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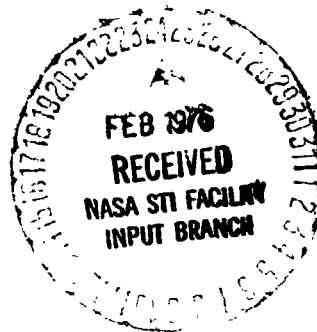
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## SKYLAB MATERIALS PROCESSING FACILITY EXPERIMENT DEVELOPER'S REPORT

By P. G. Parks  
Materials and Processes Laboratory

July 1, 1975



**NASA**

*George C. Marshall Space Flight Center  
Marshall Space Flight Center, Alabama*

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| 16. ABSTRACT<br><br>The development of the Skylab M512 Materials Processing Facility is traced from the design of a portable, self-contained electron beam welding system for terrestrial applications to the highly complex experiment system ultimately developed for three Skylab missions. The M512 experiment facility was designed by the George C. Marshall Space Flight Center to support six in-space experiments intended to explore the advantages of manufacturing materials in the near-zero-gravity environment of Earth orbit. Detailed descriptions of the M512 facility and related experiment hardware are provided in this report, with discussions of hardware verification and man-machine interfaces included. An analysis of the operation of the facility and experiments during the three Skylab missions is presented, including discussions of the hardware performance, anomalies, and data returned to Earth. |  |  |  |   |                       |
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## FOREWORD

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## ACKNOWLEDGMENT

This document describes the results of the work of many dedicated engineers, technicians, and administrators in both government and private industry, who over some ten years conceived, designed, developed, built and tested the Skylab M512 Material Processing Facility. This engineering accomplishment, now recognized as a key forerunner and major foundation in leading the way for practical utilization of space exploration, will serve as a base for technology study for years to come — to these many devoted people, I am most grateful.

I would like to especially thank W. A. Wall for his contribution and support in the design and qualification of the electrical system, and to J. E. Evers for his meaningful contribution and support in the design of the mechanical system.

I would also like to thank Dr. B. W. Schumacher and the Westinghouse Research Laboratories for the development of the self-contained electron beam system.

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#### DEFINITION OF SYMBOLS

| <u>Symbol</u>                 | <u>Definition</u>               |
|-------------------------------|---------------------------------|
| C                             | Capacitor                       |
| CB                            | Circuit Breaker                 |
| °C                            | Temperature, Degrees Celsius    |
| C <sub>3</sub> F <sub>8</sub> | Perfluoropropane                |
| °F                            | Temperature, Degrees Fahrenheit |
| GaAs                          | Gallium Arsenide                |
| J                             | Electrical Receptacle           |
| K                             | Relay                           |
| P                             | Electrical Plug                 |
| Q                             | Semiconductor Device            |
| R                             | Resistor                        |
| RJ                            | Thermocouple Reference Junction |
| S                             | Switch                          |
| SF <sub>6</sub>               | Sulphur Hexafluoride            |
| T                             | Transformer                     |

## ABBREVIATIONS

|                               |   |
|-------------------------------|---|
| AAP                           | Apollo Applications Program                   |
| AM                            | Airlock Module                                |
| CCW                           | Counterclockwise                              |
| CM                            | Command Module                                |
| CRES                          | Corrosion Resistant Steel                     |
| CSR                           | Crew Station Review                           |
| CW                            | Clockwise                                     |
| C <sup>2</sup> F <sup>2</sup> | Crew Compartment Fit and Function Review      |
| DAC                           | Data Acquisition Camera                       |
| DC                            | Direct Current                                |
| DOD                           | Department of Defense                         |
| EB                            | Electron Beam                                 |
| EVA                           | Extra Vehicular Activity                      |
| e.g.                          | for example                                   |
| etc.                          | and so forth                                  |
| FO                            | Functional Objective                          |
| GMT                           | Greenwich Mean Time                           |
| GSE                           | Ground Support Equipment                      |
| HOSC                          | Huntsville Operations Support Center          |
| ICD                           | Interface Control Document                    |
| i.e.                          | that is                                       |
| JSC                           | Lyndon B. Johnson Space Center                |
| KSC                           | John F. Kennedy Space Center                  |
| kV                            | kilovolt                                      |
| kW                            | kilowatt                                      |
| MDA                           | Multiple Docking Adapter                      |
| μF                            | microfarad                                    |
| MSFC                          | George C. Marshall Space Flight Center        |
| NASA                          | National Aeronautics and Space Administration |
| PDR                           | Preliminary Design Review                     |
| rpm                           | revolutions per minute                        |
| SCR                           | Silicon Control Rectifier                     |
| SL-1/2                        | First Skylab Manned Mission                   |
| SL-3                          | Second Skylab Manned Mission                  |
| SL-4                          | Third Skylab Manned Mission                   |
| V                             | Volt  |

TECHNICAL MEMORANDUM X-64977

SKYLAB MATERIALS PROCESSING FACILITY  
EXPERIMENT DEVELOPER'S REPORT

SUMMARY

The development of the Skylab M512 Materials Processing Facility is traced from the design of a portable, self-contained electron beam welding system for terrestrial applications to the highly complex experiment system ultimately developed for the three Skylab missions. The M512 experiment facility was designed by the George C. Marshall Space Flight Center (MSFC) to support six in-space experiments intended to explore the advantages of manufacturing materials in the near-zero-gravity environment of Earth orbit. The six experiments, initially developed for use in the M512 facility were:

- M551 - Metals Melting
- M552 - Exothermic Brazing
- M553 - Sphere Forming
- M554 - Composite Casting\*
- M555 - GaAs Crystal Growth
- M479 - Zero-Gravity Flammability

\*Replaced by experiment M566, Aluminum-Copper Eutectic, performed in the M518 Multipurpose Electric Furnace Facility with ten other experiments (not covered in this report).

Detailed descriptions of the M512 facility and related experiment hardware are provided in this report, with discussions of hardware verification and man-machine interfaces included. An analysis of the operation of the facility and experiments during the three Skylab missions is presented, including discussions of the hardware performance, anomalies, and data returned to Earth. No attempt has been made to interpret the scientific significance of the data; individual experiment findings and conclusions will be published by the respective experiment Principal Investigators.

It is concluded from the Skylab operations that the M512 facility performed as expected. A malfunctioning relay in the electron beam welder turn-off circuitry did not prevent the crew from completing M551 or M553, although M553 was terminated early because of the lack of available mission time. Experiments M552 and M479 were fully completed. It must be

noted that the welder circuitry was essentially designed in 1966 with minimal upgrading. Incorporation of new circuit technology due to advances in the "state-of-art" undoubtedly would have reduced power consumption and weight and improved the hardware's reliability and performance. Nevertheless, the versatile M512 system proved to be extremely successful. Even the questionable malfunctioning welder circuitry did not cause the termination of any experiment.

Relative to safety consideration, an extensive test program was implemented and conducted to evaluate the potential hazards associated with the operation of the processing facility and each associated experiment. Simultaneously with facility and experiment design maturity, various tests were performed to assure hardware, experiments, and facility operational safety well beyond all NASA regulations.

The effort was a continuing cycle of extensive review, design, evaluation, and testing relative to safety matters throughout the development of the experiment system. Safety considerations were a key factor in the development, design and implementation of the experiment facility and associated experiments. Extensive testing was conducted covering all facets, e.g., note three key documents: Qualification Test Report for Experiments, No. 70TRI-95M10500-1, August 18, 1975; Test and Analysis Report Pre and Post Qualification Checkout Experiments M512/479, QUAL-AE-R-39, August 2, 1972; an Experimental Investigation of the Skylab Experiment M479 Operating Hazards and Contamination Potential, No. EP72-1. Many tests were conducted in Skylab atmosphere - 70/30 O<sub>2</sub>/N<sub>2</sub> at 5 psia.

Consideration parameters covered:

Gasses

- o Toxicity
- o Combustion

Temperature

- o Chamber
- o Battery
- o EB System
- o Experiments

Radiation

- o Chamber
- o Vacuum Ports

Electrical

- o Failure Safety
- o Insulation

For the benefit of future materials processing projects, a number of recommendations are made, summarizing the more important lessons learned from this undertaking.



## SECTION I. INTRODUCTION

This report provides a description of Skylab's M512 Materials Processing Facility and related experiments, traces the history of their development, and evaluates their performance on the three Skylab manned missions. The M512 facility, developed by MSFC, was designed to provide a common spacecraft interface in which several manufacturing in-space/material science experiments could be performed. The experiments designed to be performed in the M512 facility included:

- M551 - Metals Melting
- M552 - Exothermic Brazing
- M553 - Sphere Forming
- M554 - Composite Casting
- M555 - GaAs Crystal Growth
- M479 - Zero-Gravity Flammability

During the development of the hardware, experiment M554 was deleted from the Skylab Program and replaced by M566, Aluminum-Copper Eutectic, performed in the Skylab M518 Multipurpose Electric Furnace System. This system was also operated in the M512 facility but is not discussed in this report since it was a separately developed system. However, the M512 facility support provided for the operation of the 11 M518 experiments is described.

Also included in this report are discussions of the methods used to verify the M512 hardware for manned space flight and the lessons learned during the development and operations of the experiments.

## SECTION II. EXPERIMENT DEVELOPMENT HISTORY

The first appearance of the electron beam process was in 1907 when a concentrated beam of electrons was applied to a furnace, as a heat source, to melt refractory metals. However, it was not until 1954 that electron beam (EB) welding was researched in France, and 1956 in the United States. By the close of 1959 the MSFC, Manufacturing Engineering Laboratory had designed, built, and operated an Electron Beam Welding System. Also in 1959, the Laboratory made a technical presentation titled, "Hand Held Electron Beam Gun for Repair in Space". By this time a great deal of early planning on the system had been performed and a continuing research effort was well underway. EB welding is considered an exotic process by some engineers because the process requires a high vacuum and a sophisticated power source for its operation. By way of reference a typical commercial system, including vacuum chamber, power supply and controls, has a mass of 6800 kilograms (15000 pounds) and requires 5.66 cubic meters (200 cubic feet) of space.

### A. The Saturn Application Electron Beam Welding System

In 1964 the Westinghouse Electric Corporation, under contract MSFC, initiated the development of a lightweight, self-contained EB welding system for terrestrial applications. This Saturn application system was designed for limited weld fabrication, or weld repair within a portable vacuum chamber. The system was to be designed to these six general specifications:

1. The mass of the complete unit--gun, power supply, and controls--would be no more than 34 kilograms (75 pounds).
2. The system would be capable of operating continuously for 2 minutes.
3. The maximum operating potential would be no more than 20,000 volts.
4. The system would be operable in a pressure range of  $1.3 \times 10^{-2}$  newtons per square meter ( $10^{-4}$  torr), or lower, down to  $1.3 \times 10^{-7}$  newtons per square meter ( $10^{-9}$  torr).
5. The system would have a gun-to-work distance range from 6.4 to 38 millimeters (0.25 to 1.5 inches).
6. The beam diameter at the work piece would be no greater than 0.51 millimeter (0.02 inch).

The Saturn application system, shown in Figure 1, more than met these six specifications. The unit had a mass of 27.7 kilograms (61 pounds), was 53.4 centimeters (21 inches) long, and 30.5 centimeters

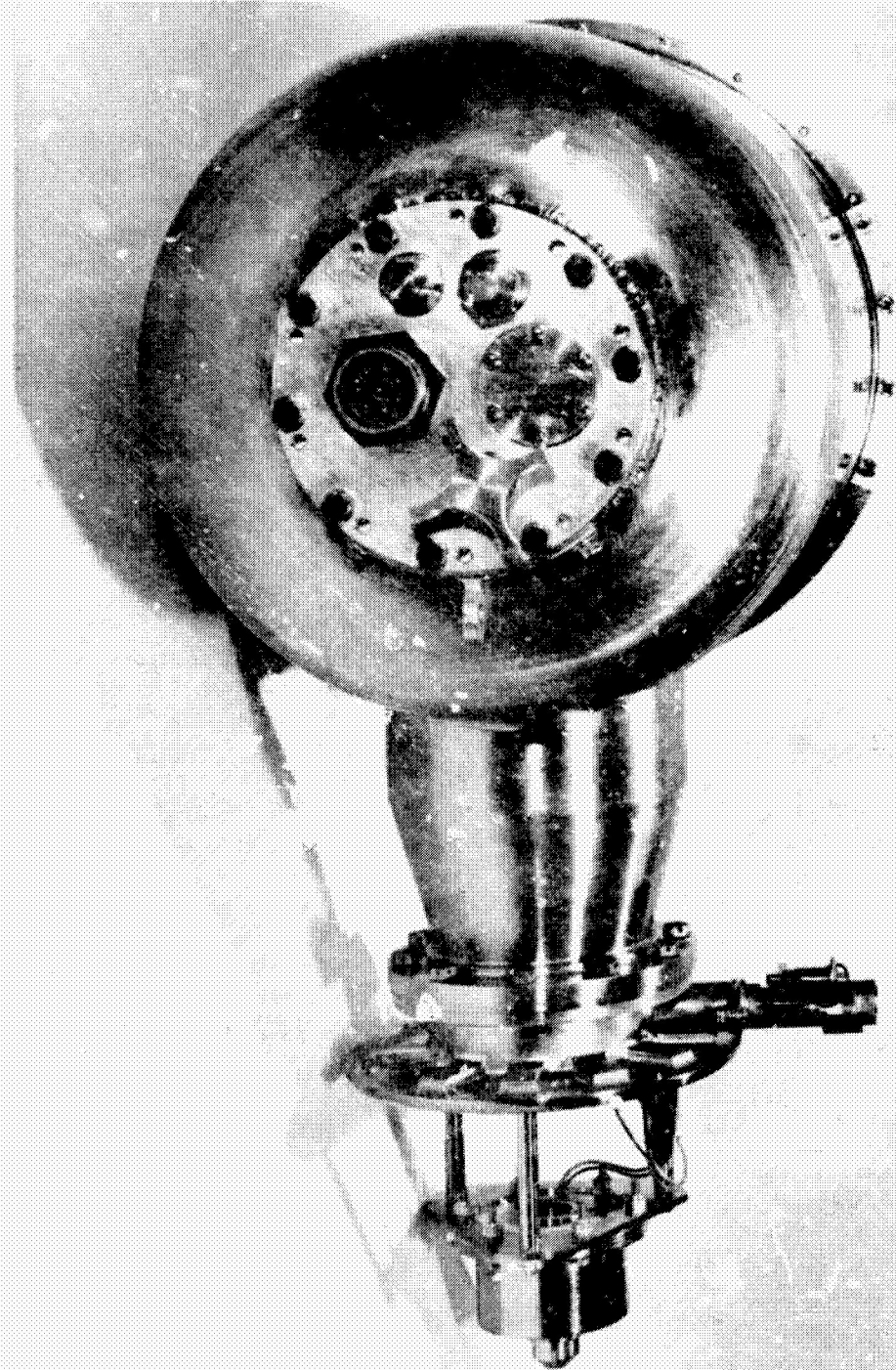


FIGURE 1. SATURN APPLICATION ELECTRON BEAM WELDING SYSTEM

(12 inches) in diameter. The EB gun assembly protruded 25.4 centimeters (10 inches) below the body of the unit. It could be operated at 98 milliamperes and 20,000 volts for as long as 5 minutes without overheating. In addition, the unit could be operated independent of its self-contained battery power supply; this feature eliminated the dependency on batteries and increased the potential usefulness. This gun was capable of welding aluminum and stainless steel up to 6.4 millimeters (0.25 inch) thick at speeds up to 1.0 meter (40 inches) per minute. The technical significance of this development is recognized by comparing the Saturn application system with the typical commercial EB welding system previously described.

#### B. Construction and Repair in Space

Concurrent with the development of the Saturn application EB welding system, studies made by General Electric, Westinghouse, Hamilton Standard and Hughes Aircraft indicated that EB welding held the most promise for weld repair and assembly in orbiting spacecraft. Earth orbiting satellites had telemetered atmospheric information to Earth indicating that vacuum in space was approximately  $1.3 \times 10^{-4}$  to  $1.3 \times 10^{-5}$  newtons per square meter ( $10^{-6}$  to  $10^{-7}$  torr). Therefore no problem was anticipated operating the electron beam welder in the space environment. With the successful development and functional use of the Saturn application unit, it was proposed that the system be adapted for welding on one of the early flights of the Apollo Applications Program (AAP) (later to become Skylab).

In parallel with the planning to perform an EB welding experiment on AAP, investigations into the use of the exothermic brazing technique for joining tubular steel assemblies in the space environment were also being made. These investigations were the outgrowth of North American's B-70 program, where exotherm packages were used to join tubular assemblies in inaccessible areas of the airframe. Exothermic packages seemed to offer another solution to the assembly and repair of structures in the space environment. The results of these investigations led to a contract between MSFC and SOLAR, a division of International Harvester Inc., to study high vacuum applications of exothermic packages.

1. MSFC Experiment 36 - Welding in Space. By late 1964, MSFC had completed the conceptual design of the welding in space experiment. This concept is shown in figure 2. The experiment consisted of a self-contained EB welding system which was moved across the weld specimens by a drive motor. The electron beam would be used to weld aluminum, stainless steel and titanium plates of varying thickness.

a. Experiment objectives. The specific objectives of the welding in space experiment were to develop and demonstrate the capability for welding in space environments. Determination would also be

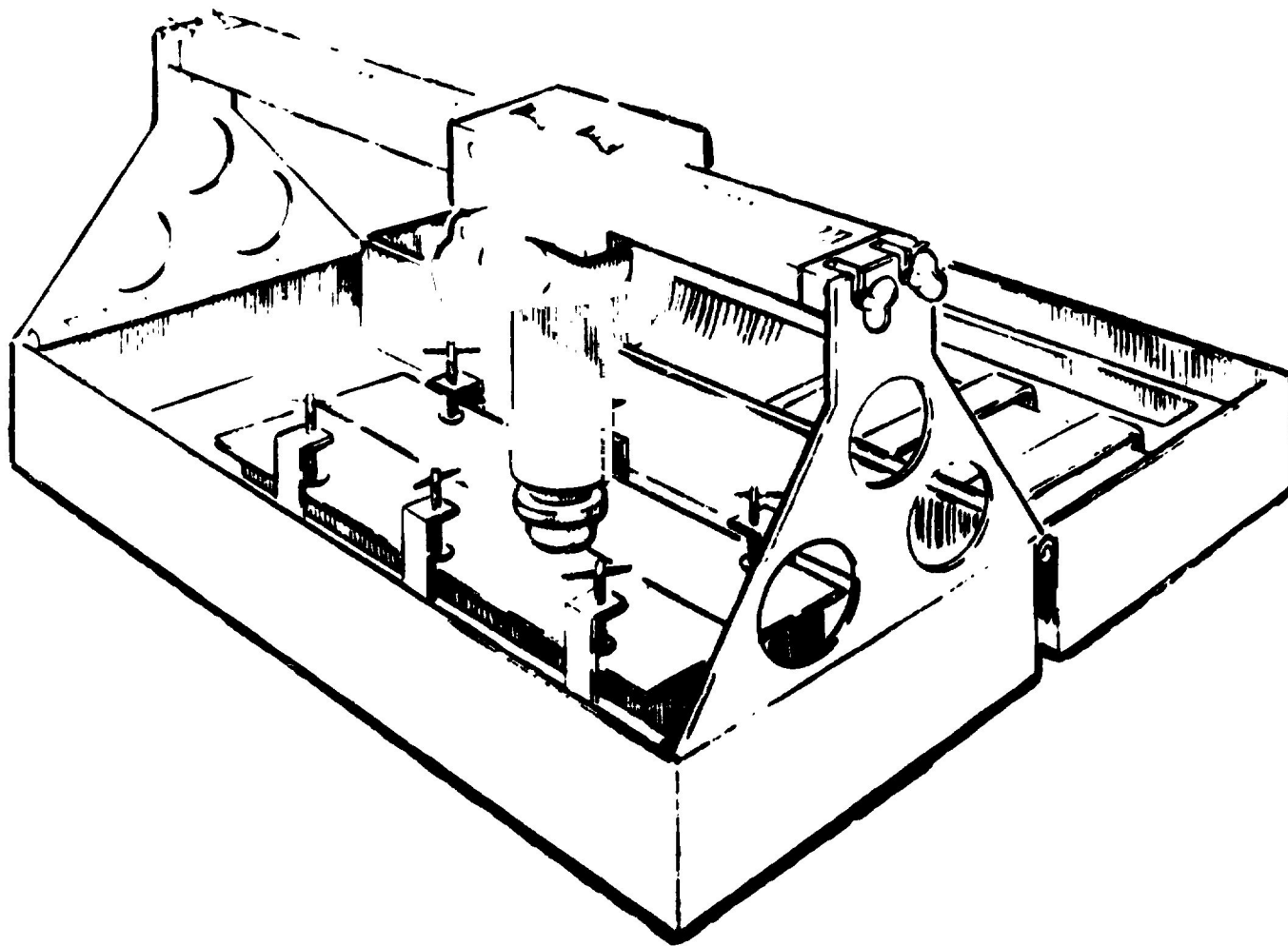


FIGURE 2. MSFC EXPERIMENT 36 - WELDING IN SPACE

made of the flow and splatter characteristics of the molten weld puddle at zero gravity and high vacuum, performance parameters of welding equipment at zero gravity and high vacuum, and the performance of the weld joints.

b. Experiment description. The first experiment concept used the Saturn application electron beam welding system "right angle" configuration as shown in figure 1 and was to be launched in an unpressurized area of the spacecraft and operated in space vacuum. The weld specimens and 16-millimeter motion picture film were to be returned to Earth for evaluation. The total experiment package had a mass of 60.5 kilograms (133 pounds) and occupied a volume of 0.09 cubic meters (3.1 cubic feet). Astronaut and mission safety considerations were of major importance relative to this conceptual design and operating approach, e.g., operating and manipulating the experiment system outside the Skylab during an extravehicular activity (EVA) period. A careful investigation would have been made to define all possible hazards.

2. MSFC Experiment 35 - Tube Brazing. The conceptual design of MSFC's tube brazing experiment is shown in figure 3. This design was also completed by late 1964. The experiment package contained stainless-steel tubes, braze fittings, exotherm packages, and an ignition battery. The mass of the experiment was 3.6 kilograms (8 pounds) and occupied a volume of 0.006 cubic meters (0.2 cubic feet). Like the welding in space experiment, the tube brazing experiment was to be launched and performed in an unpressurized area of the spacecraft.

Experiment objectives of the tube brazing experiment were to develop and demonstrate the capability for joining tubular steel assemblies in the space environment by the exothermic brazing technique. Determination would also be made of the flow and wetting characteristics of the braze alloy; outgassing factors of the process; the effects of storage in high vacuum and zero gravity on the performance of exothermic packages; and the joint strength, metallurgical properties and leak tightness by subsequent ground evaluation.

