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SNAP-27

PROGRAM

REVIEW

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SNAP-27 PROGRAM REVIEW

(Work performed under Contract No. AT(29-2)2581)

BY

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I. ABSTRACT

The SNAP-27 ~~Radioisotope Thermoelectric Generator~~ (RTG) System was designed, developed, and fabricated for the US ~~Atomic Energy Commission~~ (AEC) as the prime power supply for ~~the National Aeronautics and Space Administration~~ (NASA's) Apollo Lunar Surface Experiments Package (ALSEP). The RTG program was carried out by the General Electric Company's Missile and Space Division under the technical direction of the Sandia Laboratories. The program began in late 1965 and the first electrically heated generators were on test in late 1966. Initial electrical power requirements of 56 watts were exceeded and each of the five flight units is expected to produce more than 67 watts after one year of lunar surface operation. The last flight hardware was delivered in May of 1969. The SNAP-27 Program has been successfully concluded and the AEC has provided NASA with Plutonium 238 isotopic power system of proven performance and reliability.

II. PROGRAM DESCRIPTION

The SNAP-27 RTG developed for the ALSEP mission was an outgrowth of earlier power system studies performed for the AEC. An earlier AEC study resulted in a conceptual definition of a lightweight, high performance 40 watt RTG to power a lunar roving vehicle. This study focused attention on the use of beryllium as prime structural and radiator material for the RTG. Based on these results and the continued interest of the AEC to upgrade RTG capability, a technology program, SNAP-27, was defined. The objectives of the program were to investigate beryllium as a structural material and to select appropriate lead telluride type elements to best achieve high specific power and long term performance.

While this technology program was being pursued, NASA-MSC was choosing the scientific experiments which would be left on the moon during the Apollo program. RTG's were a natural candidate to provide power for the experiments due to its potential of lightweight and ability to produce full electrical power during the lunar night and lunar day cycles. Subsequently, a systems integration study was sponsored using the SNAP-27 concept to evaluate the performance of the RTG as the prime power supply and to determine its ability to be readily integrated in the existing LM considering thermal, structural, electrical, and deployment facets. The results of this study were positive and NASA requested the AEC to provide the RTG for the one year mission. A major hardware program was initiated in the fall of 1965.

Two basic SNAP-27 concepts were considered relating to the placement of the isotopic fuel capsule on the LM during the earth to lunar surface transportation phase. One approach, referred to as Integral Shipment, required that the fuel capsule or heat source be installed in the basic converter (generator assembly - GA) before launch and the fueled system then integrated thermally, structurally and electrically in the LM internal compartment with the ALSEP experiment package. The second approach referred to as Separate Shipment separates the heat source from the converter permitting an inert generator assembly to be integrated without concern to thermal and electrical constraints. As a result, the heat source is located on the most advantageous section of the LM external surface consistent with the needs of thermal integration and the experiment deployment. Separate Shipment was the selected concept.

The overall program consisted of four major hardware elements and a safety program. The elements are:

- Generator - which consists of the thermopile, structure and heat rejection system.
- Fuel Capsule - which contains the isotopic fuel in a separate hermetically sealed structure to prevent release of fuel.
- Graphite LM Fuel Cask (GLFC) - which supports the fuel capsule during the trip to the moon. The GLFC is

mounted on the outside of the LM descent stage. It will provide thermal and blast protection to the FCA in the event of a pad abort or an abort in space resulting in re-entry.

- Auxiliary Support Equipment - which provide for storage, ground and flight handling and testing of the generators, fuel capsule and GLFC.

- Safety Program - a program of analysis, test, and evaluation.

Three design/fabrication phases were conducted to achieve acceptable flight hardware. The engineering phase which served to demonstrate feasibility of the initial design, the qualification phase in which the final design was tested and the production phase which included fabrication of all flight hardware. The overall program is illustrated in Figure 1.

The AEC was required to deliver an engineering generator to NASA for ALSEP development testing in December 1966 only 15 months after program go-ahead. The AEC elected to provide a parallel technology and development program which would assure that the RTG would perform as required and would be delivered on schedule. This was accomplished by initiating a comprehensive component technology and test program in support of the parallel design and development of the basic flight hardware. This approach is illustrated in Figure 1 which shows that the systems and componen testing were proceeding concurrent with the three generator design/fabrication cycles. Changes were made as necessary to incorporate the results of test data.

Safety capability for the SNAP-27 system was a primary design consideration from the inception of the program. Results of the comprehensive safety evaluation indicated that the SNAP-27 has adequate safety margins.

SNAP-27 is a total system of components consisting of both the actual flight hardware and all necessary ground support and checkout equipment. The program end-items are tabulated in Figure 2.

During the program, technical, contract and administrative interfaces were maintained between many agencies and major contractors. The major interfaces were:

a) AEC Hdqs (SNS), Program Direction
b) AEC ALO, Contract Administration
c) GE-MSD, Prime SNAP-27 Contractor
d) Mound Laboratory, Fuel production/heat source fabrication
e) Sandia Corporation, Technical Direction for AEC and safety analysis and test support
f) NASA-MSC, Apollo Program Direction
g) Bendix Systems, Prime ALSEP Systems Contractor

III. ALSEP INTEGRATION AND MISSION PROFILE

The SNAP-27 flight components are located in two sections on the LM descent stage during transportation to the lunar surface. The inert generator assembly is bolted to the ALSEP Subpackage No. 2 pallet, and is stowed in the right hand LM Scientific Equipment Bay, (SEQ Bay), see Figure 3. The Flight Handling Tool is also stowed in Subpackage No. 2 pallet. Subpackage No. 1 containing a various assortment of experiments is stowed in the left hand SEQ Bay. To the left of the SEQ Bay, and mounted externally on the LM by means of the ALSEP Support Structure, is the GLFC containing the fuel capsule. This arrangement was selected to minimize heat input into the LM compartments. Access to the fuel capsule is such that the astronaut can easily remove it for insertion into the generator. The deployment sequences of the SNAP-27 and the ALSEP experiments are illustrated in Figure 4.

During earth storage, Subpackage No. 2 is housed in a pressurized container filled with Argon. The pressurized environment provides positive assurance that the generator thermopile cover gas (argon) pressure will be a maximum at time of installation in the Lunar Module regardless of the storage time on earth. Prior to launch, approximately T-84 days, the fully checked out ALSEP Subpackages are installed in the LM. The generator is subjected to the launch and boost dynamic environments generated by the launch vehicle. From the time the astronaut fuels the generator until the system is placed "on the line", the generator power leads are maintained short circuited to minimize the hot junction temperature during generator warm-up. After deployment, the astronaut removes the short circuit (at the main connector) and the generator begins to operate at its control point of 16 volts dc which is maintained by the Bendix shunt regulator operating at 16 $\pm$ 0.2 volts. The ALSEP Subpackage No. 2 pallet baseplate becomes the baseplate on which the RTG rests when deployed for normal operation on the lunar surface. The baseplate has been designed to withstand a conducted heat flow of 20-80 watts from the generator mounting feet. Since the generator "sees" the baseplate, a thermal surface is provided with an emittance of at least 0.85 and an α/ϵ ratio which is a minimum, all of which results in a flat temperature profile for both hot and cold junction

temperatures. The geometry and the coating characteristics of the heat rejection surfaces result in a worst case effective sink for the RTG of 170°F which occurs at approximately 10 or 2 o'clock sun position. The lunar night sink is -280°F.

The GLFC, without fuel capsule, is installed on the LM descent stage at T-22 days prior to lift off. At approximately T-15 hours, the fuel capsule is brought to the base of the launch vehicle in an AEC van at which time the following sequence of events occurs: (See Figure 5)

a. The fuel capsule is removed from Ground Shipping Cask and inserted into the portable SLA Transfer Cask.

b. The SLA Transfer Cask with FCA is transported via elevator up to a 3A platform of the service structure.

c. The Port Entry Trough is partially inserted into the SLA through a 10" SLA port located at the 260 foot level of Saturn V.

d. The fuel capsule is removed from the SLA Transfer Cask using the SLA Handling Tool, placed in the horizontally supported Port Entry Trough and then slid through the SLA panel into the interior to waiting loading personnel. The tool remains attached to the capsule during this procedure. In all cases the fuel capsule and GSE are tethered to prevent loss should they be accidentally dropped.

e. The fuel capsule with the SLA Transfer Tool attached is lifted from the trough and carried to the open GLFC. The capsule is then inserted into the GLFC cavity and latched.

f. After insertion, the fuel capsule latch fittings are checked to insure proper locking.

g. The GLFC dome is then installed and the ALSEP Support Structure assembly bands tightened.

h. Cooling air is continuously provided upward over the GLFC surface so that the graphite surface temperature is maintained below 350°F.

After launch heat from the GLFC (~1500 watts) is radiated to the inner wall of the SLA until after the SLA panels are removed prior to transposition and docking. Prior to this the GLFC surface reaches its maximum temperature, 800°F. With the panels open, the GLFC rejects heat to space and operates at a slightly lower temperature.

After the LM reaches the lunar surface, the astronaut removes the fuel capsule from the GLFC. Figure 6 shows an actual GLFC (instrumented for test) with fuel capsule inserted, mounted on a simulated LM. Figure 7 shows the astronaut pulling a lanyard to "cut" support trunnion bolts, and rotate the GLFC to a position slightly below horizontal. Figure 8 shows the astronaut removing the dome from the GLFC. Figure 9 shows the fuel capsule being removed from the GLFC. Figures 10 and 11 show the final operation of "fueling" the generator.

IV. HARDWARE DESIGN AND PERFORMANCE

A. Converter Design, Performance Technology

The SNAP-27 Generator Assembly designed and built for the ALSEP using 3N and 3P lead telluride thermoelectric conversion elements was shown, by actual long term testing, to satisfy the program power requirements with considerable margin. Tests on a flight qualification generator showed no thermoelectric degradation after 7700 hours in a thermal vacuum environment simulating the lunar day-lunar night cycle. Generator performance was also verified by a parallel supporting technology test program investigating the effects of varying operating parameters on the SNAP-27 thermoelectrics. Two such test programs were established and are still in progress. One program utilizes 19 10-couple flat-plate modules fully instrumented and tested under various hot and cold junction temperatures, thermopile cover gases and gas pressures, and element contact pressures. The other program makes use of several 104-couple modules with the thermocouples mounted exactly as they are on SNAP-27. The 104-couple module is basically a 1/4th length generator. They are fully instrumented and tested similarly to the 10-couple modules. These two module endurance programs have provided the data required to develop a complete understanding of the degradation phenomenon such that long term (say five year) mission applications using 3N and 3P can be made with confidence. The following paragraphs present a brief summary of the SNAP-27

generator design and performance and the 10 and 104-couple program.

