0.286	0.230	0.441	0.0010
		Flight valves	0.0855	1.258	0.0014	0.872	0.0019	0.388	0.0010
		Spare valves	0.0715	1.059	0.0012	0.736	0.0016	0.324	0.0008
	(-Y) BOOM #2	Flight Boom	0.1651	1.897	0.465	1.085	0.460	0.810	0.0033
		Spare Boom	0.1511	1.752	0.447	1.008	0.446	0.746	0.0030
		Boom w/o valves	0.0799	0.696	0.225	0.271	0.221	0.423	0.0012
		Flight valves	0.0852	1.255	0.0014	0.869	0.0019	0.388	0.0010
		Spare valves	0.0712	1.056	0.0012	0.733	0.0016	0.324	0.0008

Notes: All axes are parallel to respective S/C axes,

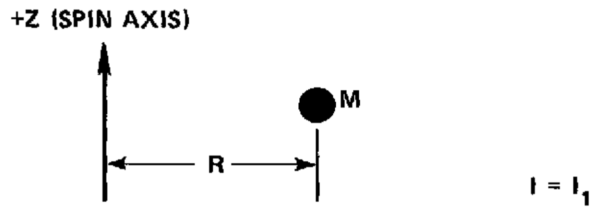
1) with respect to S/C spin axis and C.G.
2) with respect to component C.G.
3) Data is for booms without balance weights.
4) Booms folded: in launch config. with full 4th stage.

Section C — EFM Antenna Deployment

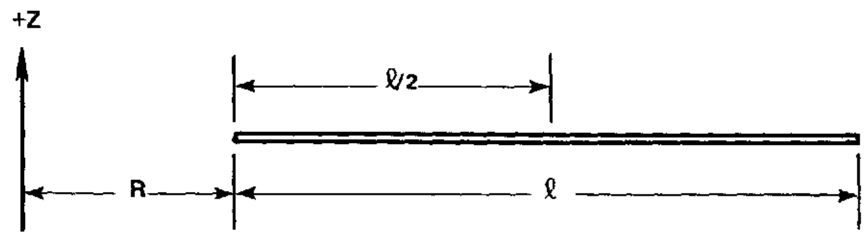
One of the scientific experiments carried onboard the IMP-J spacecraft required the use of an Electric Field Measurement (EFM) antenna. Unlike the tubular elements used on IMP-I, the IMP-J antennas were solid wire devices with insulation extending over a portion of the length. The experiment required four equally spaced elements, approximately 200 ft in length each, and deployed radially in a plane perpendicular to the spin axis as shown in Figure 24. During launch, the antennas were carried on reels and extended in pairs only after the spacecraft had been placed in its preliminary orbital configuration. Although the EFM antenna deployment had no significant effect on the spacecraft weight or center of gravity, it did produce a rather large change in spin axis moment of inertia and, due to conservation of angular momentum, the spin rate decreased accordingly. Consequently, one main function of the ACS was to maintain the required spin rate throughout the deployment sequence.

The EFM antenna deployment operation and the associated changes in moment of inertia were analyzed in the following manner.

Retracted:



Deployed:



where

ℓ	is the deployed length; one antenna (ft),
R	is the displacement from the spin axis (ft),
d	is the linear density (lb/ft),
I	is the total spacecraft moment of inertia about the Z axis (sl-ft^2),
I_1	is the measured moment of inertia with the EFM retracted (sl-ft^2),
$M = d\ell/g$	is the mass of deployed antenna (sl).

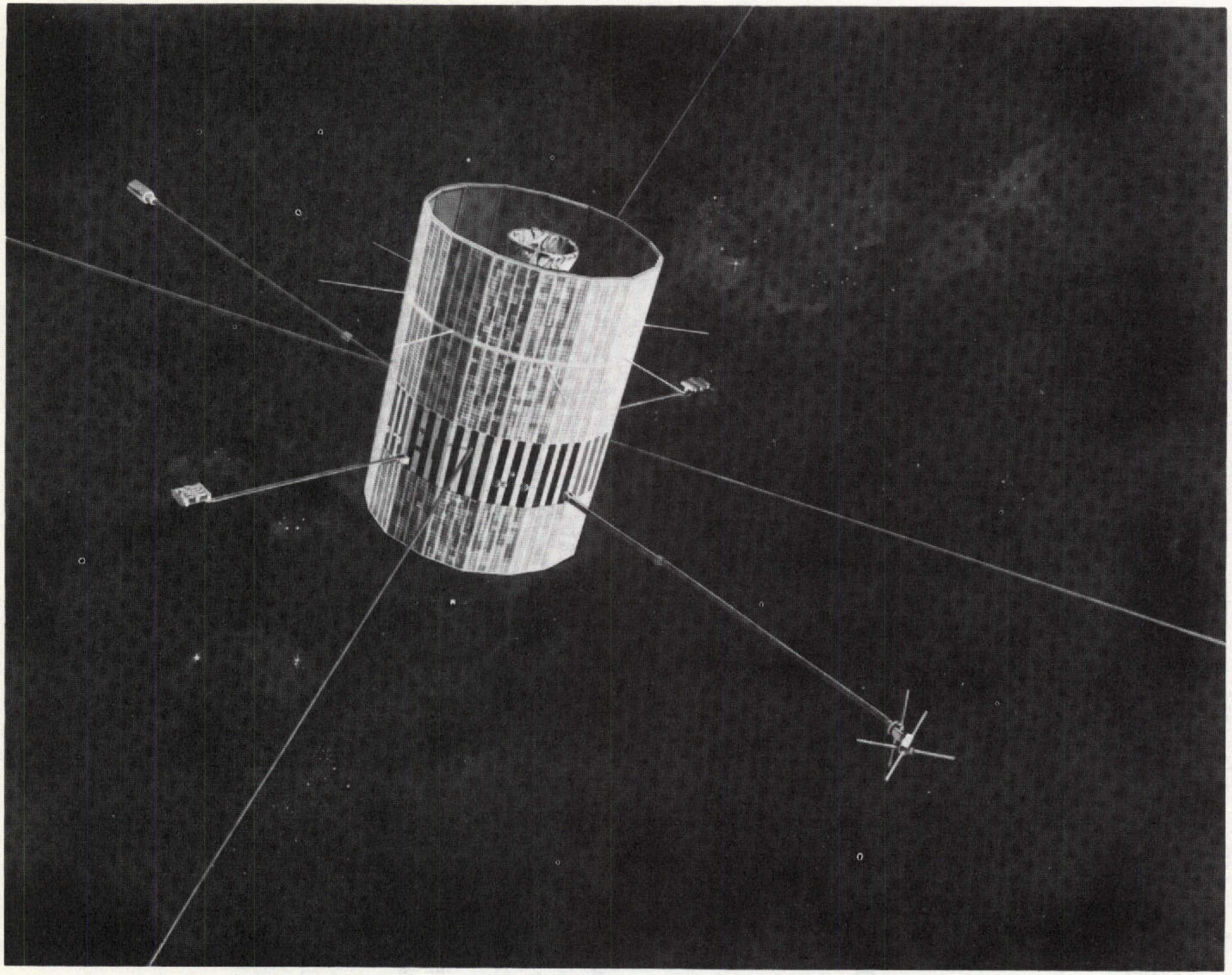


Figure 24. IMP-J Fully Deployed

At any point during the deployment sequence,

$$
\begin{aligned}
I &= I_1 - MR^2 + 1/12(M\ell^2) + M(R + \ell/2)^2 \\
&= I_1 - MR^2 + 1/12(M\ell^2) + MR^2 + MR\ell + 1/4(M\ell^2) \\
&= I_1 + 1/12(M\ell^2) + 1/4(M\ell^2) + MR\ell \\
&= I_1 + 1/3(M\ell^2) + MR\ell \\
&= I_1 + 1/3M\ell\ (\ell + 3R)
\end{aligned}
$$

Similarly, with a tip mass, m (sl),

$$
\begin{aligned}
I &= I_1 - mR^2 + m(\ell + R)^2 \\
&= I_1 - mR^2 + m\ell^2 + 2\ m\ell R + mR^2 \\
&= I_1 + m\ell\ (\ell + 2R)
\end{aligned}
$$

Finally, with 4 antennas, each with a tip mass,

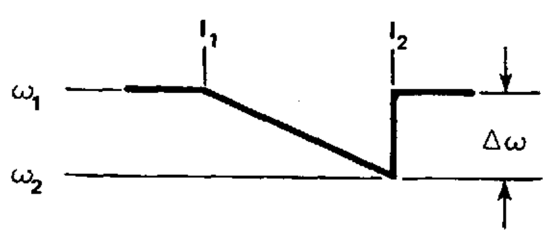
$$I = I_1 + 4d\ell^2/3g\ (\ell + 3R) + 4\ m\ell\ (\ell + 2R),$$

and the change in moment of inertia is,

$$\Delta I = 4\ [d\ell^2\ /3g\ (\ell + 3R) + m\ell\ (\ell + 2R)]\ .$$

As previously mentioned, an increase in moment of inertia results in a reduction in spin rate and, nominally, the spin rate following the EFM antenna deployment is desired to be the same as prior to the deployment operation so that the $\Delta\omega$ increment added by the ACS is exactly equal to the $\Delta\omega$ lost due to the extension of the EFM antennas. In practice, there are two ways of accomplishing this; the $\Delta\omega$ can be added by a spin-up maneuver just prior to the deployment operation, or it can be added at some time immediately following the deployment. In either case, the amount of propellant consumed and the total impulse added will be the same, but the actual $\Delta\omega$ will be different due to the difference in moment of inertia. The angular velocity changes were analyzed as follows.

(1) With spin-up following deployment:



$\Delta\omega = \omega_1 - \omega_2$ or $\omega_2 = \omega_1 - \Delta\omega$
and $\Delta I = I_2 - I_1$

$$
\begin{aligned}
I_1\omega_1 &= I_2\omega_2\\
I_1\omega_1 &= I_2(\omega_1 - \Delta\omega)\\
I_1\omega_1 &= I_2\omega_1 - I_2\Delta\omega\\
I_2\Delta\omega &= \omega_1(I_2 - I_1)\\
I_2\Delta\omega &= \omega_1\Delta I
\end{aligned}
$$

and $\Delta\omega = (\omega_1/I_2)\Delta I$ due to deployment beginning at ω_1.

But for the ACS at $I = I_2$,

$$\Delta\omega = \left(\frac{60}{2\pi}\right)\left(\frac{I_{SP}L}{I_2}\right)\Delta W,$$

so that

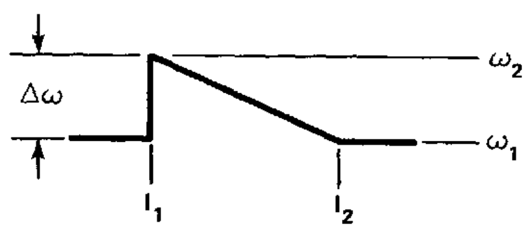
$$\left(\frac{\omega_1}{I_2}\right)\Delta I = \left(\frac{60}{2\pi}\right)\left(\frac{I_{SP}L}{I_2}\right)\Delta W$$

and

$$\Delta W = \left(\frac{2\pi}{60}\right)\left(\frac{\omega_1\Delta I}{I_{SP}L}\right),$$

where ΔW is the amount of propellant required to maintain the ω_1 spin rate through an inertia change of ΔI.

(2) With spin-up prior to deployment:



$\Delta\omega = \omega_2 - \omega_1$ or $\omega_2 = \omega_1 + \Delta\omega$
and $\Delta I = I_2 - I_1$

$$
\begin{aligned}
I_2\omega_1 &= I_1\omega_2\\
I_2\omega_1 &= I_1(\omega_1 + \Delta\omega)\\
I_2\omega_1 &= I_1\omega_1 + I_1\Delta\omega\\
I_1\Delta\omega &= \omega_1(I_2 - I_1)\\
I_1\Delta\omega &= \omega_1\Delta I
\end{aligned}
$$

and $\Delta\omega = (\omega_1/I_1)\Delta I$ due to deployment beginning at ω_2.

But for the ACS at $I = I_1$,

$$\Delta\omega = \left(\frac{60}{2\pi}\right)\left(\frac{I_{SP} L}{I_1}\right)\Delta W\,,$$

so that

$$\left(\frac{\omega_1}{I_1}\right)\Delta I = \left(\frac{60}{2\pi}\right)\left(\frac{I_{SP} L}{I_1}\right)\Delta W$$

and

$$\Delta W = \left(\frac{2\pi}{60}\right)\left(\frac{\omega_1 \Delta I}{I_{SP} L}\right),$$

where ΔW is the amount of propellant required to maintain the ω_1 spin rate through an inertia change of ΔI. It should be noted that for this case only,

$$\omega_2 = \left(\frac{I_2}{I_1}\right)\omega_1\,.$$

The following basic information for the EFM antennas was provided.

Measured length:

S/N 11 in facet 2	197 ft
S/N 12 in facet 6	196-1/2 ft
S/N 13 in facet 10	198 ft
S/N 14 in facet 14	195-1/2 ft

The average length of 197 ft was used for calculations.

Linear density: (1 lb = 453.6 grams)

wire element, 197 ft	0.4244 gm/ft
insulation, inner 150 ft	0.1755 gm/ft

Tip mass	3 gm each
Coating, insulation	FEP, black teflon
Wire material	305 stainless steel
Deployment rate	0.14 ft/sec

In calculating the change in moment of inertia, a displacement of 2 ft was used with the following results.

Full deployment, 197 ft: ($g = 32.16$ ft/sec^2)

$$I = 126.53 + 4\left[\frac{0.4244(197)^2(203)}{453.6(3)32.16} + \frac{0.1755(150)^2(156)}{453.6(3)32.16} + \frac{3(197)(201)}{453.6(32.16)}\right]$$

$$I = 126.53 + 4\left[76.40 + 14.08 + 8.14\right]$$

$$= 126.53 + 4(98.62)$$

$$= 126.53 + 394.48 = \underline{521.01 \text{ sl-ft}^2}$$

or $\underline{\Delta I = 394.48 \text{ sl-ft}^2}$

and at 23 rpm, $\underline{\Delta W = 3.28 \text{ lb.}}$

Since there was an advantage to performing the ACS spin-up prior to deployment in that perturbations to the delicate wire antennas would be minimized, it was calculated that a spin-up from 23 rpm to 94.71 rpm would be required for the entire 197 ft extension. However, it was later decided that scientific measurements would benefit from a two stage deployment and the following procedure was prepared.

(1) Initial stage of EFM antenna deployment:

Achieve X antenna pair deployed to 120 ft and Y antenna pair deployed to 200 ft (197 ft).

The incremental moment of inertia calculations were performed as follows.

$$A = \frac{0.4244}{453.6(3)32.16} = 9.69762 \times 10^{-6}$$

$$B = \frac{0.1755}{453.6(3)32.16} = 4.0102 \times 10^{-6}$$

$$C = \frac{3}{453.6(32.16)} = 205.6516 \times 10^{-6}$$

40 ft pair: $2A[(40)^2(46)] = 1.43$

$2B[(0)^2(0)] = 0.00$

$2C[(40)(44)] = 0.72$ $\underline{2.15 \text{ sl-ft}^2}$ total

80 ft pair: $2A[(80)^2(86)] = 10.68$

$2B[(33)^2(39)] = 0.34$

$2C[(80)(84)] = 2.76$ $\underline{13.78 \text{ sl-ft}^2}$ total

120 ft pair: $2A[(120)^2(126)] = 35.19$

$2B[(73)^2(79)] = 3.38$

$2C[(120)(124)] = 6.12$ $\underline{44.69 \text{ sl-ft}^2}$ total

160 ft pair: $2A[(160)^2(166)] = 82.42$

$2B[(113)^2(119)] = 12.19$

$2C[(160)(164)] = 10.79$ $\underline{105.40 \text{ sl-ft}^2}$ total

197 ft pair: $2A[(197)^2(203)] = 152.80$

$2B[(150)^2(156)] = 28.15$

$2C[(197)(201)] = 16.29$ $\underline{197.24 \text{ sl-ft}^2}$ total

From this information, the final spacecraft total moment of inertia was calculated to be 368.46 sl-ft^2 and it was further determined that a spin-up to 66.98 rpm was required prior to the operation. Finally, the actual deployment sequence was planned according to Table 13.

(2) Final stage of EFM antenna deployment:

Achieve all four antennas deployed to 200 ft (197 ft).

This maneuver was planned to begin with a spin-up to 32.52 rpm, followed by a two step deployment sequence which is also shown in Table 13.

