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EVOLUTION OF THE 1-mlb MERCURY ION THRUSTER SUBSYSTEM

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ABSTRACT

A general description and review of the auxiliary Electric Propulsion program, which led to the present 1-mlb (4.5 mN) thruster system, is presented. The developmental history, performance, and major lifetests of each component of the system are traced over the past 10 years. Major components include the 8-cm diameter ion thruster, the power processor, and the propellant reservoir and distribution system.

INTRODUCTION

The purpose of this paper is to define the present 1-mlb mercury ion thruster subsystem and key technology milestones in its development. In 1977, the fabrication of the first Engineering Model Subsystem and the first six Engineering Model (EM) 8-cm ion thruster was completed. Testing of the thrusters and subsystem began in the summer of 1977 and is continuing at the time of this writing (Jan. 1978). The results of these tests have been presented by others (refs. 1 to 3).

The 1-mlb thruster subsystem consists of an 8-cm diameter ion thruster mounted on 2-axis gimbals, a mercury propellant tank, a power electronics unit (PEU), a controller/digital interface unit (DCIU), and necessary electrical harnesses plus propellant tankage and feed lines. This thruster subsystem is described in detail by reference 4. Basic elements of the 8-cm diameter thruster have designs that were firmly established based on results of testing conducted in 1976 or earlier (refs. 5 to 19). Plans for an approved 1981 flight test of a mercury ion auxiliary propulsion system, which contains two 1-mlb thruster subsystems, are discussed in references 20 to 22.

This paper will discuss the historical evolution and characteristics of each major component and element that comprise the 1-mlb thruster subsystem. Definitions of terms used are listed in the appendix following the Concluding Remarks.

THRUSTER SUBSYSTEM FUNCTION AND DESCRIPTION

The 1-mlb thrust subsystem was developed primarily to provide for north-south stationkeeping of geosynchronous satellites with masses between 500 and 2000 kg. The subsystem can also provide for attitude control, east-west stationkeeping, and station change in addition to the n-s stationkeeping function. The specific design is directed toward mission durations of about seven years. Provision for other length missions is available merely by variation of propellant loading and/or tankage with no change required in any other subsystem component. Normally, an auxiliary propulsion system consisting of a minimum of two mercury ion thruster subsystems is required on satellites of present interest.

A functional diagram of the 1-mlb thruster subsystem is shown in figure 1 and a photograph of the first Engineering Model Thruster Subsystem is shown in figure 2. The major components of the thruster subsystem are given in table I along with the general function of each. A description of the salient characteristics and status of each component will be presented separately below.

A. 8-cm thruster/gimbal/beam shield

1. Description

An Engineering Model 8-cm thruster/gimbal/beam shield is shown in figure 3 and a cutaway showing the critical thruster elements is presented in figure 4. The major characteristics of the thruster are given in table II. The thruster consists of several critical elements: the discharge chamber, the two cathode-isolator subassemblies, the accelerator grids, and the beam shield. These elements are integrated by the support structure and surrounded, except for the downstream end, by the ground shield. A detailed description of the evolution of these components and detailed descriptions of function, requirements, and status is given later.

2. Summary Status

The thruster has been developed to the Engineering Model level. The documentation is presently sufficient to allow thruster replication by part number by the present vendor. At present, six Engineering Model Thrusters (EMT's) have been fabricated and two have successfully demonstrated all functions in a thruster subsystem level test. The other four await testing in various aspects of the 1981 flight and auxiliary propulsion technology programs (refs. 2, 20 to 22). The

structural design has been verified by launch level vibration testing of a thruster structurally identical to the EMT.

Nearly all aspects of the EMT design have been successfully verified in one or more long duration functional tests on the thruster component and/or element level. Of particular significance was a successful 15 000 hour 460 cycle test of a pre-EMT design. This test, while completely successful, did point out several areas of design weakness. These areas were addressed and solutions incorporated on the present 8-cm EMT design. In addition, an accelerated 5000 cycle (the number of cycles appropriate for 14 years of north-south stationkeeping) test has been completed and two cathode-vaporizer-isolator tests are successfully in progress at 8000 cycles. Most of the critical technology elements of the 8-cm EMT have been verified on the ground and in space over the many years of the auxiliary electric propulsion technology program.

The beam shield is a relatively new addition to the thruster and only limited thruster testing with this component has been completed. Verification tests of this component are in progress (ref. 1), and two long duration tests of the 8-cm EMT with a beam shield are presently planned. The beam shield is considered a mission-specific element of the thruster subsystem.

B. Propellant Tank, Valve, and Feed Unit

1. Description

Figure 5 shows a functional diagram of the Propellant Tank, Valve, and Feed Unit (PTVFU) and figure 6 shows a cutaway of the propellant tank showing critical components. The propellant tank is the blow-down type with a butyl rubber diaphragm separating the pressurant (N_2 plus 20 percent krypton for leak checking) from the liquid mercury. The major characteristics of the propellant tank are given in table III. Other major elements of the PTVFU for the 1981 flight are: a temperature transducer mounted on the propellant tank, a pressure transducer plus the solenoid latching valve between the tank and the thruster. A flexible metal tubing section which allows for thruster gimbaling is located within the gimbal support structure.

2. Summary Status

The propellant tank has been developed to Engineering Model status and sufficient documentation is established to allow industry replication by part number. One EM level tank has been fabricated along with several pre-EM tanks (of identical design). The propellant tank technology is identical to that developed for the

SERT II thruster system which was successfully qualified and has been verified in space (four tanks) for almost eight years (ref. 28). Two ground tests of 12 000 and 14 000 hours duration were successfully completed with tanks of the EM design (ref. 10). In summary, the tank technology and design is firmly established and ready for flight application.

Qualification of a propellant valve design will be carried out in the SAMSO-601 flight project activity. A solenoid latching valve has been selected and has undergone preliminary testing. Long term testing of the valve will be done in ground endurance testing of a complete EM subsystem. A spiral coil of propellant feed line, to provide gimbal flexibility has been designed into the gimbal support structure and verified in functional tests.