1. Generator Assembly: The SNAP-27 generator assembly with the fuel capsule installed is shown in isometric cutaway in Figure 12. The heat source is not permanently assembled into the generator and can be removed or inserted as required by ground operational considerations. Heat from the nominal 1480 watt $^{238}PuO_2$ fueled capsule is transmitted to the generator hot frame by radiation coupling. Both surfaces are coated with a high emissivity iron titanate coating, with the heat source having a minimum emissivity of 0.85 and the hot frame 0.80. Temperatures during normal operation on the lunar surface are 1350°F for the capsule and 1125°F for the hot frame. The hot frame itself is fabricated Inconel 102 alloy. Heat received by the hot frame is transmitted to the thermoelectric couple hot side by passing first through electrical insulator, then an electrode, and finally a hot button. Total temperature drop through these components is 25-45°F, which establishes the SNAP-27's hot junction temperature at 1080°F to 1100°F. Heat flow (~1250 watts) through the system's thermoelectric couples is such that the cold side thermoelectric temperature is maintained at 525°F in the normal operating mode (lunar environment). Heat loss due to leakage between the couples is kept to a minimum by the high density packing of powdered Min-K insulation with a thermal conductivity of 0.04 Btu/ft^2-hrs.

The thermoelectric material selected for the SNAP-27 couple design was 3M Company's developed and proven 3N, 3P lead telluride used extensively in their commercial converters and in AEC programs, such as SNAP-17, SNAP-21, and SNAP-23. Each element forming the couple (one N and one P) is integrally assembled such that the hot side interface is free and the cold side soldered to spherical caps. Between the caps and the actual element material are an electrode and a barrier disk. Two series strings of couples connected in parallel with each couple electrically laddered to prevent string loss, given a couple open failure, comprise the electrical arrangement. Nominal operating voltage of the thermopile is between 14 and 16 volts dc. Each element is preloaded into its hot button by individual springs sized and shimmed to establish a bearing pressure of 150 psi.

The heat, after having flowed through the couples, is transferred into beryllium oxide followers which interface directly on the cold cap. The heat then flows into a massive beryllium cold frame which serves to "smear" out any possible temperature gradients and which in turn results in constant couple temperatures. Thermal gradients between the cold frame and the outer case are minimized by a shrink fit with a maximum interference of 0.002 inch.

The outer case is the prime structural member of the generator. It is a hot-pressed block beryllium structure with a 0.060 inch thick cylindrical wall with eight (8) cross-rolled sheet beryllium fins integrally attached by brazing. Two (2) transition rings of 19-9 DL, are also brazed into each end of the cylindrical case.

After shrink fitting the outer case to the thermopile the Min-K insulation is packed into the thermopile and the seals are welded. The generator is then processed and backfilled with argon cover gas at 25 psia operating temperature. The cable attachment is made of Kovar pins welded into the aft seal.

Magnetic field generation of the SNAP-27 has been kept within 1γ at 3 meters by careful selection of materials and the use of degaussing loops, which can be seen in Figure 12.

2. Generator Tests: The generator test program was conducted to confirm the generator design and to develop experimental data for any future improvement modifications.

Three generators, MOD 5, MOD 8B and a prime flight qualification generator Mod 10, were life tested in environmental thermal vacuum test chambers. The tests were terminated on July 10, 1968, July 11, 1968 and July 12, 1968 for MOD 8B, MOD 5, and MOD 10, respectively. These generators accumulated 28,203 hours with MOD 5 accumulating 12,165 hours. Thermal sink conditions for all generators were cycled from +170°F to -280°F every two weeks to simulate maximum temperatures for lunar day and lunar night operation. A performance summary is given in Table 1. Note that MOD 5 was reduced to a power input of 1485 W after 10,000 hours to simulate the fuel decay. Figure 13 shows the performance (I/V) map for predicted and actual performance of the MOD 10 generator.

Table 2 summarizes the performance characteristics of each of the five (5) flight units prior to AEC acceptance. Each generator has its performance

characteristics determined for a possible variation in heat source thermal loading (1415-1505 watts) and the maximum temperature extremes representative of lunar day and lunar night. Each generator was acceptance tested not less than 500 hours, of which at least 200 hours are in a thermal-vacuum environment. Note the consistency in performance and weight. Since each heat source is very close to 1480 watts, power for the ALSEP mission will be approximately 67 watts at the end of one year.

3. 10-Couple Module Tests: The SNAP-27 generator program was supported by a comprehensive thermoelectric test program utilizing 10-couple modules operating at both reference design and off design conditions. Nineteen modules were built - two with beryllium to assess materials compatibility - sixteen modules are operating at this time. Figure 14 shows a typical 10-couple module and Table 3 outlines the 10-couple module test series. Testing was terminated on two short-term stability modules, B-1 and C-3, one to evaluate compatibility and one due to a severe module leak. Module C-12, designed to investigate low pressure effects, operated at 2.5 psia and was taken off test after power had dropped to 60 percent of its theoretical value. On all other modules, testing is being continued and, as of 6/30/69, 3.70 x 10^6 couple hours had been accumulated without any couple failure. The oldest module, B2, has been on test over three years.

A summary of results for the various test conditions is given in Figures 15 through 17. It should be noted that the power ratios given here are the ratios of the actual power output of the module divided by the theoretical output, based on the same hot and cold junction temperatures and operating conditions. Power ratios larger than one, which are sometimes experienced, do not reflect inaccuracies in the reduction technique, but show a slightly higher performance of the actual material than the nominal theoretical data used in the SNAP-27 design.

In Figure 15, the influence of hot junction temperature is summarized. All modules below 1200°F show a normal and expected performance-time history. The sudden change in slope for the modules operating at 1200°F around 5000 hours reflects a change in leg geometry due to sublimation losses and creep deformation.

Figure 16 shows the sensitivity of performance to gas pressure. This is due to the same sublimation effects, as mentioned above, which is suppressed at higher surrounding gas pressures. On Module C12, a post-test analysis was conducted and a substantial material loss on the N-leg was found with an appreciable geometry change.

Figure 17 displays the effect of higher spring pressure on the elements. It can be seen that higher spring pressures have a pronounced effect on "burn-in" characteristics at BOL which are an important factor for low temperature operation. Furthermore, equivalent resistance increases are experienced at considerably later times. The performance of the modules which were subjected to an accelerated lunar cycle simulation (35 cycles for C13 and 24 cycles for C17) showed that cycling does not have any detrimental effects on performance. This experience was further confirmed on the 104-couple module series and the generators. Higher cold junction temperatures (up to 625°F) were also found to have no effect upon long term performance.

4. 104-Couple Module Tests: The 104-couple module test program extended the objectives of the 10-couple program to provide an experimental basis for predicting generator performance. The module itself was designed and fabricated in a manner identical to a SNAP-27 generator, except that it was highly instrumented and shorter. Use of identical materials, parts, and processes provides the 104-couple modules with the same susceptibilities that the actual generator would have and removes the idealism of the 10-couple module design. Figure 18 shows a typical 104-couple module thermopile.

Table 4 summarizes the 104-couple module testing. As of 6/30/69, a total of 12.96 x 10^6 couple hours were accumulated with no failures. The oldest module has 20,521 hours.

B. SNAP-27 Fuel Capsule Assembly

The design features of the SNAP-27 Fuel Capsule Assembly are shown in Figure 19. The device is a complete weldment which offers maximum design margins for containing the fuel during the normal operational mode and in cases where aborts occur. The latter is significant since the heat source must contain the fuel during and after an impact of the fuel capsule on a graphite block. This containment feature has been demonstrated by test with the capsule impacting at any angle, at velocities of 195-215 fps and capsule temperatures at 850°F. Figure 20 illustrates the containment capability of the SNAP-27 capsule.

The capsule comprises two fuel compartments integrated into a single high strength superalloy outer structure. Each of the two fuel compartments contains a nominal loading of 740 watts thermal of $^{238}PuO_2$ microsphere fuel fabricated in the 50 to 250 micron size. The fuel itself is held in an annular configuration. The resulting void volume adds significant life to the capsule for long term storage and mission use and also results in low fuel temperatures by providing containment volume for the helium generated by the fuel. The welded structure is 2-1/2 inches in diameter and approximately 16-1/2 inches long. A backplate provides the interface for handling and securing the capsule. Total weight of the assembly is less than 15 pounds.

Selection of the two compartment concept was an outgrowth of early development testing where the secondary forces from angular impacts results in "slap down" and a tendency to fracture the capsule in the center. This phenomenon will exist for geometries where the L/D exceeds 3. Therefore, the fuel and the fuel containing liners were removed from this critical center area. Inspection of Figure 20 shows two capsules that have separated into two halves.

Fuel production and assembly of the heat source with its accompanying inspection were performed by Mound Laboratory. Six (6) units were fabricated for delivery to the program, each exhibiting an exceptional degree of consistency in terms of weight and performance. Measured thermal loading for each source was:

Flight 1	1487 watts
2	1485 watts
3	1479 watts
4	1483 watts
Flight B/U	1485 watts
Qual Unit	1484 watts

After fabrication, iron titanate coating with demonstrated long-term emissivities of greater than 0.85 was applied by plasma torch to the outer surface of the capsule.

The heat source has been fully qualified by passing tests simulating the ALSEP/Saturn V qualification level environments. Operating temperatures of interest during the mission profile of the capsule are:

a. Steady State - In air, 850°F

b. Ground Storage in Ground Shipping Casks, 500°F

c. Lunar Transit in GLFC and mounted on LM, 1400°F

d. In Generator Assembly - Lunar Mission, 1350°F.

C. Graphite LM Fuel Cask

The Graphite LM Fuel Cask (see Figure 21) supports the Fuel Capsule Assembly during the operational mission from launch to lunar surface deployment and, in the event of a postulated abort provides re-entry protection and enhances containment of the fuel.

The GLFC is a cylindrical container consisting of a primary heat shield, secondary thermal shield and fuel capsule support structure.