Table 13

EFM Antenna Deployment Sequence

1. Initial Stage: ACS Spin-up to 66.98 rpm			
X Antenna Pair (ft)	Y Antenna Pair (ft)	Iz (sl-ft^2)	ω (rpm)
0	0	126.53	66.98
40	0	128.68	65.86
40	40	130.83	64.78
80	40	142.46	59.49
80	80	154.09	55.00
120	80	185.00	45.81
120	120	215.91	39.25
120	160	276.62	30.64
120	197	368.46	23.00
2. Final Stage: ACS Spin-up to 32.52 rpm			
X Antenna Pair (ft)	Y Antenna Pair (ft)	Iz (sl-ft^2)	ω (rpm)
120	197	368.46	32.52
160	197	429.17	27.92
197	197	521.01	23.00

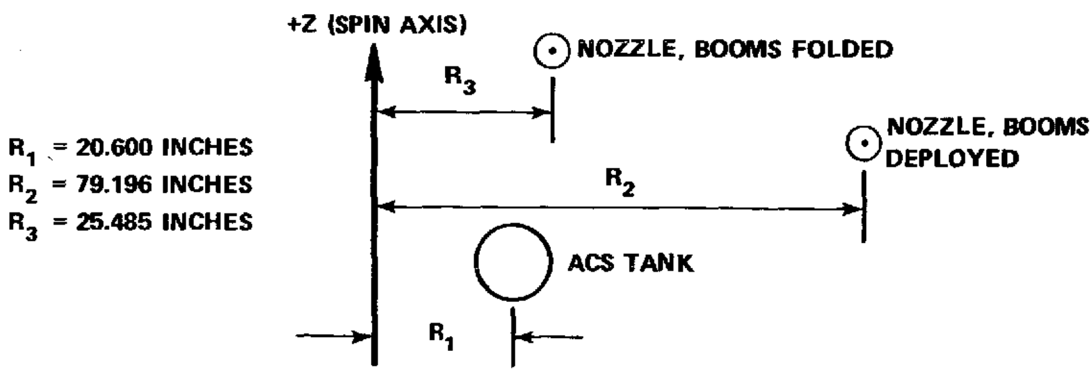
One other important aspect of the EFM antenna operation was the tensil load experienced by the antennas during deployment. A detailed investigation revealed that, for the deployment schemes described above, the peak tension would occur at the point where the moment of inertia had reached a value equal to 1-1/2 times the initial value. At this point, the maximum tension was calculated by,

$$T_{max} = 0.29119\, \omega_o^2 \sqrt[3]{\frac{\rho l_o^2}{16}}.$$

Using an average wire density of $\rho = 0.556$ gm/ft, the tension is 0.687 lb for the initial stage and 0.681 lb for the final stage.

Section D — Gas Motion Despin

A spinning spacecraft must experience a change in spin rate due to any translation of mass in a radial direction. This effect is the result of the Coriolis force and also applies to the small quantities of propellant transferred from the ACS tanks to the thruster nozzles during any operation of the system. In this case the mass flow is in a direction of increasing radius so that a decrease in spin rate is produced. For the IMP-J, this situation was analyzed from a static standpoint where only initial and final conditions were considered along with small changes in moment of inertia. Inasmuch as the displacement of a quantity of propellant from the tanks to the nozzles causes a corresponding spin rate change, the spacecraft moment of inertia does not increase because the propellant is expelled upon reaching the nozzles. There is, of course, a small decrease in moment of inertia due to the loss of propellant, and this has been neglected in the overall calculations. Actually, the contribution of this mass is less than 1% of the total and the resulting performance error is also about 1%. A further simplification assumed there was no cumulative effect and that the ACS maneuvers were performed with the spacecraft in a configuration as originally calculated. It should be noted that the actual amount of despin is proportional to the spin rate and that the analysis was done per pound of propellant consumed, and in the following manner.



Moment of inertia of one pound of propellant located at each radius:

$$Ip_1 = \frac{1}{32.16}\left(\frac{20.600}{12}\right)^2 = 0.092 \text{ sl-ft}^2$$

$$Ip_2 = \frac{1}{32.16}\left(\frac{79.196}{12}\right)^2 = 1.354 \text{ sl-ft}^2$$

$$Ip_3 = \frac{1}{32.16}\left(\frac{25.485}{12}\right)^2 = 0.140 \text{ sl-ft}^2$$

From the conservation of angular momentum:

$$I_1\omega_1 = I_2\omega_2 \quad \text{or} \quad \omega_2 = I_1\omega_1/I_2$$

where $I_2 = I_1 - Ip_1 + Ip_{2,3} = I_1 + \Delta I$

so that $\omega_2 = \dfrac{I_1\omega_1}{I_1 + \Delta I}$

The amount of despin (rpm) is given by $\Delta\omega_D = \omega_1 - \omega_2$ per pound of propellant.

Some representative calculations of $\Delta\omega_D$ are presented below.

(1) Launch Configuration: $\omega_1 = 46$ rpm, $I_1 = 67.77$ sl-ft^2

$$\omega_2 = \frac{67.77}{67.82}(46) = 45.966 \text{ and } \underline{\Delta\omega_D = 0.034 \text{ rpm/lb}}$$

(2) Intermediate Configuration: $\omega_1 = 48$ rpm, $I = 65.88$ sl-ft^2

$$\omega_2 = \frac{65.88}{65.93}(48) = 47.964 \text{ and } \underline{\Delta\omega_D = 0.036 \text{ rpm/lb}}$$

(3) Preliminary Orbit Configuration: $\omega_1 = 23$ rpm, $I_1 = 126.53$ sl-ft^2

$$\omega_2 = \frac{126.53}{127.79}(23) = 22.773 \text{ and } \underline{\Delta\omega_D = 0.227 \text{ rpm/lb}}$$

(4) Final Orbit Configuration: $\omega_1 = 23$ rpm, $I_1 = 521.01$ sl-ft^2

$$\omega_2 = \frac{521.01}{522.27}(23) = 22.945 \text{ and } \underline{\Delta\omega_D = 0.055 \text{ rpm/lb}}$$

In addition, Figure 25 shows the $\Delta\omega_D$ as a function of spin rate.

In actual application, the amount of gas motion despin is also a function of time or flow rate, and appropriate adjustments must be made for each of the three types of ACS maneuvers. Specifically, the spin-up performance will be retarded and the despin performance will be enhanced, whereas the precession will be negligibly affected, as can be seen from the following.

(1) Spin-up: $\Delta\omega = (60/2\pi)\ (IspL/I)\Delta W\ = C(\Delta W)$ where C is in terms of rpm/lb.

However, $\Delta\omega$ is reduced by the amount of $\Delta\omega_D$, so that $\Delta\omega = (C - \Delta\omega_D)\Delta W$

and $\underline{\Delta W = \Delta\omega/(C - \Delta\omega_D)}$

(2) Despin: $\Delta\omega = (60/2\pi)\ (IspL/I)\Delta W\ = C(\Delta W)$; in this case, $\Delta\omega_D$ aids in the despin, so that $\Delta\omega = (C + \Delta\omega_D)\ \Delta W$

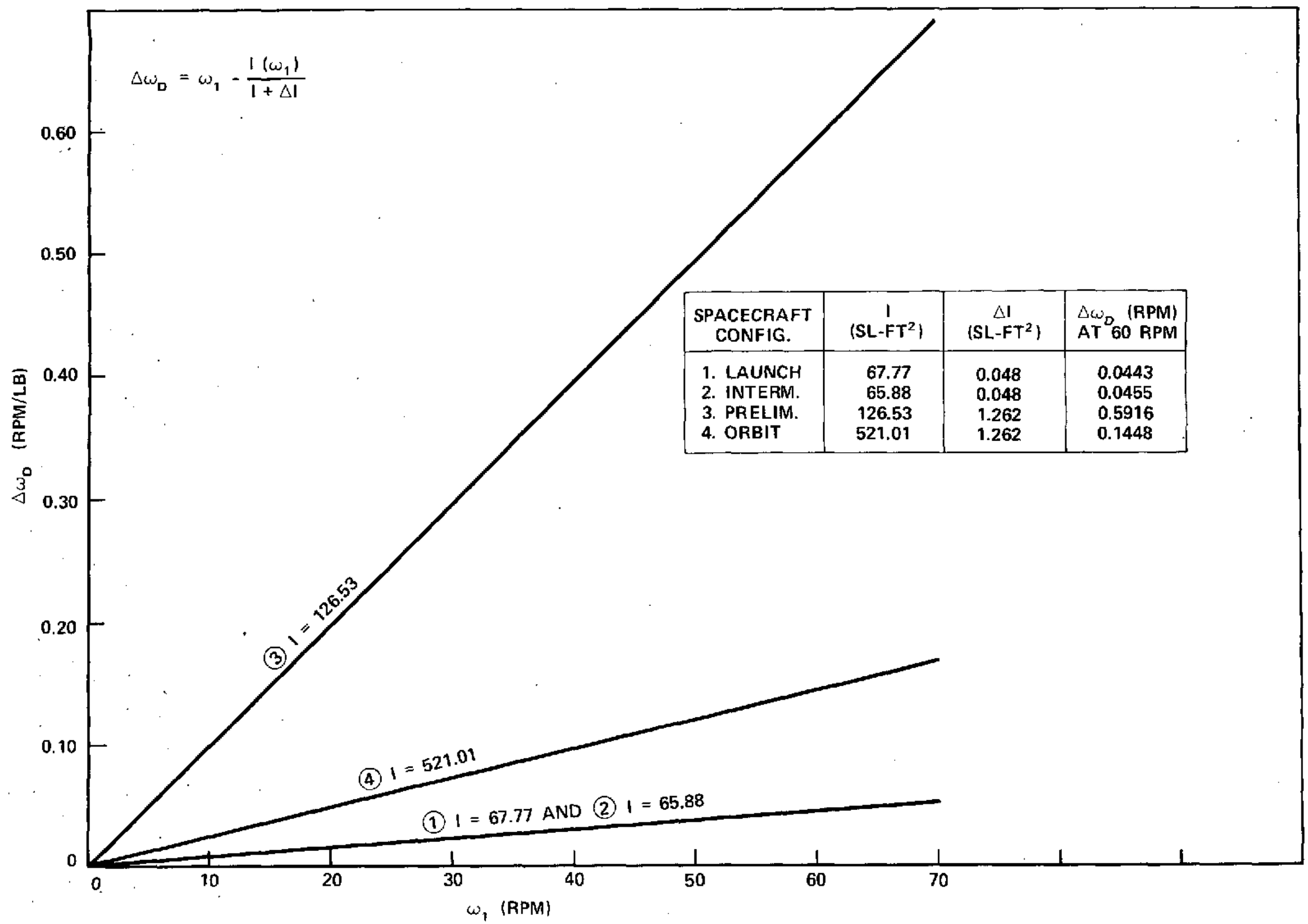
and $\underline{\Delta W = \Delta\omega/(C + \Delta\omega_D)}$

(3) Reorientation: $\Delta\omega = (\pi/180)\ (2\pi/60)\ (I\omega/IspL)\ \Delta\theta = F(\Delta\theta)$ where F is in terms of lb/deg.

Then F $(\Delta\omega_D)$ is rpm/deg or the decrease in spin rate per degree of attitude change.

In all cases, $\Delta\omega_D$ must be determined for each particular spacecraft configuration, taking into account the moment of inertia and spin rate. In the above analysis, ΔW is the amount of propellant required to accomplish the desired changes, either $\Delta\omega$ or $\Delta\theta$.

Table 14 is a tabulation of the various IMP-J spacecraft configurations, including all significant spin rates, and shows the gas motion despin characteristic and its affect on other ACS parameters. Also, Figure 26 shows the variation in the C parameter for both spin-up and despin commands. In this case, the configurations with ACS booms folded have been omitted because the effect is small. It should be noted that since the gas motion despin is a linear function of rpm, both the spin-up and despin performance must be calculated for the average spacecraft spin rate during the particular anticipated maneuver. However, for small spin rate changes involving one full command or less, the use of the value for the initial rpm is sufficiently accurate. In practice, these calculations are used primarily for estimating or predicting the ACS performance, and in the execution of any particular maneuver, partial commands are used to provide a precise trim for either spin rate changes or reorientation in order to remove any accumulated errors.



SPACECRAFT CONFIG.	I ($SL\text{-}FT^2$)	ΔI ($SL\text{-}FT^2$)	$\Delta\omega_D$ (RPM) AT 60 RPM
1. LAUNCH	67.77	0.048	0.0443
2. INTERM.	65.88	0.048	0.0455
3. PRELIM.	126.53	1.262	0.5916
4. ORBIT	521.01	1.262	0.1448

Figure 25. Gas Motion Despin

Table 14

Gas Motion Despin

Item	Configuration							
	1	2		3				4
I (sl-ft^2)	67.77	65.88		126.53				521.01
ΔI (sl-ft^2)	0.048	0.048		1.262				1.262
Ratio $I_1/(I_1 + \Delta I)$	0.9993	0.9992		0.9901				0.9976
C (rpm/lb)	13.466	13.853		22.414				5.444
$\Delta\omega_D$ at 60 rpm	0.0443	0.0455		0.5916				0.1448
ω_1 (rpm)	46	48	18	9.37	14	23	67	23
$\Delta\omega_D$ (rpm/lb)	0.034	0.036	0.014	0.092	0.138	0.227	0.662	0.055
(rpm/sec)	0.0001	0.0001	0.00004	0.0003	0.0004	0.0007	0.0020	0.0002
(rpm/CMD) (S) or (D)	0.0073	0.0078	0.0030	0.0199	0.0299	0.0490	0.1429	0.0119
(rpm/CMD) (orient)	0.00007	0.00007	0.00007	0.0009	0.0009	0.0009	0.0009	0.0002
C - $\Delta\omega_D$ (S)	13.432	13.817	13.839	22.322	22.276	22.187	21.752	5.389
C + $\Delta\omega_D$ (D)	13.500	13.889	13.867	22.506	22.552	22.641	23.076	5.499
F (lb/deg)	0.0373	0.0354	0.0133	0.0073	0.0109	0.0179	0.0522	0.0737
F ($\Delta\omega_D$) (rpm/deg)	0.00127	0.00128	0.00019	0.00067	0.00150	0.00406	0.03454	0.00406

(S) = Spin-Up
(D) = Despin

Based on flow rate of $\dot{w}$ = 0.003 lb/sec and 0.216 lb/CMD.

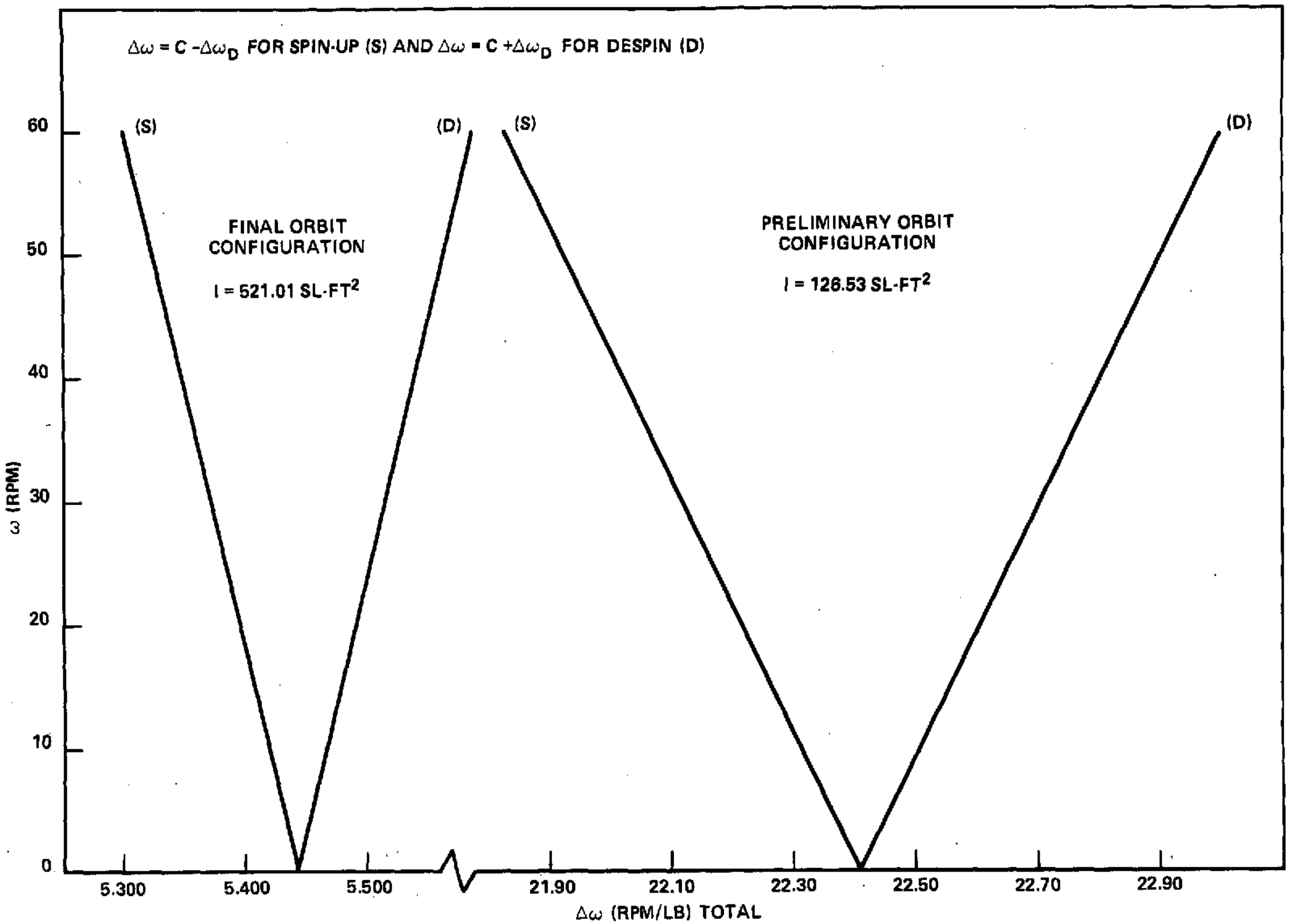


Figure 26. Variation in ACS Parameters

Section E — ACS Performance

The ACS performance calculations for the IMP-J utilized the basic equations developed in Part I, which were then modified to incorporate the gas motion despin characteristic. Consequently, it was necessary to consider the spin-up maneuver separately from the despin maneuver, and involved the following relationships.