C. Gimbal

1. Description

Figure 7 shows the 8-cm EMTS gimbal and its critical components. The major characteristics of the gimbal system are given in table IV. Gimbaling is provided in two orthogonal directions ($\pm 10^\circ$ in each axis) by a two-actuator drive design. The design does not require mechanical lockdown devices to withstand launch loads. Bearing surfaces are made of Vespel* and, therefore, are self lubricating. The gimbal requires powder only when active gimbaling occurs. The gimbal angle, which is not directly sensed in the present design, is specified by initial location documentation and knowledge of subsequent gimbal command history.

2. Summary Status

The gimbal design was produced by the Lewis Research Center and is at the Engineering Model level. The documentation is sufficient for replication by industry. Three EM level gimbals have been fabricated. Two at the Lewis Research Center and one at the vendor. The design was structurally verified by launch vibration level tests with a thruster mass dummy and further characterized by low level vibration tests with a lab model thruster. Thermal vacuum testing of the gimbal has been limited to date to a short (~200 hr) thruster subsystem test (with the vendor supplied gimbal). This test confirmed the basic compatibility of the design with the vacuum and thruster environments. Functional cyclic operation of the in-house fabricated gimbals has been successfully demonstrated by tests at the Lewis Research Center in ambient pressure. Tests with the vendor produced gimbal were generally successful with the exception of a binding

* Vespel is a trade name for DuPont polyamide plastic.

difficulty experienced during a 10-cycle thruster subsystem test. The cause of the binding has been determined and mechanical tolerance specifications have been changed to address the problem. Present gimbal tests at temperature extremes of 70° and -20° C indicate no problem (ref. 4).

D. Beam Shield

1. Description

Figure 3 shows a beam shield mounted on the thruster. The beam shield is intended to protect spacecraft surfaces such as solar arrays from deposition of thruster efflux. The efflux of most concern is the molybdenum atoms, sputtered from the thruster accelerator grid. This shielding may be required when body-mounted thrusters are used for n-s stationkeeping.

The beam shield is made of a graphite fiber-reinforced polyimide composite. It is 0.11-cm thick and has a mass less than 0.3 kg. It is formed from a 160° section of a 25-cm diameter cylinder, which allows the interception of thruster efflux that is more divergent than a 45° half angle at the azimuthal center of the shield. The beam shield cylindrical axis is colinear with the thrust axis of the thruster. The beam shield is electrically insulated from the thruster.

2. Summary Status

The beam shield has been developed to the Engineering Model level and sufficient documentation is established to allow replication by part number. The mechanical strength was proven in successful vibration tests in which the shield was attached to a thruster mounted on a gimbal structure assembly.

The functional capability was demonstrated: (1) by attaching a beam shield to an EM thruster and measuring thruster efflux patterns and beam shield erosion (ref. 1); and (2) by extensive measurements of the ion beam plasma with and without a beam shield (ref. 30). Major ground life tests of an 8-cm thruster subsystem, including a beam shield are planned.

E. Powder Electronics Unit

1. Description

Figure 8 shows a functional diagram of the Powder Electronics Unit (PEU). Major characteristics of the PEU are given on table V.

The major functions of the PEU are to process the power for nine separate thruster power loads and to provide the interface with the primary spacecraft

power system. The PEU is comprised of six modules, five of which provide processed power to the thruster with the remaining module providing for input filtering, line regulator, and other executive level power processor functions. The PEU is designed to be tolerant of and self protective from all anticipated output load conditions.

2. Summary Status

One Engineering Model of the PEU was fabricated and functional capabilities verified in vacuum during the thruster subsystem level test. One design deficiency was uncovered in this test and has been rectified. In addition, a thermal vacuum breadboard, using the same basic circuitry, was fabricated and has been operated extensively with a thruster at the Lewis Research Center.

In summary, the PEU circuitry is well established and operationally verified. Extended testing of both the breadboard and EM PEU is planned to provide additional confidence in the design.

E. Digital Interface Unit

1. Description

The DIU consists of individual circuit cards physically integrated into a box. Major characteristics are listed in table VI. The DIU presently is a separate component of the thrust subsystem, but later will be physically incorporated with a controller. The combined component will be called a Digital Controller Interface Unit (DCIU). For purposes of this paper the DIU and Controller will be discussed separately.

The DIU interfaces 16 bit serial commands and provides 8 bit data response from the spacecraft to the PEU. It also provides for (1) automatic thruster recycle following a H. V. overload; (2) main and neutralizer vaporizer flow control loops; (3) a limit for the PEU input power of 200 watts; (4) drive to the gimbal motors; (5) provides conversion of input digital commands into analog control signals to the PEU; and (6) provides conversion of analog telemetry signals from the PEU into 8-bit digital data output.

2. Summary Status

One EM model of the DIU has been fabricated and tested. Engineering drawings exist and are suitable for fabrication by the contractor. Operational capability has been demonstrated. Static and dynamic load tests indicated ability to withstand all expected electrical transients. These tests included a 10-cycle,

thermal-vacuum, test with the EM PEU and first 8-cm EM thruster. For these tests, a consol enabled command and logic signals to be fed into the DIU.

F. Controller

1. Description

A microprocessor and associated peripheral circuits of the RCA CDP 1802 family have been selected as suitable for meeting the major 1 mlb thruster subsystem requirements. These circuit components have been fully certified to MIL-M-38510C in the 2nd Quarter 1977 by the RADC (Rome Air Development Center). Lewis personnel have verified with RADC that these circuits are qualified and available to satisfy the flight schedule. In addition, a fully licensed second source exists for these devices.

No special criteria exist other than that normally applied to the fabrication of CMOS technology, aerospace hardware. The packaging concept should allow for sufficient modularity, such that memory can be easily replaced or added should different memory types be desired (RAM, PROM, ROM). A flight package concept will include all controller boards in the DIU box by slight extension of the length with no change in width or height.