The primary heat shield which forms the external shell of the GLFC consists of a cylinder and two nominally hemispherical end caps. The graphite used in the primary heat shield is Hitco's Pyrocarb-406, formed by infiltrating a pyrolized square weave graphite composite cloth layup with pyrolitic graphite. The primary heat shield protects the fuel capsule during re-entry by heat sink, reradiation, and ablation modes. The heat rejected by the fuel capsule in normal vacuum operational conditions is transmitted through the secondary heat shield and absorbed by the primary heat shield where it is both reradiated to external environment and conducted to the GLFC Support Structure.

The end caps are attached to the cylinder by means of a tantalum-ceramic spline which is inserted into a hole formed by matching grooves in the cylinder and end cap at their interface. A tantalum pin is attached to a tantalum wire strung with aluminum oxide beads which extends further into the curved length of the hole. Upon installation, the tantalum wire deforms and takes a permanent set which prevents the tantalum pin from vibrating loose during launch or re-entry.

The secondary thermal shield consists of a beryllium cylinder. The beryllium is coated with successive layers of silver, rhodium, and radifrax to provide oxidation resistance and a high emissivity surface to promote radiant heat transfer. During normal operation the heat rejected by the fuel capsule will be radiated to the beryllium cylinder, conducted through it, and reradiated to the graphite cylinder.

In event of re-entry the beryllium cylinder will act as a heat sink to protect the fuel capsule.

The cylinder is supported at the forward end on the flanges of a segmented Inconel ring which is bolted to the forward capsule support. These flanges fit into slots cut into the end of the beryllium cylinder. The slots are designed to allow radial and longitudinal thermal expansion of the beryllium cylinder.

The aft capsule support is a titanium fitting which furnishes a latching point for the fuel capsule backplate latching mechanism. It is clamped to a thick internal flange on the graphite cylinder by nine titanium bolts and tabs. The overall fitting design and the clamping arrangement are such as to minimize thermal stresses developed due to differential expansions of titanium and graphite materials.

The forward capsule support consists of a titanium housing ring and a Haynes alloy guide ring to support the capsule. The guide ring is mounted to the housing ring in such a way that it floats free at room temperatures but, at higher temperatures caused by fuel capsule heat rejection, it seizes to provide a firm support due to differential temperature expansions of the guide and the housing. The housing ring is mounted to the forward end cap. In addition to structural support, the housing ring provides a heat path from the capsule.

To protect the ends of the fuel capsule during re-entry heating, fiberfrax insulation is placed in both end caps to prevent radiation to the capsule ends. To reject heat from the forward end of the capsule during normal operational conditions, a titanium dome is attached to the ends of the forward capsule support housing. Heat is radiated to the dome, conducted to the housing ring, and then to the graphite shield. At the aft end, the fuel capsule backplate titanium fitting provides a similar heat rejection path.

The combination of rings, backplate, secondary thermal shield, and forward capsule support provides an independent internal structure designed to maintain safety integrity during postulated Saturn V pad aborts.

The GLFC has been successfully static and dynamically tested to the Saturn V qualification environments.

D. Ground Support Equipment

1. Ground Shipping Cask: The Fuel Capsule Assembly is stored, while on earth, in a specialized container designed to offer complete protection to the capsule during long-term containment, ground handling and transportation loads. This container is referred to as the SNAP-27 Ground Shipping Cask and is shown in Figure 22. Dimensions of the cask, including skids, are 3 feet by 4 feet by 4 feet high.

The cask accepts the coated capsule assembly in a center cavity.

Small diameter nickel shot is poured and packed between the outer capsule wall and the cask inner cavity. This shot provides a ready heat transport media for the capsule and serves to keep the capsule wall temperature at less than 500°F for maximum ambient conditions. Prior to capsule removal, the shot is drained from the cask bottom and stored for future use. Between the structural cavity and the outer stainless steel cylinder to which cooling fins are welded is a water tight lid fitted with ethelyene glycol and a radial array of copper fins. The purpose of these features is to provide a smooth heat path to the cask outer surfaces for heat rejection and also provide sufficient liquid volume to obtain effective gamma and neutron shielding.

By actual measurement during storage of fueled capsule, the measured radiation is less than 10 milliroentgens (mr) per hour at 1 meter from the cask, compared with 100 from a bare capsule, and the cask surface temperature did not exceed 145°F.

2. SNAP-27 Ground Handling Tool: The SNAP-27 Ground Handling Tool, shown in Figure 23, is a device which permits handling of the SNAP-27 fuel capsule in and out of the Ground Shipping Cask, Generator, and/or GLFC. The tool is approximately 2-1/2 feet in length and has a melamine handle and a titanium jaw assembly. Sliding/rotating parts of the jaw assembly are coated with molybdenum disulfite for lubrication.

The tool is activated by rotating a knurled knob at the end opposite the end engaging the heat source. This knob connected to the jaw assembly by metal tubing causes a metal plate (with machined helical groove) in the jaw to rotate. The jaw assembly also has three movable fingers which slide in and out and are moved through the action of a projection (from the finger) riding in the rotating helical

groove. When engaging a capsule, the knob is turned clockwise, causing the fingers to slide inward. The fingers slide into special recesses in the capsule backplate and are guided into place by dowel pins mounted on the finger projections. A knurled ring located directly under the activating knob is turned clockwise and the heat source is locked securely to the handling tool. The reverse of the foregoing disengages the tool from the heat source.

For ground handling operations, the tool handle remains sufficiently cool for comfortable operation without the need of protective gloves.

3. Test Consoles: The test consoles, Figure 24, were designed to be versatile and accurate, having the capability to operate and check out the generator with and without the heat source. The performance map panel consisting of a resistance thermometer readout section provides the means for manual selection and analog display of three hot junction (T_H) and three GA cold junction (T_C) temperature sensors in degrees Fahrenheit. These sensors have a T_H range of 600 to 1200°F and a T_C range of 0 to 600°F. The performance map section provides the means for monitoring and visually displaying the potential in volts dc, current in amperes, power in watts, and variable load resistance in ohms and also measures the elapsed time of the monitored functions. The voltage monitor and display will monitor dc voltage over the range of 0 to 40 vdc in two ranges and will provide analog display of the voltage to an accuracy of $\pm$ 2 watts. A load resistor with a variable resistance between 0 to 20 ohms with a step to open circuit is provided. The elapsed time indicator and display will measure elapsed time of monitored functions and will provide a digital display of elapsed time in hours and tenths of hours.

The Electric Fuel Capsule Simulator (EFCS) power control panel provides the means for controlling, monitoring, and visually displaying the EFCS output. The power controller utilizes power sensing techniques; it is adjustable from 1200 to 1700 watts and maintains a particular power setting in this range to an accuracy of $\pm$ 1 percent in the 25 to 115 volt range. The safety monitor monitors one selected T_H sensor and de-energizes the EFCS power source when a predetermined T_H level is exceeded. The level set is variable from 1100°F to 1175°F.

4. Generator Shipping Container: The SNAP-27 Generator Shipping Container, shown in Figure 25, is a reusable device designed to protect the inert generator assembly during transportation, handling, long-term storage. The container is a hermetic enclosure fabricated of 6061-T6 aluminum alloy structure comprised of upper and lower sections and in integral handling skid. A shock-isolated mounting baseplate in incorporated in the lower section. The generator bolts directly to this baseplate, and the cable is wrapped around the generator and secured by Velcro hook-type fasteners. Three axis shock indicators are mounted on the baseplate to ensure that excessive handling load environments are detected.

Prior to generator storage, the container is energized with dry gas comprosed of pure argon and one percent helium. Pressure during storage is kept at 17 psia minimum.

V. SAFETY

The Safety Program for the SNAP-27 System encompassed four major areas:

1. Design - Design the systems, (FCA and GLFC), to have the maximum possible margins. Contain fuel in the event of postulated extreme environments.

2. Assessment - Evaluate the response of the fuel capsule and GLFC.

3. Test - Conduct tests to verify design margins and/or substantiate the analytical assessment.

4. Reports - Provide reports throughout the program summarizing the work. These reports provided the input data to the various appointed safety subpanel organizations.

The overall safety program was conducted with the assistance of two organizations - Sandia Corporation and Mound Laboratory. Sandia provided rechnical assistance in the definition of postulated environments such as explosion yields; fireball characteristics and fragmentation distribution typical of the Saturn V. Additionally, key testing utilized the special Sandia facilities. Mound Laboratory conducted tests assessing the behaviour of fuel in contact with various materials and media under conditions resulting from potential environments.

VI. SUMMARY

The SNAP-27 Program is being brought to a successful conclusion. The program, in total, has accomplished the following:

a. Produced highly reliable and fully predictable RTG for a primary space power application.

b. Made all User deliveries on schedule.

c. Provided a technology base for future RTG applications.

d. Illustrated that nuclear safety can be readily incorporated into an RTG system for use with very complex launch vehicle with little or no performance penalties.