### C. The Common Experiment Facility

By late 1966, NASA Headquarters had given developmental approval to the welding and brazing experiments and had assigned program experiment numbers to them; M492 - Tube Joining in Space and M493 - Electron Beam Welding. Additionally, with the advancement of the Apollo Applications Program, a decision was made to conduct both experiments within the pressurized environment of the passivated S-IVB workshop. This led to the obvious requirement for an experimental work chamber that could be evacuated to the vacuum of space. However, the entry envelope of the EVA hatch would not accommodate the "right angle" configuration welding system with a work chamber attached. Therefore, Westinghouse was contracted to develop a self-contained, "in-line" electron beam welder capable of performing the welding experiment and controls for initiating

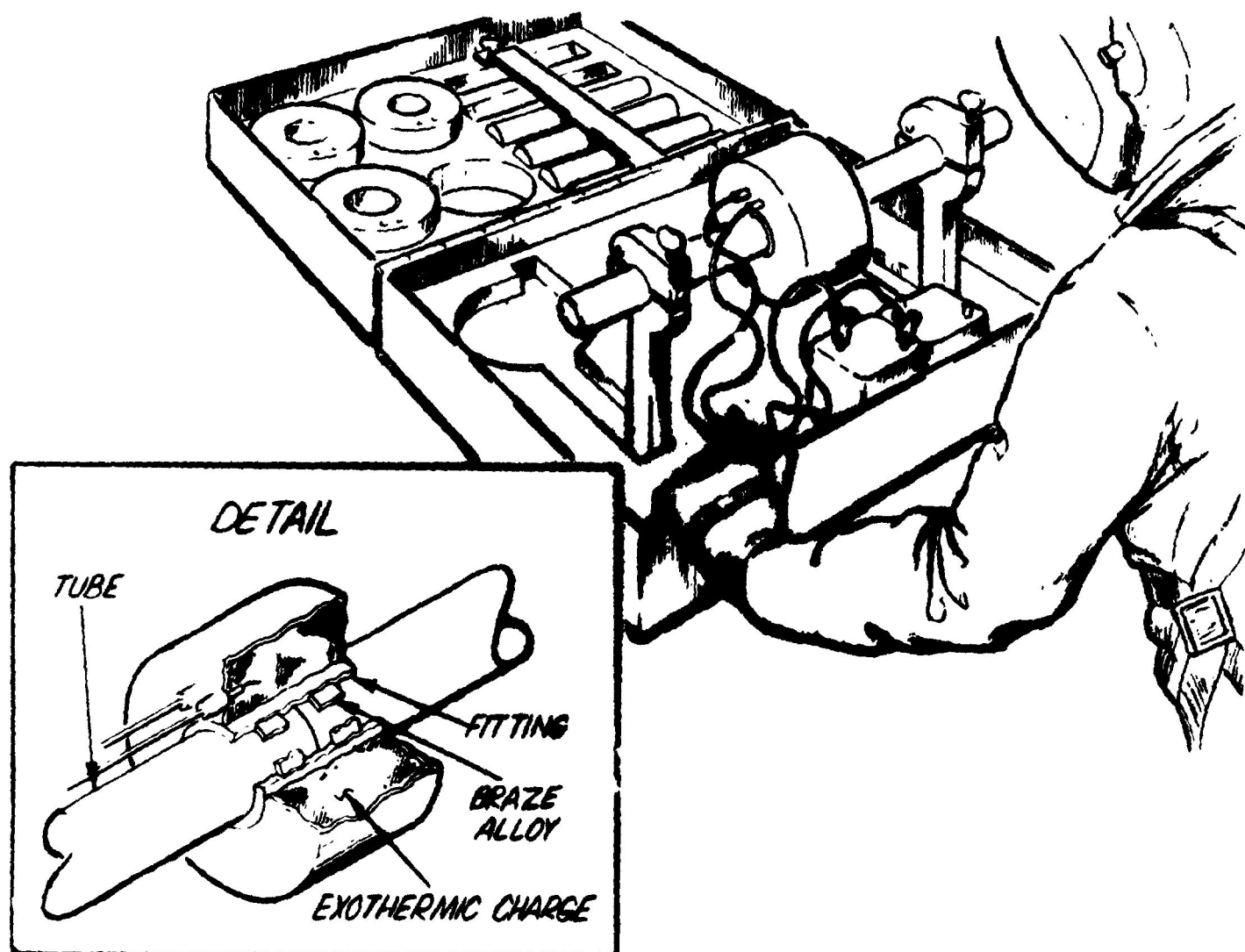


FIGURE 3. MSFC EXPERIMENT 35 - TUBE BRAZING

the brazing experiment. The vacuum work chamber, welding and brazing modules, and experiment mounting provisions would be built by MSFC. The vacuum vent line for the chamber would be provided in the S-IVB workshop. Figure 4 is a schematic of the structural design of the M492/M493 facility.

1. Space Electron Beam Unit. Figure 5 shows the completely self-contained space electron beam unit that was designed and built by Westinghouse. The battery-powered 2000 watt, 20,000 volt electron beam system had a mass of approximately 45.4 kilograms (100 pounds). The weight increase over the Saturn application unit was the result of integrating the control provisions and the use of space-rated components. Battery, power-conditioning circuits, electron gun and lens were mounted in a cylinder 76.2 centimeters (30 inches) long by 30.5 centimeters (12 inches) in diameter. The inverter in the center section of the case was insulated with sulfur hexafluoride ( $\text{SF}_6$ ) at a pressure of  $2.1 \times 10^5$  newtons per square meter (30 pounds per square inch) gauge.

a. Control panel. The early model control panel, figure 6, contained all controls and displays required for the operation of the welding and brazing experiments. Direct control was provided to adjust the electron beam current and lens current to optimize beam focus on the work piece. The high voltage output of the inverter power supply was maintained at 20,000 volts, regulated to  $\pm 200$  volts, with no adjustment required. Meters monitored the beam voltage and current, and vacuum level inside the work chamber. Switches were provided for the high-voltage power supply, the magnetic lens, the weld specimen drive motor, the exotherm firing controls, and lights that were required for the two recording cameras.

b. Battery package. The unit's power source was a Gemini-rated missile battery pack which provided up to 100 amperes at a nominal 28 volts for approximately 10 minutes. Included in the batteries' capacity were the power requirements for the EB gun, exotherm firing, lights, weld drive motor, and camera operation.

c. Inverter power supply. The inverter power supply employed two stages: a saturable-inductor power oscillator and a 2000 watt inverter consisting of two banks of silicon transistors. Each power transistor was separately fused so that failure of any one transistor would not cause additional failures.

d. Gun system. The EB gun consisted of an anode, grid, and filament as shown in figure 7. The anode was at ground potential; the filament and grid operated at a high negative voltage relative to the anode and were insulated from the anode by a glass envelope. The glass envelope also acted as a seal between the  $\text{SF}_6$  pressurized power supply section and the high vacuum required for the gun. The gun



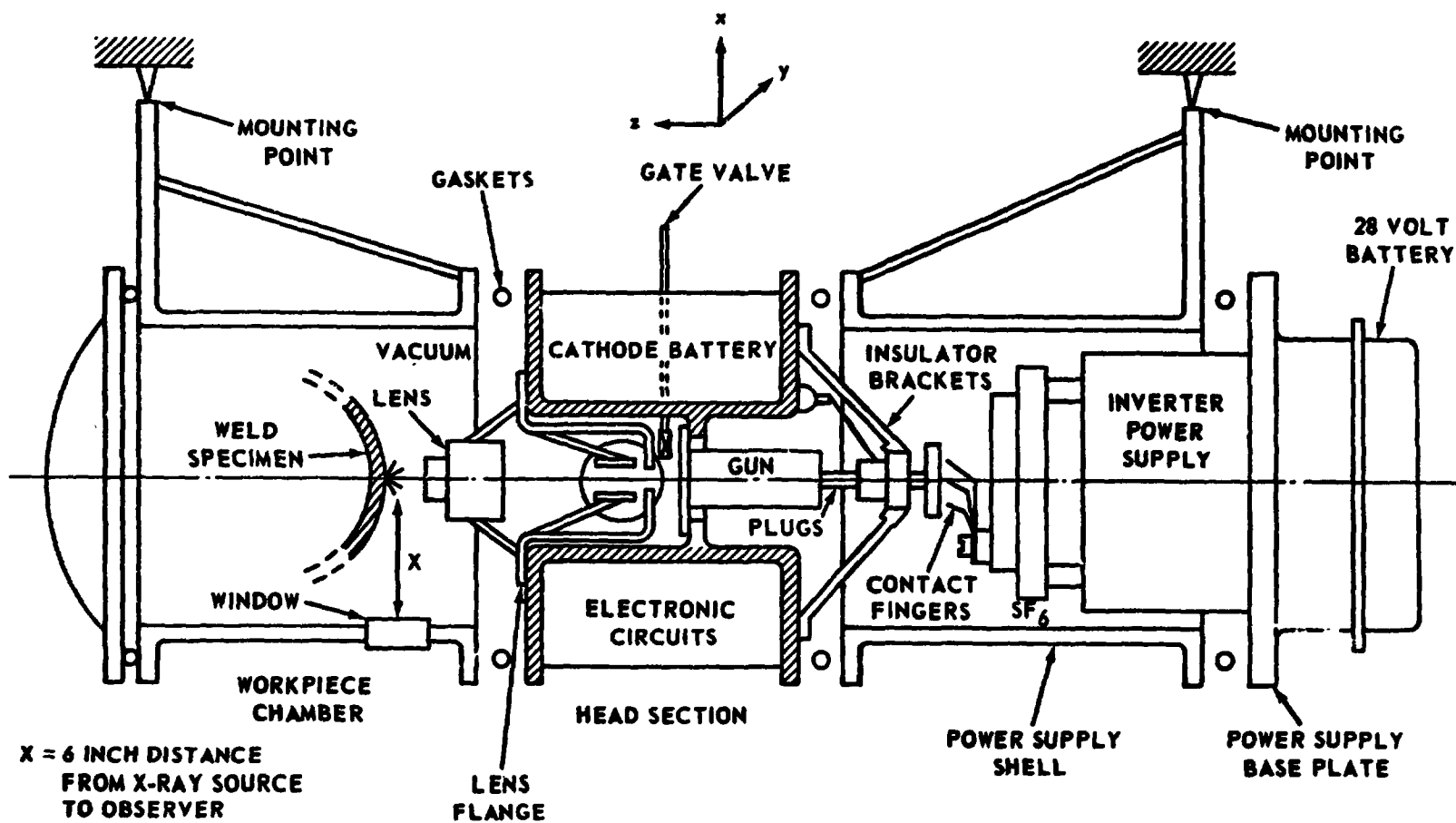


FIGURE 4. STRUCTURAL SCHEMATIC OF THE M492/M493 EXPERIMENT FACILITY

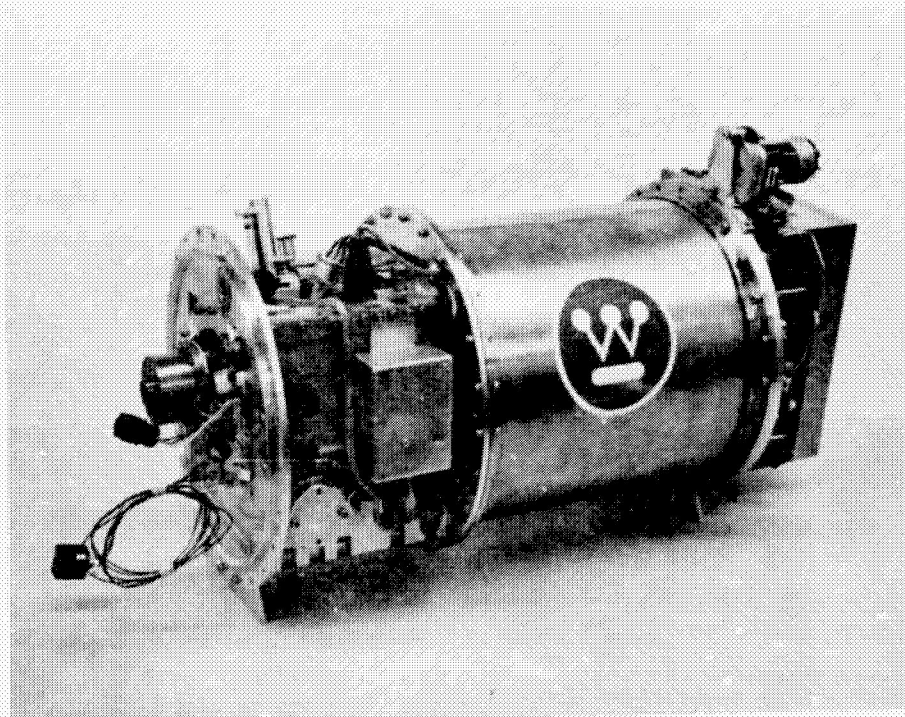
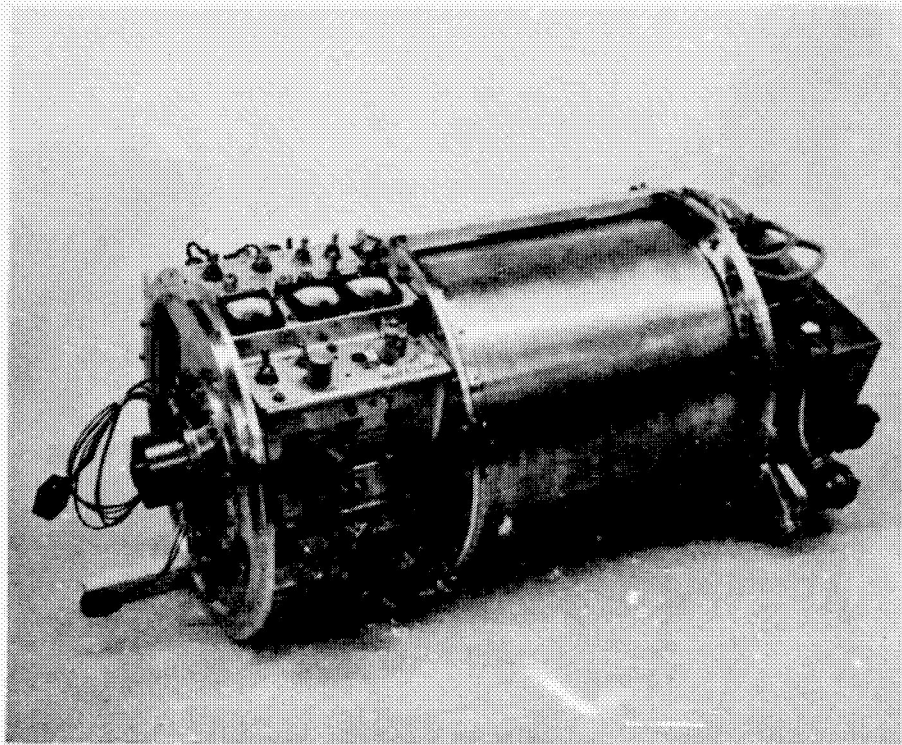


FIGURE 5. SELF-CONTAINED ELECTRON BEAM WELDING UNIT

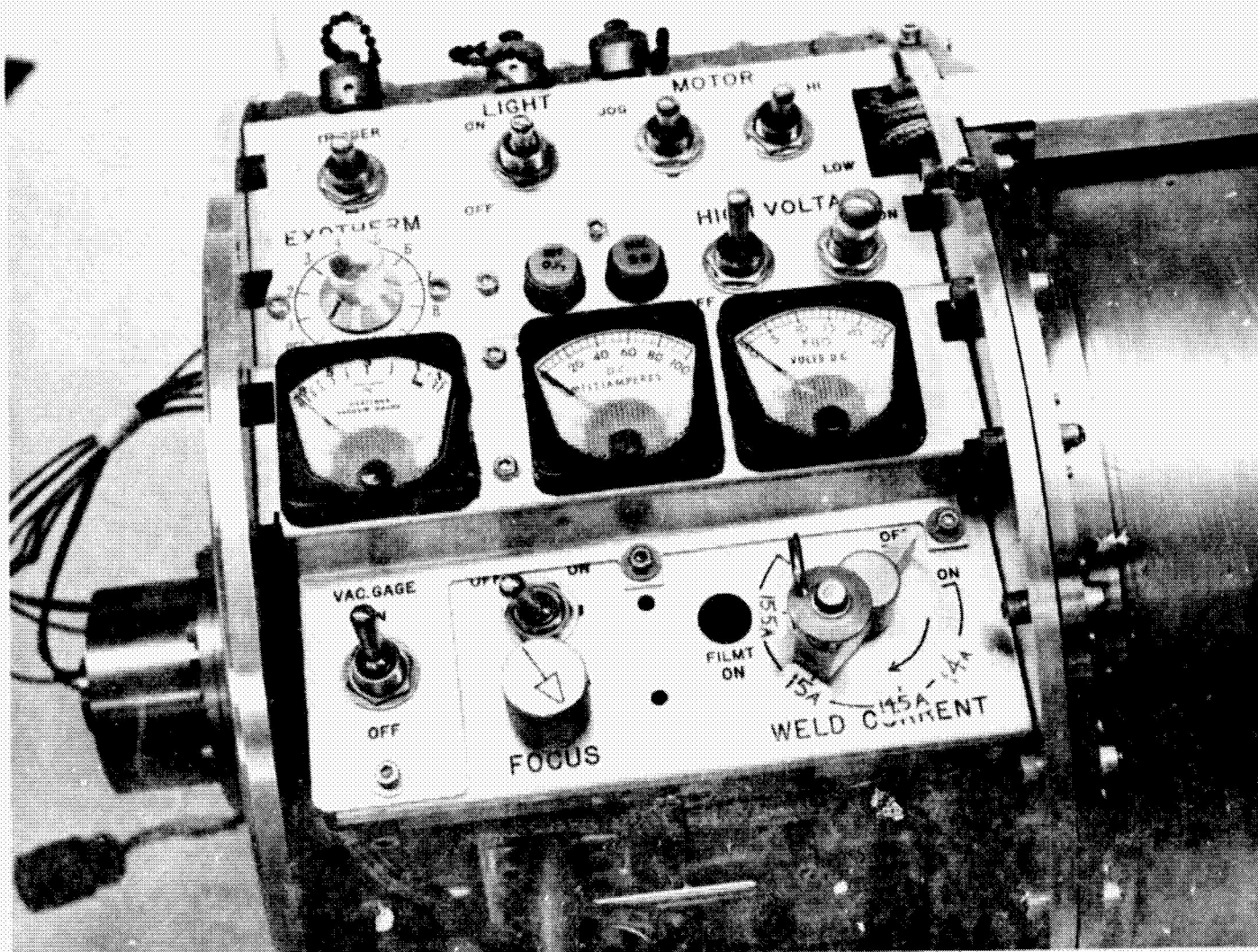


FIGURE 6. CONTROL PANEL FOR THE ELECTRON BEAM WELDING UNIT

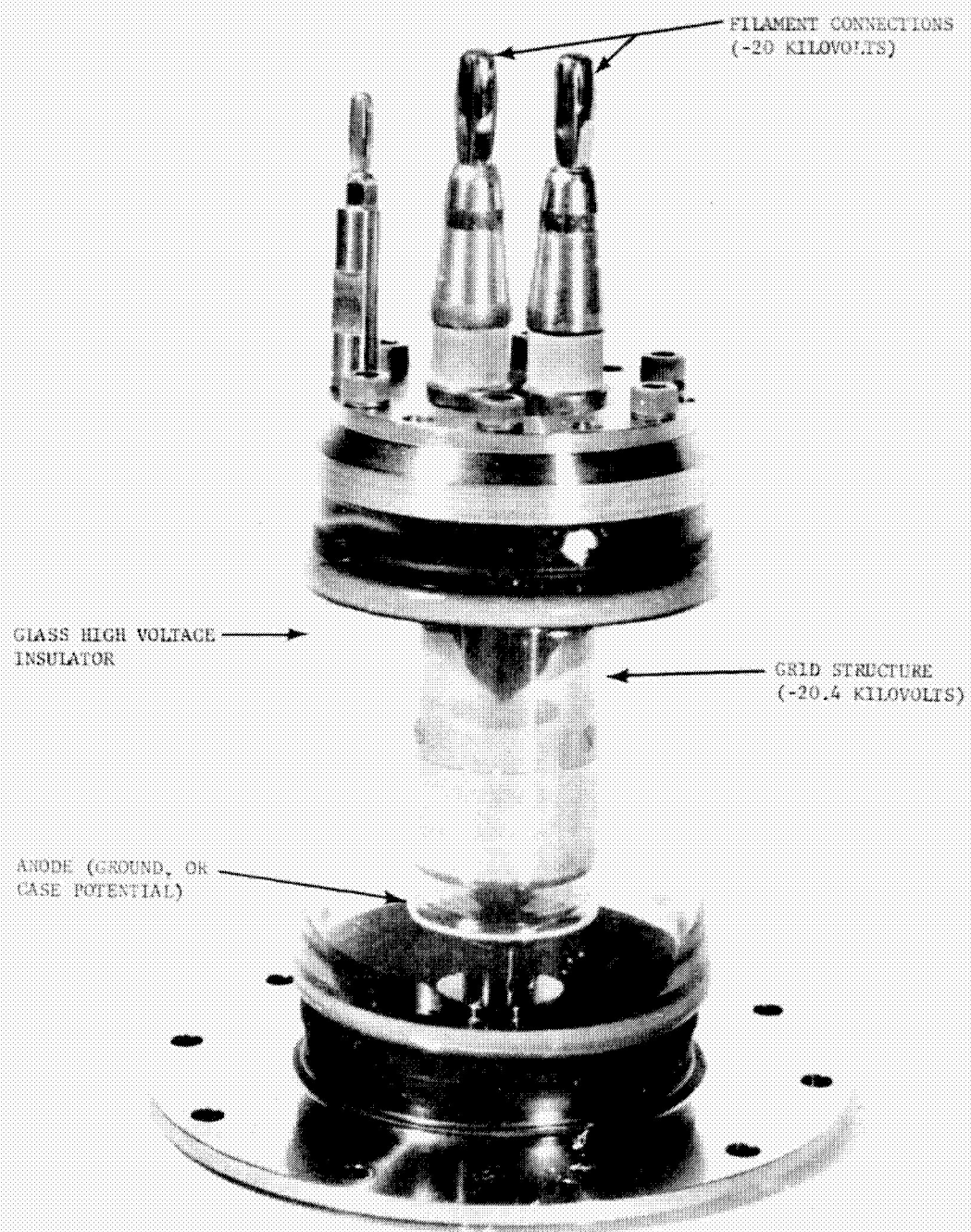


FIGURE 7. ELECTRON BEAM GUN FOR WELDING UNIT

filament was a pure tungsten ribbon. The last section of the gun was the magnetic lens that was used to focus the beam at the work piece. The axis of the lens was moved 19 millimeters (0.75 inches) from the axis of the electron beam gun and two electromagnetic deflection zig-zag coils were added to steer the beam from the former axis to the latter. This was required to reduce the possibility of gun damage by droplets of metal being ejected from the molten weld pool and floating into the gun elements.

2. Vacuum Work Chamber. The vacuum work chamber was attached to the EB gun end of the welder to provide the controlled environment for the welding and brazing experiment performance. The chamber was a cylinder, 33 centimeters (13 inches) long and 30.5 centimeters (12 inches) in diameter, with a hatch at the cylinder end opposite the gun as shown in figure 8. The chamber contained two viewports, one for astronaut viewing and the other for photography. Viewports were made of leaded glass to shield from X-rays. A 7.5 centimeter (3 inch) diameter vacuum port was also provided for connecting to the S-IVB workshop vacuum vent line.

3. M492/M493 Experiment Facility. The M492/M493 experiment facility consisted of the described "in-line" electron beam unit and vacuum work chamber, and provisions for installing the facility inside the S-IVB workshop. The complete facility, figure 9, had a mass of 64 kilograms (140 pounds) and occupied a volume of 0.074 cubic meters (2.6 cubic feet). Although the operational location for the facility was to be in the pressurized spacecraft, the launch location was still in an unpressurized area of the launch vehicle, attached to a strut. After S-IVB passivation, the facility would be retrieved during an extravehicular activity and installed in the workshop as shown in figure 10.

By early 1968 the evolution of the orbital workshop eliminated the requirement for the external launch of the facility, and both the launch and operational locations were moved to the multiple docking adapter (MDA) of the spacecraft. The facility remained unchanged except that the requirement for the vacuum vent line was changed from the 7.5 centimeter (3 inch) diameter line to a 10 centimeter (4 inch) diameter line, a maximum of 122 centimeters (48 inches) long. This vent line and its valves would now be provided by the MDA contractor.

Also by 1968, the welding and brazing experiments had been developed to the point that an additional storage container became necessary. This container, figure 11, housed both weld and exothermic samples and had a mass of 8.2 kilograms (18 pounds) and occupied a volume of 0.013 cubic meters (0.45 cubic feet).