2. Summary Status

Basic functional algorithms using a proto EM 8-cm thruster have been determined and programed for a microprocessor which controls the thruster subsystem over its nominal startup, operate, and shutdown cycle. Development of flight software will require additional algorithm development to provide for nonnominal operation, component aging, and mission peculiarities.

EVOLUTION OF THE 1-mlb THRUSTER SUBSYSTEM

A summary block diagram depicting the evolution of the 1-mlb thruster subsystem is shown in figure 9. This figure also will serve as an outline for the following sections of the paper. The development history of each subsystem element of component is roughly represented by a downward flow to the present 1-mlb thruster subsystem represented within the dashed-line area at the bottom of the figure. The evolution of each element or component will be discussed individually below.

8-CM EM THRUSTER

In 1961 to 1962 a research program was carried out to determine scaling laws for the Hg-bombardment thruster (ref. 23). This program included evaluation of 5-cm, 10-cm, and 20-cm diameter thrusters and led to establishment of basic thruster scaling laws. Included among these were the discoveries that for optimum performance of the discharge, magnetic field strength should be proportional to the reciprocal of the diameter and that the chamber length remain approximately constant. Subsequent to this activity the electric thruster technology effort focussed on primary propulsion applications and specifically on the SERT I development program. This development culminated in a successful flight test in 1964 with a 10-cm thruster. This effort pointed out the need for shielding the high voltage surfaces of a thruster from the thruster-induced plasma. This shielding may be solid or perforated to permit gas to escape. SERT I tests showed that the perforations need not be any smaller than one-third the distance from the perforation to the thruster 3 kV surface. SERT II thruster shielding had no design problems. The 8-cm thruster uses solid shielding because outgassing is low and gas can escape through the accelerator grids without problem.

In 1964 to 1966 time frame technology efforts continued to concentrate on primary electric propulsion and a 15-cm size thruster (6.3 mlb) was selected as (1) being typical of primary propulsion needs as then envisioned and (2) that to be flown on the proposed SERT II mission (ref. 24). As a possible backup to the SERT II program and to address emerging interest in auxiliary propulsion applications, a six-month development program was conducted in 1965. This program used the 5-cm thruster of 1962 as a starting point, optimized its discharge chamber configuration, and added then present state-of-the-art cathode technology. The cathodes used a metal brush coated with BaO. While capable of 4000-hour life, they required high heating power and refurbishment after each exposure to air. In an attempt to further increase cathode life, a magnetic cathode pole piece was added to raise the magnetic field strength near the cathode. The cathode pole piece did not improve the cathode life; but the new magnetic configuration resulted in higher discharge chamber performance. The cathode pole piece concept has been retained in all thrusters designs that have subsequently evolved.

The SERT II flight project was approved in 1966. Several thruster technology improvements were developed and/or initially evaluated during the SERT II project. Hollow cathodes were developed, which possessed significant advantages over previous thermionic emitter designs. These included longer lifetimes, lower heater requirements, and very important, the ability to be used

after exposure to atmosphere without refurbishment. In addition, the use of baffles between the main cathode and the anode was required with hollow cathodes. This concept was borrowed from earlier HRL work with liquid metal cathode thruster technology. The baffle served to control the impedance of the main discharge and allowed optimization of discharge chamber performance consistent with long lifetime. The use of both hollow cathodes and baffles has been retained in all subsequent electron bombardment thrusters. In 1969 with the SERT II technology development program nearly completed, serious attention was again directed to auxiliary propulsion. SERT II technology was applied to the 5-cm thruster design and an optimization program was carried out (ref. 25). This program (1969 to 1971) introduced the concepts of a single propellant flow to the main discharge chamber through the main cathode. This concept remains as the present small-thruster flow philosophy. In addition, the important innovation of an enclosed cathode keeper was added to the 5-cm thruster design. The enclosed keeper resulted in power efficient main and neutralizer discharges, also, the enclosed keeper enabled the neutralizer to operate at low propellant flow rates which resulted in higher thruster system efficiency.

At this time (1971 to 1972), a contract was awarded to structurally integrate the 5-cm thruster (ref. 16). The concept of structurally and thermally integrated Cathode-Isolator-Vaporizer (CIV) and Neutralizer-Isolator-Vaporizer (NIV) assemblies was developed. The cathode used a SERT II hollow cathode-type design with a tantalum-rolled foil BaO-coated insert and a flame-sprayed heater (ref. 26). The isolator used a design that was originally conceived by Hughes Research Laboratories for the SERT II program, and adequately met the isolator voltage requirement (1.1 kV) of the 5-cm structurally integrated thruster (SIT-5) (ref. 16). The vaporizer used the SERT II vaporizer design of a porous tungsten plug. The porous plug controls the mercury liquid interface and when heated passes a controlled flow of vaporized propellant. The CIV and NIV technology stemmed from SERT II and has remained without need for major change over the past six years. The mechanical design of the CIV, NIV, and thruster body was verified through the successful completion of vibration testing and thermal operation.

A 5-cm thruster of the SIT-5 design was life tested for 9715 hours with the test ending in 1972 (ref. 9). This test indicated that the Hg-bombardment 1/2-mlb thruster did have the lifetime capability required for 5- to 10-year on-orbit station-keeping missions. Several thruster design changes were made as a result of this test to further increase the thruster lifetime: (1) Flake control procedures were instituted, i.e., mesh surfaces to retain flakes and graphite baffle to reduce erosion (ref. 12); (2) The electrostatic vector accelerator grid concept was dropped because no easy way was seen to increase the design life; (3) The neutralizer flow was increased in order to reduce neutralizer cathode tip erosion

(ref. 10); and (4) Both cathode insert designs were changed to an impregnated porous tungsten type because of commercial availability and less functional dispersion between cathodes (ref. 27). Also by this time (1972) the probable mass of future synchronous satellites had increased, and to obtain a higher thrust without sacrificing lifetime, the thruster diameter was increased from 5 to 8 cm (ref. 10).