SNAP-27 PROGRAM SCHEDULE

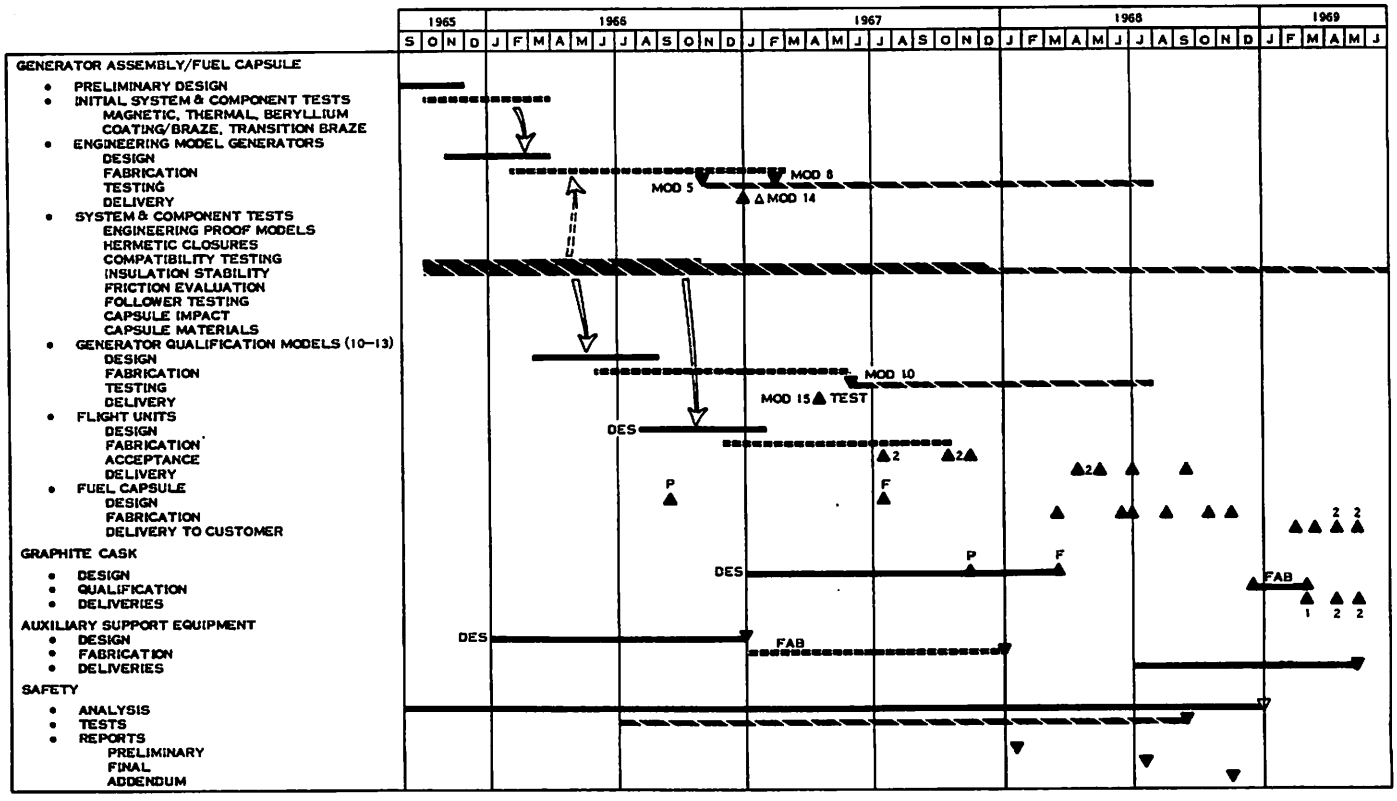


Figure 1

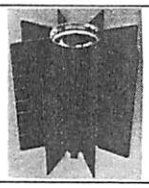
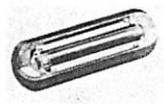
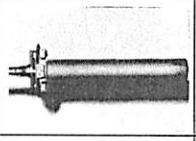
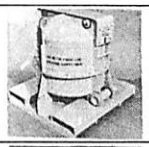
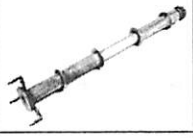
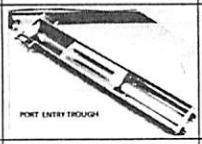
	TITLE	PHOTO	PERTINENT FEATURES	USE	QUANITY FABRICATED
FLIGHT HARDWARE	GENERATOR ASSEMBLY (GA)		BERYLLIUM STRUCTURE WITH HIGH EMISSIVE RADIFRAX COATING 3N–3P LEAD TELLURIDE ELEMENTS CONVERSION WELDED HERMETIC SEAL ARGON COVER GAS = 25 PSIA 442 COUPLES–2 SERIES PARALLEL STRINGS TH = 1100°F/TC = 525°F POWER AT EOM (MIN): 63.5 WATTS FOR 1415 WATTS THERMAL INPUT WEIGHT: 28 LB WITH 10–FT CABLE AND CONNECTOR TESTED TO SATURN V LAUNCH VEHICLE LOADS MAGNETIC FIELD FUELED 1γ @ 3 METERS RELIABILITY 0.995 STORES WITHOUT CAPSULE UNLIMITED THERMAL CYCLES	ON LUNAR SURFACE	10
	GRAPHITE LM FUEL CASK (GLFC)		GRAPHITE STRUCTURE: PYRO CARB 406 BERYLLIUM HEAT SINK COATED WITH RHODIUM AND HIGH EMISSIVE RADIFRAX COATING ADJUSTABLE CAPSULE SUPPORT DESIGNED FOR EARTH ORBITAL, SUPERORBITAL RE-ENTRY NO FUEL RELEASE DURING RE-ENTRY ABORTS NO RELEASE MECHANISM REQUIRED TESTED TO SATURN V LAUNCH LOADS HIGH IMPACT CAPABILITY PREVENTS CAPSULE OR FUEL MELT WEIGHT: 26 LB	SUPPORTS HEAT SOURCE DURING EARTH TO LUNAR TRANSIT RE–ENTRY HEAT SHIELD	10
	FUEL CAPSULE ASSEMBLY (FCA)		PU–238 MICROSPHERES (1480 ± 30 WATTS) SUPER ALLOY STRUCTURE (HAYNES) WITH HIGH EMISSIVE RADIFRAX OUTER COATING HELIUM VENT PROVIDED FUEL CONTAINMENT CAPABILITY–AT IMPACT LAUNCH TEMPERATURE: 1400°F RE–ENTRY TEMP. MAX. AVG: 2300°F TESTED TO SATURN V LAUNCH VEHICLE LOADS 2–YEAR EARTH STORAGE CAPABILITY WEIGHT: 14.7 LB	HEAT SOURCE TO GENERATOR–LUNAR SURFACE	6
	FLIGHT HANDLING TOOL		LIGHTWEIGHT DESIGN (0.4 LB) TITANIUM GOLD–PLATED SURFACE TO REFLECT CAPSULE HEAT < 10 IN–LB OPERATING TORQUE	MOUNTS ONTO THE ALSEP FUEL TRANSFER ASSEMBLY TOOL USED BY ASTRONAUT TO REMOVE CAPSULE FROM GLFC FOR INSERTION INTO GA	12
SUPPORT HARDWARE	GENERATOR ASSEMBLY SHIPPING CONTAINER		PROVIDE GAS STORAGE ENVIRONMENT SHOCK ATTENUATED MOUNTINGS (< 15G) PROVIDES UNLIMITED EARTH STORAGE OF GA REUSABLE	EARTH STORAGE CONTAINER FOR GENERATOR ASSEMBLY	6
	FUEL CAPSULE GROUND SHIPPING CASK		STAINLESS STEEL CONSTRUCTION WATER SHIELDED – 10 MREM/HR SURFACE TEMP < 180° F CAPSULE TEMP < 400° F COMPLIANCE TO AEC AND ICC REGULATIONS SHIPPING FIRE CAPABILITY QUALIFIED TO MIL STD 810A SPECIFICATIONS	STORES HEAT SOURCE ON EARTH	6
	TEST CONSOLE		ELECTRIC HEATER POWER SUPPLY: 0–1800 WATTS GENERATOR LOAD RESISTANCE: 0–20 Ω TEMPERATURE READ OUTS GENERATOR VOLTAGE, CURRENT, POWER READOUTS	OPERATES AND CHECKS OUT GENERATORS ENERGIZED EITHER WITH NUCLEAR HEAT SOURCE OR ELECTRIC HEAT SOURCE	10
	ELECTRIC FUEL CAPSULE SIMULATOR		SIMULATES HEAT SOURCE 1800 WATT CAPACITY DYNAMIC CAPABILITY (SATURN V ENVIRONMENT) AIR/VACUUM OPERATION WEIGHT/STIFFNESS SIMULATION	PERMITS TESTING OF GENERATORS AND GLFC'S	17
	GROUND HANDLING TOOL		TITANIUM/MELAMINE CONSTRUCTION LOCK DEVICE TO SECURE CAPSULE MAX GRIP TEMP < 125°F	HANDLES HEAT SOURCE ON EARTH	10
	CAPSULE BACK PLATE LOCK CHECK TOOL		STEEL FITS CAPSULE BACK PLATE LATCH PLATES	ASSURES HEAT SOURCE IS PROPERLY LOADED INTO GLFC PRIOR TO LIFT–OFF	3
	SLA HANDLING TOOL		TITANIUM/MELAMINE SAFETY LOCK MECHANISM FOR CAPSULE	USED FOR LOADING OF LOAD SOURCE INTO GLFC ON LAUNCH PAD PRIOR TO LIFT–OFF	6
	PORT ENTRY TROUGH		ALUMINUM CONSTRUCTION FITS IN 10 IN. DIA. HOLE OF SATURN V ADAPTER WEIGHT < 20 LB HANDLE TEMPERATURES < 160°F	PERMITS HEAT SOURCE TO BE INSERTED THROUGH SATURN LM ADAPTER (SLA)	2
	SLA TRANSFER CASK		MAX SURFACE TEMP < 90 °F SCREENED FOR HANDLING PROTECTION WEIGHT < 29 LB	PORTABLE SUPPORT STRUCTURE FOR CAPSULE AT LAUNCH SITE	8