4. Experiment M492 - Tube Joining in Space. While the basic objectives of the brazing experiment remained unchanged, the experiment



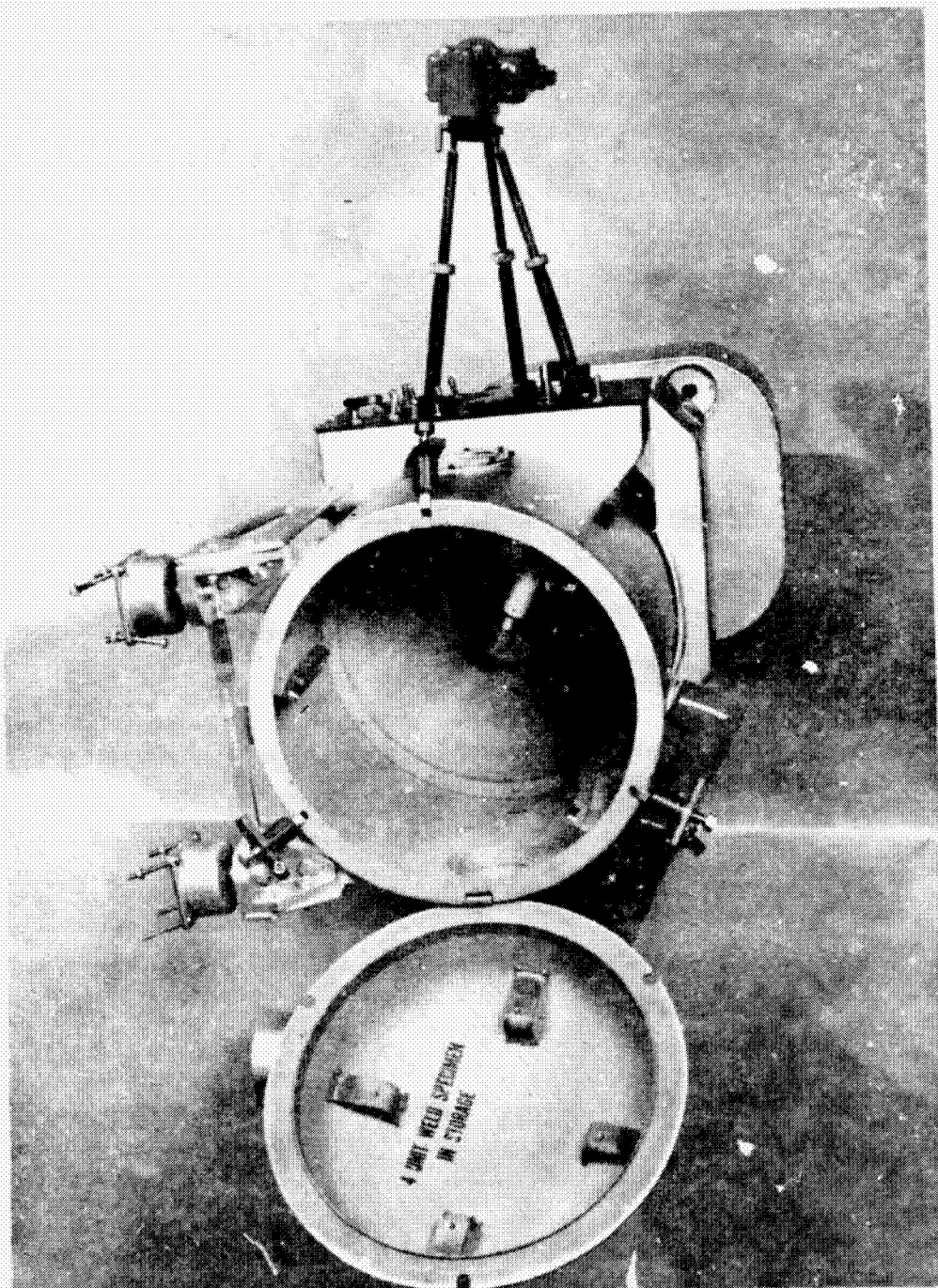


FIGURE 8. M492/M493 VACUUM WORK CHAMBER

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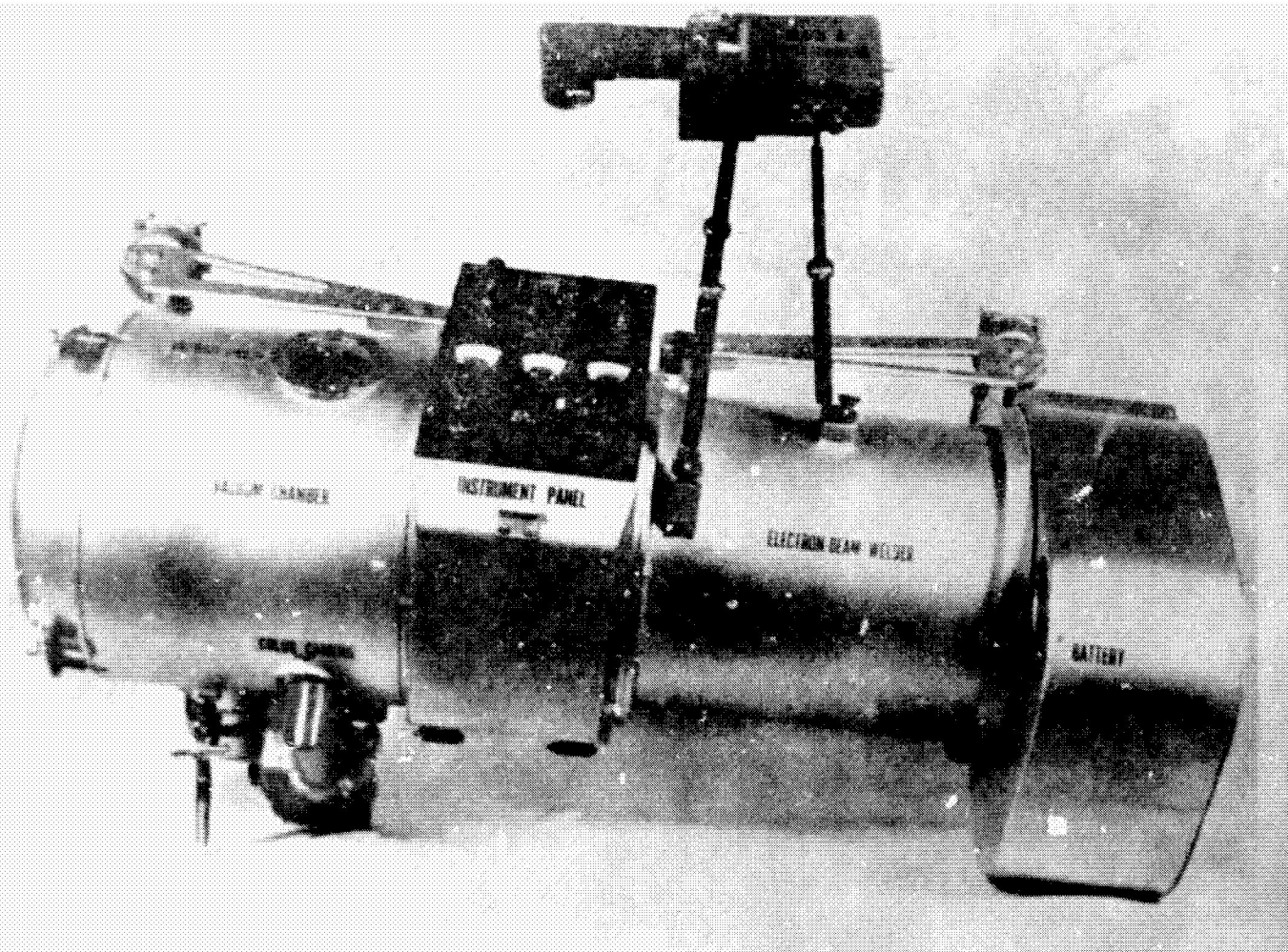


FIGURE 9. EXPERIMENT M492/M493 FACILITY

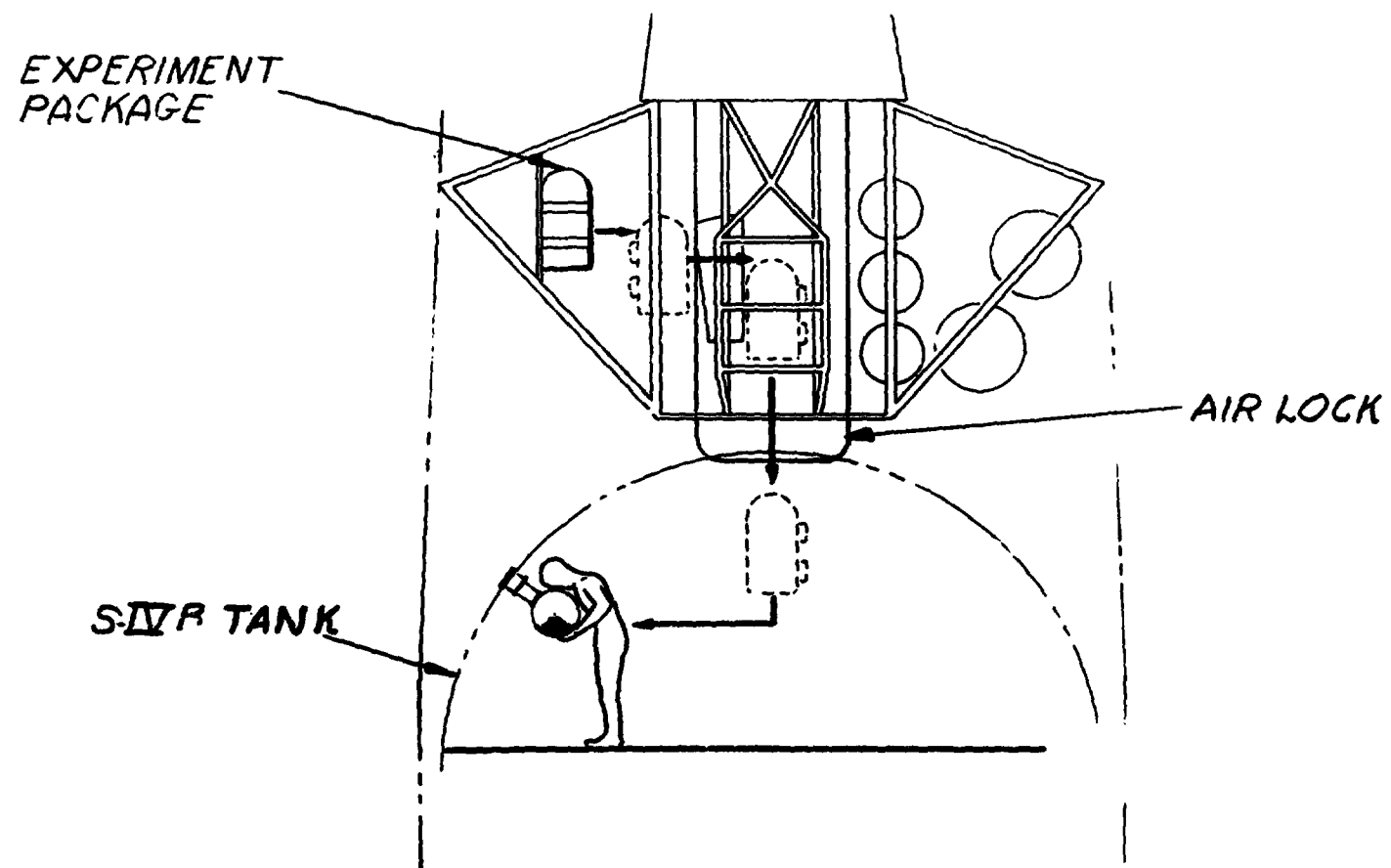
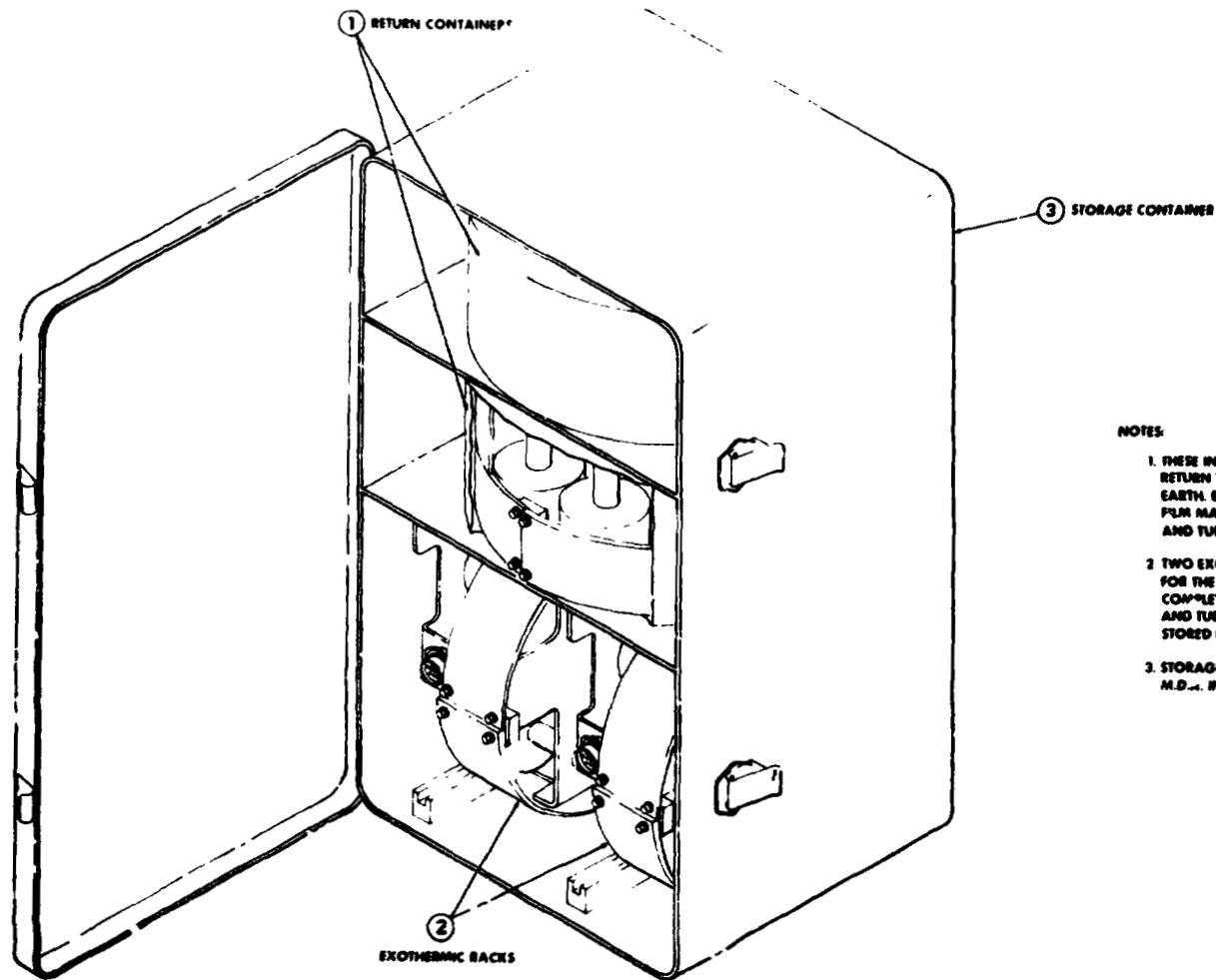


FIGURE 10. EXPERIMENT M492/M493 FACILITY STORAGE AND HANDLING





NOTES:

1. THESE INDIVIDUAL CONTAINERS WILL BE USED ONLY TO RETURN THE PRODUCTS OF THE EXPERIMENTS BACK TO EARTH. EACH WILL HOUSE TWO WELD RING SAMPLES, FILM MAGAZINES AND A NUMBER OF EXOTHERMIC PELLET AND TUBE ASSEMBLIES.
2. TWO EXOTHERMIC RACKS WILL CARRY MORE SAMPLES FOR THE BRAZING AND WELDING EXPERIMENT. AT THE COMPLETION OF THE EXPERIMENT THE EXOTHERMIC PELLET AND TUBE WILL BE REMOVED FROM THE RACK AND STORED IN THE RETURN CONTAINERS.
3. STORAGE CONTAINER WILL BE HARD MOUNTED IN THE AREA OF THE ELECTRON BEAM WELDS.

FIGURE 11. EXPERIMENT M492/M493 SPECIMEN STORAGE CONTAINER

packaging concept was revised to be consistent with the constraints of the vacuum work chamber. The braze specimens were packaged in a cluster of eight specimens, with the cluster being capable of being installed into the work chamber. Figures 12 and 13 illustrate this packaging concept. The firing of each exotherm specimen was controlled from the facility control panel through an electrical connector in the work chamber.

5. Experiment M493 - Electron Beam Welding. The weld samples to be used in the vacuum work chamber were mounted on a 25.4 centimeter (10 inch) diameter wheel as shown in figures 13 and 14. Welding speed was controlled by the rate of rotation of the wheel. The wheel was rotated by a drive motor installed in the work chamber, controlled by switches on the control panel. Thickness of the "brake shoe" type of samples, figure 15, varied from 0.51 millimeters (0.02 inches) to 9.5 millimeters (0.375 inches) to give weld conditions equivalent to burn-through, over, under and optimum penetration of the electron beam.

#### D. Additional Experimentation

Throughout 1967, 1968 and early 1969 the development of the M492/M493 facility proceeded and finally culminated with the construction of a flight qualification apparatus (figure 16). However, by mid-1968, preliminary studies were started to explore the possibilities of performing additional manufacturing in space experiments. These studies were to show how the M492/M493 experiment facility could be utilized as an early "materials processing in space" facility. In early 1969, NASA Headquarters approved three additional experiment tasks for development, all of which were to be performed in the original facility. The experiment, with five tasks, was also renamed at this time to M512 - Materials Processing in Space. An early concept of the M512 facility with the five experiment tasks is shown in figure 17. Modifications to the basic facility were mainly in the form of control circuitry for the new tasks; the electron beam welder remained essentially unchanged except for the requirement that "space-rated" components be used. The following paragraphs describe the 1968 concepts of the experiments.

1. Experimental Task 1 - Metals Melting. The metals melting task was a modification of the M493, Electron Beam Welding experiment, in which experiments on molten metal would be performed. Various metals and alloys, each sample ranging in thickness from 0.51 millimeters (0.02 inches) to 6.4 millimeters (0.25 inches), would be mounted on a rotating fixture in the vacuum chamber and the electron beam allowed to hit the convex side of the sample as in the M493 experiment. The sample was designed so that the electron beam would not penetrate through the 6.4 millimeter portion and would actually separate the metal in the 0.51 millimeter portion. The electron beam would make a nominal bead weld on plate during the intermediate 75° of the sample.

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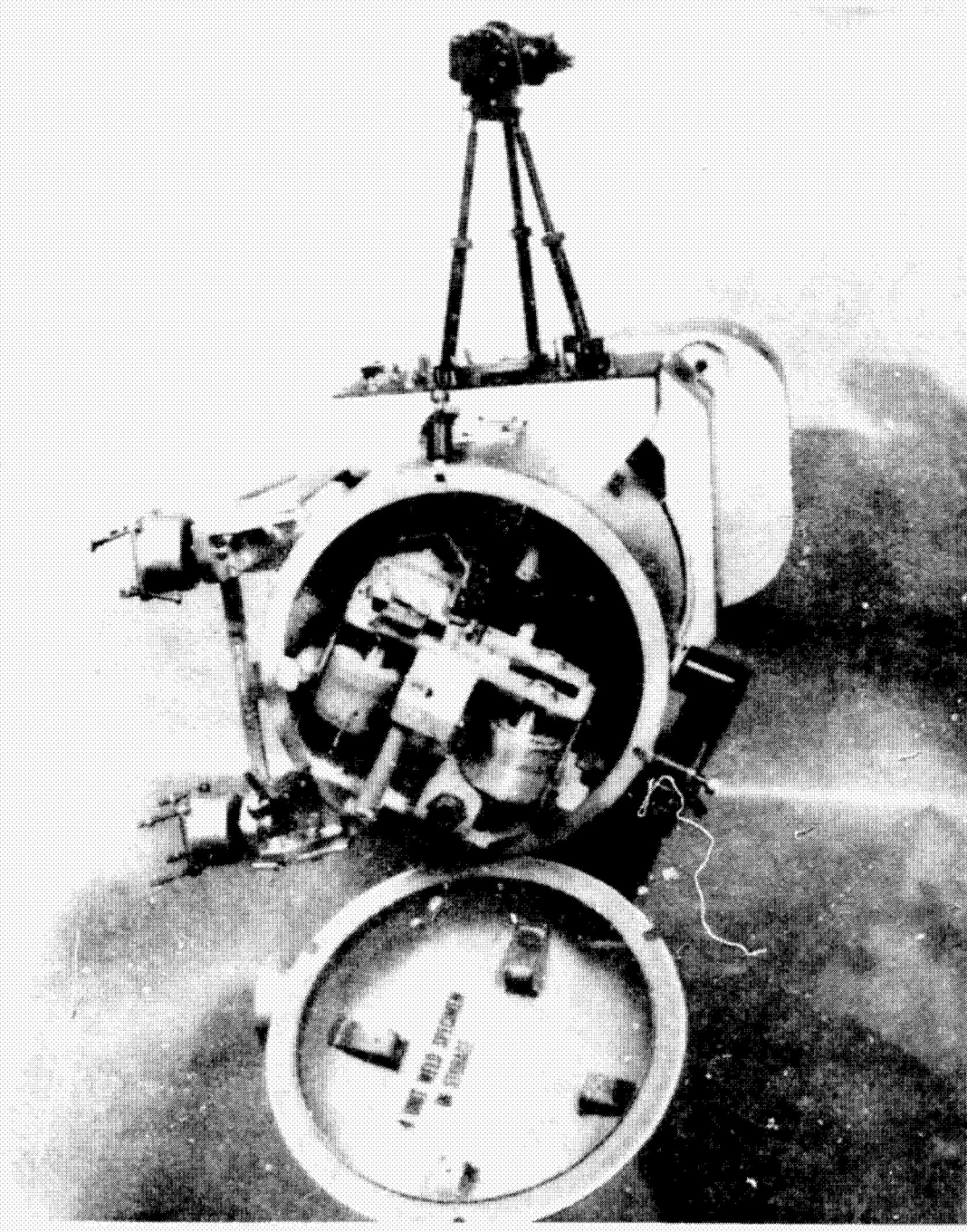