$\Delta W = \Delta\omega/(C - \Delta\omega_D)$ for spin-up, $\Delta W = \Delta\omega/(C + \Delta\omega_D)$ for despin,
where $C = (60/2\pi)\ (\mathrm{IspL/I})$.

For reorientation, the amount of precession was essentially unaffected by the gas motion despin, since the decrease in angular momentum was negligibly small for most maneuvers. However, the actual amount of despin was included in the tabulation for the purpose of applying a spin rate correction following any large reorientation maneuver. For attitude changes, the performance equation was as follows.

$$\Delta W = (2\pi/60)\ (\pi/180)\ (I\,\omega/\mathrm{IspL})\ \Delta\theta = F\ (\Delta\theta).$$

In addition, a total system flow rate of 0.003 lb/sec was used for the IMP-J performance and was based upon a detailed analysis of both the IMP-H actual performance in orbit and the test history data for the IMP-J flight ACS components. This, together with an average measured command duration of 72 sec for spin-up and despin commands, resulted in a propellant consumption rate of 0.216 lb/CMD. The above total flow rate was also applied to the reorientation commands as well, but the consumption rate and command duration both varied according to the spin rate.

As mentioned in the previous section, the gas motion despin characteristic is a function of spin rate and consequently, any spin change maneuver would experience a variation in the performance parameters throughout the duration of the particular maneuver. However, the relationship is linear and the effective parametric value of $(C \pm\Delta\omega_D)$ can be determined, for each individual maneuver, by using the value corresponding to the average spacecraft spin rate during the maneuver. Simple interpolation between the given values can be used for determining the average effective value, or it may be obtained, for the average spin rate, from Figure 25 or Figure 26. This has been done in the case of the first despin maneuver for IMP-J and is shown in the tables.

The calculated spin-up performance parameters have been compiled in Table 15 and the related propellant consumption is shown in Figure 27. The corresponding despin parameters are presented in Table 16 and Figure 28. Similarly, the calculated reorientation performance is shown in Table 17 and Figure 29.

Table 15

IMP-J Spin-up

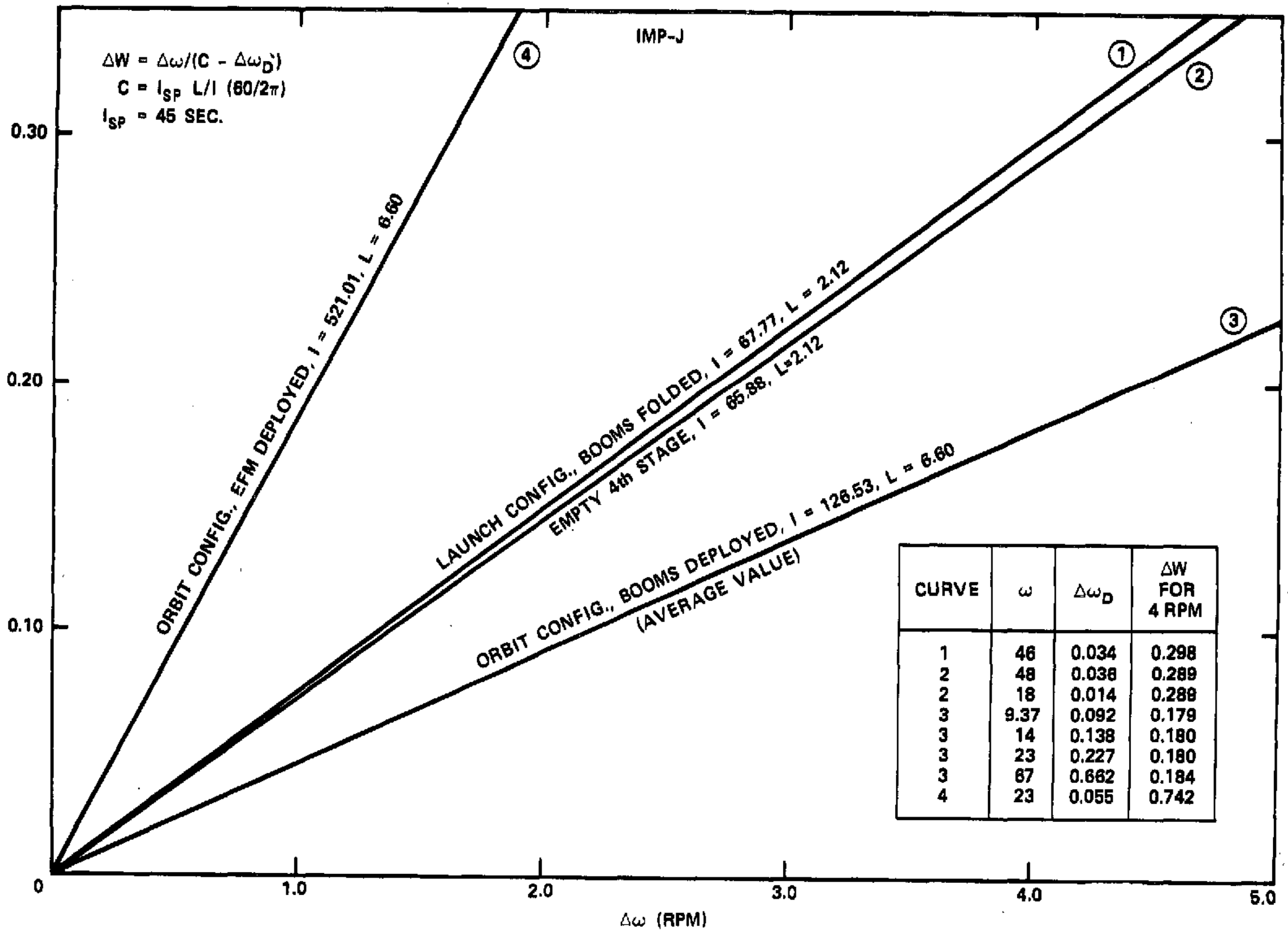
Parameter	Configuration			
	1 Launch	2 Intermed.	3 Prelim.	4 Orbit
I (sl-ft^2)	67.77	65.88	126.53	521.01
ω (rpm)	46	33*	23	23
Moment Arm (ft)	2.12	2.12	6.60	6.60
Torque (ft-lb)	0.276	0.276	0.858	0.858
C-$\Delta\omega_D$ (rpm/lb)	13.432	13.828	22.187	5.389
(lb/rpm)	0.0744	0.0723	0.0451	0.1856
Change (rpm/CMD)	2.901	2.987	4.792	1.164
Change (rpm/sec)	0.0403	0.0415	0.0666	0.0162
(CMD/rpm)	0.345	0.335	0.209	0.859
(sec/rpm)	24.81	24.10	15.02	61.85
Change ($\Delta I\omega$/CMD)	196.6	196.8	606.3	606.5
Change ($\Delta I\omega$/sec)	2.731	2.734	8.421	8.423
Change ($\Delta I\omega$/lb)	910.3	911.0	2807.3	2807.7

*Average Nominal Spin Rate Between 48 and 18 rpm.

Also Command Duration: 72 sec

Flow Rate: 0.003 lb/sec

Consumption: 0.216 lb/CMD



CURVE	ω	$\Delta\omega_D$	ΔW FOR 4 RPM
1	46	0.034	0.298
2	48	0.036	0.289
2	18	0.014	0.289
3	9.37	0.092	0.179
3	14	0.138	0.180
3	23	0.227	0.180
3	67	0.662	0.184
4	23	0.055	0.742

Figure 27. Propellant Required for Spin-up

Table 16

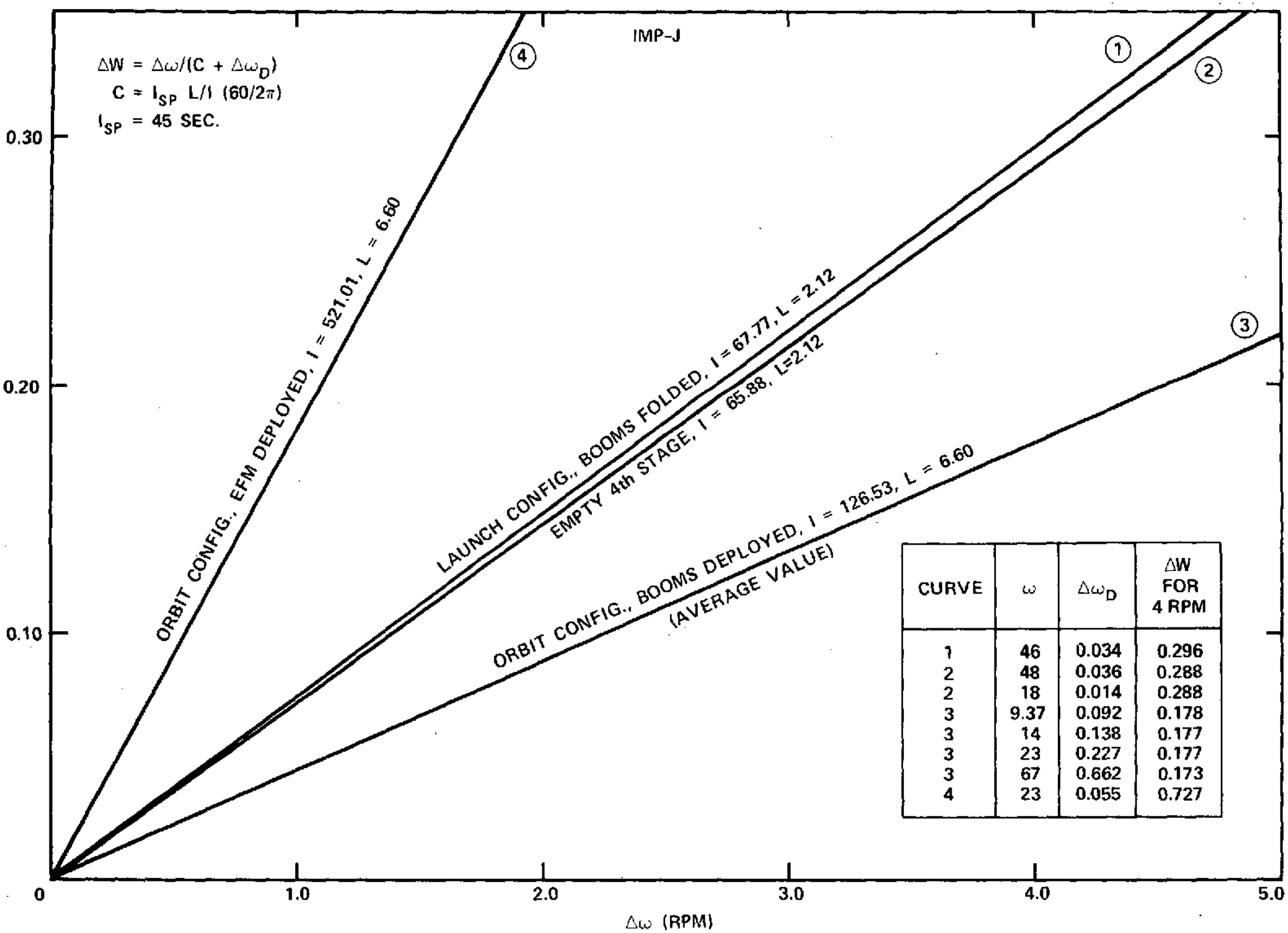
IMP-J Despin

Parameter	Configuration			
	1 Launch	2 Intermed.	3 Prelim.	4 Orbit
I (sl-ft^2)	67.77	65.88	126.53	521.01
ω (rpm)	46	33*	23	23
Moment Arm (ft)	2.12	2.12	6.60	6.60
Torque (ft-lb)	0.276	0.276	0.858	0.858
C + $\Delta\omega_D$ (rpm/lb)	13.500	13.878	22.641	5.499
(lb/rpm)	0.0741	0.0721	0.0442	0.1819
Change (rpm/CMD)	2.916	2.998	4.890	1.188
Change (rpm/sec)	0.0405	0.0416	0.0679	0.0165
(CMD/rpm)	0.343	0.334	0.204	0.842
(sec/rpm)	24.69	24.02	14.72	60.62
Change ($\Delta I\omega$/CMD)	197.6	197.5	618.8	618.8
Change ($\Delta I\omega$/sec)	2.745	2.743	8.594	8.595
Change ($\Delta I\omega$/lb)	914.9	914.3	2864.8	2865.0

*Average Nominal Spin Rate Between 48 and 18 rpm.

Also

Command Duration: 72 sec
Flow Rate: 0.003 lb/sec
Consumption: 0.216 lb/CMD



CURVE	ω	$\Delta\omega_D$	ΔW FOR 4 RPM
1	46	0.034	0.296
2	48	0.036	0.288
2	18	0.014	0.288
3	9.37	0.092	0.178
3	14	0.138	0.177
3	23	0.227	0.177
3	67	0.662	0.173
4	23	0.055	0.727

Figure 28. Propellant Required for Despin

Table 17

IMP-J Reorientation

Parameter	Configuration							
	1	2		3				4
I (sl-ft^2)	67.77	65.88		126.53				521.01
Moment Arm (ft)	3.39	3.63		6.60				6.60
Torque (ft-lb)	0.441	0.472		0.858				0.858
ω (rpm)	46	48	18	9.37	14	23	67	23
Iω (sl-ft^2-rpm)	3117.4	3162.2	1185.8	1185.6	1771.4	2910.2	8477.5	11983
Spin Period (sec)	1.304	1.250	3.333	6.403	4.286	2.609	0.896	2.609
Pulse Time (sec)	0.0815	0.0781	0.2083	0.4002	0.2679	0.1630	0.0560	0.1630
F Factor (lb/deg)	0.0373	0.0354	0.0133	0.0073	0.0109	0.0179	0.0522	0.0737
1/F (deg/lb)	26.774	28.263	75.368	137.06	91.734	55.838	19.168	13.561
Change (rad/lb)	0.467	0.493	1.315	2.392	1.601	0.975	0.335	0.237
(lb/rad)	2.140	2.027	0.760	0.418	0.625	1.026	2.989	4.225
Change (rad/CMD)	0.0009	0.0009	0.0066	0.0230	0.0103	0.0038	0.0009	0.0009
(CMD/rad)	1095.3	1082.3	152.1	43.5	97.2	262.3	1112.6	1081.1
Change (deg/CMD)	0.0524	0.0530	0.3768	1.3164	0.5896	0.2184	0.0515	0.0530
(CMD/deg)	19.08	18.87	2.65	0.76	1.70	4.58	19.42	18.85
Change (deg/pulse)	0.0065	0.0066	0.0471	0.1646	0.0737	0.0273	0.0032	0.0066
(pulses/deg)	152.8	151.0	21.23	6.08	13.57	36.62	310.7	150.8
Flow (lb/CMD)	0.0020	0.0019	0.0050	0.0096	0.0064	0.0039	0.0027	0.0039
Flow (lb/pulse)	0.0002	0.0002	0.0006	0.0012	0.0008	0.0005	0.0002	0.0005
Ave. Rate (deg/sec)	0.0050	0.0053	0.0141	0.0257	0.0172	0.0105	0.0036	0.0025
Rate at $\dot{W}$ (deg/sec)	0.0803	0.0848	0.2261	0.4112	0.2752	0.1675	0.0575	0.0407
Total Time (sec/deg)	199.3	188.7	70.8	38.9	58.1	95.5	278.2	393.4
F($\Delta\omega_D$) (rpm/deg)	0.00127	0.00128	0.00019	0.00067	0.00150	0.00406	0.03454	0.00406
K_C	1.179	1.186	1.075	1.040	1.059	1.095	1.246	1.095
K_G	1.0025	1.0026	1.0010	1.0041	1.0062	1.0102	1.0304	1.0102