Figure 2

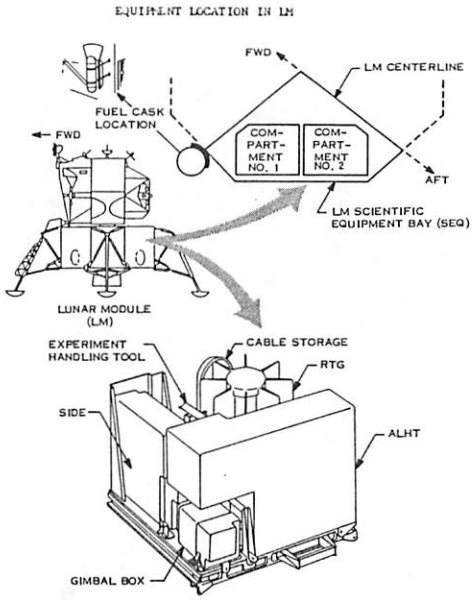


Figure 3

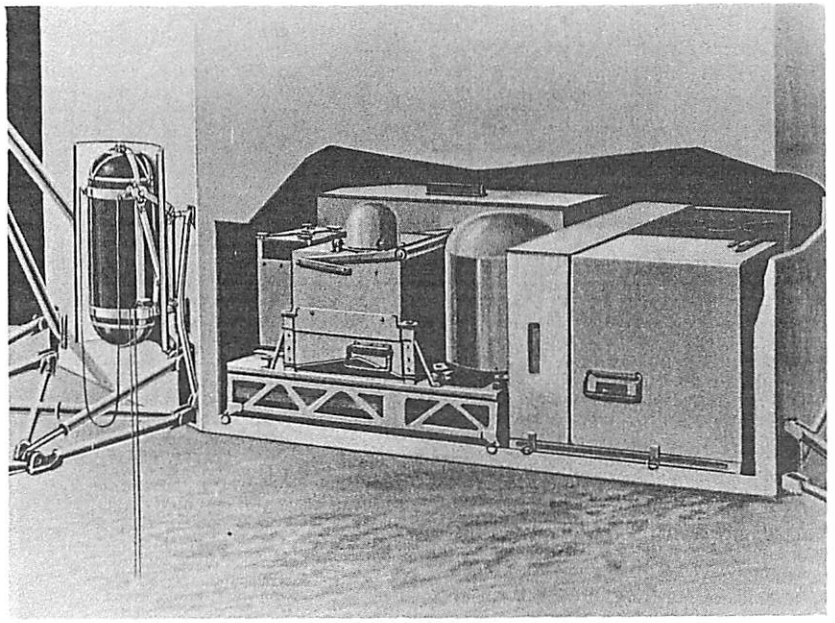


Figure 4 B

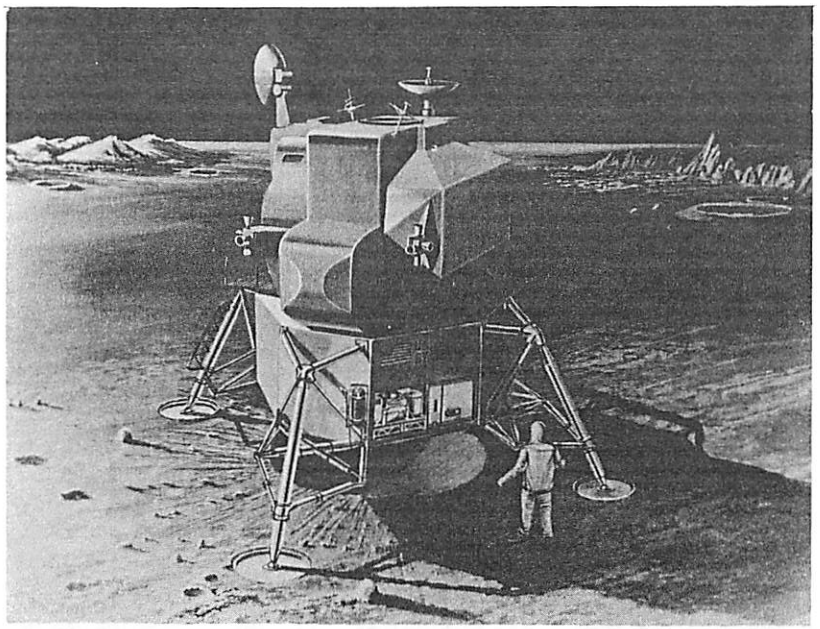


Figure 4 A

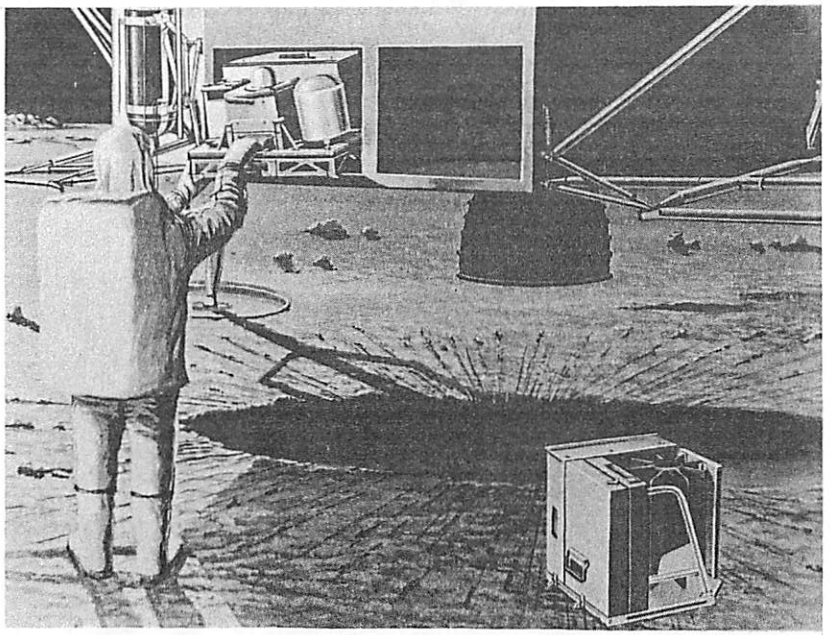


Figure 4 C

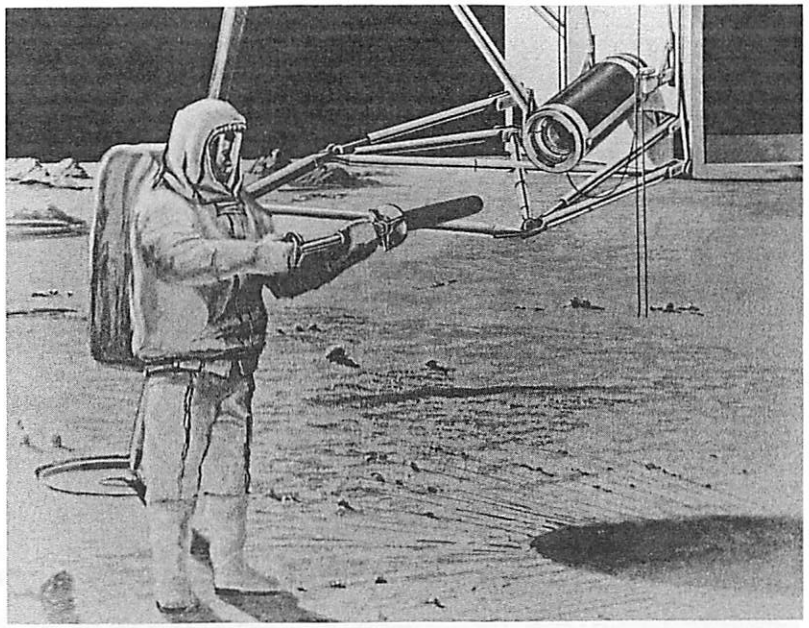


Figure 4 D

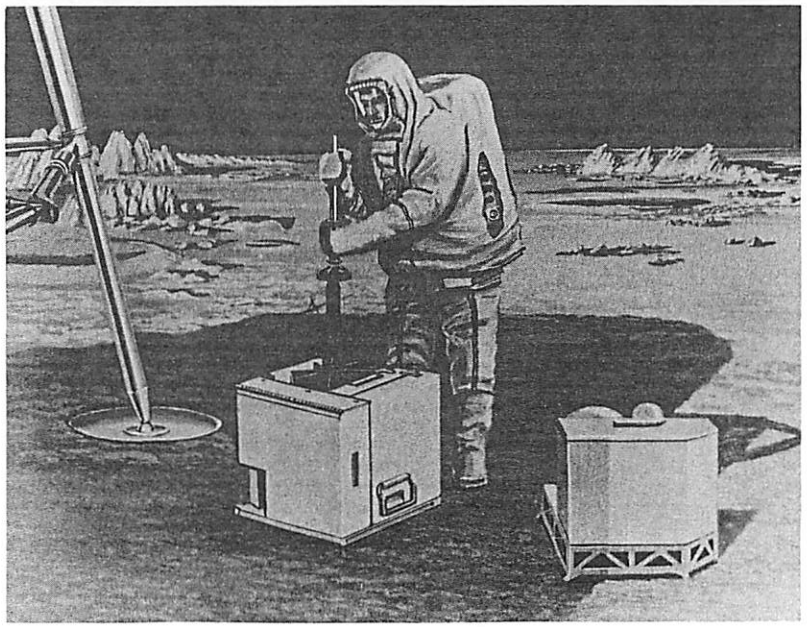


Figure 4 E

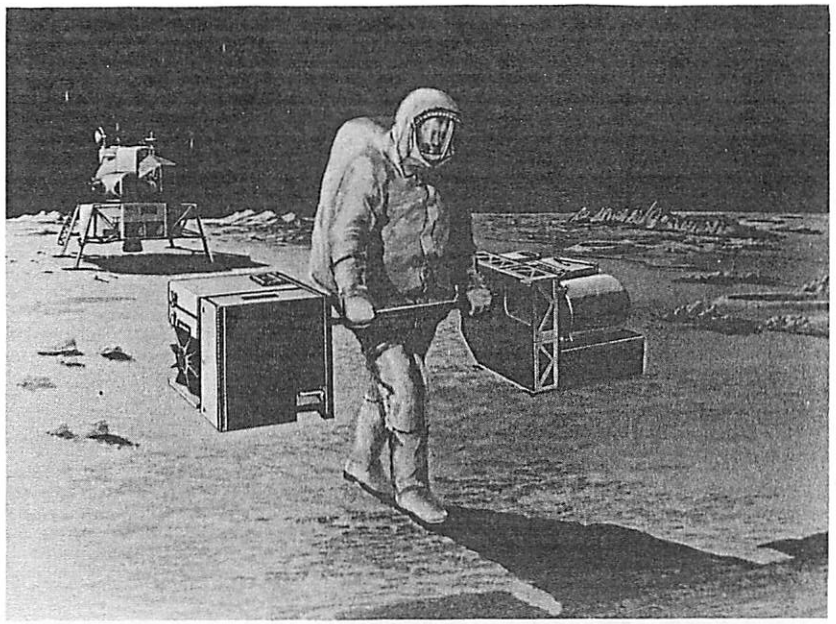


Figure 4 F

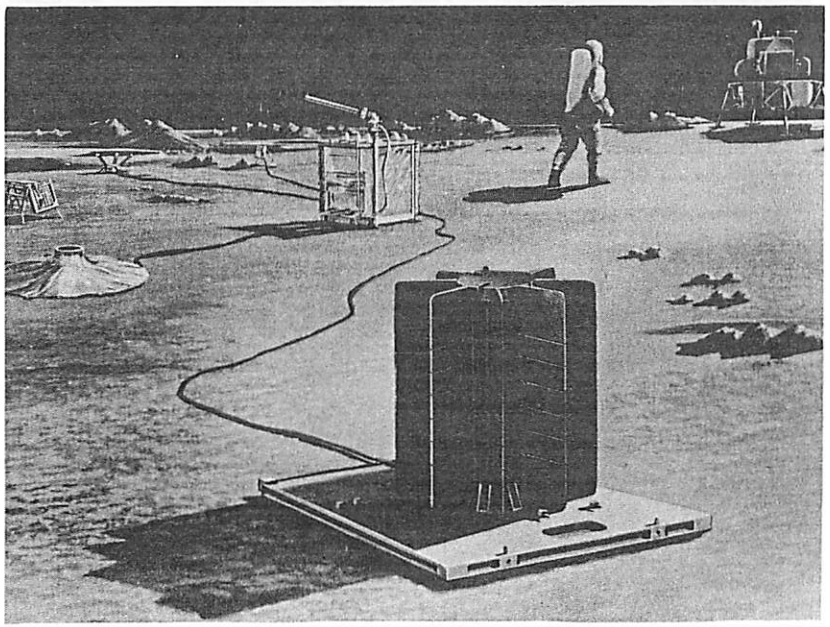