FIGURE 12. M492 BRAZE CLUSTER INSTALLED IN WORK CHAMBER

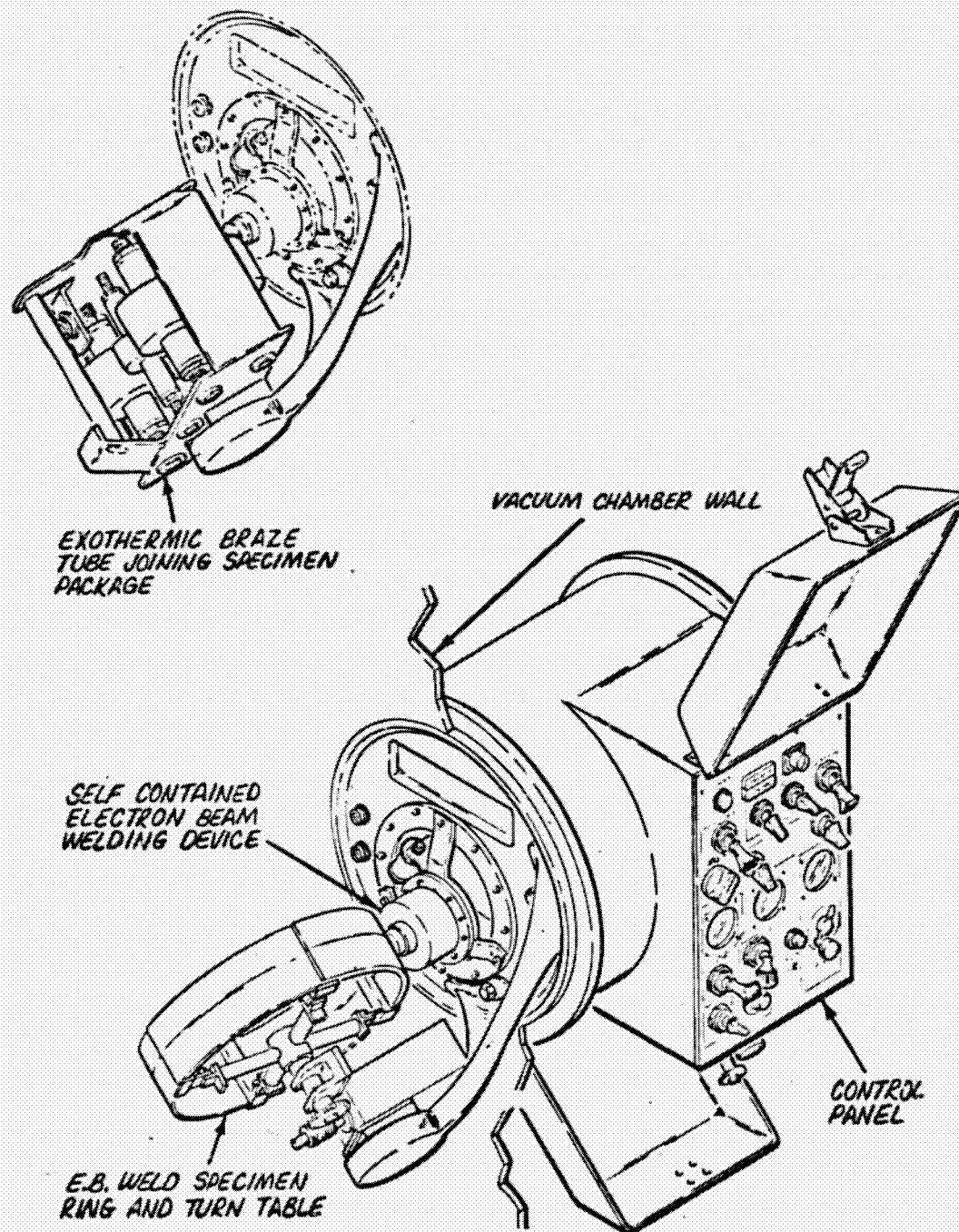


FIGURE 13. OPERATIONAL CONCEPTS OF M492 AND M493 IN THE VACUUM WORK CHAMBER



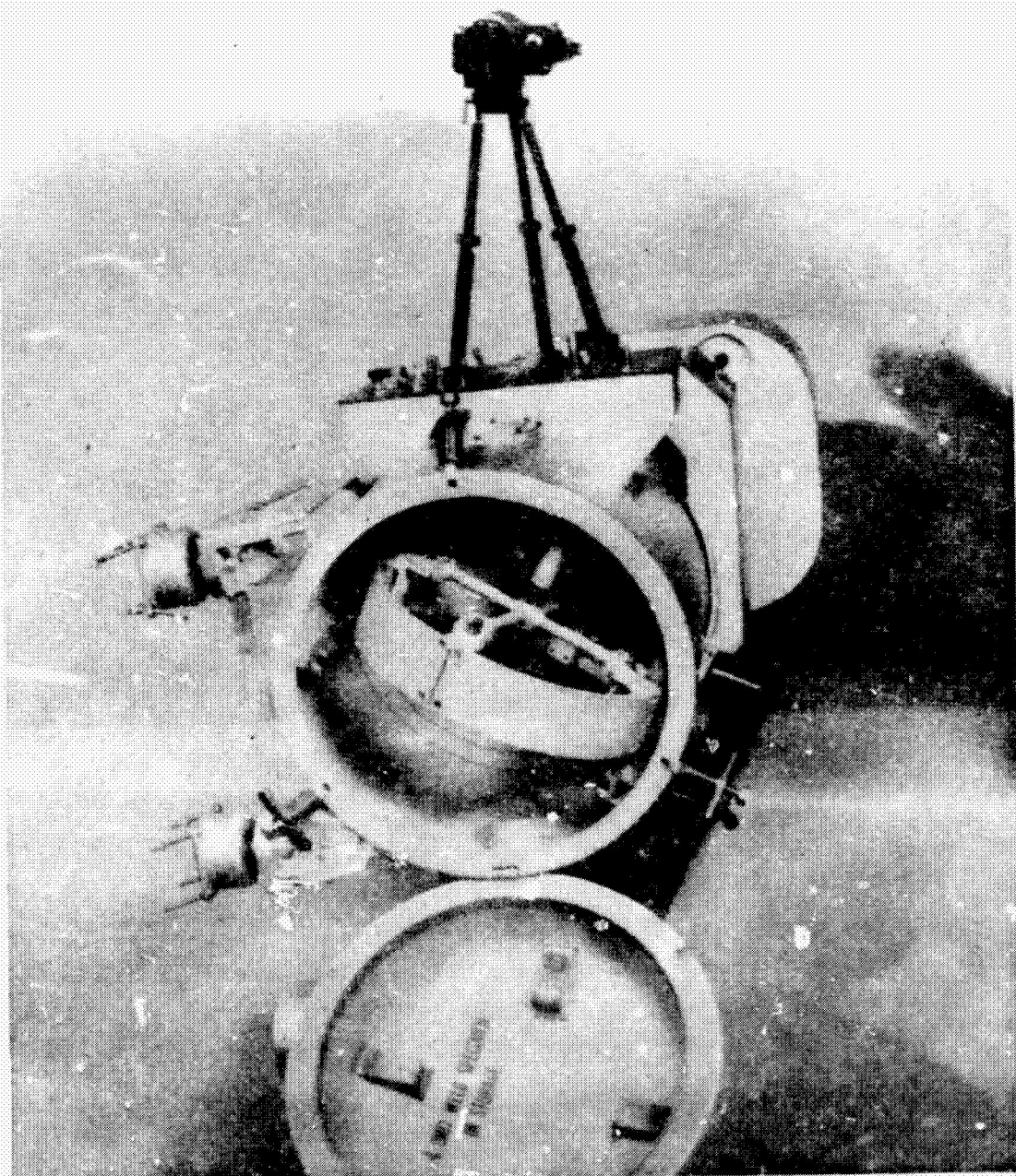


FIGURE 14. M493 WELD SPECIMEN INSTALLED IN WORK CHAMBER

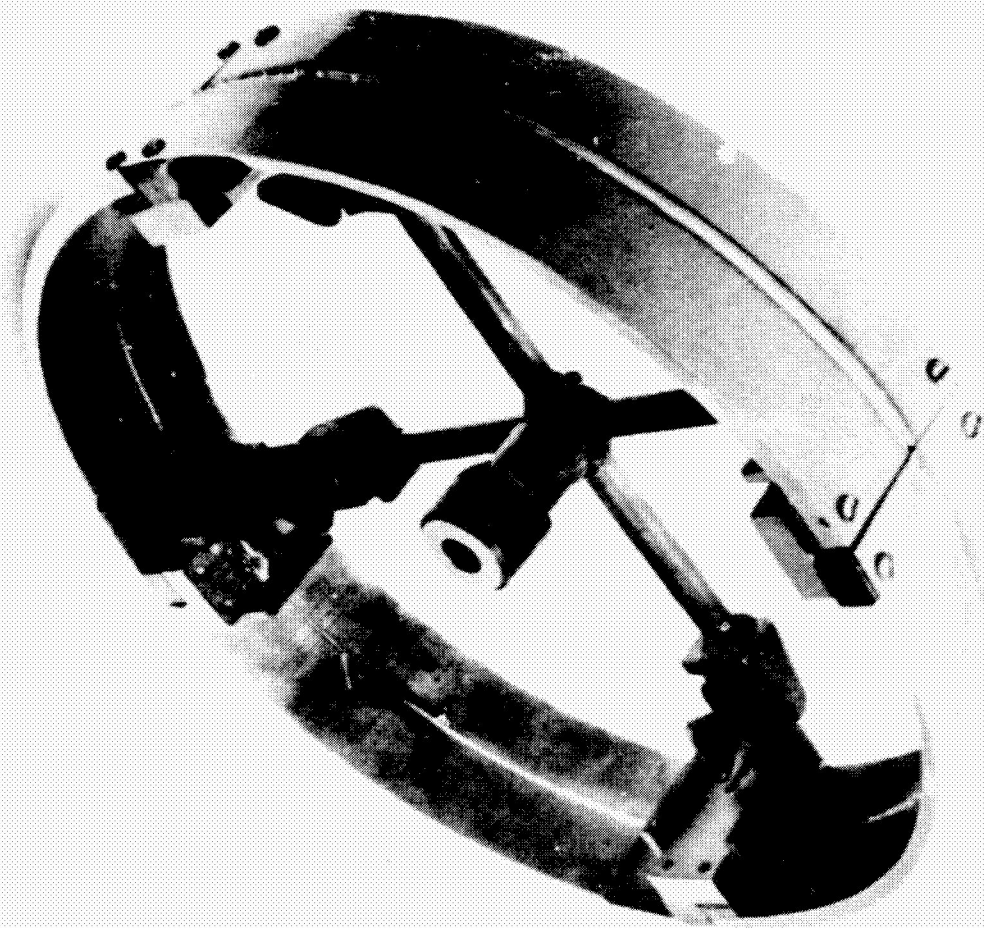


FIGURE 15. M493 WELD SPECIMEN

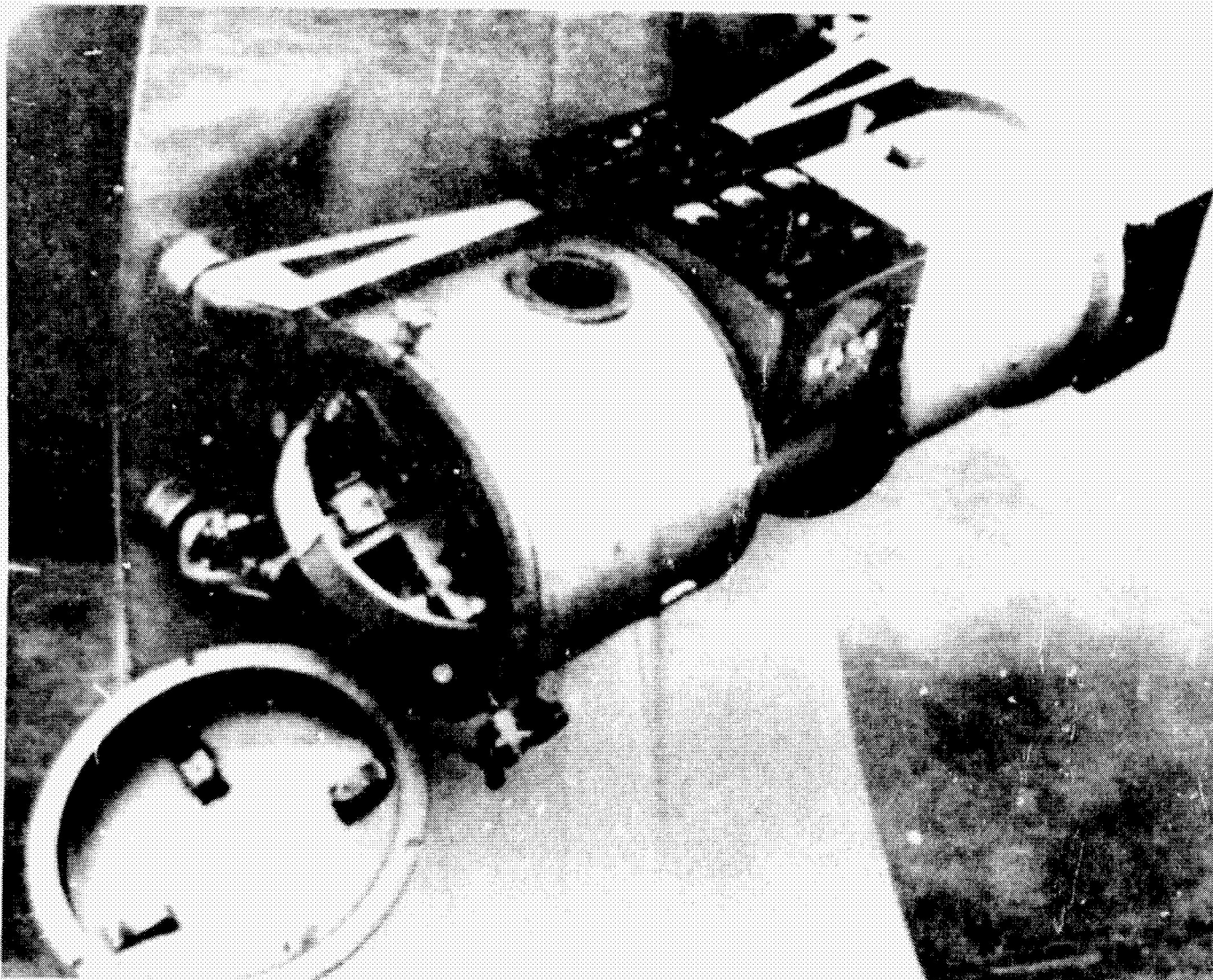


FIGURE 16. M492/M493 FLIGHT QUALIFICATION FACILITY



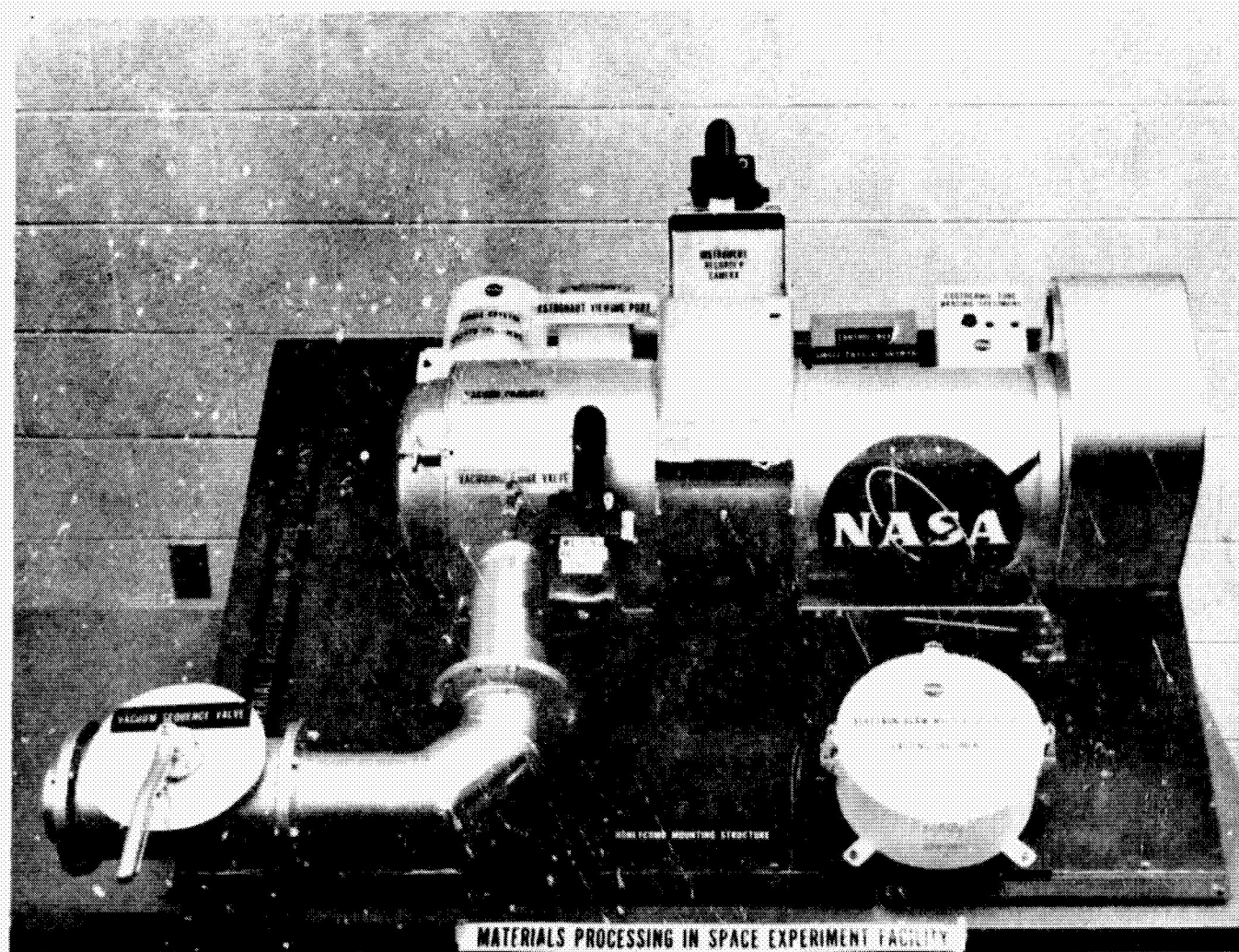


FIGURE 17. EARLY CONCEPT OF M512 MATERIALS PROCESSING IN SPACE FACILITY



Some samples for melting and cutting would have gaps machined into their centers to compare the effects of melting in zero gravity when gaps other than ideal were present between the abutting surfaces. The sample rotation speed, beam current, and focus current were the variable parameters to study the molten metals.

2. Experimental Task 2 - Exothermic Brazing. The purposes of this task, similar to experiment M492, were to develop a stainless-steel tube joining technique for assembly and repair in space; to study and evaluate the flow and capillary action of molten braze material; and to demonstrate the feasibility of the exothermic reaction in space. In this study of capillary action in space, 6.4 millimeter (0.25 inch) and 19 millimeter (0.75 inch) diameter tubes were to be joined by a gold-nickel braze alloy. The heat source to perform the braze was to be an exothermic material. The astronaut would load and unload the vacuum chamber and depress an ignition switch on the facility control panel. Some ten specimens were to be brazed in space and returned to Earth for examination.

3. Experimental Task 3 - Growth of Single Crystals. In this first step of crystal growing in space, efforts were made to answer as many technical questions as possible related to the fabrication of single crystals in space. Since it was desired to produce a unique single crystal with high potential value, to demonstrate the capability of containerless liquid control, and to show the effects of density variations in the solidifying liquid, it was recommended by a panel of industrial and university scientists to use gallium arsenide as the crystal material.

The gallium arsenide would be heated to just below its melting point in a furnace over a period of 2 hours. Eight matched tungsten or tantalum filament heating elements operating from 28 Vdc would supply the heat. Special high-quality vacuum insulation would be used around the crystal and heating elements to reduce the amount of heat required. Temperature gradients within the crystal were to be very low.

As the specimen approached its melting temperature, the heating energy would be reduced to a temperature holding level. The end heating element, element 1, would then carry increased power to melt the specimen at that end. As the melt zone increased, element 2 would be increased in power and element 1 reduced to a holding level (the same as elements 3 through 8). The insulation was arranged so that the primary heat flow was out of the seed end of the system. Thus, crystal growth would be from the seed and primarily unidirectional.

As zone 1 solidified and zone 2 was melted, heating element 3 would be increased in power with elements 1, 2, and 4 through 8 at the holding level. This sequence would be repeated as the molten zone was moved along the specimen. Care would be taken not to completely melt either end of the specimen. Each end of the specimen would be secured

in graphite so that surface tension would support the molten crystal in essentially its original diameter. The total growth process was estimated at 100 hours, and an astronaut would be required to observe and adjust the heat inputs. The crystal would be returned to Earth for evaluation.

4. Experimental Task 4 - Fiber Whisker Reinforced Composites.

This experiment was to determine the uniformity of dispersion of silicon carbide whiskers in an aluminum-alloy matrix when melted and solidified in a zero-gravity environment. The specimens for this experiment were to be the same size as the tube assemblies to be brazed in the exothermic brazing experiment, and would be heated by similar exotherm packages. The ignition of the exotherm, in the facility vacuum chamber, would melt the aluminum matrix metal and cause encapsulation and wetting of the silicon carbide whiskers inside. The samples would be returned to Earth for evaluation.

5. Experimental Task 5 - Spherical Casting. The purpose of this task was to fabricate spherical shapes in the absence of a strong gravitational field. It was anticipated that almost perfect spheres could be obtained by allowing a molten mass to solidify under controlled conditions. The driving force for this experimentation was to make perfectly spherical hollow ball bearings for use on Earth without further machining operations.

Based on this consideration, titanium carbide was selected as the test material. Three permutations of this material were to be used:

- a. Melting of a sintered ball of titanium carbide.
- b. Melting of a sintered ball of 80 percent titanium carbide - 20 percent cobalt to form a sphere upon solidification.
- c. Melting of a sintered ball of titanium carbide and cobalt containing a metal core, such as bismuth, so that upon solidification a hollow sphere would be formed.

Since the gravitational forces found during orbital maneuvers would be sufficient to cause sample displacement, it was necessary to position the sample with respect to the electron beam heating source. This would be accomplished by the use of a supporting sting that fastened the specimen to a rotary device, much like the metals melting motor, and positioned the sample in the electron beam's path. Several "specimen-sting" assemblies would be mounted on an adapter that could be rotated by the metals melting drive motor. When one specimen had melted and solidified, the motor would be indexed to position the next

sample in the electron beam's path and the melting and solidification repeated. The processed samples would be returned to Earth for evaluation.

#### E. Addition of Flammability Studies

In mid-1969, NASA Headquarters directed the incorporation of experiment M479, Zero-Gravity Flammability, into the M512 facility. This experiment, involving the burning of various materials in near-zero gravity, required a complete redesign of the vacuum work chamber. In conjunction with the chamber redesign, M479 required an oxygen supply system, water system, added storage, and a control system. The added weight of these changes also required structural changes to the M512 facility mounting system.

1. Facility Mechanical Changes. The zero-gravity flammability experiment required a chamber with a 38 centimeter (15 inch) diameter flame propagation area and a smooth interior surface to aid in clean-up operations after tests. This requirement necessitated an enlargement of the existing 30.5 centimeter (12 inch) diameter chamber and removal of the rotary drive mechanism for the metals melting and spherical casting tasks. Additionally, the existing chamber was designed to operate only with a vacuum, whereas the flammability experiment required igniting materials in a  $3.44 \times 10^4$  newtons per square meter (5 pounds per square inch) oxygen atmosphere.

To properly photograph the flame propagation, a larger viewport in the chamber would be required. The existing photographic system viewed the metals melting and sphere casting tasks through a mirror system which limited and confined the camera's field of view. A modification to the vacuum line valve was also required to slowly bleed the vacuum chamber during the experiment to slow the process of flame reduction by vacuum to a rate which could be easily filmed and analyzed.

In addition to a new vacuum work chamber, hardware had to be designed to provide a 1.14 cubic meter (40 cubic foot) oxygen supply, a 0.34 kilogram (0.75 pound) water supply, and a sample storage container. All support hardware was to be mounted on a platform common with the complete facility.

2. Facility Instrumentation Changes. The heart of the M479 zero-gravity flammability experiment was the electrical control and photographic systems. To combine this experiment with the M512 facility, a new control station had to be designed. The control station would provide operational control to initiate each test of the series, photographic lighting and photographic recording. The additional requirements are outlined as follows:

- a. A complete redesign of the electrical wiring system within the vacuum chamber was necessary to accommodate M479.

- b. A floodlight was required to provide safe, adequate illumination of each specimen was required to operate in both oxygen and vacuum and operate in both oxygen and vacuum and provide  $24 \times 10^4$  to  $32 \times 10^4$  candelas per square meter (75 to 100 lamberts) at the specimen for color photography.
- c. A redesign of all photographic mirrors to permit removal by an astronaut and relocation of the camera viewport was required for M479. Additionally, the camera mounting mechanism was reconfigured to allow the use of lenses of different focal lengths.
- d. A pressure readout sensor and two temperature sensors (wall and atmosphere) were required in the vacuum chamber.

### 3. Impact of M512 Facility Redesign to M512 Experimental Tasks.

The required changes to the M512 facility caused by the incorporation of the flammability experiment were actually very beneficial for the M512 experiment tasks. While no modifications were made to the electron beam system, the enlarged and redesigned vacuum work chamber allowed significant improvements to the experiment tasks. A heat sink was incorporated into the chamber with a designed thermal impedance for the performance of the crystal growth task. The enlarged chamber allowed the design of the sphere casting task to utilize its own indexing motor and permitted incorporation of release mechanisms into the sample attaching stings to allow the molten specimens to free-float in the chamber while solidifying. The metals melting task concept was revised from the "brake-shoe" type specimens to a flat disk rotated perpendicularly in front of the electron beam. Figure 18 illustrates the initial concept of the M512 facility showing the redesigned work chamber, the five experiment tasks, and experiment M479.

### F. M512 Design Evolution

At the same point in time that the M512 facility was undergoing its major redesign, several contracts were awarded by MSFC to evaluate the scientific merit of the experiment tasks and to recommend materials and procedures to be used in the flight experiments. Whittaker Corporation was contracted to study the exothermic braze task and also to supply the exotherm packages for the flight experiment. Westinghouse was contracted to design and build the crystal growth experiment. The A. D. Little Company studied and made material recommendations for both the sphere casting and composite casting experiments.

By early 1970, NASA Headquarters had assigned the M512/M479 experiments to Skylab; the facility was to be permanently installed in

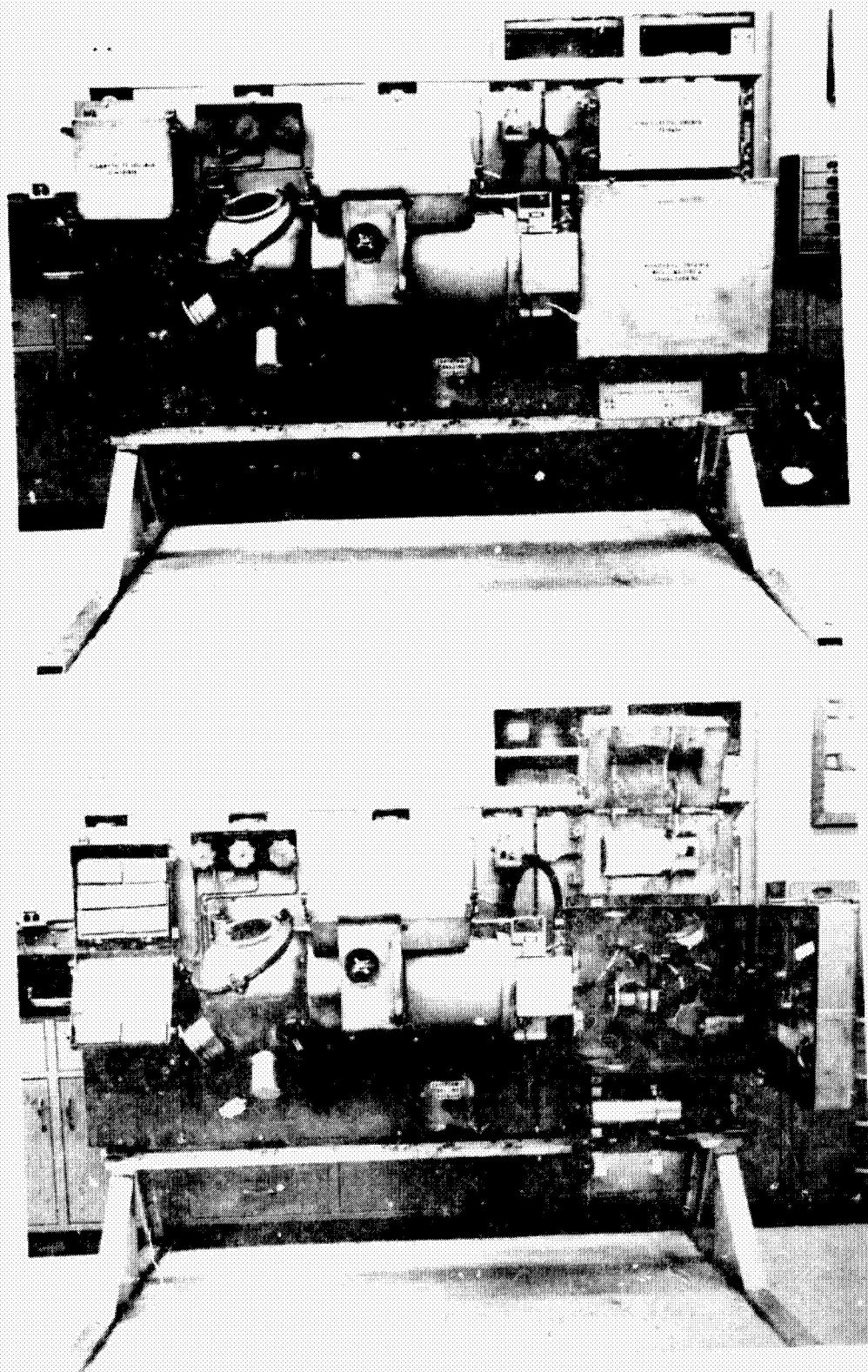


FIGURE 18. DESIGN CONCEPT OF M512 FACILITY WITH REDESIGNED WORK CHAMBER

the MDA. The experiment design was subjected to a series of reviews and by mid-1971 each experiment task was assigned a separate experiment number as follows:

- M551 - Metals Melting
- M552 - Exothermic Brazing
- M553 - Sphere Forming
- M554 - Composite Casting
- M555 - GaAs Crystal Growth

It must be noted that experiment M554, Composite Casting, was deleted from the Skylab Program in June 1972, and replaced by the M518 Multipurpose Electric Furnace System which also used the M512 work chamber and controls. The scientific objectives of the M554 experiment were fulfilled by an identical experiment, M566, Aluminum-Copper Eutectic, performed in the M518 system.