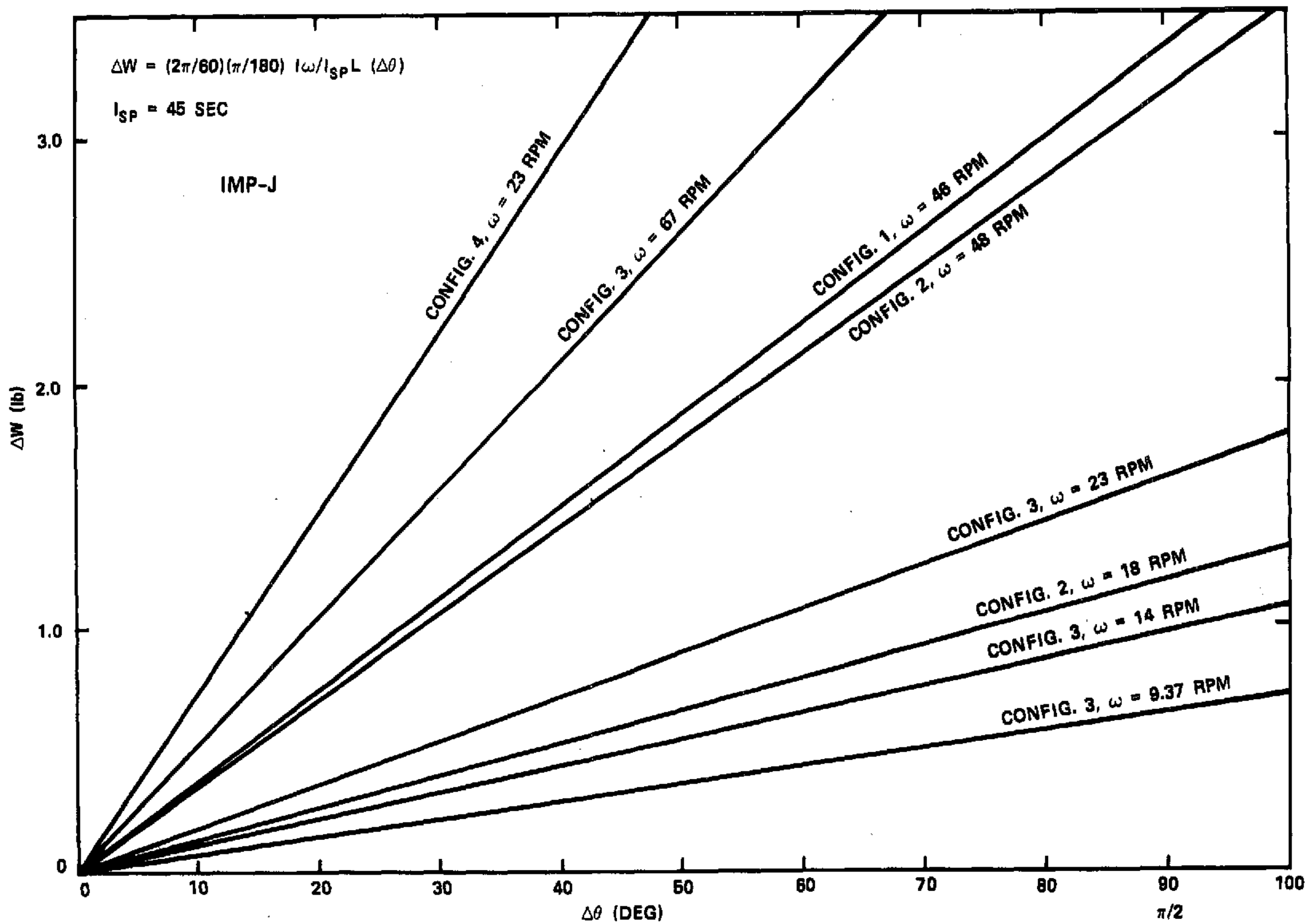


Figure 29. Propellant Required for Reorientation

Further calculations were made to determine the combined effect of both gas motion despin and the characteristic delay examined in Part II. Since the gas motion despin had already been incorporated into the spin-up and despin parameters, only its affect on attitude changes was considered. Similarly, the characteristic delay also only affected the attitude change maneuvers, and both were functions of spin rate. A simple treatment was devised in which correction factors, K_c for the characteristic delay and K_g for the gas motion despin, were calculated and could be used to determine the increase in propellant consumption resulting from the above characteristics. It was presumed that any particular attitude change required in a cardinal direction would be followed by an appropriate attitude correction to remove the delay error and also a spin-up maneuver to recover the despin due to propellant motion during the reorientation. Only first order effects were considered. The net effect was an increase in the propellant requirements, and the correction factors used to account for this were calculated in the following manner.

$$K_C = \frac{1 + \cot \epsilon}{\csc \epsilon} = \sin \epsilon + \cos \epsilon$$

and

$$K_G = 1 + \frac{\Delta\omega_D}{(C - \Delta\omega_D)_{SPIN\text{-}UP}}$$

These values have been included in the list of reorientation performance parameters in Table 17.

In practice, the specific correction factors were selected for the particular spin rate and multiplied by the other spacecraft characteristics as well as the desired amount of attitude change, in order to determine the total propellant required for the maneuver. Since the spacecraft moment of inertia, spin rate, thrust moment arm and propellant specific impulse had all been combined into the F values, the propellant consumption equation simply reduces to,

$$\Delta W = K_C\, K_G\, F(\Delta\theta)$$

and includes all maneuvers required to accomplish an attitude change of $\Delta\theta$ in a cardinal direction. However, it is possible that a complex attitude change would be desired involving components in two of the cardinal directions. In this case, the characteristic delay may actually aid in the maneuver and consequently reduce the propellant requirement. In such situations, the specific total maneuver would be thoroughly examined and planned so as to be accomplished in the most efficient manner. The precise propellant requirement would also be calculated by means of the appropriate equations.

Section F — Thermal Vacuum Test

One of the most rigorous and revealing prelaunch tests performed on the flight unit spacecraft is the Thermal Vacuum test. In general, various subsystems and boom mounted components must operate and be qualification tested within a temperature range of -30°C to +45°C prior to integration. The flight spare units must experience only -20°C to +35°C, with the exception of the solar panels which are subjected to a temperature of -50°C. However, the entire flight unit spacecraft must be exposed to and operate between the temperature limits of -20°C and +35°C and under vacuum conditions of less than 5×10^{-6} torr. In addition, it must survive, in a dormant state, the expected shadow temperature of -45°C for a 3 hour period. It is this extreme cold period during which most difficulties occur for subsystems, especially the ACS.

The entire test encompasses a two week period with several cycles between the above temperature limits and durations of 24 to 44 hours, nominally, at each temperature extreme. Throughout the period, ACS pressures and temperatures, as well as the chamber pressure, are monitored in order to detect any conditions which may cause damage to the high voltage experiments by means of corona discharge or otherwise indicate an ACS problem. Also the chamber atmosphere is periodically analyzed by a mass spectrometer, searching for traces of Freon-14, in order to determine the overall ACS leak rate at various temperatures. Typical measurements have usually been less than 2×10^{-3} scc/sec during stabilized conditions at temperatures of -20°C or higher. However, during the IMP-J thermal vacuum test, a significant increase in leakage developed as the temperature was lowered for the simulated shadow. The actual recorded excursions of the four primary ACS parameters monitored throughout the test are shown in Figure 30, and a detailed description of the leak problem analysis and corrective action is presented below.

The following is a summary and explanation of the leakage problems experienced with the ACS on the IMP-J spacecraft. It is intended as: (a) a presentation of the detailed factual information which was available or obtained, (b) an interpretation of the logical conclusions drawn therefrom, and (c) a description of the steps taken to remedy the difficulties. This report was made available in support of the IMP-J Flight Readiness Review.

The first indication of an ACS leak problem occurred during the pumpdown at the beginning of the IMP-J spacecraft thermal vacuum test on 7 July 1973.

In changing the ambient condition from 1 atmosphere to a vacuum, the regulator reference also changes and the result is an excess pressure remaining in the low pressure portion of the system. Some of this pressure is normally vented through

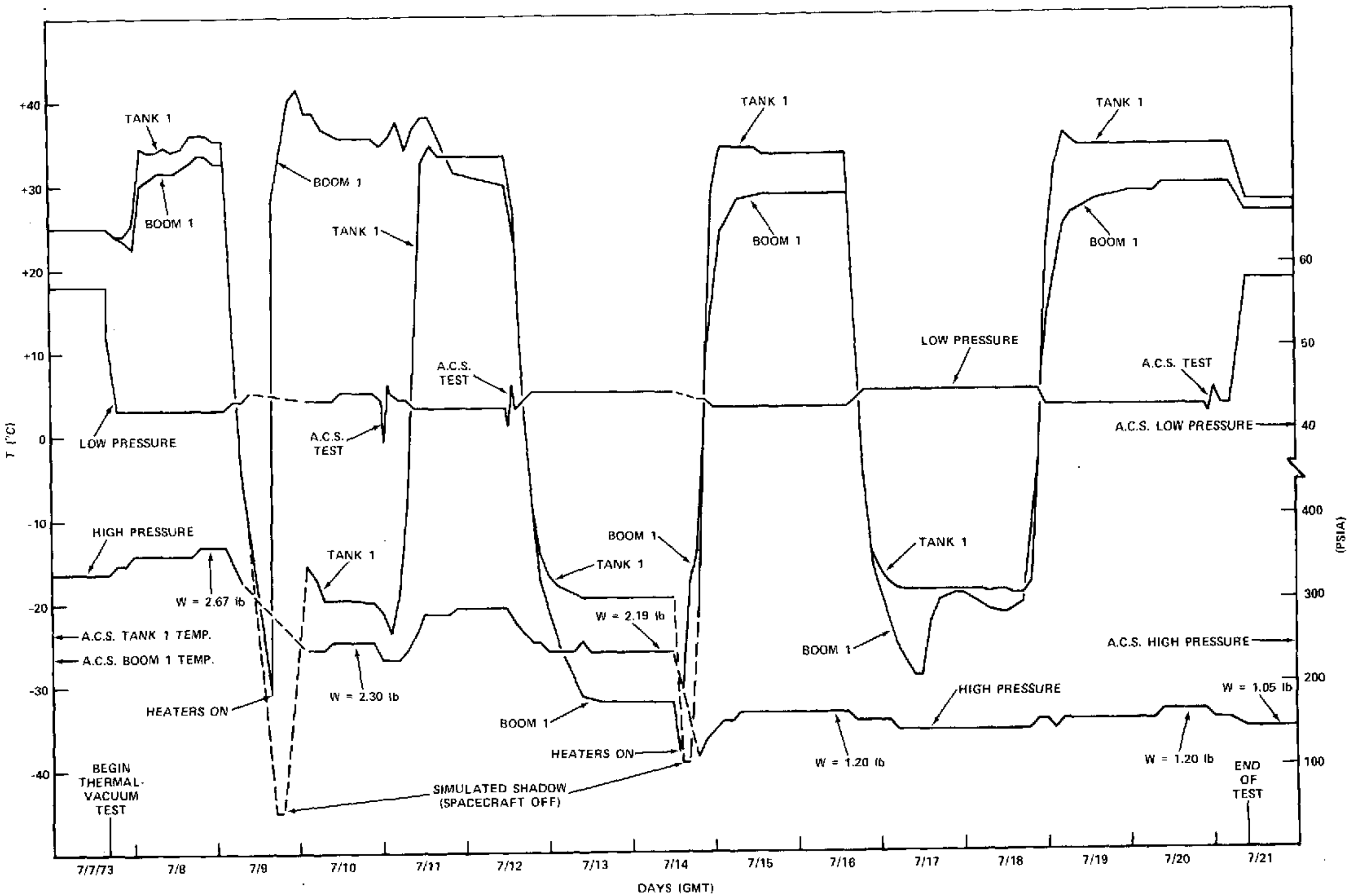


Figure 30. IMP-J Thermal Vacuum Test

a relief valve until the reseat pressure is attained. On IMP-J this occurred at approximately 52 psia; down from 58 psia at ambient. However, during the following 2 hour period, the pressure continued to drop until 43 psia, where the regulator maintained the pressure in spite of any leakage. A pressure drop of 4 psi per hour calculates to a leak rate of approximately 10^{-2} scc/sec. The IMP-J system leak specification is 10^{-3} scc/sec, which amounts to 1/4 lb of Freon-14 per year. The above leak occurred at room temperature.

Subsequent evidence of this leak occurred following each functional test of the ACS when the low pressure would drop several psi as the solenoid valves were opened, and then returned to a pressure 1 or 2 psi above the steady state value as the regulator would lock up when flow stopped. However, this one or two extra psi would slowly bleed out over the next twenty minutes or so until the steady state value was again reached. This occurred during all three ACS tests and at both the hot and cold temperature and indicates a low pressure leak.

No significant overall leak rate data could be obtained from observations of the high pressure readings due primarily to normal gas loss during the functional tests and large losses during the two shadow tests. However, a controlled observation between the third hot soak and the fourth hot soak showed only 0.08 lb of gas lost in a 4 day period. This is a very gross calculation due to the coarseness of the telemetry data, which reads in 10 psi increments, and only indicates that there is <u>not</u> a large leak between -20°C and +35°C. This test of the ACS was somewhat compromised by the fact that all but 358 psi of the normal 1900 psi gas supply was removed from the ACS prior to the thermal vacuum test and thus prevented a realistic examination of the leak rate of a fully loaded system.

Another point offered for clarification is the fact that the exchange of the number 2 despin nozzle, which occurred during a functional test several months prior to the thermal vacuum test, could in no way affect the leak rate of the ACS. Upon audible examination and feeling by hand, it was determined that this particular nozzle was apparently producing a lower flow rate than all the other nozzles and it was replaced by another spare nozzle which had normal flow. Microscopic examination revealed rough machining burrs in the throat area which could have been distorting the normally supersonic flow. Since the nozzles are downstream of two solenoid valves, they are not exposed to pressure until the valves are actuated, and therefore cannot contribute to any leakage at either hot or cold temperature.

The two shadow tests, to about -45°C, also produced severe leakage. During the first shadow transistion, leakage began to increase when a thermistor mounted on a swivel joint indicated -37°C. The leak rate rapidly increased by 2 orders of magnitude above the initial 6×10^{-3} scc/sec measured by the T&E mass spectrometer, and the chamber pressure rose to 7×10^{-4} torr. It should be pointed out that during temperature transistion there is a significant temperature variation among the spacecraft components and it is impossible to determine where the leak occurred or precisely at what temperature, with this limited instrumentation. Shortly after the leakage increase, the heaters attached to the Valve-Nozzle assemblies were turned on and quickly reached a temperature of approximately +30°C. This did not appear to have any significant effect on the leak rate. Several hours later a temperature transistion to cold soak at -20°C was begun and the leak rate began to diminish when the aforementioned thermistor was indicating -33°C. Within an hour the leak rate was being measured at 5×10^{-3} scc/sec, and continued to drop to 2.4×10^{-3} scc/sec. Observation of the high pressure readings showed that approximately 0.30 lb of gas had been lost due to leakage during the shadow test which lasted about 7 hours. Again, this is a coarse estimate due to low resolution of the telemetry data and the fact that the gas property charts are inaccurate in the region of the low pressures which were contained in the ACS tanks at the time. A special test at the end of the first cold soak in which the heater on boom #2 was turned off, thus allowing that Valve-Nozzle assembly to be cooled, produced no significant results. The temperature was allowed to drop from +35°C to +25°C and no change in leak rate or chamber pressure was observed.

The second shadow test was very similar to the first, with leakage increasing rapidly as the temperature, measured by the same swivel joint thermistor, reached about -33°C. In this test, only the boom #1 heater was turned on at first, with the valves at -35°C, then raised to -20°C, and no significant change in leak rate or chamber pressure was noted. About 20 minutes later, the boom #2 heater was also turned on, with the valves at -38°C, then raised to -20°C, and still no changes were observed. When the temperature transistion to hot soak was begun, the chamber pressure began to recover, from a peak of 1×10^{-3} torr., as the swivel joint thermistor indicated -33°C. Full recovery to initial conditions was achieved shortly thereafter. The high pressure readings indicated a gas loss of approximately 1 lb during this shadow test which lasted about 6 hours. Again this is a rough estimate.

The conclusions drawn from the thermal vacuum test were that the ACS had a small low pressure leak at room temperature and down to -20°C, and a large leak at cold temperature which was suspected to be somewhere other than the Valve-Nozzle assemblies. The swivel joints and the pressure regulator were the suspicious areas. A special test was arranged in order to investigate the leak problem. The regulator was of particular interest because it was observed that as the temperature was lowered, the regulator was regulating to higher and higher pressures. At +35°C the pressure was 43 psia, but at -20°C the pressure was up to 45 psia. No data was available at a colder temperature since the spacecraft was turned off, but a trend had been established. Corresponding to this, it was noticed from the component acceptance test data that the pressure at which the relief valve opened decreased with temperature. It was suspected that possibly these two pressures might become equal during the cold of the shadow test and thus explain the very large leak. Another item contributing to the problem was the fact that by this time the high pressure was way below the allowable inlet pressure for the regulator, which is 300 psia, and the regulator could not be expected to hold any consistent outlet pressure. If it regulated high, relief pressure might be reached. Special testing would be needed to determine the actual situation.