Figure 4 G

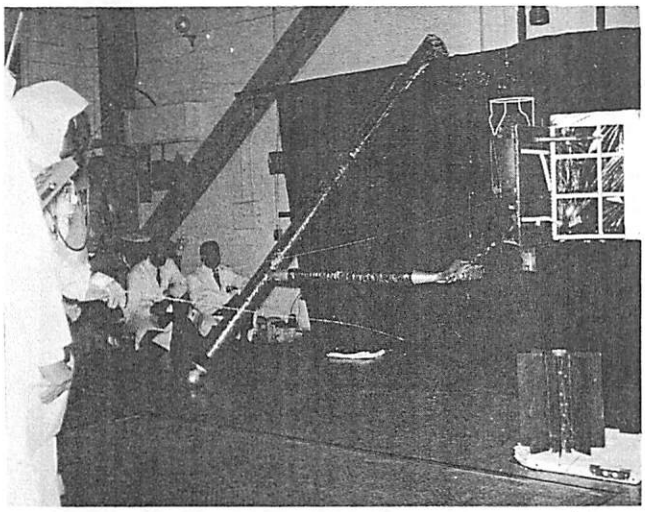


Figure 5

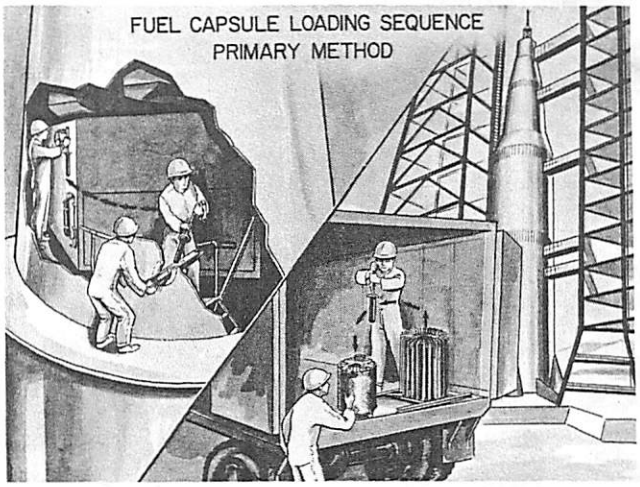
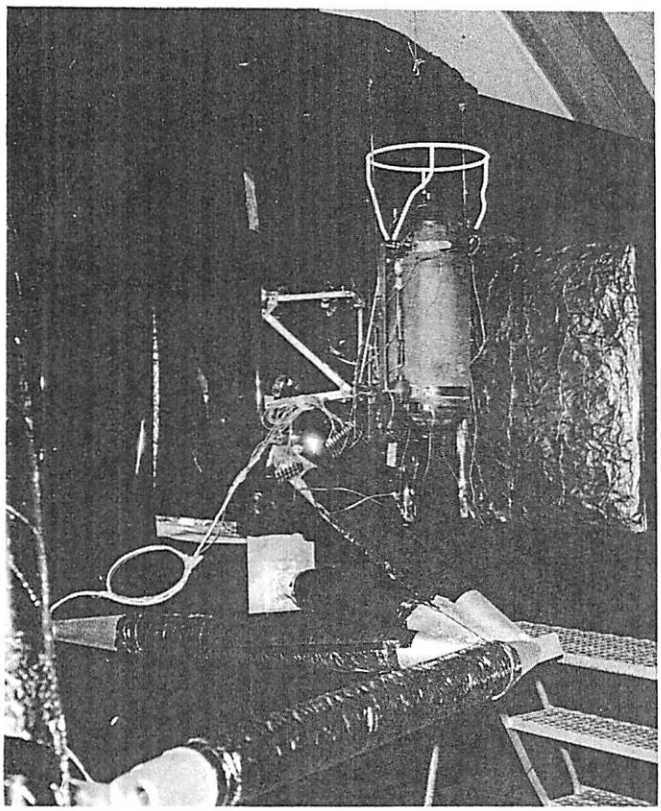


Figure 7



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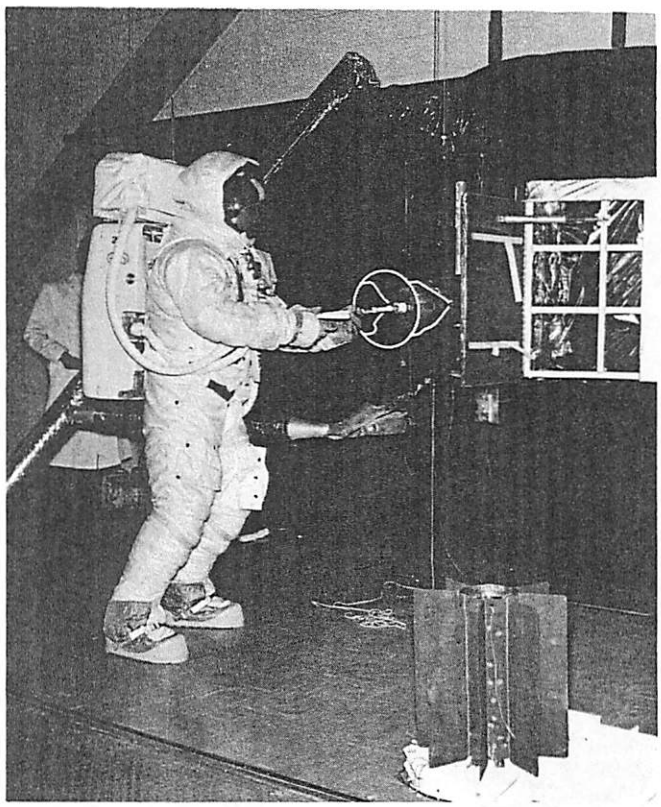
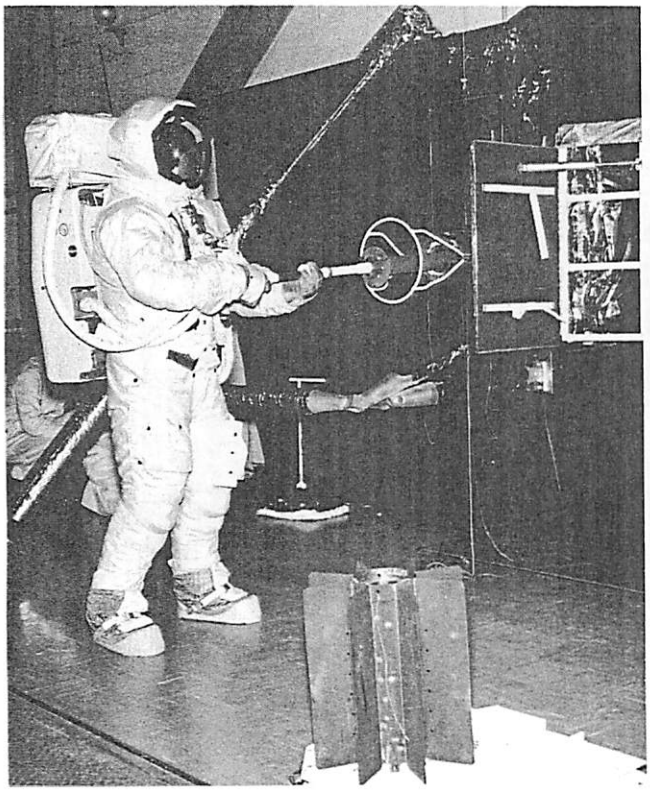


Figure 8



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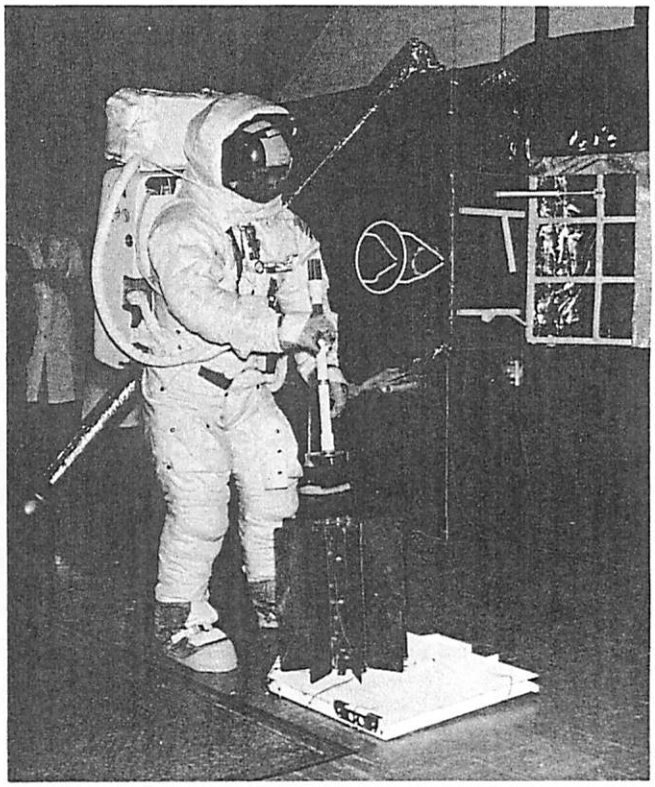