Numerous detail changes were made to the M512 facility and experiments prior to their operation on Skylab. The finalized objectives, concepts, and hardware descriptions for each of the approved experiments as well as the facility are discussed in detail in Section III of this report.

### SECTION III. SYSTEM DESCRIPTION

This section of the M512 Developer's Report describes the mechanical, electrical and interface systems of the facility and associated experiment hardware as they were flown on Skylab. The M512 hardware with few exceptions was developed and built at MSFC and consisted of both common facility equipment and accessory hardware items used during the performance of one or more of the associated material science experiments. For purposes of this report, the facility is considered to include all provisions for the operation of all or most of the individual experiments, such as the work chamber, power, vacuum, water supply, controls, equipment storage. Special hardware items required to perform a particular experiment (such as motors, mirrors, shield, etc.) are included in the individual experiment discussions. Some overlapping is inevitable, in that some items were developed as common equipment required in more than one experiment operation. Detailed discussions of the development of the actual experiment material samples, beyond size and weight descriptions, are not within the scope of this report; they are covered in reports prepared by the individual experiment Principal Investigators.

#### A. Mechanical Description

The M512 Materials Processing Facility and associated experiments (figure 19) were hard mounted on two honeycomb mounting panels that were shock mounted to longerons 4 and 5 in the Skylab multiple docking adapter module (figure 20). These longerons run parallel to the MDA X-axis, which was the direction of the Skylab launch thrust vector. The facility was located at position 17 in the forward MDA area, adjacent to the axial docking port (figure 21).

1. M512 Materials Processing Facility. The M512 Materials Processing Facility, including experiment equipment in its flight configuration, weighed 188 kilograms (414.2 pounds), with an envelope of 2.13 meters (84.0 inches) in length by 0.99 meters (38.94 inches) in height by 0.52 meter (20.0 inches) in depth. Figure 22 is a schematic of the facility systems.

a. Objective. The objective of the facility was to provide a basic apparatus and a common spacecraft interface for performance of metallic and non-metallic materials processing experiments, utilizing the advantages of the near-zero gravity and vacuum conditions afforded by the Skylab workshop.

b. Concept. The facility approach provided the flexibility to perform a series of experiments, investigating various areas of

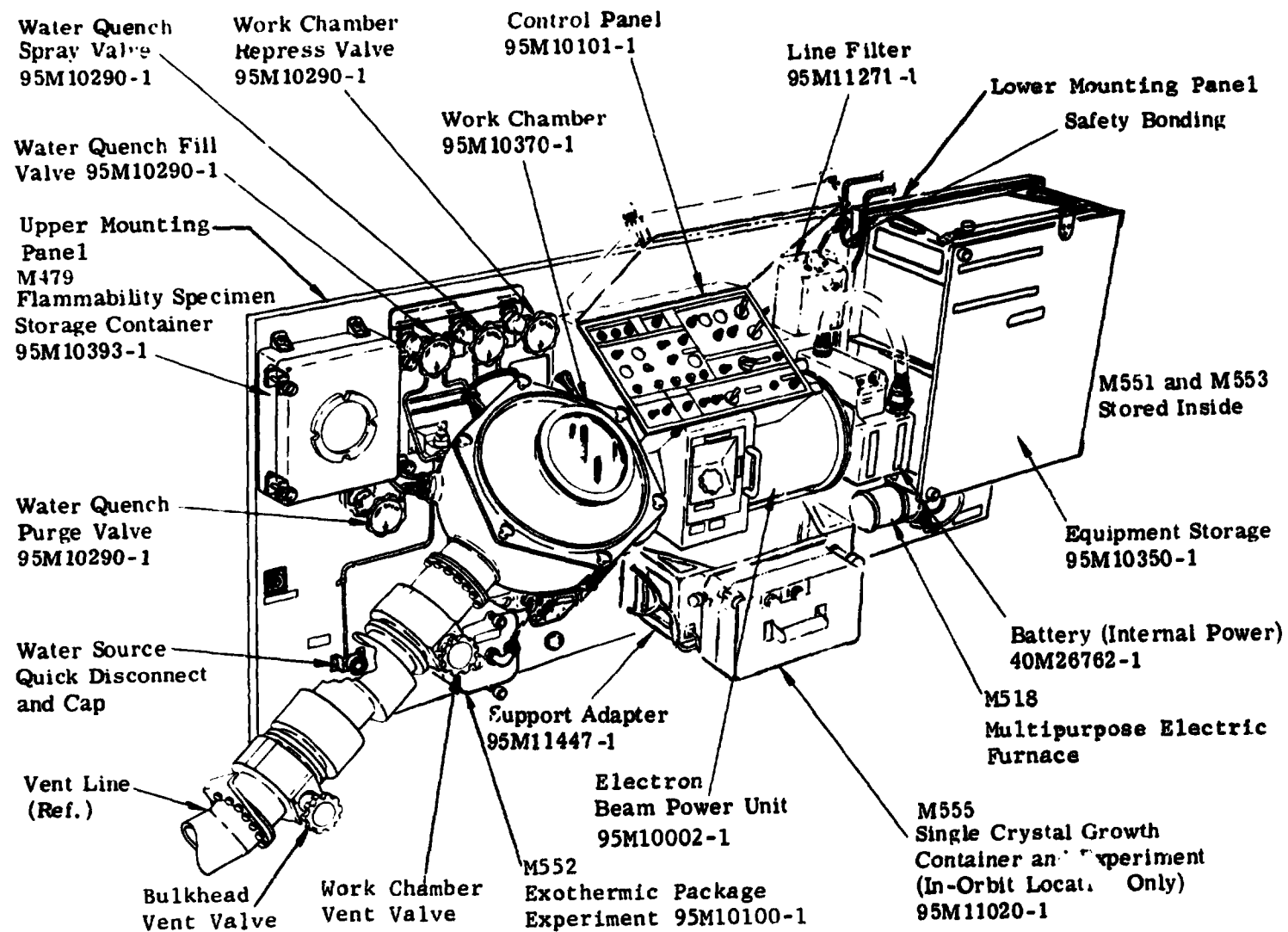


FIGURE 19. M512 MATERIALS PROCESSING FACILITY



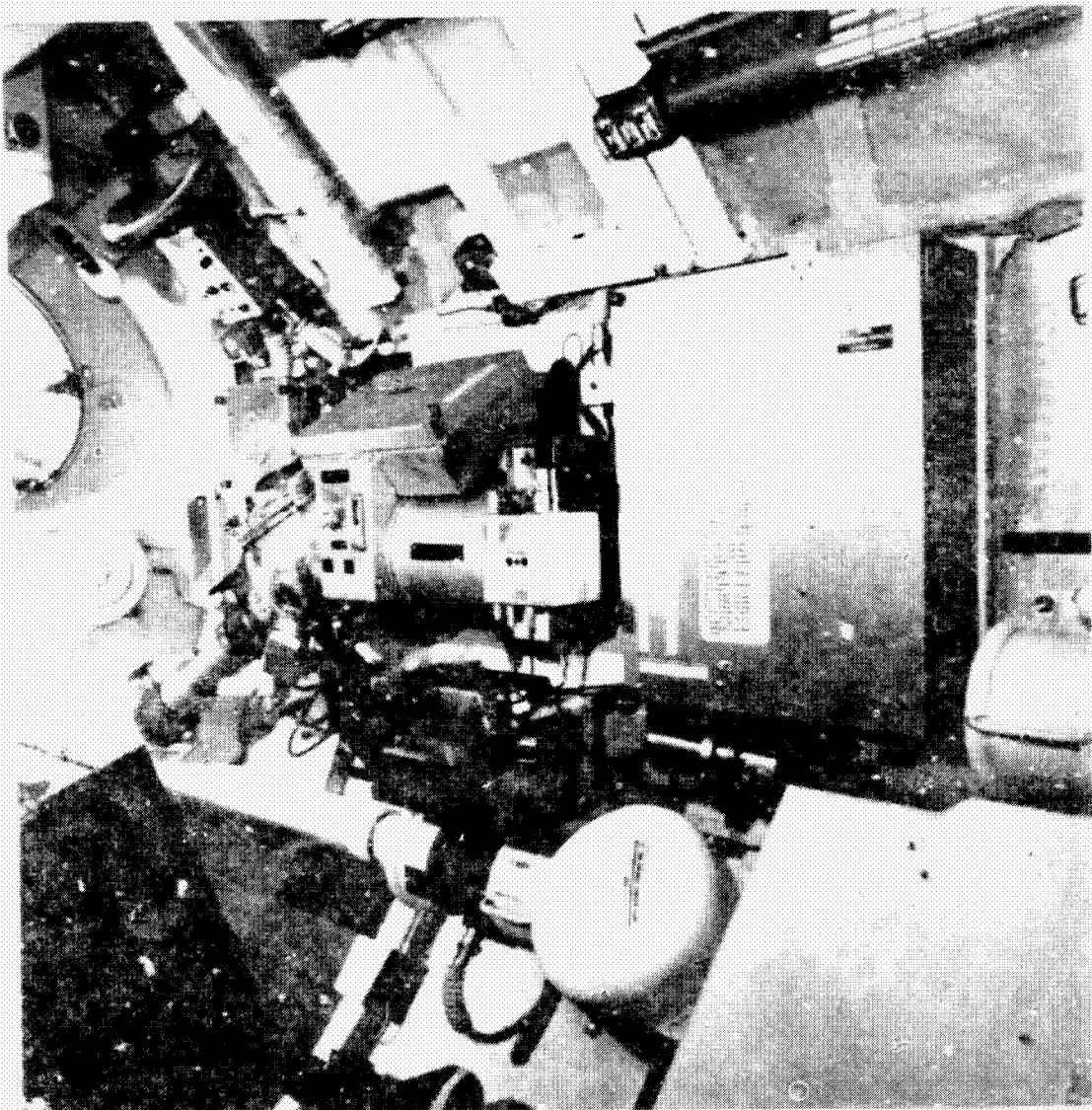


FIGURE 20. M512 FACILITY INSTALLED IN MDA

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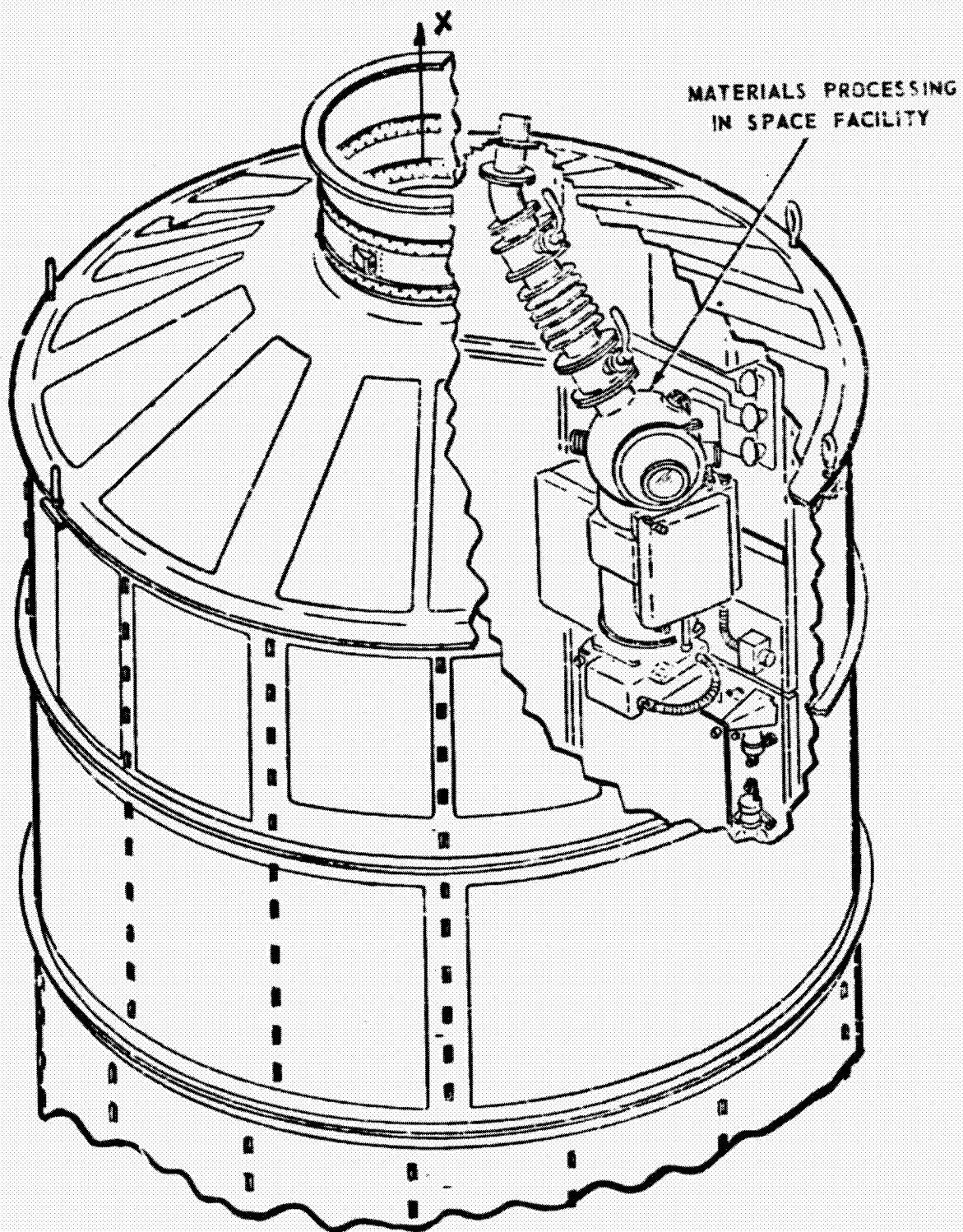


FIGURE 21. M512 FACILITY LAUNCH LOCATION

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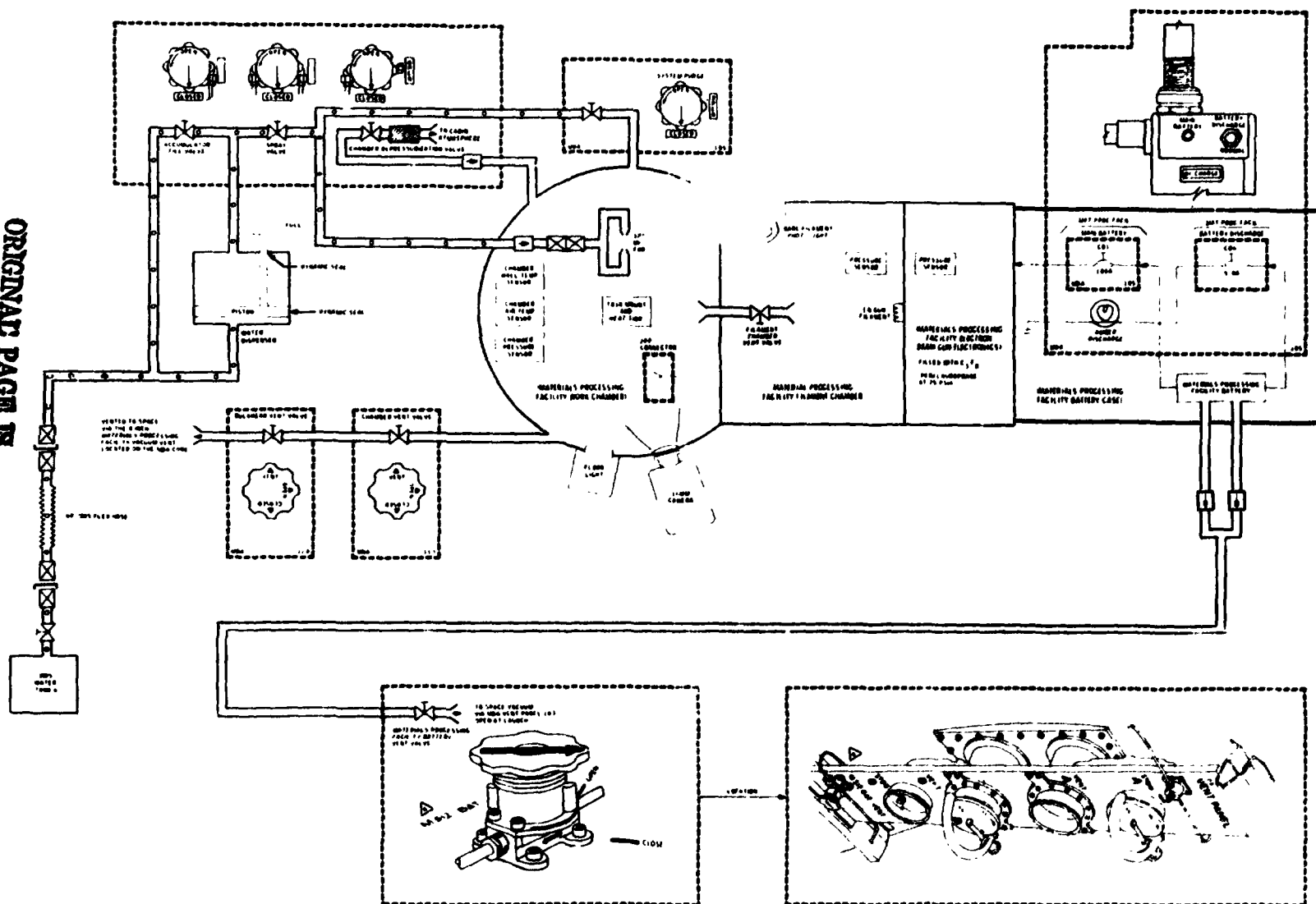


FIGURE 22. FACILITY SYSTEM SCHEMATIC

materials science, utilizing one common experiment system. The low-gravity environment was readily available in Skylab; however, experimentation requiring vacuum conditions on previous space programs had been constrained to extravehicular operations. The M512 facility was designed to, for the first time, allow experimentation under vacuum conditions inside a spacecraft.

Data from the experiments were obtained from analysis of the returned material samples and selected returned experiment/facility hardware, motion picture records of the two electron beam experiments and M479 (Zero-Gravity Flammability) plus comments of the operating crewmen.

c. Hardware description. The facility consisted of the following major subsystems/assemblies: vacuum work chamber assembly, electron beam subsystem, control panel assembly, electrical power subsystem, pressure subsystems, water quench subsystem, equipment storage, and facility/experiment mounting assemblies.

(1) Vacuum work chamber assembly. The work chamber was a 41.4 centimeter (16.25 inch) diameter stainless steel sphere weighing 27.3 kilograms (60.0 pounds), with a hinged hatch (figures 19 and 23). The use of stainless steel instead of lightweight aluminum was necessary for the added X-ray radiation shielding provided by steel. The chamber was capable of withstanding a maximum differential pressure of  $13.8 \times 10^4$  newtons per square meter (20 pounds per square inch) and was mounted to one of the honeycomb panels that served as a heat sink. The interface with the space vacuum environment was through a 10 centimeter (4 inch) diameter vacuum vent line supplied by the spacecraft. One wall of the chamber interfaced with the electron beam subsystem (figure 23) so as to allow the electron beam to pass through the center of the chamber. If part or all of the beam missed the specimen, the beam would strike a tungsten beam absorber plate permanently mounted in the chamber wall opposite the electron beam gun, thus precluding damage to the chamber wall.

(a) Hatch assembly. The chamber hatch assembly was hinged and secured by six Calfax fasteners (figure 19). Two Viton-A O-rings formed the seal between the hatch and the vacuum chamber. The assembly also contained a viewport which is discussed in subparagraph (e) following:

(b) Heat sink. The chamber wall contained a recessed cavity called the heat sink, located at the interface with the mounting panel labelled in figure 23. Figure 24 shows a cross-section of the work chamber/honeycomb panel interface with the heat sink cavity. The purpose of the heat sink was three-fold: (1) to house the experiment furnaces, M555 (Gallium Arsenide Crystal Growth) and M518 (Multipurpose Electric Furnace), which operated at high

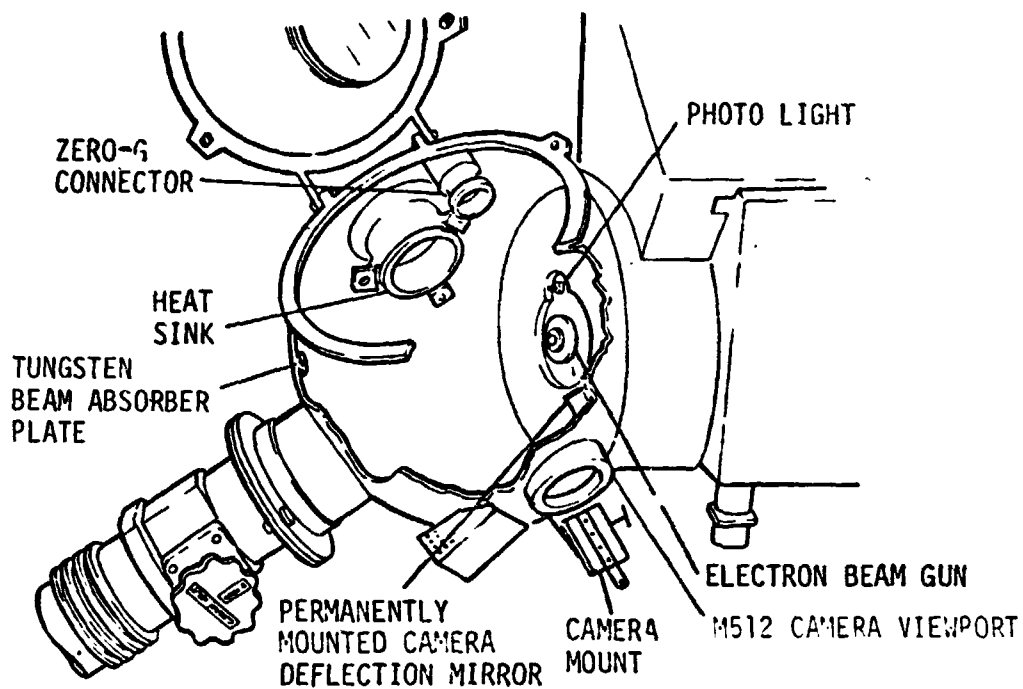


FIGURE 23. CUTAWAY OF WORK CHAMBER

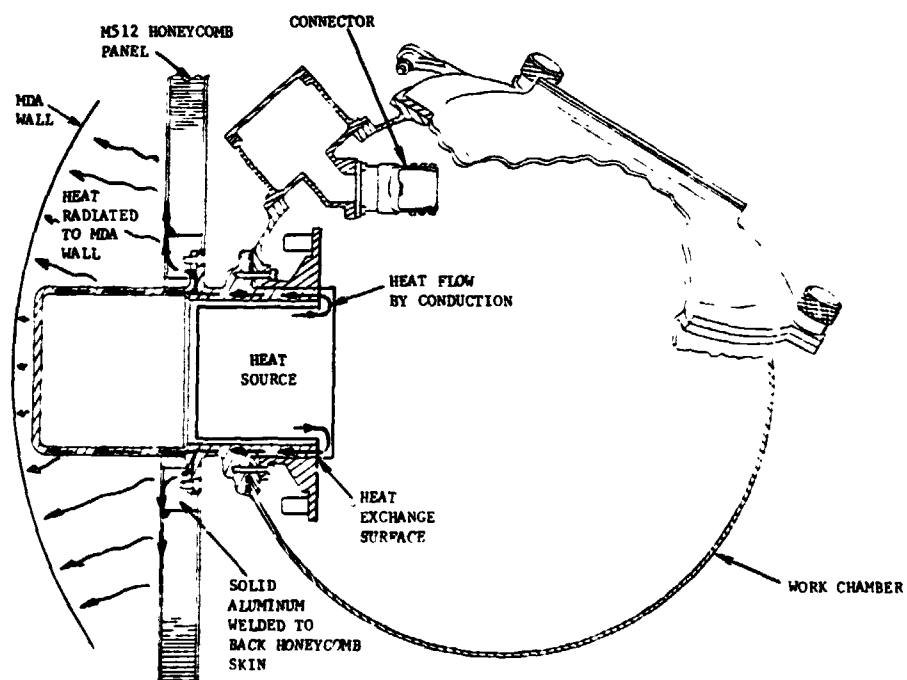


FIGURE 24. WORK CHAMBER CROSS-SECTION

temperatures over extended time periods, (2) to provide a tripod mounting base for all the other experiments (except M479) as shown in figure 25, and (3) to provide a thermal conduction path to the honeycomb panels for removal of heat produced during experiment operations. The heat sink was capable of heat dissipation at the rate of 150 watts per hour while maintaining a chamber "touch" temperature of 40.5°C (105°F). The heat sink was a one-piece, 6061-T6 aluminum alloy shell which was bolted directly to a solid aluminum ring welded to the honeycomb mounting panel as shown in figure 24. The heat-sink interior surface was highly polished for low heat absorption which resulted in the heat sink operating in vacuum much like a vacuum bottle. The outer surface had a high emissivity finish for radiation to the MDA wall. These conditions established heat flow paths as shown in figure 24. The success of this configuration, although not quantitatively measured, was verified by SL-3 Pilot Lousma during the performance of the M518 experiments when he described the temperature behind the heat sink as a cold cup of coffee.