At the end of the thermal vacuum test and with the spacecraft still in the chamber with the door open, the ACS was probed with a Veeco in a sniff test at ambient temperature and pressure. Only a very small leak was detected in the regulator relief valve reference port. The Veeco does not give quantitative results, but it was estimated from the needle deflection that this leak was substantially smaller than the 10^{-3} scc/sec standard leak used as a part of the leak test procedure. Also during this leak test sequence, the manual shut-off valve was closed in an effort to observe any pressure drop due to leakage. Some pressure loss was noted, but the results were inconclusive due to possible temperature effects over a short period of time and the fact that a standard leak was installed in the system. Subsequently, the low pressure portion of the ACS was backfilled to raise the pressure by one atmosphere in an effort to duplicate the initial conditions of the thermal vacuum test where an excess pressure existed in the system. It was noted that the relief valve opened at 68 psia. This is low but acceptable, and consistent with the 52 psia observed during thermal vacuum pumpdown. Some pressure drop was noted over a period of time which was attributed to slow reseating of the relief valve as well as the same difficulties mentioned above.

The next step was to cool the swivel joints using dry ice and to monitor the temperature by means of thermistors. They both were cooled to approximately -40°C and no leakage was detected with the Veeco. The regulator, with the thermal blanket removed, was also cooled using dry ice and a large leak was detected in the relief valve at approximately -35°C. An attempt was made to cool the manual shut-off valve but access was difficult and the attempt was abandoned.

It was concluded that the large cold leak was due to the regulator relief valve, but the small ambient leak was not easily detectable and would require a considerable amount of time to locate and repair. With a very tight schedule and a fear that any disassembly for leak testing might invalidate the qualification testing of the spacecraft, it was decided to discontinue the search until the spacecraft was moved to the mechanical lab.

In the meeting that followed, it was suggested that the small ambient leak might be acceptable for flight and that the large cold leak could be solved by capping the relief valve. The small ambient leak would lose just over a pound of gas per year and a like amount could also be lost during each shadow from the other leak. However, the bulk of the maneuvering would take place within the first 3 months and before any shadows, and it would be possible to dump the remaining gas so as to avoid any perturbations due to leakage in a shadow. The loss of the relief valve function was inconsequential because in the event of an internal regulator failure, the flow rate of the relief valve was so much smaller than that of the regulator that it could not likely prevent high pressure exposure, and even in such a case, the low pressure portion of the system probably could withstand such pressure without catastrophic failure anyway. It of course has not been tested to pressures in excess of 200 psia, but most components have a burst pressure in excess of 2000 psia.

The relief valve was capped and rechecked for leakage at the cold temperature with dry ice. When no leakage was detected, a special ACS thermal vacuum shadow test was begun. A special GSE cable had been attached to the low pressure transducer to monitor the pressure during pumpdown in hopes of observing the same pressure decrease which occurred during the first thermal vacuum test, but equipment difficulties prevented gathering this information. By the time the problem was solved, vacuum had been achieved, and the low pressure being at 43 psia indicated that indeed the excess pressure had already leaked out just as had happened before, but now the time rate could not be determined. The test proceeded with a measured leak rate of about 8×10^{-3} scc/sec and a steadily falling temperature. In this test a thermistor had been placed on each swivel joint as well as on the regulator, and the thermal blankets had been removed from both Valve-Nozzle assemblies but the heaters and thermistors were still attached. It was noted that below -20°C the nozzles, being closest to the wall, ran cooler than the regulator or swivel joints which followed each other very closely. As the regulator reached about -34°C, the valves were at -38°C and the leak rate began to increase rapidly. Its peak rate could not be determined because the mass spectrometer had to be secured at 5×10^{-2} scc/sec, but the chamber pressure only reached 1×10^{-4} torr. As the regulator temperature reached -45° C, the chamber was reversed and warming began. Throughout the test, the nozzle heaters had not been turned on. When the regulator returned to -43° C, the valves were at -47°C and the leak had nearly returned to the original value, and full recovery occurred shortly thereafter.

This test indicated that the leak problem had not yet been solved. The small ambient leak was still there, and the large cold leak had improved only slightly. The slight improvement was indicated by the fact that leakage began at a lower temperature, did not produce as large a chamber pressure, and sealed up much sooner than in the previous tests. Again, the swivel joints and regulator were suspected, especially the relief valve reference port.

The records revealed that this particular regulator, serial number 5, had experienced a leakage problem in this area in the past. A significant ambient leak was detected at the relief reference port and was attributed to a faulty bellows assembly. Without disassembly or further investigation the unit was returned to the manufacturer, Carleton Controls Corp., for rework. It was received sometime later and subjected to complete acceptance testing, between +65° C and -44 °C, and was found to be functioning properly and without detectable leakage. This unit was selected for the IMP-J flight unit because of the more recent testing than the other available unit and because the rework meant that fresh o-ring seals had been installed. Subsequent subsystem testing of the shelf assembly revealed no problems with the regulator and it was installed on the spacecraft. It was only during the thermal vacuum test that the relief valve bellows problem began to reappear and it was feared that the leak may progressively worsen. Therefore, a test was devised to check the remaining spare unit in hopes of offering it as substitute. There was a possibility of simply exchanging the relief valve sections and thus avoid extensive disassembly and substantial time delay.

The spare unit, not to be confused with the flight spare shelf assembly which remains qualified and intact, was disassembled to examine the complexity of the exchange process and then reassembled in preparation for a test. It was pressurized with flight type gas and checked for relief valve actuation and then tested for leakage at room temperature. No leaks were found. It was then cooled to below -45°C and again no leaks were found. It was decided to attempt the exchange when the spacecraft was moved into the mechanical lab.

The plan was to verify that the leak was still detectable in the lab with the air currents present in order to possibly explain why it may not have been detected under the same conditions in the leak test prior to the thermal vacuum test. When the presence of the leak had been verified, the next step was to vent the remainder of the gas in the system. Following this the relief valves were exchanged without difficulty, and the original dispersion cap was reinstalled. The system was then refilled to about 500 psia and a sniff test was performed to verify proper installation as well as to check the entire system for leaks. Plastic bags had been placed over each Valve-Nozzle assembly in order to accumulate any leaking helium. When no leaks were detected, dry ice was applied to both swivel joints until a temperature of -40° C was reached. Again no leaks were detected. Similarly, the regulator was cooled and no leaks were detected at either the relief valve or its reference port. The manual shut-off valve was also cooled and a large leak developed near the stem at about -35° C. The manual outlet valve was similarly tested with the same results. However, the outlet valve was tested in the open position whereas it is normally closed for flight and as such the valve packing is not exposed to pressure. The next step was to back fill the low pressure portion of the ACS up to the relief pressure, which was recorded at 67 psia. The relief valve appeared to reseat around 61.9 psia and several hours later the pressure had dropped to 57.9 psia where the regulator maintained it.

Subsequent testing of representative or spare components proceeded in another lab. The defective relief valve was assembled to the spare regulator and pressurized. Again a small leak was detected at the relief valve reference port and when the entire unit was cooled, in a test chamber, both the relief valve and its reference port showed a large leak at about -45°C. Next, a spare manual valve was tested to -45°C and no leakage was found. The manufacturer rates these valves, with a Buna "N" o-ring packing, as good only to -40°C. The next item tested was the spare shelf assembly which includes a regulator and 2 manual valves. Again no leakage was found at -45°C. Finally, 2 spare swivel joints were tested and no leakage was found as low as -40°C. Some leakage did occur in one unit with neoprene o-rings at a lower temperature.

Meanwhile, at the spacecraft the low pressure was holding steady at 57.0 psia and it was decided to close the shut-off valve. In one hour the pressure dropped to 52.4 psia and in another hour it was down to 48.3 psia. The total drop after 3 hours was 12.6 psia, indicating a low pressure ambient leak of about 10^{-2} scc/sec. From this information and the previous test results, it was recommended that further leak testing be done and that the manual shut-off valve packing be replaced.

At this point there was the possibility that an ambient leak existed in one or both of the Valve-Nozzle assemblies. A check of the component test records revealed that the number 1 assembly originally experienced a leaking V-seal which was replaced prior to installation on the boom. These V-seals are very delicate items and little test data is available for them. They were selected because they are metal and have nearly the same coefficient of thermal expansion as the adjacent metal components and are rated by the manufacturer for temperatures between -325°F and 1300°F. They were used with good results for the solenoid valve acceptance tests at a temperature of -70°C, and are used in place of the elastomeric o-rings used in both IMP-I and H. Such a replacement was sought because of the minimal o-ring squeeze and cold temperature leakage characteristics of other seal materials used with this valve design. Further testing would be required in order to isolate any leakage in the Valve-Nozzle assemblies.

After a normal ACS functional test was performed without difficulty, further steps were taken in order to locate the low pressure ambient leak. First the special GSE cable was attached to allow for remote pressure transducer readings. Next, the tubes leading to both Valve-Nozzle assemblies were disconnected and capped off to isolate the solenoid valves. In this configuration, the low pressure was monitored and a drop of 1.7 psi was noted over a 3 hour period. This must be compared to the 12.6 psi drop recorded in the previous test. Next, the number 2 Valve-Nozzle assembly was reconnected and the pressure again monitored. Once more a pressure drop of 1.7 psi was observed after 3 hours. This would indicate that the number 2 Valve-Nozzle assembly was not the source of the original leak. Finally, the number 1 Valve-Nozzle assembly was also reconnected and this time a pressure drop of only 1.3 psi was noted after 3 hours. It should be noted that this amount of pressure drop indicates a leak of about 10^{-3} scc/sec which is acceptable for the system. At this point the system was back in the original flight configuration except for the closed shut-off valve, and essentially was no longer leaking.

The only conclusion that can be drawn from this series of tests is that the ambient leak must have been in the fittings at the inlet to the Valve-Nozzle assemblies, either one or both, since these were the only items manipulated for this test besides the shut-off valve. It does not appear that these fittings contributed to the large cold leak because they are so close to the heaters which apparently did not affect the cold leak when energized. The cold leak appears to have been in the regulator relief valve including the bellows and in the manual shut-off valve packing. It should be pointed out that the dry ice method of producing a cold leak can be somewhat misleading. First of all, a large temperature gradient, or thermal shock, is produced within the component and this may cause a leak where there would not otherwise be one. Secondly, there is much difficulty in determining and maintaining the precise temperature of the component in order to correlate the temperature at which leakage occurs.

The question still remains, though, as to why the ambient leak in the fittings was not detectable by the Veeco during the many sniff tests. It must be pointed out that the sniff leak test method is actually a very crude means of leak detection. Its main advantage is the convenience and simplicity of the entire operation. It has the disadvantages of being compromised by any air currents, of lacking quantitative measurement, and of being subject to the various peculiarities of the specific leak mechanism under study. For instance, the leaking gas may have been escaping in a definite stream and unless the probe was placed directly in that stream, no leak would have been detected. For this same reason the leaking gas may not have been captured in the plastic bag which was placed over the valves. The primary effort on the booms was directed at the valves themselves, although access was severely limited, and at the swivel joints, and little concentration was placed on the inlet fittings. It may have simply been missed. There is even the remote possibility that the leak may have been in the solenoid valves, which would require both a seat leak plus an o-ring leak, and that the actuation of the valves during the functional test somehow cleared up the problem. But this is all speculation; there is no definite explanation of why the leak was not detected. It does, however, appear to have been repaired as a result of this concerted effort.

The final step in this effort was to replace the manual shut-off valve packing. Preliminary to this task, a pressure drop test was made using the same standard leak as is utilized as part of the leak test procedure. It was installed in the outlet port and the shut-off valve was closed. In one test the pressure dropped 15.2 psi in 15 minutes, and in the second test the drop was 14.5 psi in 15 minutes. The standard leak is rated at 9.8×10^{-3} scc/sec with helium. One more test was done without the standard leak and the pressure dropped only 0.6 psi in 15 minutes. Following this test, the inlet fittings, which had been reconnected after the previous leak test, were checked for leakage and none was found. The system was then vented and the shut-off valve packing was replaced. The specific items changed were from a valve which had been cold tested in a separate test and included the valve stem with its KEL-F seat, the o-ring and its retainers, and the valve bonnet. Upon completion of this task, the low pressure portion of the system was backfilled up to relief pressure of 68 psia and valved off. Reseat occurred at 62 psia and the low pressure remained at this level for the next 20 minutes. The new valve stem along with all the fittings in the immediate vicinity were then checked for leakage and none was found. No dry ice was available to do a cold test. At this point the regulator thermal blanket was reinstalled, the GSE cable was removed and replaced by the flight connectors. The leak test and pressure monitoring equipment were all secured.

Subsequently, the ACS was filled to a pressure of approximately 2300 psia at 37.8°C and one final leak test was performed in order to verify all the repairs which were accomplished previously.

Next, the shut-off valve was closed and the low pressure dropped from 56.7 psia to 56.4 psia, a difference of only 0.3 psi in one hour, and represents an acceptable leak rate. Following this, the low pressure was vented for a test of the shut-off valve seat. The pressure remained at 16.1 psia for over 15 minutes, indicating a tight seal. Finally, dry ice was applied to the shut-off valve and the temperature was lowered to -40°C. When no leakage was found it was concluded that, based on all the previous testing, the entire system was now free of detectable leaks, both at ambient and cold temperatures.

Summary and Conclusions

The mass spectrometer measurement and the drop in low pressure during the thermal vacuum test indicated a small, but beyond specification, leak in the low pressure portion of the ACS at all temperatures. In addition, the large increase in chamber pressure and the measurable loss of gas, indicated a much larger leak below -35°C. The solenoid valves were eliminated due to lack of any significant change when the valve heaters were energized. When the chamber was opened, a sniff test located only one small leak in the regulator relief valve reference port at ambient temperature and a large leak in the relief valve itself at cold temperature using dry ice. When capping the relief valve failed to solve the problem, the entire relief valve was replaced. Bench testing of the original unit verified a defective relief valve. Further tests with dry ice eliminated any problem with the swivel joints but located a leaking manual shut-off valve and its packing was then replaced.

However, ambient leakage persisted and was reduced only by disconnecting and capping the Valve-Nozzle inlet fittings. Upon reconnecting and tightening these fittings, the leak was all but eliminated. At this point, the ambient leakage was within specification and the two cold leaks had been repaired, all with a minimum of disassembly and loss of time. The only possible means of verifying an acceptable total cold temperature leak rate would be to perform another thermal vacuum shadow test at a cost of at least three days.

Finally, the spacecraft was accepted in this condition, allowing that a thorough sniff leak test at the launch site would provide the final indication of system readiness. No further leakage was ever detected and the spacecraft was subsequently prepared for launch.

Section G — Propellant Allocation

The initial IMP-J mission profile was essentially identical to that for IMP-H, and the significant transfer orbit events are shown in Figure 31. Also, the planned spin rate schedule and related events are presented in Figure 32. From this information, the necessary ACS maneuvers were determined along with the specific propellant requirements. These maneuvers are described below.

(1) Reorientation following separation of the spacecraft from the burned out third stage. This maneuver was necessary to adjust the spin axis—sun angle in order to maintain acceptable temperatures and provide a reasonable antenna pattern throughout the two and one half day coast in the transfer orbit. In addition, the spacecraft was placed in a position so as to track the earth's horizon and thus permit accurate attitude determination. The spacecraft was in the launch configuration, spinning at approximately 46 rpm with all booms folded, and as much as 90 degrees of attitude change was allowed. The amount of propellant allocated for this purpose was 3.36 lb.

(2) Reorientation of the spacecraft in preparation for the fourth stage burn. Upon reaching apogee in the transfer orbit, the spacecraft was placed in a circular orbit by means of the fourth stage motor, and it was necessary that its thrust vector be properly aligned by means of the ACS prior to burning. This maneuver was also performed in the launch configuration, at approximately 46 rpm, with all booms folded. Again, as much as 90 degrees of attitude change was allowed and the amount of propellant allocated for this purpose was also 3.36 lb.