Figure 11

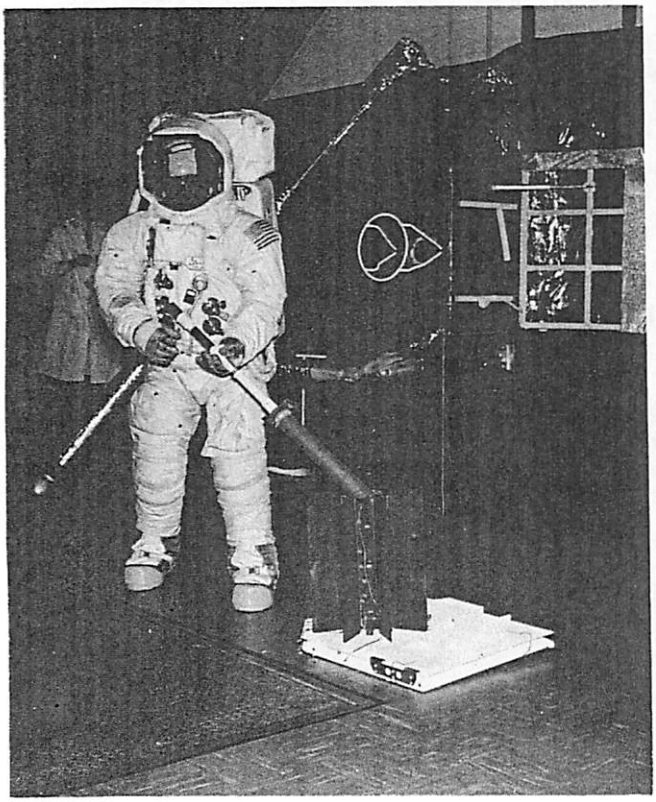
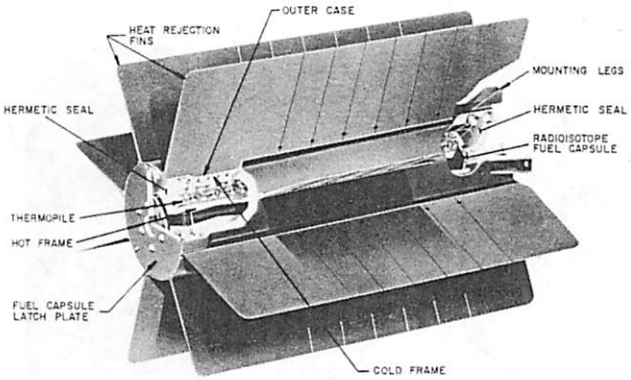


Figure 10



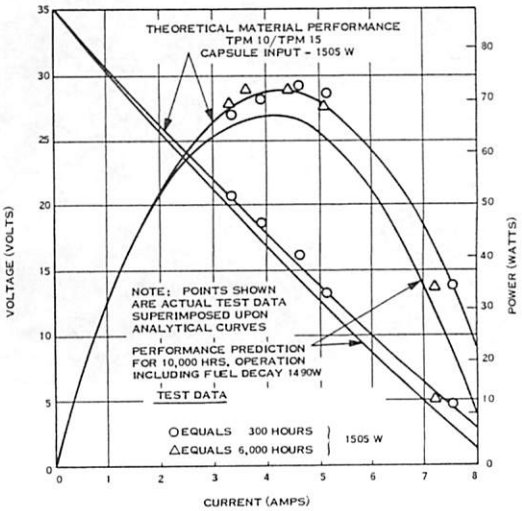


Figure 13

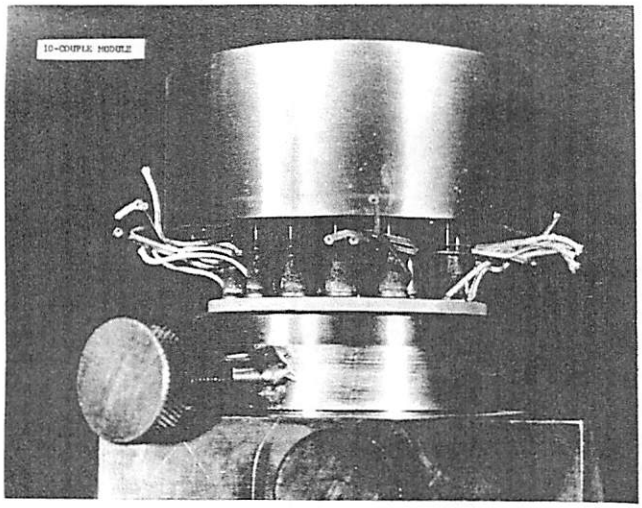


Figure 14

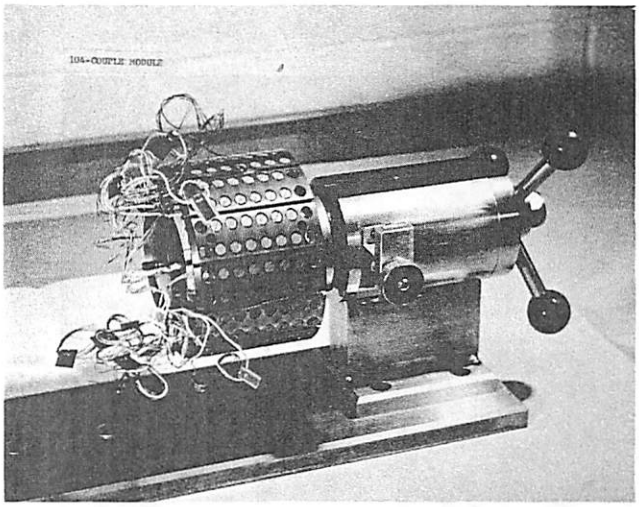
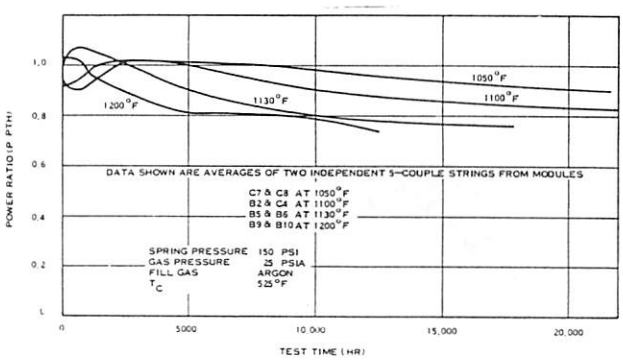


Figure 18



10-Couple Module Data Influence of Hot Junction Temperature

Figure 15

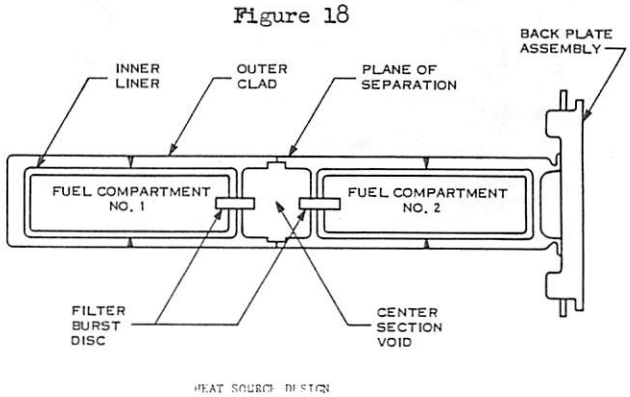
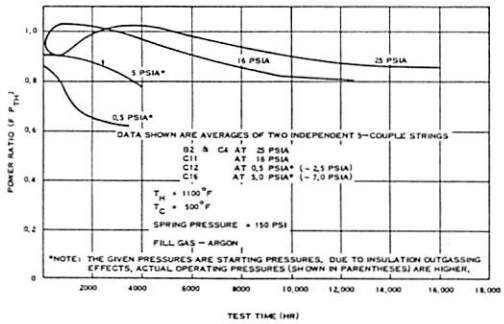