(c) Electrical connector (J6). The female end of an electrical connector was provided on the interior work chamber wall (figures 23, 24, and 25) and served as the power outlet for all experiments using the M512 facility with the exception of the M518 furnace facility. The electrical connector used on Skylab was a quick disconnect, socket-type referred to as a zero-g connector.

(d) Chamber lighting. The lighting system inside the chamber consisted of two lamps, the floodlight and photo light, operated by 28 Vdc from switches on the control panel.

1 Floodlight. The floodlight was a 20 watt lamp mounted on the outside of the chamber wall (figures 26, 27, 28, and 29) with a minimum operational life of 300 hours. The light illuminated the interior of the chamber through a lead glass window. The lamp was used for photographic identification of the M479 samples, as a photographic reference during M479 operations, as a background light during the M553 (Sphere Forming) experiment operations, and for general illumination of the chamber interior when desired. The floodlight was so positioned to illuminate the specimens without shining directly into the astronaut's eyes. A Vicor 7913 glass floodlight shield (figure 30) was installed on the inside of the floodlight port as protection against metal deposition and thermal shock during experiment operations. The shield was installed prior to the first experiment operation and removed only for cleaning if required.

2 Photo light. The photo light or bare filament light was permanently installed inside the work chamber (figure 23) and positioned to illuminate the M551 (Metals Melting) weld samples at the point of electron beam impingement for photography. The lamp had an operational useful life of 300 hours and was a modified bulb with

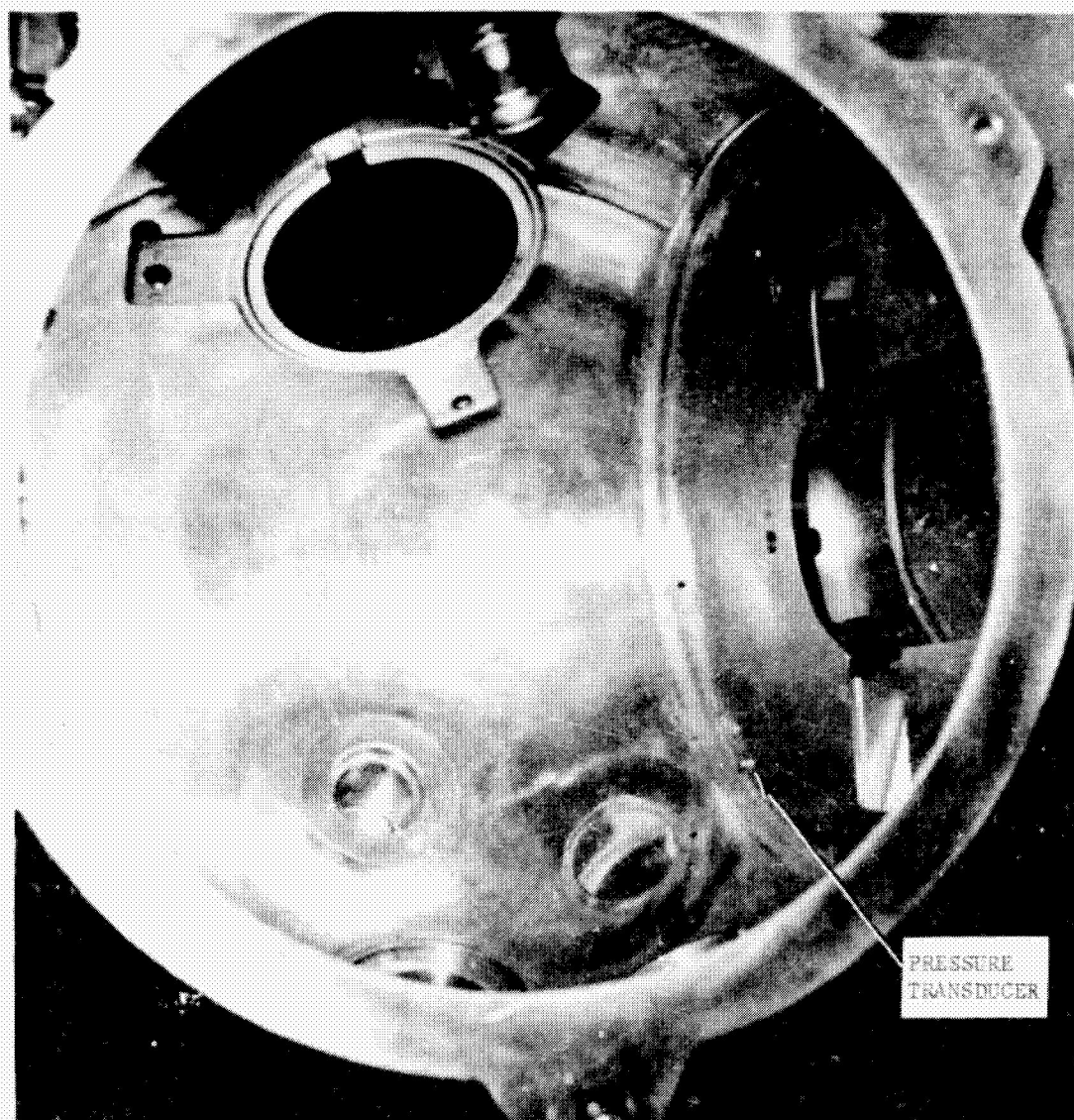


FIGURE 25. WORK CHAMBER INTERIOR VIEW

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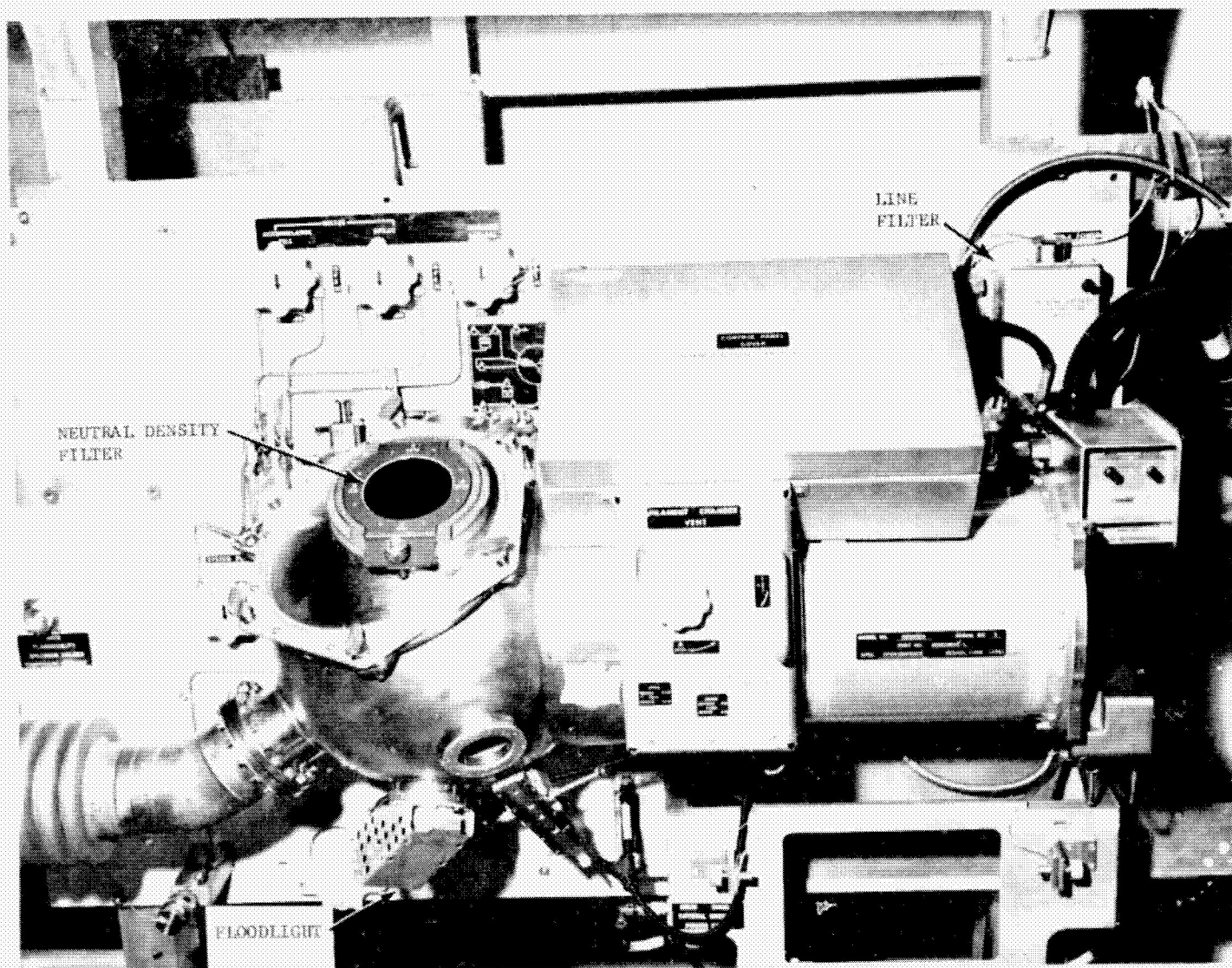


FIGURE 26. M512 FACILITY (FRONT VIEW)



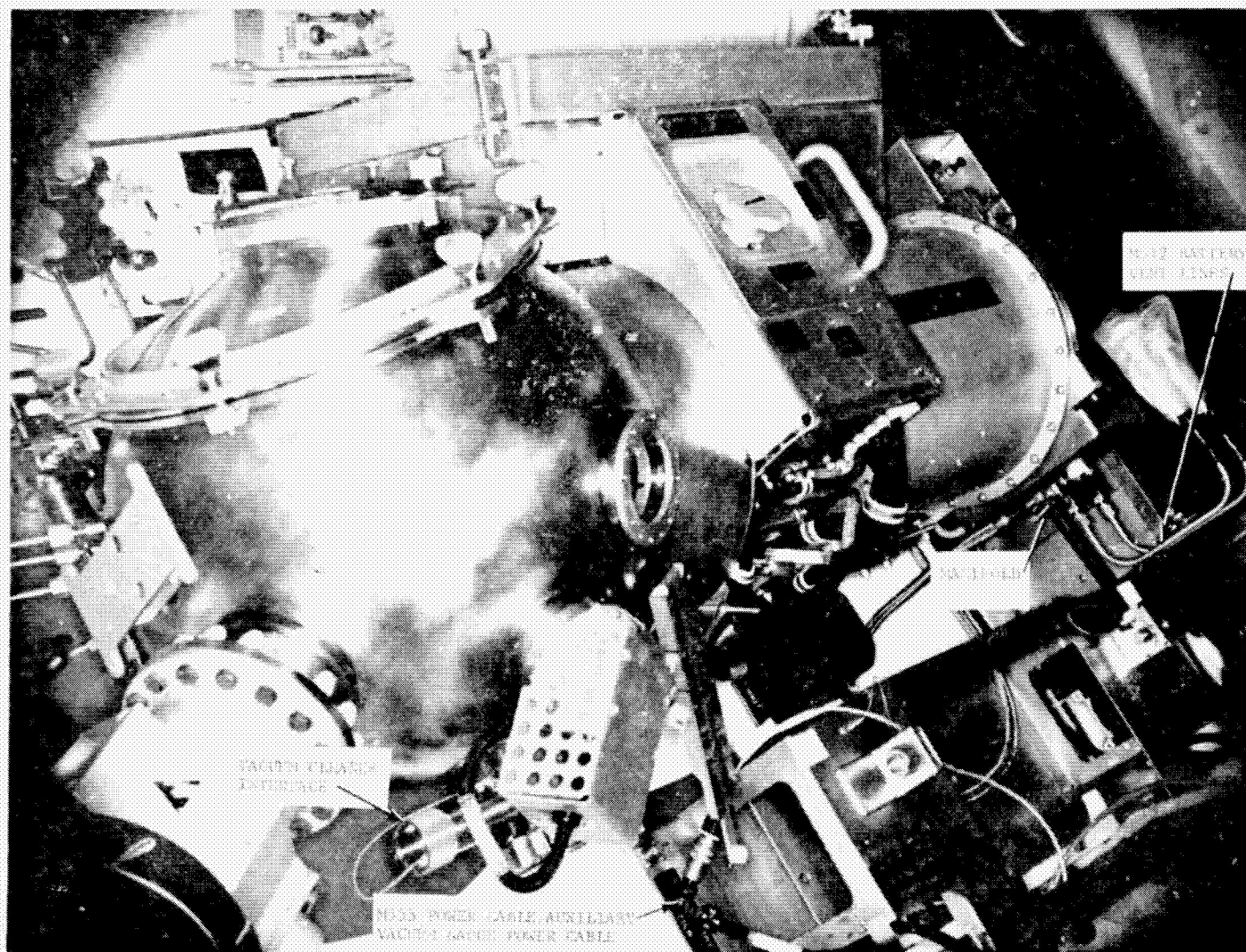


FIGURE 27. M512 FACILITY (LEFT SIDE VIEW)

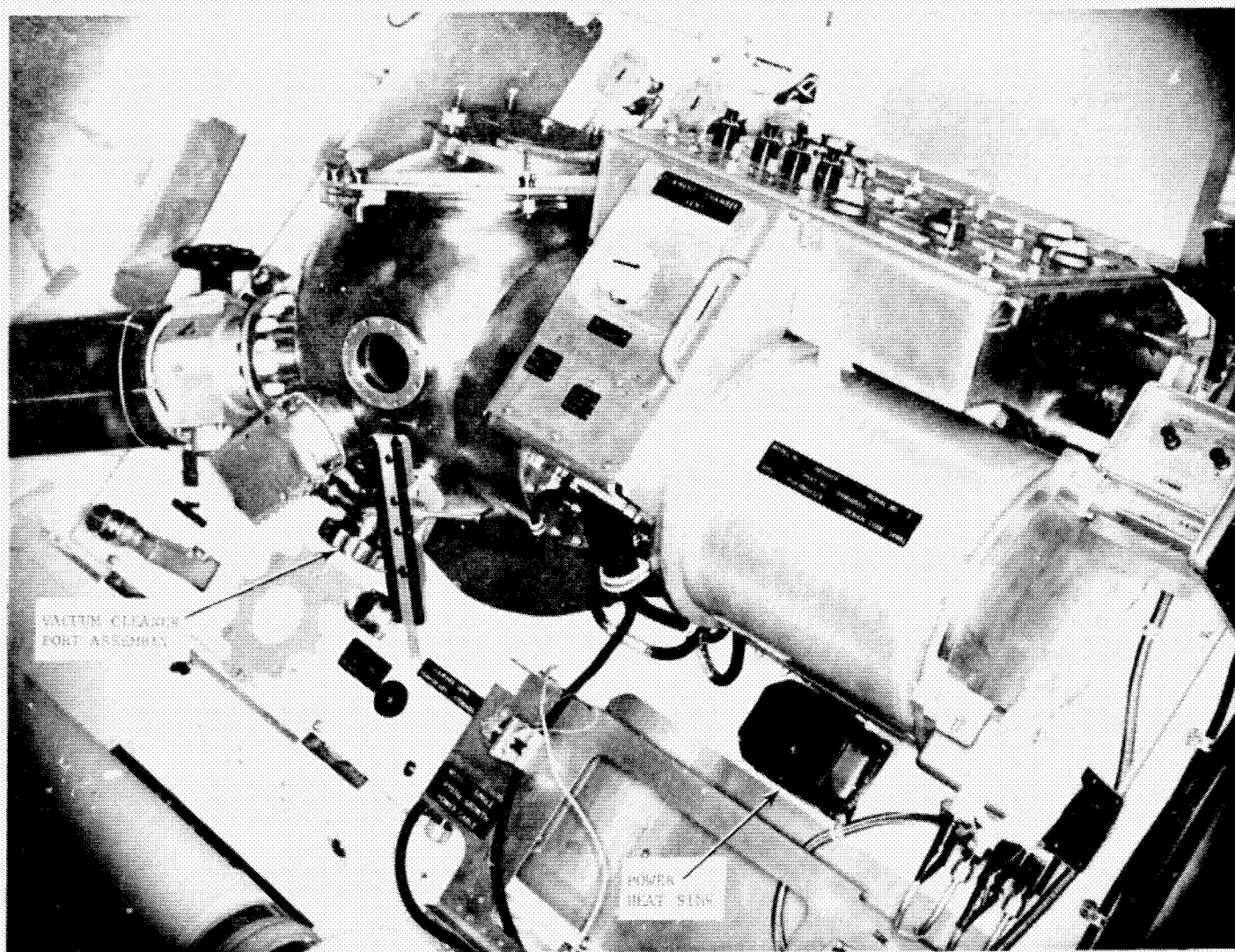


FIGURE 28. M512 FACILITY (RIGHT SIDE VIEW)

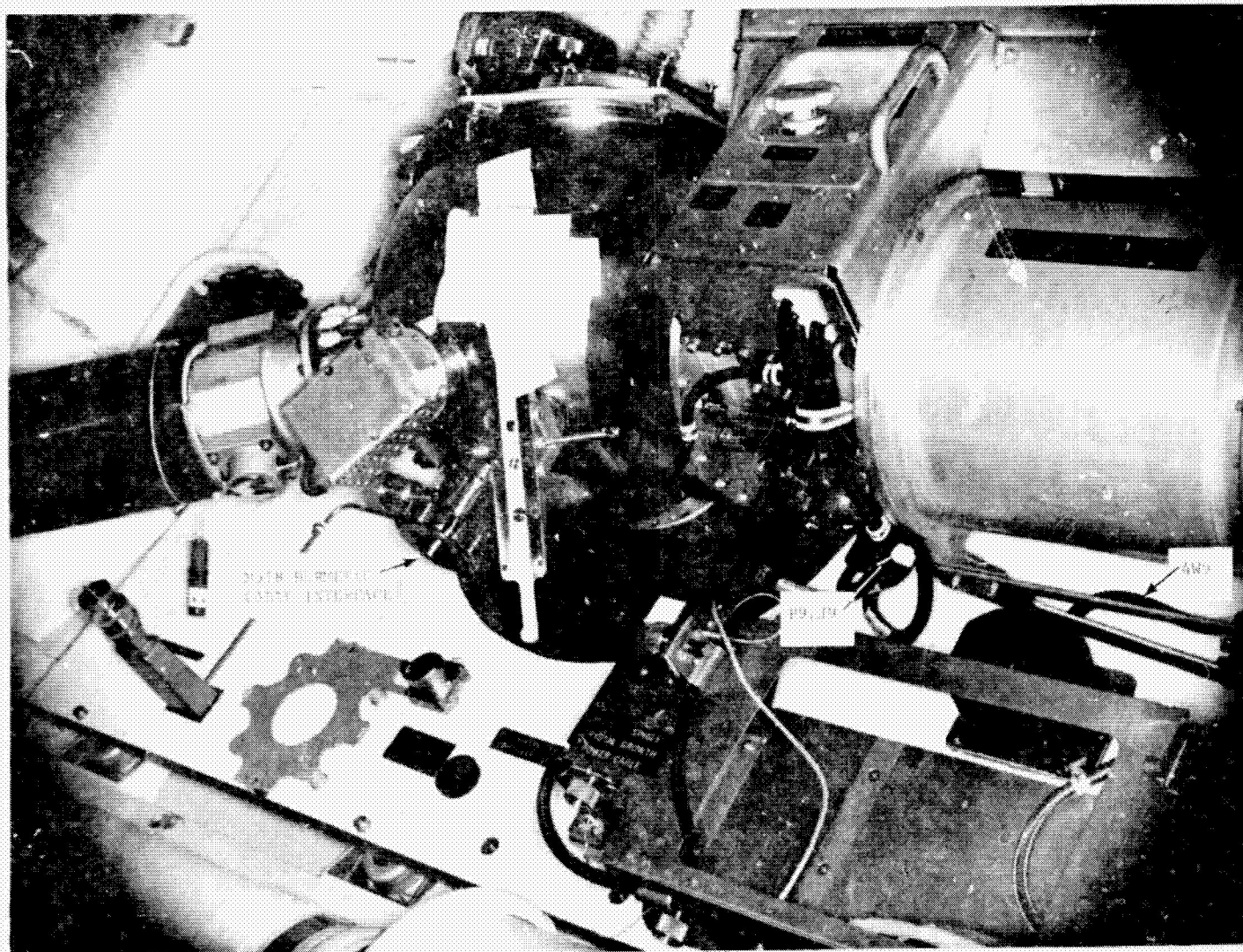


FIGURE 29. M512 FACILITY (LOWER VIEW)





FIGURE 30. FLOODLIGHT SHIELD

the outer glass cover removed to provide better illumination since metallic splatter could not coat the glass cover. However, without the glass cover, the lamp was extremely delicate and could only be operated under vacuum conditions; therefore, the photo light was electronically interlocked with the filament chamber vent valve to preclude operation in other than a vacuum environment.

(e) Optics. The chamber included two separate optical systems, one for astronaut viewing and one system for photography.

1 Viewing system. The viewing system consisted of a 15.2 centimeter (6 inch) diameter window in the chamber hatch which allowed direct viewing for all experiments except the M551 experiment operations, which required a two-mirror system that is discussed in subsection A.2 following.

The hatch viewport window consisted of two 0.64 centimeter (0.25 inch) thick glass panes. One pane was leaded glass for X-ray radiation shielding equivalent to 1.6 millimeters (0.0625 inch) of lead. The second pane was safety high strength tempered glass for fracture mechanics. The small volume between the panes was vented to the work chamber through a series of small holes drilled in the mounting frame. This configuration eliminated the establishment of a pressure differential between this volume and the work chamber during launch or experiment operations. During development testing it was determined that the glare of the electron beam operations made visual observation almost impossible. A neutral density filter was added to the exterior of the hatch viewport. The filter reduced light intensity to 0.6; the filter assembly was permanently installed, but designed with a hinge to allow the astronaut to utilize the filter at his discretion. Nomenclature (Y CCW, X CCW, Y CW, X CW) was added to the filter assembly to aid the astronaut in electron beam alignment. The hatch viewport without the neutral density filter is shown in figure 19 and with the filter installed in figure 26.

A metal protective cover was installed for launch as shown in figure 28. This cover was used only for launch and was removed prior to the first experiment operation.

2 Photography system. The 7.6 centimeter (3 inch) diameter camera port was located on the lower half of the spherical chamber (figures 23 and 28) with a bayonet adapter attached to the external chamber wall adjacent to the port for mounting the 16 millimeter data acquisition camera (DAC). The camera bayonet adapter bracket utilized a slide mechanism with three locking positions corresponding to particular photographic requirements of each experiment. Each position corresponded to a different combination of lenses and lens extenders to be used on the DAC. A right-angle camera mirror was attached to the end of the lens assembly, allowing the camera to be mounted tangent to

the chamber wall, as can be seen in the Skylab inflight photo, figure 31. The right-angle mirror assembly had to be centered on the camera port window; therefore, since the three lens assemblies were of different lengths, the three slide positions were required.

The camera viewed the center of the chamber through its right-angle mirror for all experiment operations except experiment M551, for which a two-mirror system was required to allow photography of the beam impingement on the specimen. One of the two mirrors was the camera deflection mirror, which was permanently mounted inside the work chamber (figures 23 and 25). The purpose of this mirror was to reflect the camera line of sight to the beam impingement on the weld sample. This mirror was made of fused silica 7940 with dimensions of 35 by 25 by 5.5 millimeters (1.375 x 0.984 x 0.216 inches). The complete M551 camera mirror system is discussed in subsection A.2.