In 1973, a contracted effort began to develop a structurally integrated 8-cm thruster (SIT-8). The CIV and NIV remained unchanged from the SIT-5 design. The discharge chamber and grid diameters were increased to 8-cm. Previously developed scaling laws led to a lower magnetic field strength (ref. 23). A parallel in-house program evaluated solutions to flake control (ref. 12) and neutralizer tip erosion problems (ref. 11). A 1000-hour thruster (LAB-8) test was begun to verify the use of mesh surfaces, a graphite baffle, and a conventional dished grid optics design. A delamination problem of the pyrolytic graphite baffle at 1100 hours was cured by use of isotropic graphite and the remainder of the 15 000-hour test of the LAB-8 thruster was completed (ref. 6).

The results of the 15 000-hour test led to the following design changes:

(1) substitution of tantalum for graphite in the baffle and tantalum cladding of certain chamber surfaces because tantalum exhibited a lower erosion rate than graphite; (2) the use of grit blasting of mesh surfaces to aid in flake retention; (3) replacement of the cathode insert design back to the SERT II type because the impregnated porous tungsten type required, with time, additional (and perhaps excessive) heating power; (4) reduction of accelerator grid voltage and use of Small Hole Accelerator Grid (SHAG) design to increase accelerator grid lifetime (ref. 13). The use of small holes in the accelerator grid adds four benefits to the thruster: (1) more metal remains in the grid for erosion by sputter ions; (2) the accelerator grid may be run at lower voltages which reduces sputter rate; (3) less neutrals escape through the smaller holes, producing less charge exchange sputter ions; and (4) the thruster efficiency is increased by the lower loss of neutrals (ref. 14).

All these design changes were incorporated into the SIT-8 design and a thruster was fabricated to the new design. This design, completed in 1975, remains with minor modification as the present EM design. This SIT-8 thruster was placed into thermal-vacuum and launch-level vibration tests, which led to minor structural modification (ref. 18). In operation, however, the thruster control was marginal and other minor design changes (baffle support, etc.) were made to correct the discharge loop control stability. The incorporation of these latter changes resulted in the prototype 8-cm thruster.

The 15 000-hour test proved the steady-state durability of the thruster and its cathodes, but only limited information as to the integrity of the thruster after

many restarts. To address restart stress, a proto-EM thruster was placed through 5000, 1-hour cycles (ref. 5). This test indicated little change during the first 3000 cycles, with some deterioration in the last 2000 cycles. The test may be capable of reaching 10 000 cycles, and is continuing after a brief stop to perform a thruster inspection. In parallel ongoing tests a separate CIV and NIV have been restarted 7000 times (2-hr cycle) toward a goal of 10 000 cycles (ref. 7). This test showed little deterioration up to 4000 cycles at which point, an increased cathode heater power was used to enable cathode starting. The heater increases are within the design capability of the EMT and are incorporated in the Flight System logic.

The thruster ground shield traces its design back to SERT I where it was first used to stop electrons or ions in the plasma surrounding the thruster from reaching HV surfaces of the thruster. It is a passive element and has no wear-out mode. An additional function, required of the 8-cm EM ground shield, is to shield certain electric insulators from neutral or charged efflux emanating from the thruster system or spacecraft.

The chief concerns for the ground shield are mechanical integrity and resistance to deposit peeling. The EM design has successfully passed launch level vibration testing. Deposit surfaces are grit-blasted to insure retention of the small quantity of deposition measured during the 15 000-hour LAB-8 test (ref. 12).

The result of the technology program to date has been built into six 8-cm EM thrusters. The first of these thrusters has passed thermal-vacuum and launch-level vibration as well as 10 full operating cycles using the EM PEU, DIU, and EM propellant tank (ref. 4).

POWER ELECTRONICS UNIT

The evolution of the PEU traces back to the SERT I program which used a transistor-inverter design to power the thruster. The SERT II power conditioner also used transistors and multiple inverter circuitry. The SERT II FC history includes two flight units with no element failure after 8 years in space, 200 thruster restarts, 5000 hours operation (total of two) and 30 000 spacecraft thermal cycles caused by eclipse occultation of the satellite (ref. 28). In addition, there were two major thruster system tests with the power conditioner in vacuum conducted for 8000 and 5000 hours without failure (ref. 24).

Laboratory consoles and design work for a 5-cm proposed thruster system for the Communication Technology Satellite (ref. 29) provided background information for the design of a 8-cm thruster Thermal Vacuum Breadboard (TVBB) PEU. The TVBB PEU in turn was used to design the 8-cm EM PEU. The design philosophy since SERT I has been to use state-of-the-art proven transistor and

circuitry design. Only after component technology advances were demonstrated and space qualified were they incorporated into thruster power processor designs. The bus voltage, 70 ± 20 V, was selected to be representative of future spacecraft that may use this level of bus voltage.

The TVBB PEU has successfully passed individual module performance tests, as well as thermal vacuum tests (over limited temperature range) of the completed PEU assembly. The EM PEU has been functionally tested in the first complete subsystem for short periods of time (ref. 4). The mechanical design of the EM PEU is suitable for a flight qualification program to the vibration levels of a Thor-Agena launch, but no vibration testing yet has been done. The thermal design is suitable for pallet mounting at the end of a solar array wing with 1.0 sun input from one direction and radiation cooling from nonsun directed surfaces. The EM PEU may also be located within a spacecraft body and conduct its waste heat to a base plate mounting surface.

DIU - CONTROLLER

The Digital Interface Unit was designed using state-of-the-art circuit and component technology. The input to the DIU is in 16-bit digital-word format for compatibility with an onboard spacecraft computer. A conceptual controller design exists to satisfy the requirements of the 1-mlb thrust subsystem. The controller hardware development should be one of the straightforward design and fabrication using conventional techniques. It will require developing an algorithm for the thrust subsystem operation and verifying its correctness.