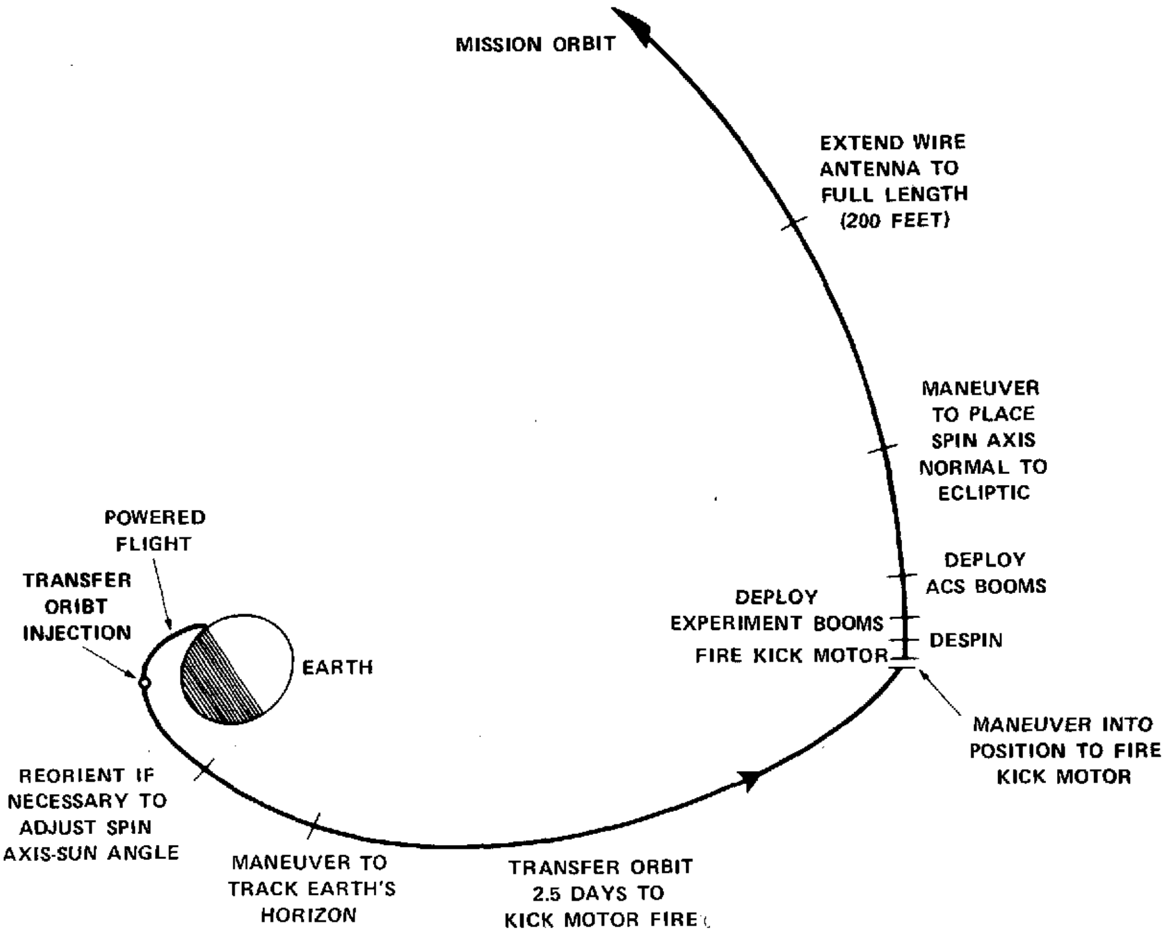


Figure 31. Transfer Orbit Events

(3) Despin in preparation for boom deployment. Throughout the transfer orbit and fourth stage burn, a high spin rate was maintained in order to improve the stability and reduce the cone angle. However, both the ACS and Experiment booms were designed for deployment at a nominal 18 rpm and the spacecraft had to be despun to this spin rate by the ACS before the deployment sequence could begin. Since a small random increase in spin rate was expected due to the fourth stage burn, it was estimated that the amount of ACS despin was on the order of 30 rpm and would require 2.16 lb of propellant with the booms in the folded configuration.

(4) Reorientation to place the spin axis normal to the Ecliptic plane. The boom deployment process was expected to reduce the spin rate from 18 to 9.37 rpm

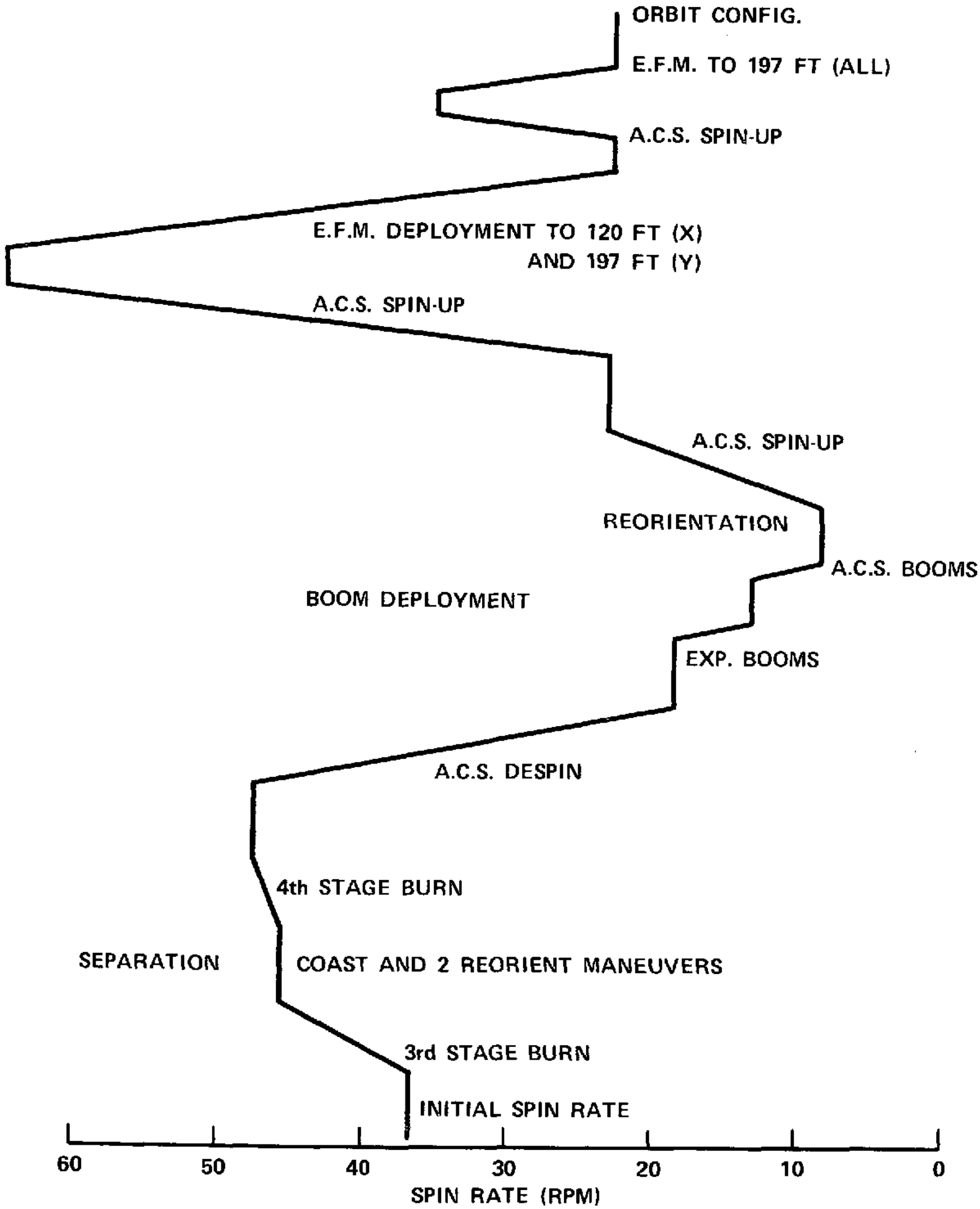


Figure 32. Spin Rate Schedule

where attitude changes could be done very efficiently. With the spacecraft in the preliminary orbital configuration, and all booms deployed, as much as 90 degrees of attitude change was allowed, and the amount of propellant allocated for this maneuver was 0.66 lb.

(5) Spin-up to mission spin rate. Both the scientific experiments and the data handling equipment onboard the spacecraft were designed to operate most effectively at a minimum of 23 rpm. The ACS was capable of producing the required spin rate changes by means of a combination of full and partial commands and thus a precise spin rate control was available. In this case, a change of 13.63 rpm was expected with a propellant allocation of 0.62 lb.

(6) EFM Antenna deployment. As previously described, the amount of propellant required to maintain a constant spin rate throughout the moment of inertia change produced by the EFM antenna deployment, was independent of the number of steps. Consequently, in order to extend the 200 ft (197 ft) wire antennas, 3.28 lb of propellant was required when both beginning and ending at 23 rpm.

(a) The spin-up for the initial stage of the deployment was planned as follows.

Spin-up to 67 rpm: $\Delta\omega = 44$ rpm

Average value of $(C - \Delta\omega_D)$: 21.969 rpm/lb,

then $\Delta W = 44\ (1/21.969) = 44\ (0.0455) = 2.00$ lb

and $2.00/0.216 = 9.27$ commands

or 9 full commands plus a 19 sec partial at a rate of 4.747 rpm/CMD

CMD No.	rpm
-	23.000
1	27.747
2	32.494
3	37.241
4	41.988
5	46.735
6	51.482
7	56.229
8	60.976
9	65.723
19 sec	67.005

(b) The spin-up for the final stage was planned as follows. ($I = 368.46$ sl-ft^2)

Spin-up to 32.52 rpm: $\Delta\omega = 9.52$ rpm

Average value of $(C - \Delta\omega_D)$: 7.603 rpm/lb,

then $\Delta W = 9.52 \ (1/7.603) = 9.52 \ (0.1315) = 1.25$ lb

and $1.25/.216 = 5.80$ commands

or 5 full commands plus a 58 sec partial at a rate of 1.642 rpm/CMD

CMD No.	rpm
-	23.000
1	24.642
2	26.284
3	27.926
4	29.568
5	31.210
58 sec	32.524

It should be noted that the total propellant requirement for the above maneuvers, 3.25 lb, compares favorably with the specified allocation, and the small difference is attributed to both round off error and the effect of gas motion despin. The allocated quantity was determined in the following manner.

For 197 ft deployment: $\Delta\omega = 71.707$ rpm;
$\Delta\omega_D$ at 94.707 rpm is 0.934 rpm/lb,
$\Delta\omega_D$ at 23.000 rpm is 0.227 rpm/lb,
and the average value is 0.581 rpm/lb.

From this, $(C-\Delta\omega_D) = 21.833$ rpm/lb,

and $\Delta W = 71.707 \ (1/21.833) = 3.28$ lb.

All of the scheduled ACS maneuvers were based upon nominal conditions, and the operations described are conservative and represent the largest changes which were expected in a normal sequence. In practice, the attitude changes were actually somewhat smaller than those listed, but the exact numbers could not be determined until after launch and orbit injection when the spacecraft attitude could be measured.

In addition to the above maneuvers which comprise a total propellant requirement of 13.44 lb, a contingency allotment of 45% was included in the total amount of ACS propellant. This extra quantity was carried to cover the wide assortment of possible situations and occurrences which were described previously for the IMP-H. However, the IMP-J contingency plans also included sufficient propellant to make one complete EFM antenna retraction and to allow for some variation in the calculated moment of inertia due to errors in the actual linear density of the antenna wires. It should be noted that retraction of the EFM antennas would require nearly the same amount of propellant as their deployment, with the small difference being attributed to the effect of gas motion despin. Such a maneuver would only be done as a last resort to prevent the total loss of the spacecraft or mission, and would consume the majority of the available contingency supply.

Other propellant quantities were budgeted for leakage and prelaunch checkout. The IMP-H experience in these areas showed that an acceptable leak rate had been achieved in orbit with the new seal materials, and also that final prelaunch checks consumed much less propellant than anticipated. Therefore these allotments were significantly reduced for the IMP-J.

In summary, the total propellant quantity is described as follows.

Scheduled ACS maneuvers	13.44 lb
Contingency at 45%	6.05 lb
Leakage and checkout	0.51 lb
Total	20.00 lb.

This amount of propellant, with a specific volume of 0.0258 ft^3/lb, represents a total impulse of 900 lb-sec, and would be contained in the ACS tanks at the pressures and temperatures tabulated below.

Temp. °R	Temp. °C	Temp. °F	Pressure (psia)		Helium %
			Total	Freon-14	
450	-23.16	-9.7	1151	914.7	20.5
460	-17.61	0.3	1248	1006.4	19.4
470	-12.05	10.3	1345	1098.2	18.4
480	-6.50	20.3	1442	1189.9	17.5
490	-0.94	30.3	1539	1281.6	16.7
500	4.61	40.3	1636	1373.3	16.1
510	10.17	50.3	1733	1465.1	15.5

Temp. °R	Temp. °C	Temp. °F	Pressure (psia)		Helium %
			Total	Freon-14	
520	15.72	60.3	1830	1556.8	14.9
530	21.28	70.3	1927	1648.5	14.4
540	26.83	80.3	2024	1740.2	14.0
550	32.39	90.3	2121	1831.9	13.6
560	37.94	100.3	2218	1923.7	13.3
570	43.50	110.3	2315	2015.4	12.9

As described previously, the fill procedure for the ACS includes a provision for using scales in order to load a precise amount of propellant. This was attempted for the IMP-J during an operation which followed the thermal vacuum testing and is described below in an excerpt from the final report.

Subsequently the ACS was filled to a pressure of approximately 2300 psia at 37.8°C. Precise pressure measurements were not possible due to lack of access for the special GSE cable. A humidity problem prevented the removal of the protective plastic bag from the spacecraft and consequently solar cell panels could not be removed to allow for cable attachment. The only access hole in the lower thermal shield was too far away from the transducer locations to permit installation from that point. It was decided to use the sensitive pressure gauge included with the high pressure cart and take readings at selected intervals.

The plan was to correlate an accurate scale weight reading with pressure and temperature data and determine the precise combinations to be used for the filling at ETR. Information obtained up to 1500 psia correlated very well, to within 0.2 lb, with the calculated values. However, at this point the scales required a range change since the weight had reached the first range limit of 320 lb on each scale. Subsequent data had discrepancies in excess of 1.5 lb; with the final numbers being 18.7 lb from the scales versus 20.6 lb calculated. A scale calibration later showed that only 18.4 lb had been added. When spacecraft data from the transducers was again available, a new calculation was made.

Although it is difficult to find fault with the calibrated values, it does seem that this change in range could have been anticipated and avoided along with its possible contribution to the weight discrepancy. Another factor affecting the accuracy of the measurements, from which the calculations were made, is the highly transient conditions under which the readings were taken. The temperature excursion during filling is fairly large and a considerable amount of time is required in order to achieve stability. There could easily be several degrees of uncertainty in the gas temperature under these changing conditions. Similarly, without the more accurate transducer reading, the pressure in the system was not known precisely. Sources of errors in pressure are line losses, a 25 psi differential required to open the check valve, and a "gauge" reading rather than an absolute number. Finally, it is possible that the pressure-temperature relationship for Freon-14 is not known or tabulated as accurately as is needed. The matter is certainly complicated by the addition of helium to produce a gas mixture for which charts do not exist. Published information on the gas properties of Freon-14 correlates very well with the tabulations used on IMP-J, but a theoretical calculation must be made to account for the helium. Taking a simple 10% was the method used on IMP-I and H with marginal success, but a variable percentage is used on IMP-J and little data has been gathered so far. First of all the gas is purchased premixed, and it is analyzed to determine the precise ratio. In the calculation, the helium is treated as a perfect gas with a linear relationship and the Freon-14 has a high compressibility region, so that the helium percentage, in terms of partial pressure, will tend to increase in that region. Beyond this region, the opposite occurs. Unfortunately the charts begin to loose resolution at the higher pressure and temperatures that occur during the filling process. In any event, the calculated weight discrepancy could be attributed to an accumulation of all the errors described above. In addition it appears that the conditions under which the weighings took place could have been controlled more precisely. For instance, the weight values were compromised by such things as air currents, a plastic bag being purged with dry nitrogen, a grounding strap, and the aforementioned range change. At this point there was some doubt as to the exact amount of gas in the system and it was not resolved until the filling at ETR which was also done on scales.

One final leak test was performed in order to verify all the repairs which were accomplished previously. In preparation for this test, the GSE cable was attached in order to obtain pressure transducer readings. The high pressure reading was 2067 psia, which is the maximum range limit of the transducer, and indicates a pressure of at least this amount, perhaps more. With a temperature of 23°C, this calculates to 20.8 lb of gas, corresponding closely to the original calculation at the time of filling. Information obtained from the IMP-H record revealed that it was filled to 1770 psia at 24.9°C and contained only 18.4 lb of propellant. The only difference between IMP-H and IMP-J is the use of premixed gas, where a large error in helium percentage would be required in order to produce a 2 lb error in the calculated weight.

The above information indicates that the discrepancy in the amount of gas placed in the system remains unresolved. There were reasons to suspect errors in both the scale reading and the calculated value, and further measurements were required to obtain an accurate figure. The final conclusion at this point was that the mechanical portion of the ACS was ready for flight in regards to leakage and, if possible excess was allowed, propellant quantity. Further testing was desirable, but the additional time and manpower was not acceptable or available, and ultimately the overall mission requirements prevailed.