The camera viewport window was constructed of 6.4 millimeter (0.25 inch) thick leaded glass for x-ray radiation shielding equivalent to 1.6 millimeters (0.0625 inch) of lead.

A metal protective cover was installed for launch only, similar to the hatch viewport protective cover previously discussed with the viewing system.

(f) Vacuum cleaner port. The work chamber was designed with a dual-purpose port located on the lower portion of the chamber near the floodlight. This port was used for retrieval of the M553 spheres (discussed in detail in subsection A.4), routing of the M518 hermetic lead cable, and general cleaning of the chamber if required. The vacuum cleaner port is shown in the chamber external photographs, figures 27, 28, and 29, and internally in figure 25. The external assembly of the port was designed to provide two separate connections for the various operations:

1 Vacuum cleaner interface. The capped interface labelled in figure 27 was used with the spacecraft vacuum cleaner. For vacuum cleaner attachment, the threaded cap was removed and the vacuum cleaner quick disconnect coupled with the larger diameter section of the port.

2 M518 hermetic cable interface. The larger capped interface labelled in figure 29 was designed to allow routing of the M518 hermetic cable from its control panel through the vacuum port to the M518 furnace inside the work chamber during M518 operations. The large cap was removed, tethered by a lanyard (not shown in figure 29), and replaced by a similarly designed M518 cap which allowed penetration of the cable while also retaining vacuum integrity.

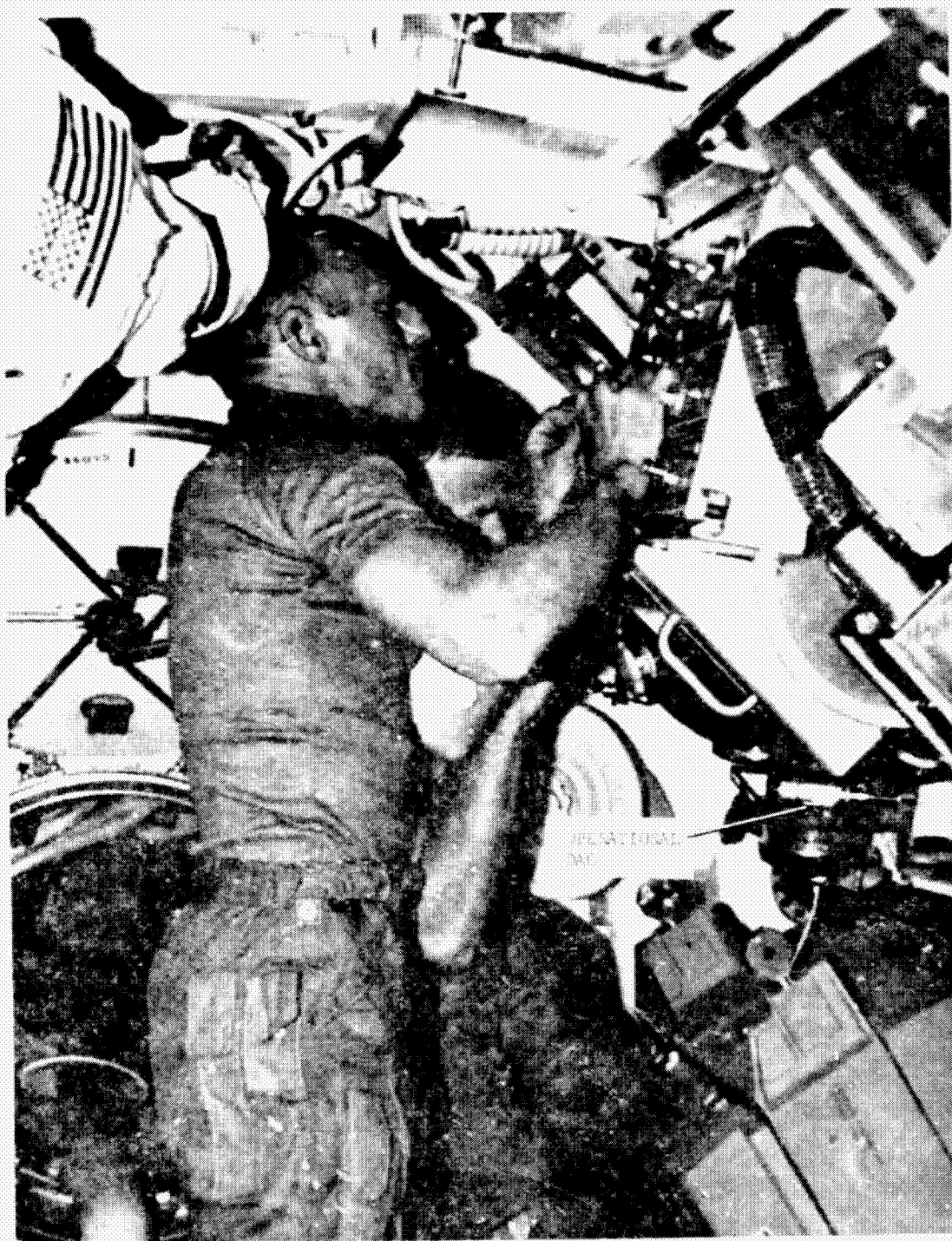


FIGURE 31. INFLIGHT OPERATION

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(g) Pressure/temperature sensors. One pressure and two temperature sensors were built into the chamber and controlled by switches on the control and display panel. These sensors are illustrated in the system schematic (figure 22).

1 Chamber pressure. The WORK CHMBR position of the INSTRUMENTATION PRESS switch selected the readout of a pressure transducer located in the chamber as shown in figure 25.

2 Chamber wall temperature. The CHMBR WALL position of the TEMP SOURCE switch selected a thermocouple located on the rear chamber wall near the chamber electrical connector (J6).

3 Chamber air temperature. The CHMBR AIR position of the TEMP SOURCE switch selected a thermocouple also located near electrical connector (J6) which measured the chamber air temperature.

(2) Electron beam subsystem. The electron beam subsystem consisted of three major sections: battery section, head section power supply, and head section. Figures 32 and 33 illustrate the basic electron beam subsystem hardware, except that the control panel shown in both figures is a separate subsystem discussed in subparagraph (4) following. The electron beam gun including electronics, filament, filament vent valve and chamber assembly, deflection and focus coils, was developed and delivered to MSFC by the Westinghouse Electric Corporation under contract numbers NAS8-20678 and NAS8-26350. The electron beam gun was a 20 kilovolt system capable of producing a 100 milliamperc beam from 28 Vdc battery power as discussed in Section II of this report. Westinghouse also designed and developed the X-Y alignment coils, although this hardware and the housings for the electron beam gun system hardware were built at MSFC.

(a) Battery section. The M512 battery served as the power source for the electron beam gun and M552 (Exothermic Brazing) experiment operations. The battery, procured by MSFC from the Eagle-Picher Company, was a 90 day wetstand, silver-zinc battery, shown in figure 34. The battery had a capacity of 30 ampere-hours after a 90 day wetstand at temperatures not exceeding  $29.4^{\circ}\text{C}$  ( $85^{\circ}\text{F}$ ). Battery voltage range was 28 Vdc minimum to 42.8 Vdc maximum, with 28 to 31 Vdc nominal, at 100 amperes for approximately 10 minutes. The battery was sealed in a stainless-steel battery case which was vented to space vacuum through redundant pressure relief valves that opened at  $10.3 \times 10^4$  newtons per square meter (15 pounds per square inch) gauge pressure and closed at  $3.45 \times 10^4$  newtons per square meter (5 pounds per square inch) gauge pressure. Figure 27 illustrates how the check valve lines were connected to a manifold from which another line ran to an interface connector on the hard mounted MDA vent line (figure 33). The MDA vent line contained a hand-operated vent valve on MDA panel 103 (figure 35)

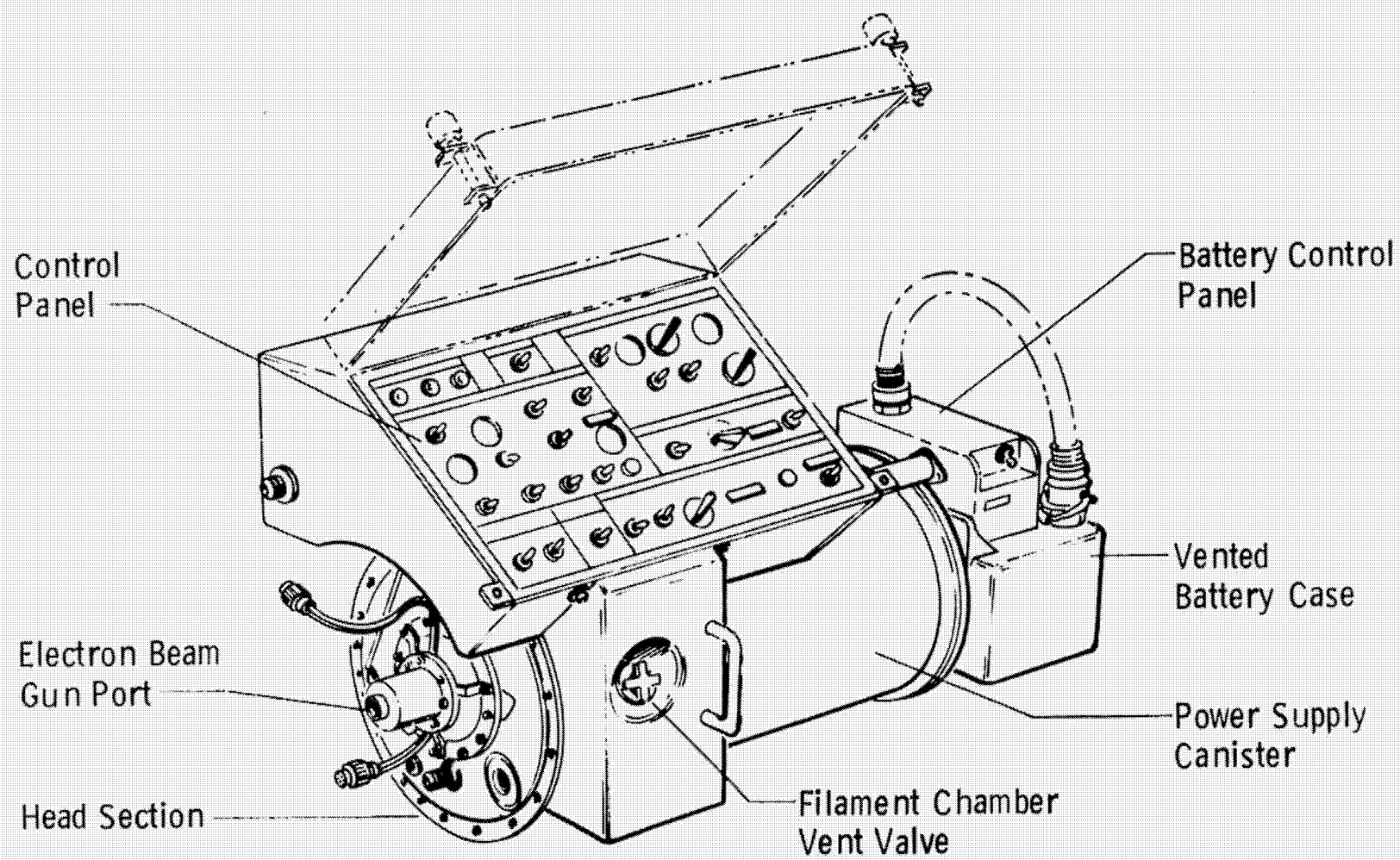


FIGURE 32. ELECTRON BEAM SUBSYSTEM

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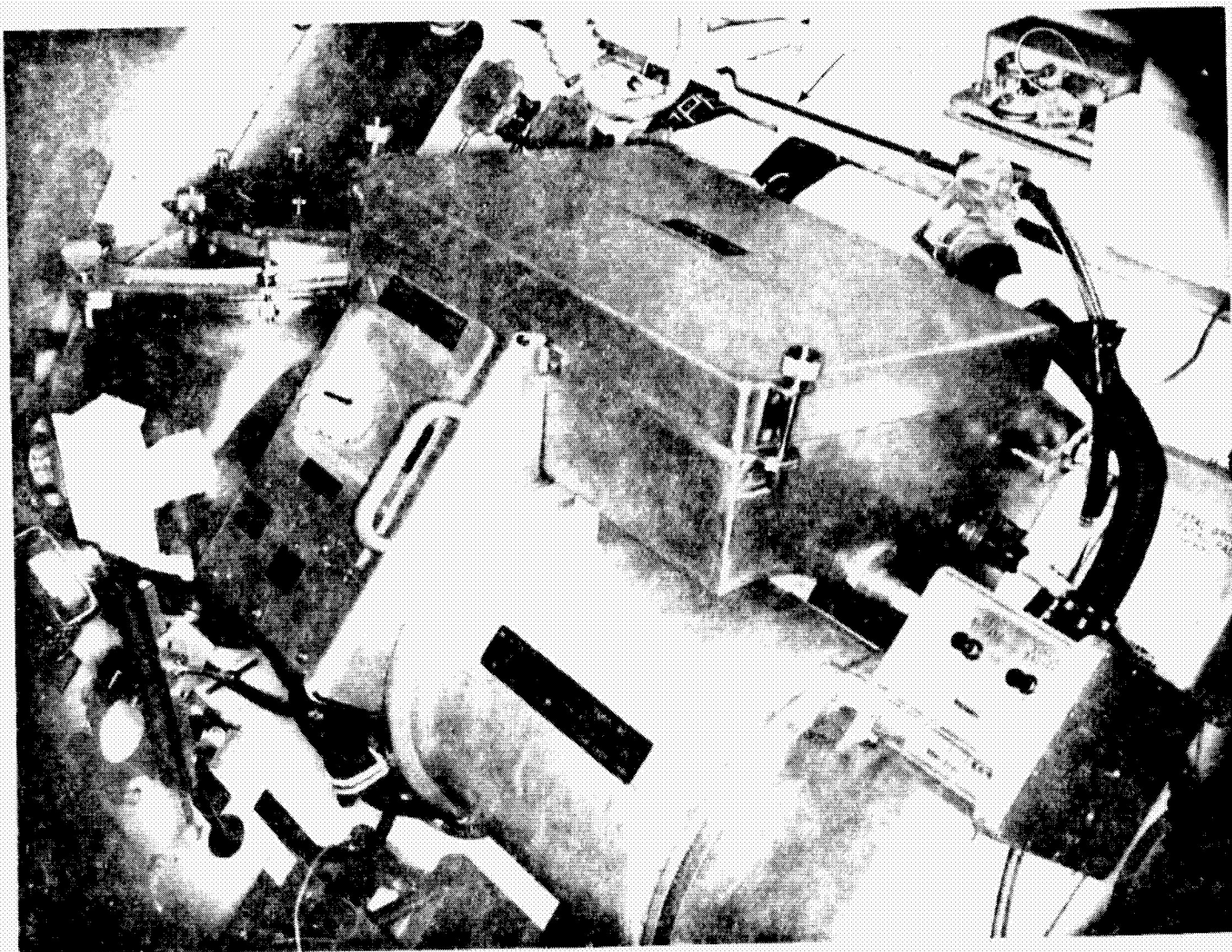


FIGURE 33. M512 FACILITY (TOP VIEW)

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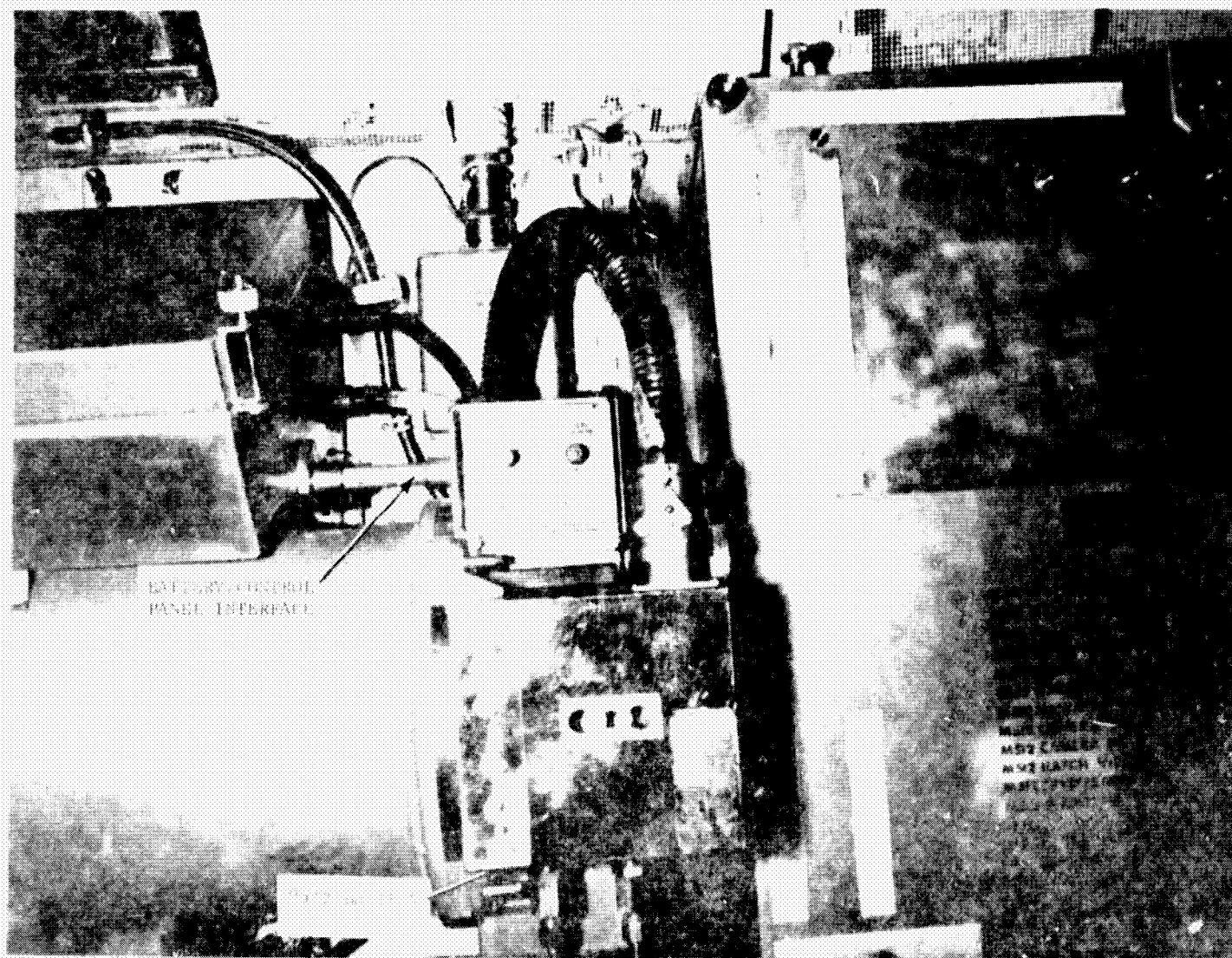


FIGURE 34. M512 BATTERY SUBSYSTEM

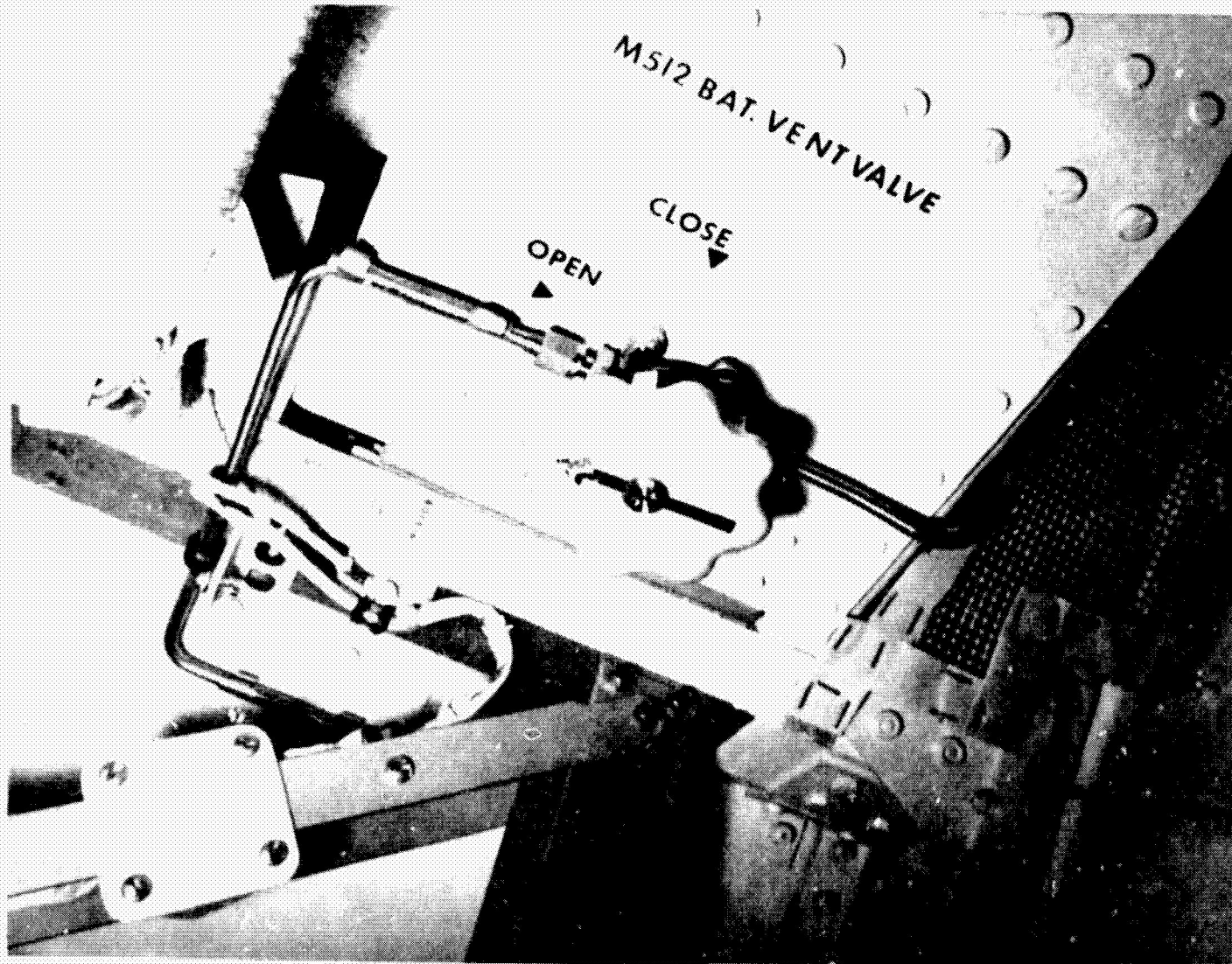


FIGURE 35. M512 BATTERY OVERBOARD VENT (MDA)

and terminated outside the MDA wall. The vent valve was open at launch and normally remained open until after battery discharge. The battery vent system was capable of withstanding a pressure differential of  $15.5 \times 10^4$  newtons per square meter (22.5 pounds per square inch). The battery control panel (figures 33, 34 and 36), located above the battery case, contained two circuit breakers and an indicator light. The MAIN BATTERY circuit breaker (CB1) was a 100 ampere, push-pull breaker which activated the battery circuit when pushed in and disconnected the battery from the circuit when pulled out. The battery was discharged as a safety consideration, after M551, M552 and M553 were completed, through the 5 ampere BATTERY DISCHARGE circuit breaker (CB6). When this circuit breaker was closed, the DISCHARGE light (L8) illuminated and the battery discharged to a resistor bank in the power heat sink on the mounting panel shown in figure 28. The system schematic (figure 22) illustrates the functions of the battery control panel discussed above.

(b) Head section power supply. This section of the electron beam system contained the electronics required to convert the low-voltage, high-current battery output to a high-voltage, low-current required by the electron beam gun electronics. The head section 2 kilowatt power supply was housed in a stainless-steel canister which was pressurized with perfluoropropane gas ( $C_3F_8$ ) that provided additional insulation against high voltage arcing. The insulating gas was changed from sulfur hexafluoride ( $SF_6$ ) as a safety consideration due to a possible toxicity problem with  $SF_6$  at a very high temperature. The canister was pressurized to  $17.3 \pm 0.7 \times 10^4$  newtons per square meter ( $25 \pm 1$  pounds per square inch) absolute, and proof-pressure tested to  $36.5 \times 10^4$  newtons per square meter (53 pounds per square inch) differential. The canister pressure was monitored when the astronaut placed the INSTRUMENTATION PRESS switch on the control panel to CSTR X3 position, which displayed the output of a pressure transducer located inside the canister. Such a pressure check was made prior to each electron beam operation, with a reading of  $14.48 \times 10^4$  newtons per square meter (21 pounds per square inch) established as a lower limit below which the electron gun could not be operated.

(c) Head section. In the head section, the output of the high-voltage inverter in the power supply section was rectified, filtered, and fed to the electron beam gun. The head section contained all the components that operated at a 20 kilovolt potential. Perfluoropropane gas was also used to provide additional insulation against arcing for these components.