A functional lab model controller has been developed and autonomous control has been demonstrated using the TVBB EMT (ref. 20). These tests demonstrated that functional algorithms can be developed for a microprocessor which controls the thrust subsystem over its nominal startup, operate, and shutdown cycle.

PROPELLANT TANK

The propellant tank technology flows, unchanged, from that of the 1970 SERT II thruster system, i. e., a stainless steel blowdown tank with a butyl rubber diaphragm separating the gaseous nitrogen from the liquid mercury (ref. 24). (Twenty percent by volume of Krypton gas is added to the N_2 to serve as a tracer gas to check for system leaks.)

The SERT II flight Hg-feed systems (four individual feed tanks) have shown no difficulty after 8 years in space, including 30 000 spacecraft thermal cycles

up to 3500 hours of Hg propellant feed and over 200 thruster start cycles (ref. 28). The same design propellant tanks successfully supplied Hg in two thruster system ground tests of 8000 and 5000 hours (ref. 24).

Testing of tanks designed for the SIT-5 or SIT-8 programs include expulsion tests of 14 000 and 12 000 hours and without problem. (No propellant tank was used for either the 9715-hour LAB-5 or the 15 000-hour LAB-8 thruster tests.) Two possible problem areas are mercury corrosion of the tank materials and N₂ leakage through "O" ring seals. Neither of these effects have been observed nor are expected to be a future problem. An EM-design tank was used to perform a 10-cycle T/V test of the first 8-cm EMTS with no propellant flow problem.

GIMBALS

The gimbal system is functionally similar to the SERT II, i. e., providing $\pm 10^\circ$ vector capability in two orthogonal directions. The actual mechanical design has been sized and designed to the mass of the 8-cm EMT. Gimbals have been used in launch level vibration tests of the EM design thruster with no problem and cyclic gimbal testing is planned in the future. The gimbals have been designed and fabricated using standard mechanical design criteria used for the SERT II gimbals. No known problem areas exist in the gimbal design.

CONCLUDING REMARKS

The 8-cm diameter, 1-mlb, mercury ion thruster is ready for flight application. An Engineering Model Thruster Subsystem has been designed and fabricated. Two Flight Thruster Subsystems will be tested in space in 1981. This paper describes the hardware and functional capability of the thruster subsystem, as well as summarizes the tests and design evolutions that led from 1962 research tests, through development tests of the early to mid 1970's, to the present (Jan. 1978) 1 mlb thruster subsystem EM design.

APPENDIX - DEFINITIONS

Mercury Ion Auxiliary Propulsion System - contains two or more, 1-mlb ion thruster subsystems.

1-mlb thruster subsystem - an 8-cm diameter ion thruster and supporting components.

Component - one of the parts of a 1-mlb thruster subsystem listed in table I.

Element - one of the major parts of a component or unit.

Engineering Model (EM) - hardware or design that is flight qualifiable without need for major change.

Engineering Model Thruster (EMT) - a thruster made to EM design

Lab Model Thruster - Functionally equivalent to the EMT, but not structurally made to EM specifications

P 80-1 - U. S. Air Force designation for shuttle-launched spacecraft that will space test a Mercury Ion Auxiliary Propulsion System in 1981.

SAMSO-601 - U. S. Air Force designation for the Mercury Ion Auxiliary Propulsion System aboard P 80-1

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TABLE I. - 1-mlb THRUSTER SUBSYSTEM COMPONENT LIST

Component	Quantity	General function
8-cm diameter thruster	1	Convert input electrical power and propellant into directed thrust. Beam diameter is 8-cm.
Beam shield (element)	1	Shield spacecraft surfaces from atom and ion efflux of thruster beam. If used, design is specific for mission.
Gimbals (element)	2	Provide for two axis orthogonal thrust vectoring.
Propellant Tank, Valve, and Feed Unit (PTVFU)	1	Store and distribute necessary propellant to the thruster. Capacity may be varied to mission requirements.
Power Electronics Unit (PEU)	1	Process raw power for the thruster.
Digital Interface Unit (DIU)	1	Provide command and telemetry interface between the spacecraft and PEU. Provide for all but spacecraft executive level control of the subsystem.

TABLE II. - 8-cm THRUSTER

Thrust level	4.9 mN (1.1 mlb)
Input power to PEU (120 W to thruster)	160 W
Propellant flow rate	0.7×10^{-3} kg/hr
Specific impulse	2670 sec
Mass of thruster	2.2 kg
Thruster envelope, without beam shield	23 × 18 cm diam
Thruster envelope, with beam shield	42 × 25 cm diam
Operational lifetime goal	20 000 hr
Cycle goal	10 000 cycles

TABLE III. - EM PROPELLANT TANK

Dry mass	1.2 kg
Propellant mass (12 500 hr)	8.75 kg
Ullage fraction ^a	2 to 5 percent
Material	Stainless steel
Blowdown ratio (empty/ful)	2:1
Pressurant (2.4 atm)	80 percent N ₂ , 20 percent K ₂
Envelope size	16 × 18 cm diam ^b

^aUllage may be varied by off-loading of propellant.

^bO. D. of mounting flange.