However, another opportunity was subsequently provided with which to make use of the scales for measuring the change in propellant load, and this occurred when the ACS was vented prior to shipment of the spacecraft to the launch site. In this case, all the necessary instrumentation was attached, and the scales indicated that 10.16 lb had been removed during the venting. Calculations showed that 9.2 lb remained in the system, indicating that only 19.36 lb was onboard originally. This number becomes more realistic in light of the fact that the system had been actuated, with the expulsion of an unknown quantity of propellant, for a sun spin test just prior to the scale readings. Although some uncertainty remained at the higher pressures, good accuracies were consistently obtained at the lower values and the 9.2 lb quantity was accepted with confidence.

The final filling operation at the launch site (ETR) was also performed utilizing a direct weight measuring method, and produced the following results.

Calculated propellant weight:

before filling	7.70 lb.
after filling	19.95 lb.

Measured change in weight:	11.50 lb.
Total using measured value:	19.20 lb.

For the purpose of determining the total spacecraft weight, the measured propellant weights were used; but for management of the ACS propellant budget, the calculated values were used, based upon the fact that the only information available from orbit via telemetry was the propellant pressure and temperature. Consequently, the following information was obtained for the ACS in a stabilized condition, prior to launch.

High pressure	2019 psia
Tank 1 temperature	23.2°C
Calculated propellant weight	20.40 lb

It should be noted that this quantity of propellant exceeded the maximum allowable working pressure of the system at ambient temperature, and that the 4 to 1 safety factor was no longer in effect. However, appropriate waivers were obtained and special precautions were taken to accommodate this situation. A more thorough treatment of this topic is presented in Section H.

The IMP-J was successfully launched on October 25, 1973, and the following ACS information was obtained shortly thereafter.

High pressure	1948 psia
Low pressure	47.6 psia
Tank 1 temperature	19.8°C
Boom 1 temperature	13.6°C
Alpha angle (θ)	111.25 degrees
Spin rate	50.75 rpm
Calculated propellant weight	20.45 lb.

Although the third stage burn had produced a spin rate which was 4.75 rpm higher than nominal, it was accepted and no despin commands were sent. In a similar manner, the sun aspect angle was less than 25 degrees from perpendicular and no immediate attitude changes were required. The following ACS information was recorded mid way through the coast phase.

High pressure	1854 psia
Low pressure	42.7 psia
Tank 1 temperature	14.8°C
Boom 1 temperature	12.3°C
Alpha angle (θ)	113.25 degrees
Spin rate	50.76 rpm
Calculated propellant weight	20.42 lb

The first reorientation maneuver involved 80 North commands and produced the following results.

$\Delta\theta$ = -2.50 degrees
ΔW = -0.22 lb

At this point, discrepancies were discovered in the sun aspect sensor and certain allowances were required in order to obtain reliable attitude information. Subsequently, a second reorientation maneuver was peformed, involving 94 North commands, and produced the following results.

$\Delta\theta$ = -4.00 degrees
ΔW = -0.24 lb

At apogee in the transfer orbit, no further attitude changes were required for the fourth stage thrust vector alignment. The fourth stage then burned for 21 sec with a maximum pressure of 705 psia, and produced an acceleration of 5.20 g. Also, a 0.25 rpm spin rate increase was obtained.

The next operation was a despin in preparation for the ACS and Experiment boom deployment, and the following ACS information was obtained prior to this maneuver.

High pressure	1759 psia
Low pressure	44.3 psia
Tank 1 temperature	11.9°C
Boom 1 temperature	19.0°C
Alpha angle (θ)	107.25 degrees
Spin rate	51.016 rpm
Calculated propellant weight	19.96 lb

Eleven despin commands were sent and produced the following changes.

$\Delta\omega$ = -32.436 rpm or -2.95 rpm/CMD
ΔW = -2.37 lb

The calculated flow rate for this maneuver was 0.00299 lb/sec. Subsequently, the Experiment booms were deployed and the spin rate was reduced from 18.58 rpm to 10.14 rpm. The ACS boom deployment further reduced the spin rate to 9.46 rpm. At this point, one spin-up command was executed with the following result.

$\Delta\omega$ = +4.84 rpm
ΔW = -0.17 lb

Prior to reorientation, the following ACS information was recorded.

High pressure	1495 psia
Low pressure	46.0 psia
Tank 1 temperature	7.2°C
Boom 1 temperature	19.2°C
Alpha angle (θ)	107.25 degrees
Spin rate	14.30 rpm
Calculated propellant weight	17.42 lb

Fourteen North commands were sent with the following response.

$\Delta\theta$ = -8.00 degrees
ΔW = -0.22 lb

In addition, approximately 95 East commands were executed, with a ΔW = -0.33 lb; but the spacecraft response was not immediately available. However, the effect of the characteristic delay was very noticeable in that a 2.50 degrees North excursion was obtained as a result of the East commands. Prior to the second reorientation sequence, the ACS data was as follows.

High pressure	1432 psia
Low pressure	45.1 psia
Tank 1 temperature	5.6°C
Boom 1 temperature	16.7°C
Alpha angle (θ)	96.75 degrees
Spin rate	14.30 rpm
Calculated propellant weight	16.87 lb

Twelve North commands were sent and produced the following response.

$\Delta\theta$ = -7.50 degrees
ΔW = -0.21 lb

In addition, one full spin-up command plus a 58 sec partial command were executed with the following result.

$\Delta\omega$ = +4.82 plus 3.80 rpm
ΔW = -0.20 lb

The next event was a penumbral shadow of approximately 2 hours duration in which the solar array current dropped from 5.93 amp to 1.53 amp, and the ACS boom 1 temperature, including the solenoid valves, dropped to as low as -3.5°C. No significant leakage was detected during this period. Several days later, an attitude trim maneuver was performed involving a total of approximately 40 commands with a propellant consumption of $\Delta W = -0.18$ lb. The following ACS information was obtained upon the completion of the above maneuver.

High pressure	1316 psia
Low pressure	45.1 psia
Tank 1 temperature	0.4°C
Boom 1 temperature	14.0°C
Alpha angle (θ)	90.75 degrees
Spin rate	22.89 rpm
Calculated propellant weight	16.13 lb

After several weeks it was determined that the R-F antenna pattern was marginal and causing difficulty in data reception. As a result it was decided to reorient the spacecraft by 180 degrees so that the spin vector was directed toward the South ecliptic pole instead of the North. In preparation for this "flip" maneuver, two despin commands, with $\Delta W = -0.34$ lb, were executed and placed the spacecraft in the following condition.

High pressure	1295 psia
Low pressure	45.5 psia
Tank 1 temperature	0.4°C
Boom 1 temperature	14.4°C
Alpha angle (θ)	81.25 degrees
Spin rate	13.20 rpm
Calculated propellant weight	15.79 lb

Approximately 300 West commands were sent along with an appropriate number of South commands to overcome the characteristic delay, and the propellant consumption was $\Delta W = -2.73$ lb. Upon completion of this maneuver, the spin rate was trimmed prior to spin-up for the EFM antenna deployment, and the following ACS information was obtained.

High pressure	1149 psia
Low pressure	43.9 psia
Tank 1 temperature	2.0°C
Boom 1 temperature	11.5°C
Alpha angle (θ)	90.75 degrees
Spin rate	22.67 rpm
Calculated propellant weight	13.06 lb

In order to provide a safety margin for the EFM antenna deployment, it was decided to spin-up to 68.00 rpm, and 9 spin-up commands were executed with the following result.

$\Delta\omega = +41.91$ rpm or 4.656 rpm/CMD
$\Delta W = -1.69$ lb

This calculates to a flow rate of 0.00261 lb/sec. In addition, a 53 sec partial spin-up command was executed and trimmed the spin rate to precisely 68.00 rpm.

The EFM antenna deployment began with the extension of the +X antenna to an indication of 12.0 ft and the -X antenna to 48.4 ft. Following this, the +Y antenna was extended to 47.2 ft and the -Y antenna to 46.1 ft. At this point, with the spin rate at 66.37 rpm, an unsuccessful attempt was made to retract the +X antenna. Subsequently, the +Y antenna was extended to 90.5 ft and the -Y antenna was extended to 88.2 ft, with a spin rate of 61.127 rpm. After a 20 minute stabilizing period, the +Y antenna was further extended to 133.5 ft and the -Y antenna was extended to 130.2 ft, and the spin rate became 50.354 rpm. At this point, another attempt was made to extend the +X antenna. When this failed, the -X antenna was retracted to 10.9 ft, and the +Y antenna was extended to 208.3 ft and the -Y antenna was extended to 209.4 ft. In this configuration the spin rate was 26.91 rpm and one despin command reduced the spin rate to 24.925 rpm. A 65 sec partial command further reduced the spin rate to 23.38 rpm and a 5 sec partial command placed the spacecraft in the orbital configuration at a spin rate of 23.17 rpm. The propellant consumed for these maneuvers was 0.33 lb and the calculated spacecraft moment of inertia was 325.42 sl-ft^2. It is interesting to note that the rate of spin rate change, based on the measured $\Delta\omega$ of 3.74 rpm, was 0.0263 rpm/sec, whereas the rate of change based on the calculated final moment of inertia was 0.0264 rpm/sec.

Several months later, on 3/4/74, the following ACS information was recorded.

High pressure	979 psia
Low pressure	44.3 psia
Tank 1 temperature	2.4°C
Boom 1 temperature	7.4°C
Alpha angle (θ)	91.25 degrees
Spin rate	23.135 rpm
Calculated propellant weight	10.42 lb

From the above information it is apparent that the propellant quantity determination has been somewhat improved over that for IMP-H. However, there still remain the same errors due to the large telemetry resolution increments and the processing of data gathered during transistion periods when the temperatures have not been stabilized. With all things considered, an estimate of the total system leak rate shows it to be as much as 2 X 10^{-3} scc/sec; but unfortunately, no deep shadows have yet been encountered which could verify the integrity of the new metal V-seals.

Finally, there is reasonable correlation between the actual spacecraft response and the calculated ACS performance parameters, including a verification of the accuracy of the moment of inertia measurements. In addition, the two large reorientation maneuvers provided an excellent example of the effect of the characteristic delay. Inasmuch as several unscheduled ACS operations were performed which consumed a small portion of the contingency allowance, other planned maneuvers were either eliminated or reduced so that an abundance of propellant remains available for future operations if necessary.

Section H — Safety Factor

The basic guidelines regarding safety factor require that a pressurized system have a burst pressure four times larger than the maximum operating pressure. A deviation to as much as a two to one ratio is permissible, for the pressure vessel only, provided an official waiver is obtained. The initial propellant requirement calculation for the IMP-J, based on IMP-H quantity determination techniques, revealed that the safety factor would be less than four to one with 22.5 lb of propellant. The following excerpt from a document issued May 24, 1972, describes the situation which existed at the time.

In the present configuration, the IMP-J can carry 19.4 lb of the 90% Freon-14, 10% Helium mixture at 1800 psi and 23° C, and still maintain the required four (4) to one (1) safety factor. Thus, there is an excess gas requirement of 3.1 lb.

The 50% contingency allowance is highly desirable, and represents changes in gas requirements due to updated moment of inertia values, higher actual EFM antenna densities, any Delta, 3rd stage or 4th stage overspins, excess and inefficient precession maneuvers, and any failure mode or unpredictable condition which may occur after launch. Similarly, a specific allowance is made for leakage and pre-launch checkout which is based on the largest allowable leak rate plus two cycles of each ACS command while on the gantry. It is only prudent to load the ACS to cover the worst case conditions.

Some suggestions have been offered as solutions to the excess gas problem. One solution is to install a third tank, but this is not feasible for the following reasons. The simple addition of another tank, anywhere but on the center line, where space is not available either, is going to cause a severe and unacceptable unbalance problem. A redesign to achieve a symmetrical arrangement of three tanks would require considerable rework of the main shelf, add about 10 lb of new hardware, increase the cost and cause a significant delay in the schedule. At least six months is required to procure new, identical tanks, and another three months is required for testing, cleaning and preparation for installation. Also, the experiment and strut arrangement is not compatible with a three tank configuration at this time.

Another solution is to utilize a yo-yo despin device in place of the first despin maneuver. Such a device has been designed on the IMP-I program; and it would add about three (3) lb to the spacecraft and result in a saving of about 3.4 lb of gas including contingency. The disadvantages of this approach are the cost of the additional hardware, the need for extensive testing on the spacecraft, and the reduced reliability due to the installation of another complex system.

The final and most desirable of the possible solutions is to permit a reduction in precession requirements for the first and second re-orient maneuvers. By reducing the requirement to 60 degrees for each maneuver, a gas saving of 3.3 lb would be realized, and thus the capacity of the tanks would not be exceeded.

In conclusion, it appears that the projected gas requirements do not drastically exceed the maximum ACS capacity, and that a finer definition of the actual needs rather than an extensive redesign and procurement, offers the best potential solution to the problem. Also, the original guidelines do not permit a significant deviation from the IMP-I design without considerable retesting and qualification.

Subsequently, the following solution to the problem was proposed, and was transmitted in a memo dated November 27, 1972.

With time, money and manpower at a minimum, the simplest approach is to reduce the safety factor requirements and fill the system with the necessary quantity of gas to satisfy all mission requirements. Based upon the current propellant estimate, the safety factor would be reduced to 3.35 to 1 in order to accommodate 22.5 lb of propellant at a pressure of 2150 psia.

This is the worst case, and several pending factors may eventually improve the situation considerably. Analysis of the IMP-H data indicates a performance better than calculated thus allowing a reduction in the IMP-J requirements. Another item is the use of pre-mixed propellant (Freon-14 plus helium) which measures only 7% (later measured at 10.2%) helium compared to 11% for IMP-H. This has the effect of reducing the maximum fill pressure without affecting the weight of propellant onboard. Finally, a refinement of the orientation maneuvers may ultimately result in a reduction in propellant requirements.

In the interest of assuring safety for all involved, it should be pointed out that the present safety factor is based upon the design burst pressure of the tanks which is 7200 psia, whereas an actual burst pressure of 9000 psia was demonstrated. Therefore, for planning purposes, it is hereby requested that the Project Office officially obtain the necessary waivers to allow a reduction in safety factor to 3.35 to 1.

The Project Office response, dated January 29, 1973, was as follows. "The Reference memo sights the possibility that the design safety factor of the IMP-J ACS tanks may be reduced from the 4:1 of IMP-H to 3.35:1 because of a requirement for additional Freon fuel. We have reviewed this situation and find it acceptable, based on the demonstrated burst pressure of the tanks. Spacecraft prelaunch operations will not be affected, except to possibly limit the number of personnel present during ACS filling operations."

With official approval thus obtained, the ACS was assembled, installed on the spacecraft, filled and proof tested in compliance with the established safety requirements. The certification of the status of the system was documented on May 1, 1973, in the following manner.

The flight unit Attitude Control System consisting of tanks, IMP-J identification code system No. IC 2-04 and IC 2-08, and Shelf Assembly IC 5-05, completely assembled on the flight spacecraft, including all associated tubing and fittings, was successfully tested to a proof pressure of 2700 psig. on January 16, 1973 at EMR. All high pressure components in this system have been designed for a burst pressure of at least 7200 psig, and an actual test performed by the manufacturer confirmed a burst pressure in excess of 9000 psig for this particular tank design.

Due to a critical weight situation the final propellant load has not been precisely determined, however, an upper limit of 2150 psia has been established based upon the maximum mission requirements. In order to accommodate this propellant quantity without major redesign, it was necessary to reduce the safety factor from 4:1 to 3.35:1. This reduction was officially approved in a memo from Mr. W. Schindler to Mr. W. Limberis dated January 29, 1973, on the subject of IMP-J ACS Safety Factor.

Finally, components of the flight spare system, consisting of tanks IC 2-02 and IC 2-09, and Shelf Assembly IC 5-03, have also been individually proof tested to 2700 psig.

The following data was supplied on June 28, 1973.

In light of the fact that the safety code presently established at ETR concerning pressurized systems treats pressure vessels differently from associated tubing and fittings, the following additional information is provided.

The check valve and filter are both rated by the manufacturer for a maximum allowable working pressure of 3000 psig, and the stainless steel tubing and fittings are rated for a maximum allowable working pressure of 4000 psig with a burst pressure in excess of 12,000 psig. In addition, a representative assembly of the high pressure components, excluding the tanks but including the temperature probes, was hydrostatically tested to 8000 psig without failure. Thus a safety factor of 4:1 can be assured for all the high pressure components with a propellant load up to 2000 psig. The low pressure components, exposed to a constant 40 psig, all have a safety factor far in excess of 4:1.

A more comprehensive test history can be found in X-722-71-30 "IMP-I-D-4.5.5 Description and Summary of Qualification Testing of the IMP-I Attitude Control System and Yo-Yo Despin System."