Figure 19



Influence of Gas Pressure

Figure 16

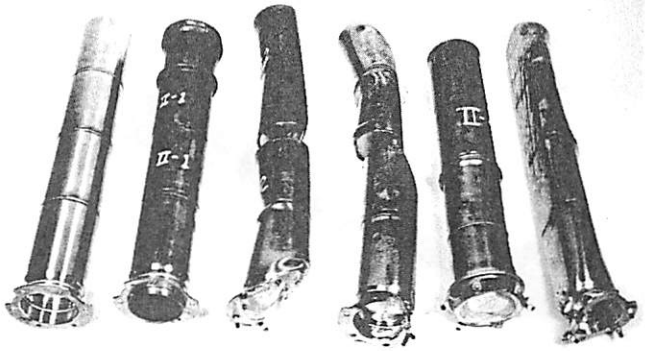


Figure 20

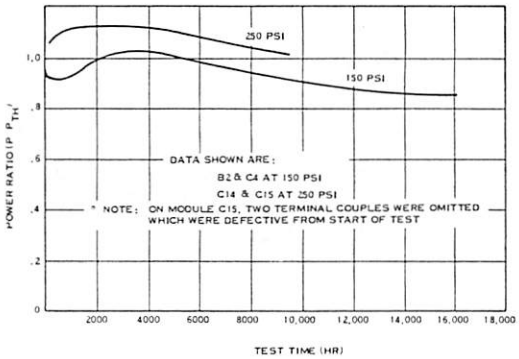


Figure 17

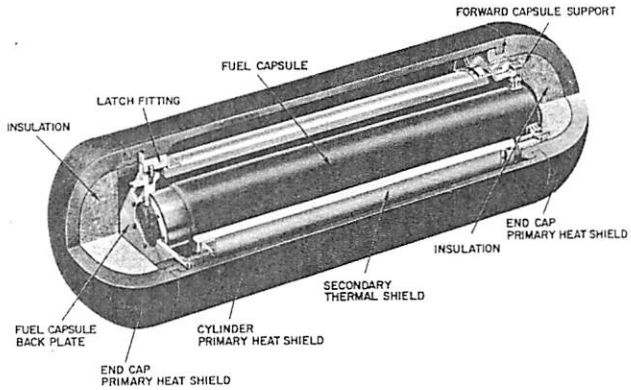


Figure 21

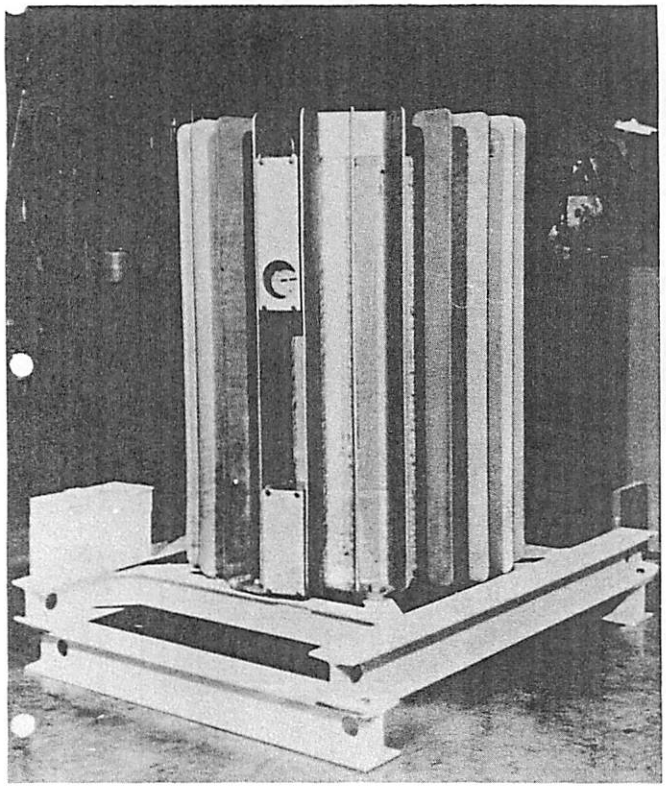


Figure 22

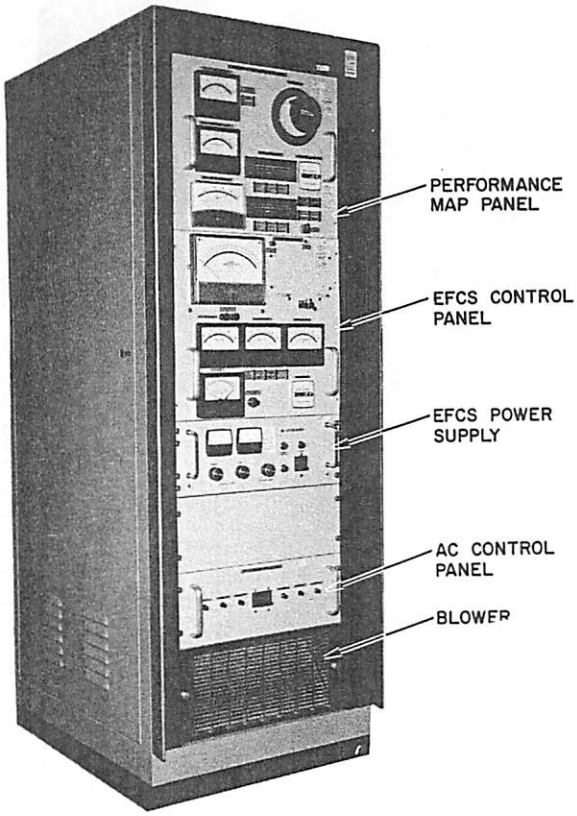


Figure 24

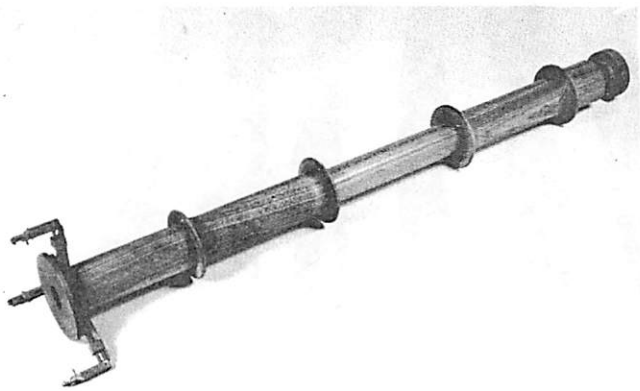


Figure 23

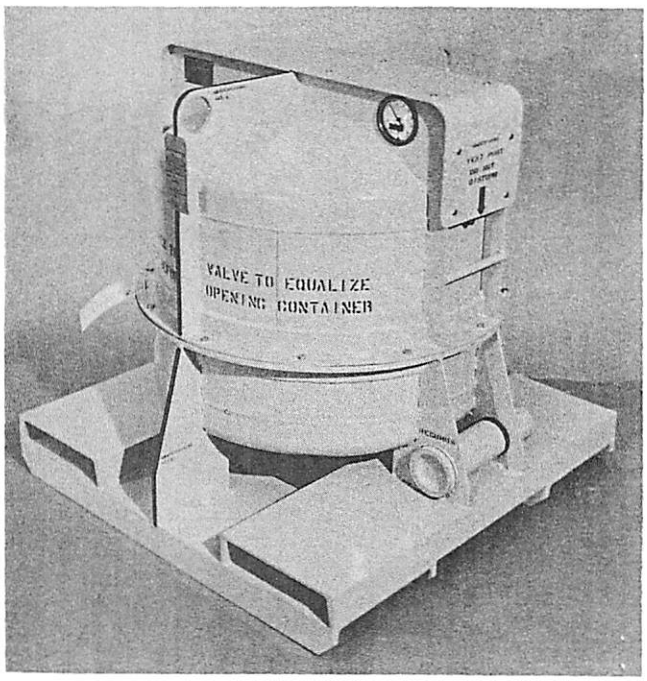


Figure 25

TABLE 1 GENERATOR TEST PERFORMANCE SUMMARY

GENERATOR	TOTAL ACCUM. TEST TIME (HRS)	POWER OUTPUT BOL		HEAT INPUT WATTS	POWER OUTPUT EOL	
		LUNAR DAY	LUNAR NIGHT		LUNAR DAY	LUNAR NIGHT
Mod 5(1)	12,165	70.8	73.0	1500 after 10,000 hr reduced to 1485 watts	66.6	68.7
Mod 8B(1)	8,341	65.0(3)	66.0	1415(3)	62.0	62.9
Mod 10(2)	7,697	71.2	73.3	1505	71.5	73.1

(1) Generators engineering models

(2) Generator flight quality - identical to five delivered flight units

(3) Mod 8B operating at reduced Q to simulate low-end tolerance on fuel capsule

TABLE 2.

POWER INPUT	EQV. LOAD	SINK TEMP (°F)	MOD 13 GA S/N 6320006	MOD 19 GA S/N 6320009	MOD 21 GA S/N 6320011	MOD 22 GA S/N 6320012	MOD 23 GA S/N 6320013
1505W	16 V	+170°F	69.8W	69.1W	68.2W	68.3W	70.7W
1455W	16 V	+170°F	67.1W	67.5W	66.0W	66.2W	67.9W
1415W	16 V	+170°F	64.3W	64.7W	63.2W	63.2W	65.0W
1505W	16 V	-280°F	72.5W	72.9W	71.3W	71.3W	72.9W
1455W	16 V	-280°F	68.8W	68.8W	66.7W	67.3W	68.9W
1415W	16 V	-280°F	65.3W	65.3W	64.0W	64.1W	65.1W
1450W	4.7 ohms	Ambient	69.6W	69.7W	67.9W	69.1W	70.2W
Total Accumulated Operational Time (Air & Vacuum) (Hours)			550	593	581	640	571
Operational Time in a Vacuum			240	264	256	303	233
Final GA leak rate in STD CC/SEC of argon while operating in a +170°F sink at 4.7 ohms load			2.50×10^{-6}	4.36×10^{-7}	1.09×10^{-6}	3.7×10^{-7}	Less than 3.92×10^{-7}
Storage Container Serial No.			6287007	6287004	6287006	6287005	6287003
Total Weight ~ Pounds, (Less protective cable sleeving).			27.83	27.77	27.96	27.86	27.80

TABLE 3.

MODULE	TEST DESCRIPTION	HOT JUNC TEMP-T_H (°F)	COLD JUNC TEMP-T_C (°F)	GAS PRES. P_G (PSIA)	SPRING PRES. P_S (PSI)	TOTAL TIME ON TEST AT 9/5/69
B1	Short Term Stability	1100	525	25	150	Terminated at 2206 hr.
B2	Short Term Stability	1100	525	25	150	28,584 hr.
C3	Short Term Stability	1100	525	25	150	Terminated at 1832 hr.
C4	Short Term Stability	1100	525	25	150	28,259 hr.
C5	Off Design Hot Junction	1130	525	25	150	26,478 hr.
C6	Off Design Hot Junction	1130	525	25	150	26,395 hr.
C7	Off Design Hot Junction	1050	525	25	150	25,901 hr.
C8	Off Design Hot Junction	1050	525	25	150	25,684 hr.
C9	Off Design Hot Junction	1200	525	25	150	26,363 hr
C10	Off Design Hot Junction	1200	525	25	150	Terminated at 23,997 hr (7/19/69)
C11	Lower Gas Pressure	1100	525	25	150	24,397 hr
C12	Lower Gas Pressure	1100	525	2.5 *	150	Terminated at ≈ 6000 hr.
C13	Lunar Cycle	1100/ 1050	525/ 460	25	150	14,767 hr - terminated 9/12/68 after 36 cycles
C14	Increased Spring Pressure	1100	525	25	250	22,413 hr
C15	Increased Spring Pressure	1100	525	25	250	23,099 hr
C16	Lower Gas Pressure	1100	525	7 **	150	17,785 hr
C17	Lunar Cycle	1100/ 1050	525/ 460	25	150	23,197 hr-cycling terminated 4/19/67 after 29 cycles
C18	Off Design Cold Junction	1100	575	25	150	23,363 hr
C19	Off Design Cold Junction	1100	625	25	150	22,868 hr

TEN COUPLE TEST MATRIX

* Module was originally set at 0.5 psia; outgassing of the insulation increased pressure to 2.5 psia

** Module was originally set at 5.0 psia; outgassing of the insulation increased pressure to 7.0 psia

TABLE 4.

MODULE	TEST DESCRIPTION	HOT JUNC TEMP-T_H (°F)	COLD JUNC TEMP-T_C (°F)	TOTAL TIME ON TEST AT 9/5/69
104-B1	Off design hot junction	1030	525	7,810 hr
104-B2	Efficiency testing with 4-zone heater	1070	525	18,227 hr
104-B3	In storage - test start postponed			
104-B4	In storage - test start postponed			
104-B5	In storage - test start postponed			
104-B6	Shock and Vibration	1100	525	Terminated 8/4/67 at 2,413 hr
104-B7	On-off cycle performance - Cycling terminated after 17 cycles	1100	525	Terminated 10/19/67 at 5,839 hr.
104-B8	Lunar cycle performance - Cycling terminated after 20 cycles	1100/ 1045	525/ 460	Terminated 5/8/58 at 9,451 hr
104-B9	Long term stability with Xenon gas	1100	525	21,890 hr
104-B10	Efficiency	1100	525	22,229 hr
104-B11	Off design hot junction	1130	525	20,757 hr
104-B12	Long term stability	1100	525	21,512 hr
104-B13	On-off cycle performance - Cycling terminated after 10 cycles. T_H reduced after 2700 hr. to 1050°F.	1100	525	21,585 hr
104-B14	Reduced hot junction	1050	525	21,318 hr
104-B15	Reduced hot junction, pring pressure 250 psi	1050	525	18,859 hr

104-COUPLE TEST MATRIX