TABLE IV. - GIMBAL AND THRUSTER SUPPORT

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Mass	1.5 kg
Power requirements:	
When gimbaling (per gimbal)	7 W
When not gimbaling	0 W
Input voltage	24 V
Input current	0.25 A
Gimbal capability	$\pm 10^\circ$
Gimbal rate	2 min, full travel
Design cycle goal	10 000 full travel
Position identification	Limit switch at end of travel + pulse counting
Envelope size	15 x 14 x 14 cm

TABLE V. - POWER ELECTRONICS UNIT

Mass, total (nominal)	7.0 kg
Efficiency	75 percent
Input primary power,	
Nominal	160 W
Maximum	200 W
Magnitude	70 V
Voltage range	50 to 90 V
Control input (analog and digital)	28 \pm 6 V
Component	
Mass	3 kg
Number	888
Reliability (7 years)	0.958
Envelope	11 x 22 x 43 cm

TABLE VI. - DIGITAL INTERFACE UNIT

Mass	3.2 kg
Efficiency	92 percent
Input power (at 28 V)	
DIU circuits	3 W
Housekeeping inverters	4 W
Gimbals (when actuated, one/two)	7/14 W
Component number	939
Reliability (7 years)	0.883
Envelope	11 x 22 x 25 cm

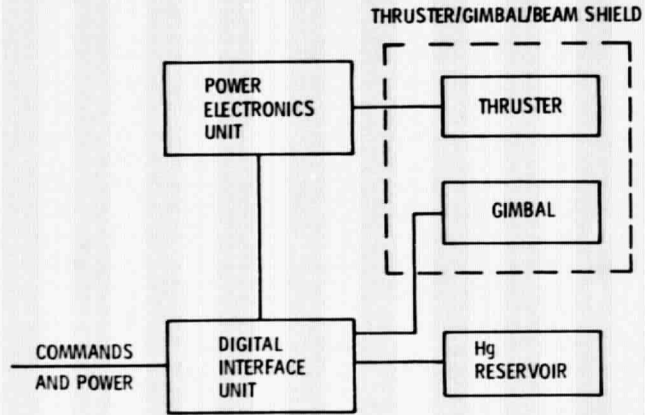


Figure 1. - Functional diagram of the 1-mlb thruster subsystem.

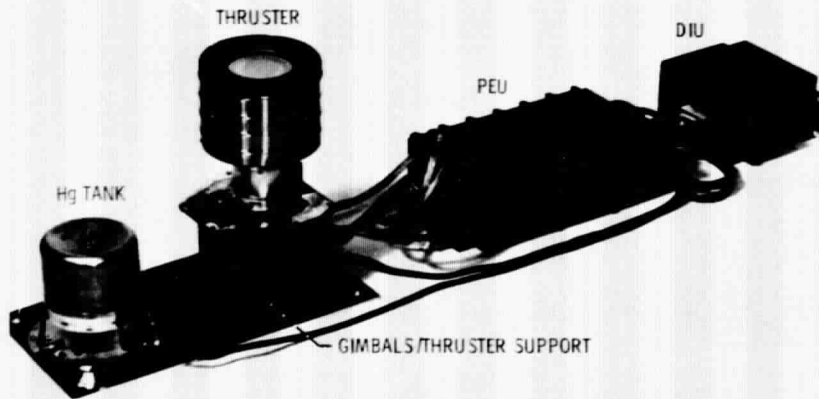


Figure 2. - 1-Mlb thruster subsystem (without beam shield).

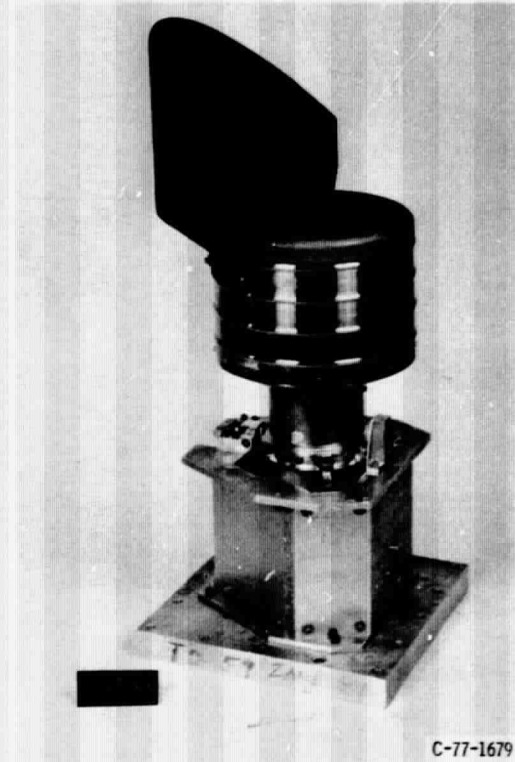
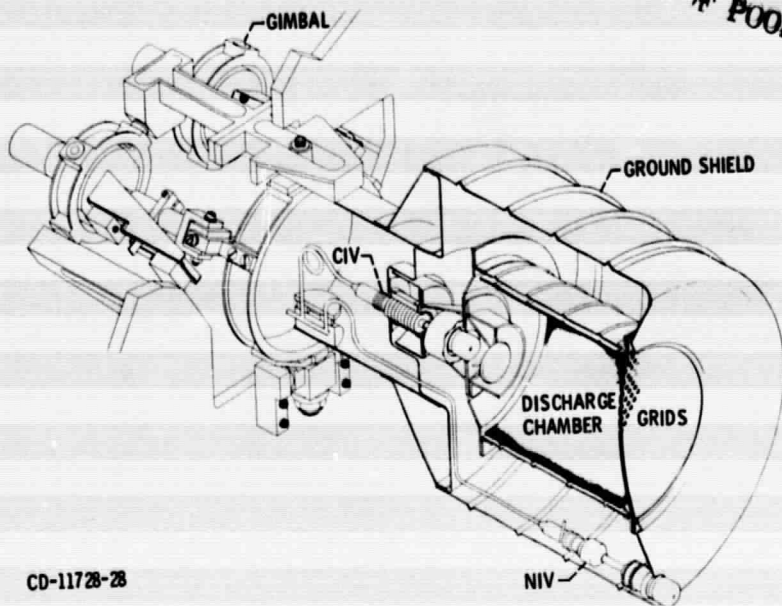


Figure 3. - 8-Cm EM thruster/gimbal/beam shield.

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Figure 4. - Engineering model 8-cm thruster showing gimbal structure.