It should be noted that the IMP-J ACS propellant requirements were eventually refined to be somewhat less than originally calculated, and the final allocation of 20 lb was as described in Section G. Also, a proof test to 2700 psig, which was slightly less than the required 1-1/2 times the operating pressure, was allowed in order to avoid exceeding the manufacturer's specifications for the regulator inlet pressure. In conjunction with this, the system was not to contain more than 1800 psig at anytime except during specific, isolated tests and following the final prelaunch filling. In such cases, personnel access was also limited to only those essential for specific spacecraft activities. In conclusion, then, the fact that no serious malfunctions or hazardous conditions were ever encountered, demonstrates that the safety requirements and precautions imposed on this spacecraft program were sufficiently adequate to ensure a safe working environment.

APPENDIX A

PYROTECHNICS

The various spacecraft configurations, and therefore the performance of the ACS, were directly related to the proper functioning of a set of pyrotechnics which had the sole purpose of actuating the ACS and Experiment boom deployment. Each pair of booms was deployed independently by firing two pyrotechnics, redundantly arranged so that the operation of either one was sufficient to release one pair of booms. Although the ACS was capable of operation with the booms in the folded configuration, the overall spacecraft mission would have been severly degraded by the failure of the Experiment booms to deploy. For this reason, as well as to ensure personnel safety, much effort was expended in the selection, handling and testing of the pyrotechnics used on the IMP-H and J spacecraft.

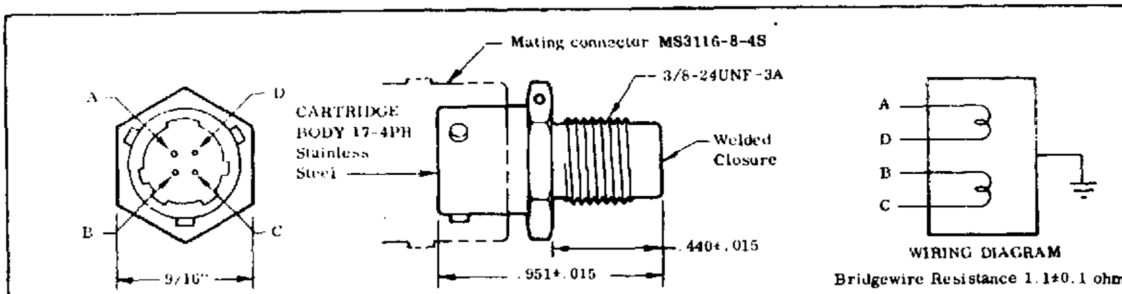
The design used in this particular application required a PC 15 Power Cartridge attached to an SL 1022 Line Cutter, and specific information on these items is shown in Figures 33 and 34, respectively. Upon receipt of the above components, a rigorous inspection and test program was established with which to verify the flight worthiness and to qualify the entire lot. This program was initially prepared for the IMP-H and is presented below.

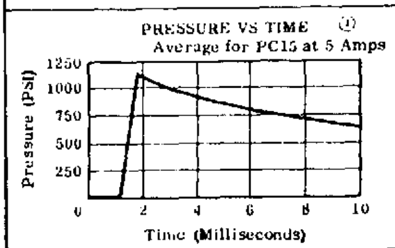
Qualification Test Program

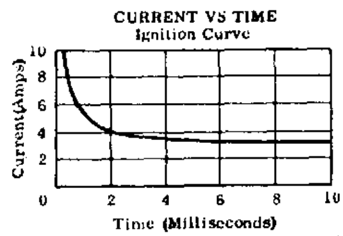
a. The Pyrotechnics intended for flight on the IMP-H spacecraft are PC-15 Power Cartridges manufactured by the Hi-Shear Corp. A quantity of 36 Power Cartridges shall be purchased from the same lot having the ignition and main charge drawn from the same mix. The lot number and date of manufacture shall be recorded.

b. Lot qualification shall be accomplished using a sample of twelve (12) power cartridges randomly selected from a single manufactured lot. All twelve (12) units shall be required to satisfactorily complete the inspections and tests prescribed in the following paragraphs. Failure of any one unit shall be cause for rejection of the entire lot.

c. These inspections and tests represent the minimum requirements for lot qualification and are in addition to those already performed by the manufacturer. The purpose for this testing is to provide screening for workmanship defects, and to determine the ability of the power cartridges to withstand the basic environment expected during the flight of the IMP-H spacecraft. The specified listing of tests does not preclude







QUALIFIED UNDER

AFMTC Ordnance Standards.
(1 amp — 1 watt no fire level for 5 minutes)
AFMTCP 80-2 General Range Safety Plan

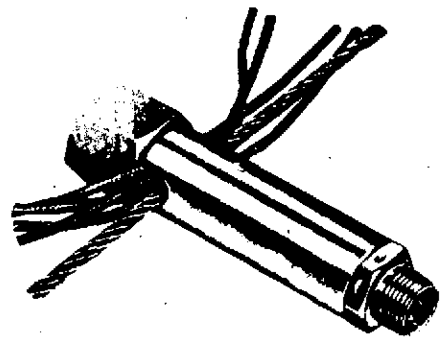
SPECIFICATION WS2383

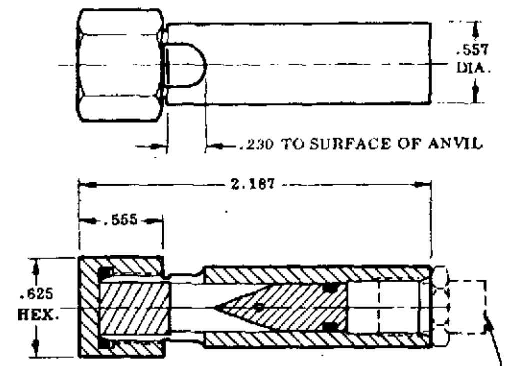
1. RECOMMENDED FIRING CURRENT
5 amps applied to one bridgewire or to each bridgewire results in an average function time of 1.2 milliseconds.
2. HIGH ALTITUDE
Has been tested to and performs satisfactorily at 550,000 feet. Can be expected to perform in conditions approaching a complete vacuum.
3. HERMETIC SEAL
All cartridges are checked at a differential pressure of approximately 10^{-5}mm of Hg for a leakage rate not to exceed 1 x 10^{-6}cc of Helium per second.
4. HIGH AND LOW TEMPERATURE
Has been tested with satisfactory performance in a temperature range of -300°F to +300°F
5. RADIATION
Irradiated in a gamma-radiation source to a total dosage of 10^9 erg/g (C) and performed within allowable limits during firing tests.
①6. MINIMUM ALL-FIRE CURRENT
Minimum recommended all-fire current is 3.5 amps to one bridgewire or to each bridgewire with time lapse.
7. ENVIRONMENTAL CAPABILITIES
Hi-Shear Power Cartridges have been designed to meet or exceed environmental conditions expected in aerospace and underwater applications. The cartridges have been tested to varied military standards and customer requirements. Details in any specific area can be supplied upon request.
8. NO-FIRE CURRENT
Cartridges stabilized to +350°F were subjected to 1-amp, 1-watt current applied for 5 minutes to both bridgewires simultaneously and were then fired at ambient temperature without evidence of degradation.
9. INSULATION RESISTANCE
100 megohms minimum insulation resistance when 500 VDC is applied between the contact pins shorted together and the cartridge body for 1 minute.
10. DIELECTRIC STRENGTH
Withstands 500 VAC (rms) applied between the contact pins shorted together and the cartridge body for 1 minute without breakdown. No arc-over, breakdown, or a transient increase in leakage current is detectable.
11. STATIC SENSITIVITY
No ignition occurs when a 500-micromicrofarad capacitor charged with 5000 volts is discharged between the contact pins shorted together and the cartridge body.
12. RADIO FREQUENCY HAZARDS
Test samples were exposed to a range of 8 megacycles to 10,000 megacycles with a power input of .10 watts to each bridgewire. All cartridges tested passed without firing or degradation as evidenced by subsequent firing tests.
13. AVERAGE PEAK PRESSURE

Cartridge	PSI (Ambient)	Test Chamber Size (C.C.)
PC15	1150	10.0

14. UNIT WEIGHT
The assembled cartridge weighs approximately .02 lb.
15. INSTALLATION TORQUE
100 ±10 inch-pounds.
16. Unless otherwise noted, data above is for local ambient conditions.

Figure 33. PC 15 Power Cartridge





"PC" SERIES POWER CARTRIDGE TO MATE WITH MINIATURE THREADED CONNECTOR (3/8-32NEF-2A Thd.) or STANDARD "PC" SERIES 3/8" POWER CARTRIDGE TO MATE WITH MS3116-E-6-4S CONNECTOR

DESCRIPTION: THE SL1022 IS A CYLINDRICAL, LIGHTWEIGHT CABLE AND WIRE BUNDLE CUTTER DESIGNED TO COMPLETELY SEVER STEEL CABLES AND WIRES UP TO 3/16THS OF AN INCH IN DIAMETER. THE BODY IS MANUFACTURED OF NONCORROSIVE STEEL, THE CUTTER BLADE OF TOOL STEEL, AND THE ANVIL AND ITS RETAINING CAP OF ANODIZED ALUMINUM. THE UNIT IS SEALED TO PREVENT GAS OR FLAME LEAKAGE FOR PROTECTION OF ADJACENT PARTS OR EQUIPMENT.

1. PERFORMANCE CHARACTERISTICS
Designed for actuation by the firing of one of Hi-Shear Corporation's PC Power Cartridges, the piston-cutter blade is restrained by a shear pin until the pressure builds up to shear the pin. The piston-blade then slams forward to the anvil, completely severing the reefing line. The line may be severed at maximum or zero tension without danger of hangup.

2. CUTTING TIME
Using the recommended PC Power Cartridge, cutting time is 5 milliseconds maximum.

3. TEMPERATURE
Functions reliably over a temperature range of from -165°F to +200°F.

4. ALTITUDE
The SL1022 Line Cutter is not affected by altitude or external pressure and is limited only by the capability of the cartridge. Hi-Shear Corporation's PC series cartridges have been qualified for use in deep space, including the Mariner 4 mid-course correction motor.

5. HUMIDITY AND SALT SPRAY
Humidity to 100% or rain and salt spray (to immersion) do not degrade operational reliability.

6. VIBRATION
The SL1022 meets or exceeds the requirements of MIL-E-5272C, Amendment 1.

7. WEIGHT
Weight of the Cutter without the Power Cartridge is 0.10 pound.

8. RECOMMENDED POWER CARTRIDGE
PC Cartridge is dependent upon diameter of line and its material. Consult our ordnance engineering staff.

9. MAXIMUM LINE SIZE
Will completely sever a steel cable or wire bundle up to 3/16ths in diameter.

10. HOW TO ORDER
Order by part number SL1022. State operational conditions and line size and type to be severed.

11. Data subject to the Limited Rights in Data clauses of ASPR Section IX, paragraph 9-203, and/or Section III, paragraph 3-506.1.

Figure 34. SL1022 Line Cutter

the requirement for special tests to determine the ability of the power cartridges to conform to sometimes unconfirmed design specifications. In instances where certain design requirements are of particular importance to the functioning or safety of the spacecraft, special tests should be conducted to confirm that the qualified lot meets these special requirements.

d. Each unit of the lot shall be examined for workmanship, packaging adequacy, indications of shipping damage and marking identification. The presence of the explosive charge within the power cartridge shall be determined by either X-Rays or Neutrographs, where practicable.

e. The bridgewire resistance of each power cartridge shall be measured and recorded, as part of the examination, using an Alinco Igniter Circuit Tester with a test current of not more than 10 milliamperes. The resistance is to be measured between pins A and D, and between pins B and C, and is to have a value between 1.00 and 1.20 ohms. The insulation resistance shall also be measured, with a megohmeter, between shorted bridgewires and the case with 500 VDC. The resistance should be greater than 100 megohms.

f. Testing will not include acceleration, but will consist of a vibration test, and separate hot and cold thermal vacuum tests. All data and test results shall be recorded according to power cartridge serial number. In order to prevent accidental firing, shorting plugs are to be installed at all times except periods of actual testing. Also the power cartridges are to be stored and transported only in a sturdy, metal container; and are to be handled only by qualified personnel. These power cartridges are designed for use with the SL 1022 cutter, also manufactured by the Hi-Shear Corp.

g. Six power cartridges shall be subjected to sine and random vibration at Protoflight Subsystems levels as specified by the Environmental Test Specification for the Interplanetary Monitoring Platform IMP-H & J Subsystems, S-320-IMP-6, revised April 1971. The sinusoidal vibration shall be according to Table IV, Schedule F; and the random vibration shall be according to Table V. In all cases, the bolt cutter shall be installed, and a rigid fixture mounting shall be used. Following the vibration tests, the bridgewire resistances shall be measured and recorded. Three of the vibrated units shall be included in the thermal vacuum cold soak, and the other three in the hot soak.

h. The thermal vacuum cold soak test is to be conducted at a pressure of 1×10^{-5} mm of mercury or lower and shall include three vibrated units plus three other non-vibrated units. Each power cartridge is to be mounted on the rigid fixture and have a bolt cutter and bolt specimen installed and secured. Firing is to take place at -60°C and after a minimum soak time of 24 hours at that temperature. In all cases, the fixture temp is to serve as the control. Four units are to be fired at the recommended firing current, 5 amps, at 4.2 volts, and the other two at the recommended firing current with 20 volts. These voltages are to be applied to both bridgewires simultaneously.

i. The thermal vacuum hot soak test is to be conducted under the same set of conditions as the cold soak test, using three vibrated and three non-vibrated power cartridges, except that firing is to take place at +40°C.

j. Qualification Test Flow Chart:

Specific serial numbers shall be assigned for each case.

Vibration (6 units)	Cold Soak:	Fire 2 at 4.2 volts
		Fire 1 at 20 volts
	Hot Soak:	Fire 2 at 4.2 volts
		Fire 1 at 20 volts
No Vibration (6 units)	Cold Soak:	Fire 2 at 4.2 volts
		Fire 1 at 20 volts
	Hot Soak:	Fire 2 at 4.2 volts
		Fire 1 at 20 volts

k. To completely qualify the power cartridges as they are used in their actual spacecraft application; it is also recommended that a full compliment be installed on the spacecraft for the vibration test and fired during subsequent deployment tests. Similarly, a full compliment of power cartridges should be installed on the spacecraft for the thermal vacuum test and fired at a time simulating flight conditions.

l. A successful firing will be indicated by an open circuit through each bridgewire and a completely severed bolt specimen.

m. If the equipment is available, a no-fire current test shall be performed on all twelve (12) power cartridges. In this test, one (1) volt is to be applied to each bridgewire for a period of five (5) minutes, with the current limited to one (1) amp, and none should fire. This test is to precede the vibration test and also include a bridgewire resistance measurement following the no-fire current application.

n. Other recorded information:

Lot number	13-31800
Date of manufacture	April 1971
Date and number received	12/1/71, 36 units
Ignition mix batch no.	021 lot 7-22-70
Main charge mix batch no.	002 lot 13-31581-1
Purchase order no.	NAS 5-18090
Flight serial numbers	89043, 89077, 89084, 89105

The IMP-J lot qualification test program was basically the same as that for IMP-H, but with the following modifications. Only six power cartridges were selected, at random, for testing. These were vibrated and then split into two groups of three each, with the first group being fired at +35°C with 4.2 volts, and the second at -20°C with 4.2 volts. No attempt was made to achieve vacuum conditions for these tests, and the voltage corresponds to the minimum all fire current at the highest allowable resistance. In addition, four power cartridges were selected at random from the remains of the IMP-H lot and were fired under ambient conditions with 20 volts. The pyrotechnics from this lot, which had been in storage for approximately one year, were assigned only to the various spacecraft environmental tests at GSFC. The IMP-J flight pyrotechnics were selected from the new lot and the pertinent information was as follows.

Lot number	13-32631
Date of manufacture	June 1973
Date and number received	7/13/73, 30 units
Ignition mix batch no.	021 lot 13-32080
Main charge mix batch no.	002 lot 13-32400
Purchase order no.	NAS 5-18985
Flight serial numbers	01955, 01961, 01963, 01972

All of the above testing was done in addition to the lot qualification tests performed by the manufacturer prior to shipment to GSFC. Upon completion of all the testing, the following information was transmitted for IMP-H and J respectively.

The IMP-H Pyrotechnic Qualification Test Program has been completed and the PC-15 power cartridges from lot no. 13-31800 are considered qualified for flight.

Of the 36 power cartridges purchased, twelve (12) were fired during the qualification test program and all performed nominally.

Testing was completed on February 4, 1972, at GSFC.

The IMP-J pyrotechnic qualification test program has been completed and the PC-15 power cartridges from lot no. 13-32631 are considered qualified for flight. Of the 30 power cartridges purchased from this lot, six (6) were fired under representative extreme flight conditions and all performed nominally. In addition, four (4) of twenty four (24) PC-15 power cartridges purchased from the same lot qualified for IMP-H, no. 13-31800, were fired under ambient conditions and all performed nominally.

Testing was completed on August 20, 1973, at GSFC.

Indications are that all pyrotechnics performed nominally for both spacecraft after launch.