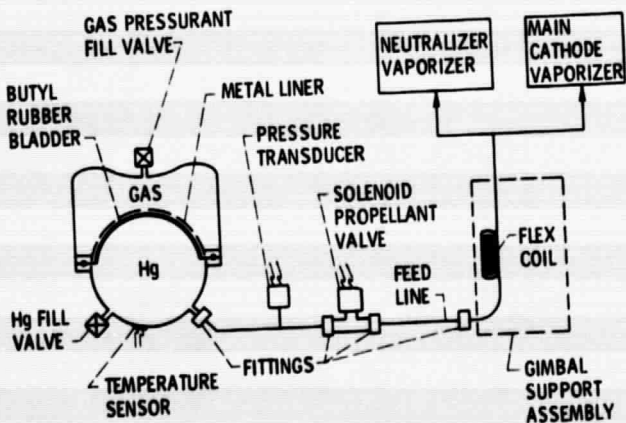


Figure 5. - Propellant tank, valve, and feed schematic for 8-cm mercury thruster subsystem.

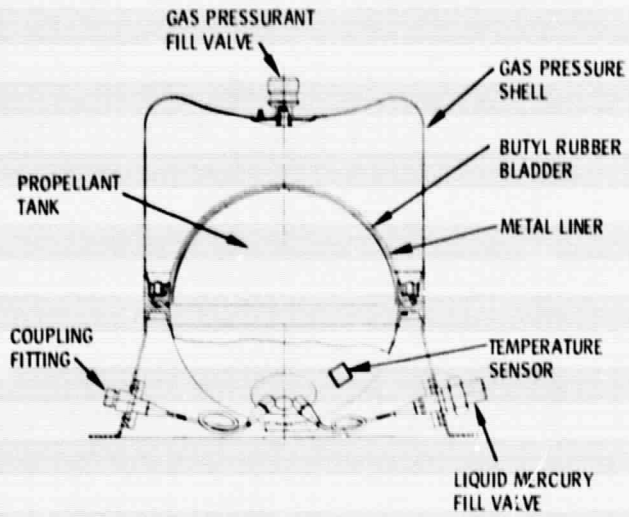


Figure 6. - Mercury propellant reservoir for 8-cm thruster subsystem.

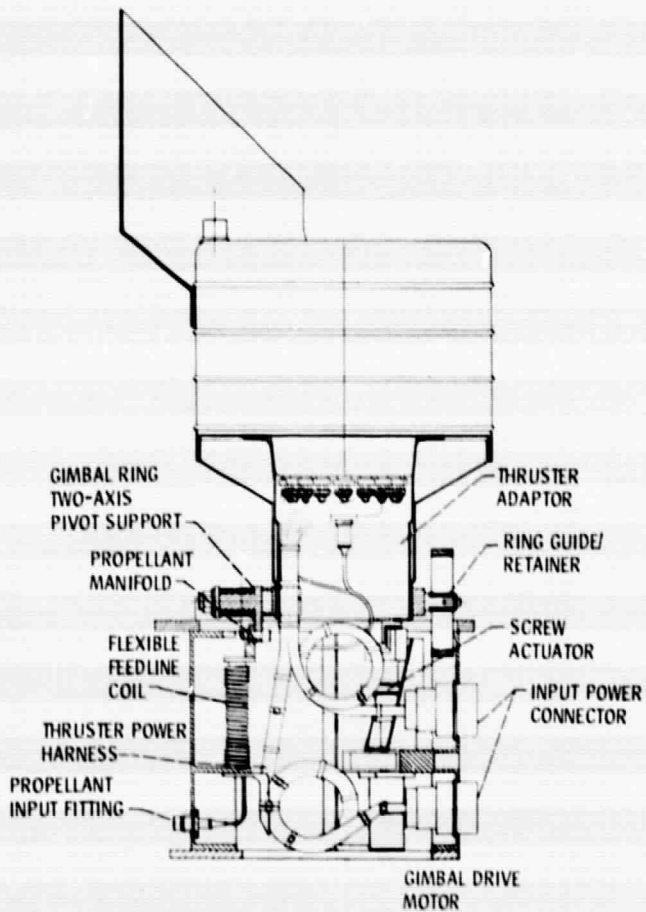


Figure 7. - Gimbal and thruster support assembly.

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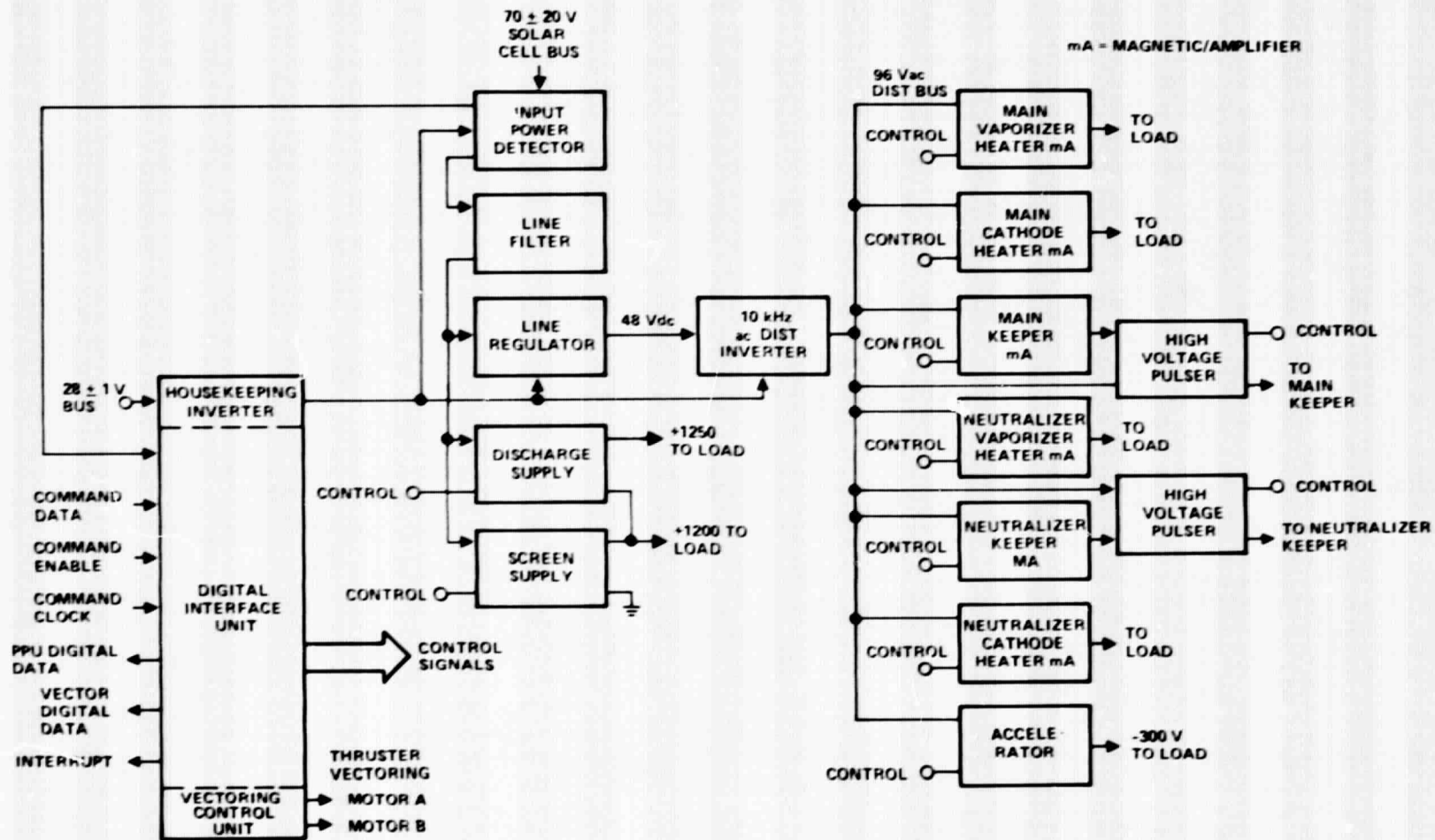


Figure 8. - Digital interface unit and power electronics unit functional block diagram.

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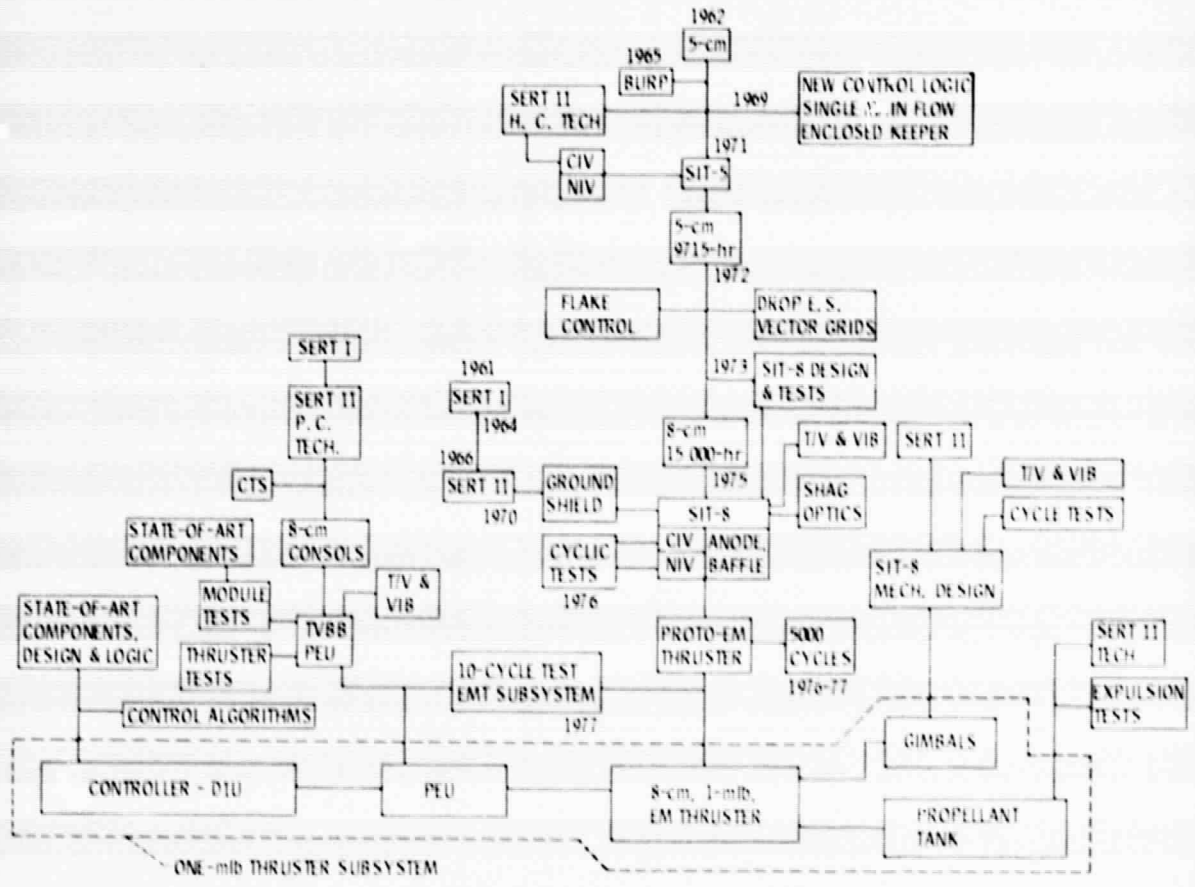


Figure 9. - Evolution of 8-cm, 1-mlb, EM, thruster subsystem.