1 Electron beam gun filament. The electron beam gun filament had an operational useful life of 30 minutes at 100 milliamperes, and 2.5 hours at 50 milliamperes beam current. The filament was housed in the filament chamber which was connected to the work chamber by a 1.9 centimeter (0.75 inch) diameter valve.



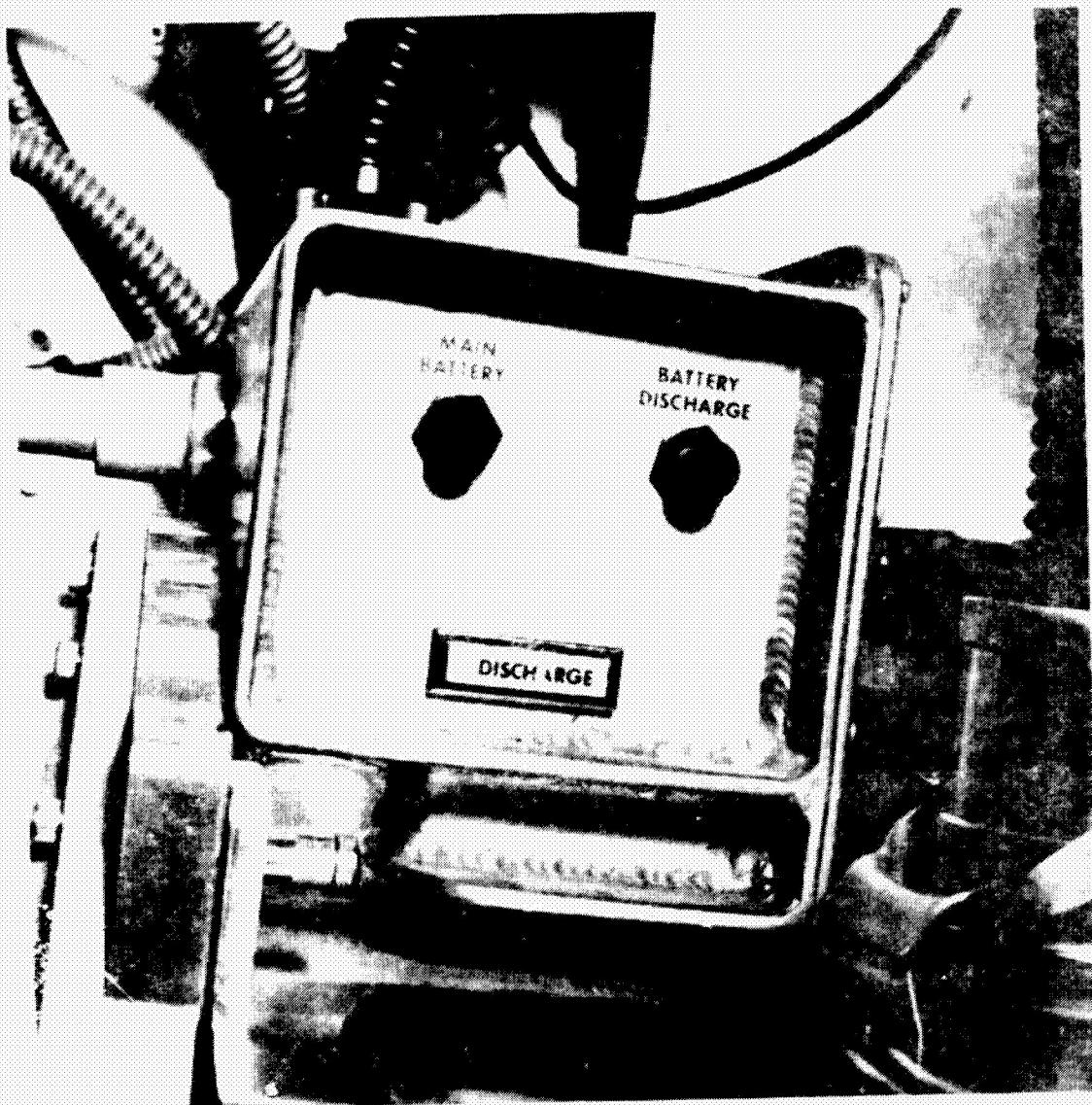


FIGURE 36. M512 BATTERY CONTROL PANEL



2 FILAMENT CHAMBER VENT valve. This valve (figure 37) was a hand-operated shuttle valve and isolated the filament chamber from the work chamber. The valve was opened to allow evacuation of the filament chamber only after the INSTRUMENTATION PRESS gauge indicated zero pressure in the work chamber. After EB gun operation and before the work chamber was repressurized with MDA atmosphere, the filament chamber vent valve was closed to prevent filament contamination/burnout by the  $3.55 \times 10^4$  newtons per square meter (5.5 pounds per square inch) absolute MDA oxygen rich atmosphere. A microswitch (S27) was connected to the valve which served as a system interlock during normal operations to preclude the inadvertent application of high voltage when the valve was closed (insufficient vacuum environment in the filament chamber).

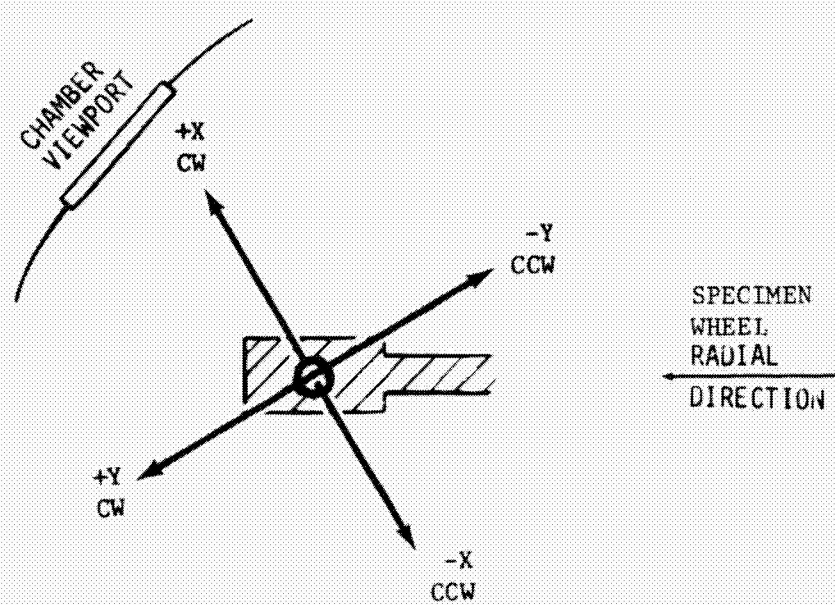
3 Filament chamber vacuum measurement. The vacuum head was a conventional thermocouple vacuum measurement device that indicated pressure in the filament chamber and displayed it on the electron beam PRESS gauge (in torr) on the control panel. Prior to activation of the electron beam, the astronaut was required to insure that the filament chamber pressure was  $1.33 \times 10^{-2}$  newtons per square meter ( $10^{-4}$  torr) or less.

4 Alignment coils. Electron beam alignment on the "X" and "Y" axes was accomplished with a series of electromagnetic coils located in the head section. These coils were in addition to the electron beam gun deflection and focus coils previously discussed in Section II. Figure 38 is a sketch of the electron beam coordinate system diagram which appeared in the astronaut operational checklist. The diagram illustrated directional movement of the electron beam associated with both clockwise and counter-clockwise adjustments of the BEAM CONTROL, ALIGN X and ALIGN Y three-turn potentiometers on the control panel. The point-of-view of figure 38 is "looking down the beam" toward the specimen. Figure 26 shows similar coordinate system nomenclature on the neutral density filter to aid the astronaut; this system is the same as figure 38 rotated 90 degrees. With the BEAM CONTROL, FOCUS ADJ, ALIGN X, and ALIGN Y potentiometers set at neutral, the point of impingement of the electron beam, 30.5 centimeters (12 inches) from the forward face of the X-Y alignment coil assembly, was within a 1.27 centimeter (0.5 inch) diameter circle centered on the X-Y alignment coil assembly center axis. With the FOCUS ADJ potentiometer set at neutral and adjustments of the ALIGN X and ALIGN Y potentiometers, the electron beam impingement would trace an "X" on the sample with its extremities lying between a 3.8 centimeter (1.5 inch) diameter circle and a 6.35 centimeter (2.5 inch) circle about the X-Y alignment coil assembly center axis.

(3) Control panel assembly. The control panel (figures 39, 40, and 41) included most of the controls and displays required for the M512 facility and associated experiment operations, with a minimum operational life of 2000 hours. The aluminum panel assembly was located



FIGURE 37. FILAMENT CHAMBER VENT VALVE



LINE-OF-SIGHT IS PARALLEL TO ELECTRON BEAM

FIGURE 38. EB COORDINATE SYSTEM

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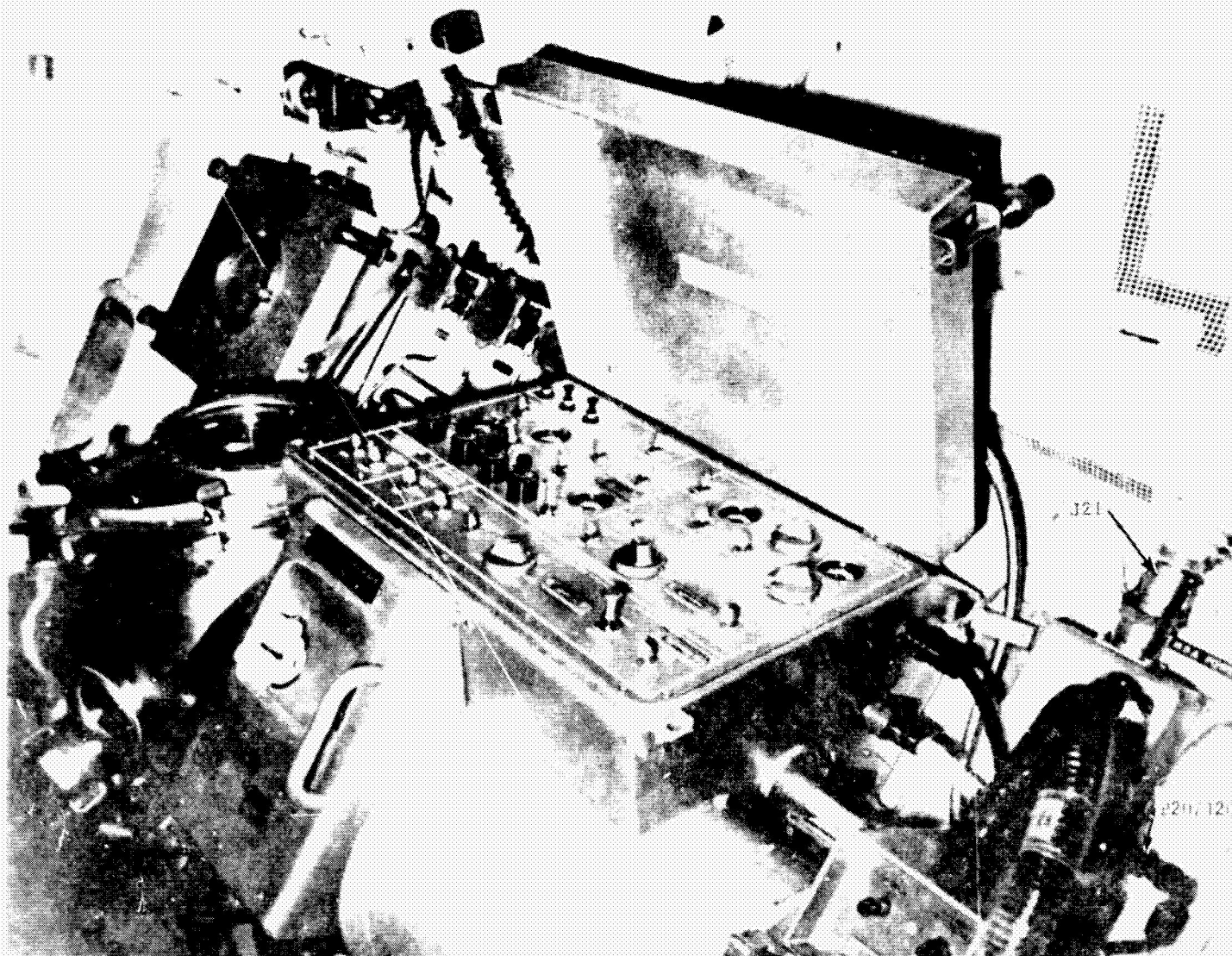


FIGURE 39. CONTROL PANEL/LINE FILTER CONNECTORS

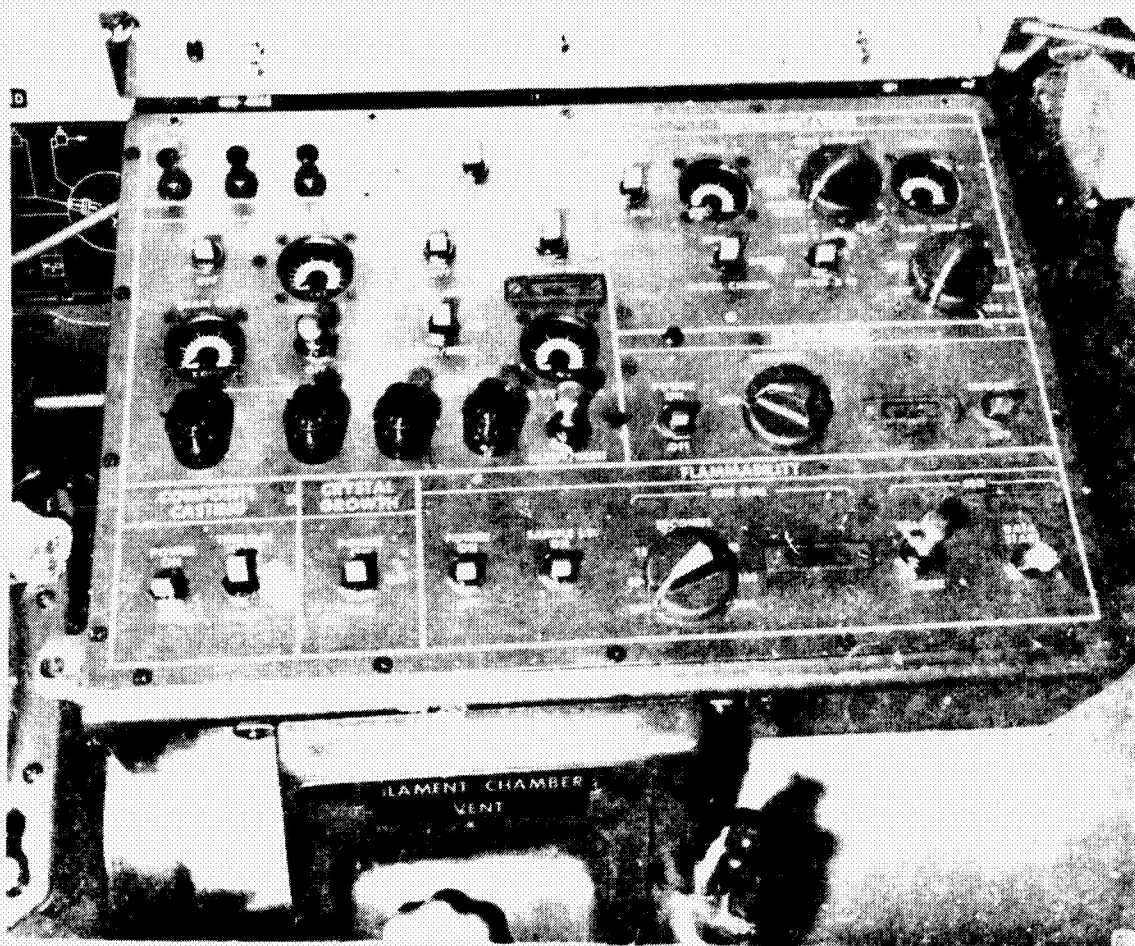


FIGURE 40. M512 CONTROL PANEL

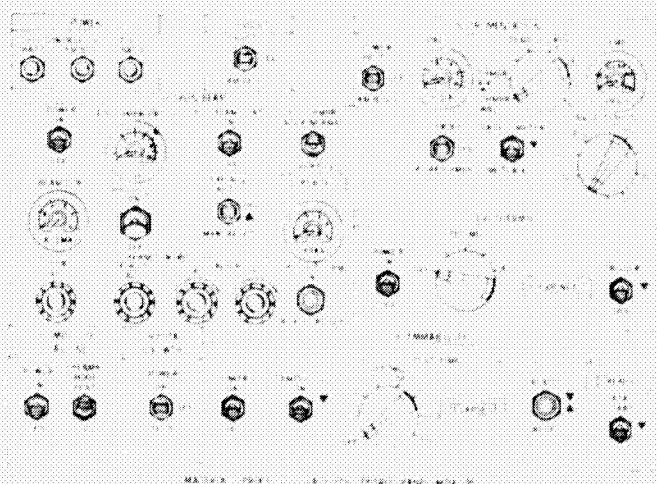


FIGURE 41. CONTROL PANEL NOMENCLATURE



on top of the electron beam system assembly and was equipped with a friction-hinged cover which remained open when lifted as shown in figure 39. The controls and displays were grouped into subpanels (figures 40 and 41), corresponding to various control functions and experiment operations. The function of each circuit breaker, switch, gauge, light, and potentiometer is included in the electrical system descriptions in subsection B.

(4) Electrical power subsystem. The 28 Vdc electrical power requirement for the M512 facility and experiments was provided by either of two sources - the M512 battery or the spacecraft Airlock Module power bus 1 (AM Bus 1).

(a) Battery power. The internal battery power system was necessary to meet the high wattage requirements during operation of the electron beam gun (experiments M551, M553) and the high current "spike" requirement of the M552 igniters. Battery power was provided to the control panel from the battery control panel through the connection shown in figure 34.

(b) Spacecraft power. The spacecraft power/M512 interface was through connector J21, as shown in figure 39. The nomenclature MDA POWER in the figure indicated the M512 external power source which was in fact AM Bus 1 routed through the MDA. Spacecraft power was 7.5 amperes at a nominal 28 Vdc; this source was used for all facility operations except M551, M552, and M553.

1 Line filter. A line filter system was designed to eliminate power surges to the M512 equipment. The electrical components were housed in the aluminum box (figures 26 and 33). Power from the line filter was provided to the control panel through connection P28/J28 and to the M555 launch container as described in the following paragraph.

2 M555 requirement. The M555 launch container required 28 Vdc spacecraft power when stored on the M512 facility mounting panel prior to M555 experiment operation. This power was supplied from the line filter through the CRYSTAL GROWTH HEATING PAD AM BUS 1 5 ampere circuit breaker (CB5), as can be seen in figure 26. The M555 single crystal growth launch container power cable was designed to connect the output of CB5 through connection P20/J20 (figure 39) to the M555 launch container through connection P47/J47 on the container (figure 42). Prior to the M555 launch container being stored on the facility, connector P47 was connected to a dummy receptacle as shown in figure 26.

3 Auxiliary vacuum gauge power cable. This cable was designed to power the filament chamber vacuum sensor and gauge during operations of experiments M555, M479, and M518. The vacuum-sensing

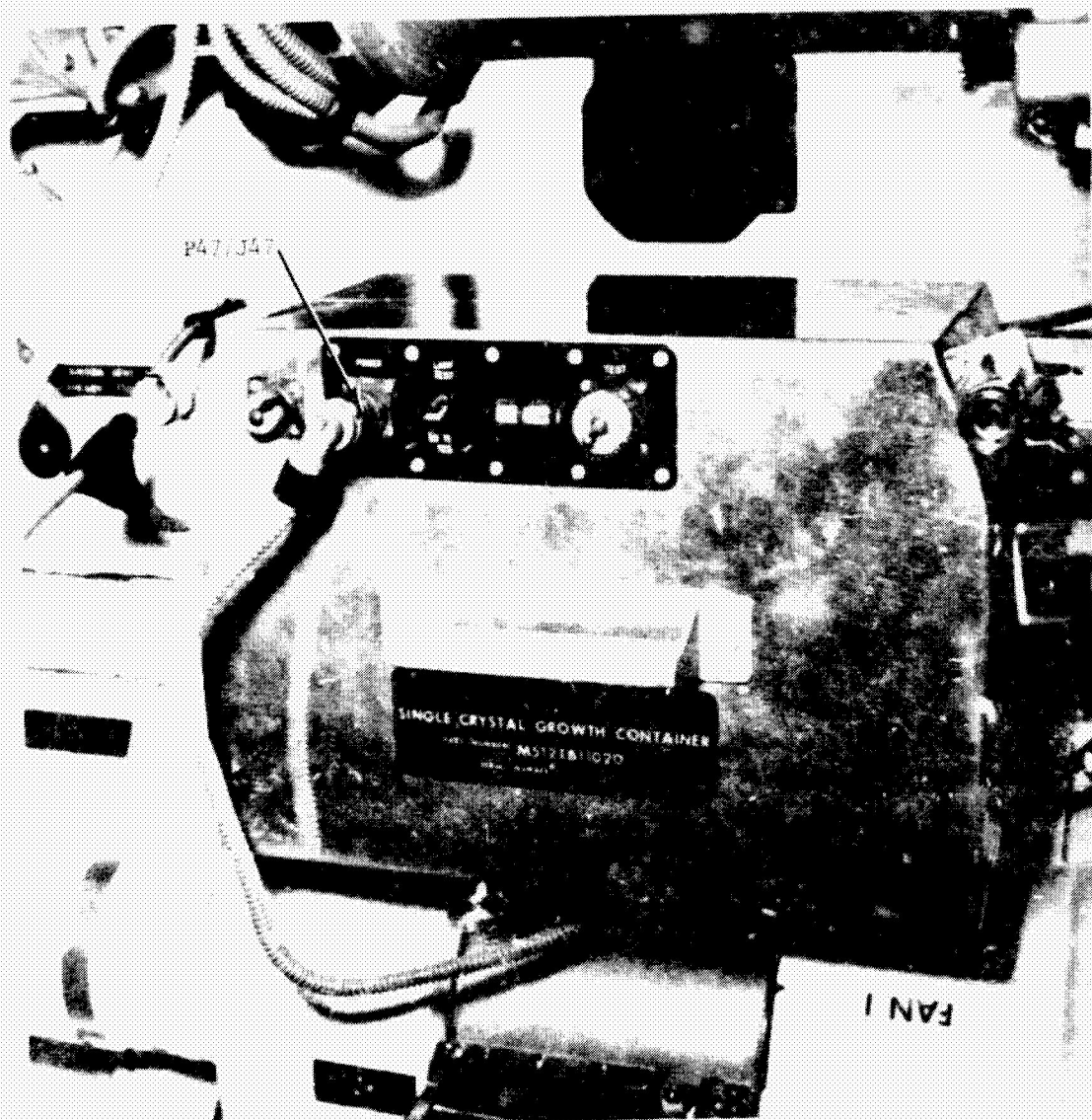


FIGURE 42. M555 STORAGE CONFIGURATION

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system was normally powered by the battery; however, a late requirement for vacuum readout for M555 and M479 necessitated the development of a cable to provide spacecraft power, since the battery would be discharged prior to operation of those experiments.

The auxiliary power vacuum gauge cable was a junction box with three connections. The astronaut was required to first disconnect the P9/J9 connection on the M512 facility (figure 29), which was the interface between the filament chamber vacuum module and both battery power and the filament chamber vacuum gauge. The junction box cable (P55) was then connected to J9 (vacuum module) and P9 (gauge cable) was connected to a junction box connector (J53). Finally, the M555 single crystal growth launch container power cable was connected to a junction box connector (J54) as shown in figure 27, thus completing a circuit to power the filament chamber pressure gauge and vacuum module with spacecraft power through CB5.

(c) Miscellaneous cables.

1 16 millimeter camera cable. A "pigtail" cable (IW7) provided power to the 16 millimeter camera through connections P19/J19 and P15/J15. Cable IW7 is shown in stowed location in figure 26.

2 Floodlight cable. Cable IW8 provided power to the floodlight through connection P16/J16 as shown in figures 27 and 28.

3 Power heat sink cable. Cable 4W9 connected the power heat sink and connection P12/J12 on the side of the control panel as shown in figures 29 and 39. This circuit was used to dissipate heat produced by control panel power transistors and to discharge the M512 battery.

(5) Pressure subsystems. There were two major pressure subsystems, vacuum vent and repressurization, that controlled the pressure environment within the M512 work chamber and EB filament chamber. The subsystems are illustrated in the system schematic, figure 22.

(a) MDA vacuum vent subsystem. The vacuum vent line was MDA-furnished equipment, but is briefly discussed because of its importance to the facility operation. The line was a 10 centimeter (4 inch) inside diameter stainless-steel line with redundant valves as shown in figure 43. The line passed through the MDA walls and terminated on the MDA external cone area as shown in figure 44. The vacuum vent valves (figure 45) were three-position hand-operated valves: fully open, fully closed, 90 percent closed (VENT). The normal operational sequence to vent the M512 facility was to place the work chamber and bulkhead vent valves to OPEN in that order. After experiment



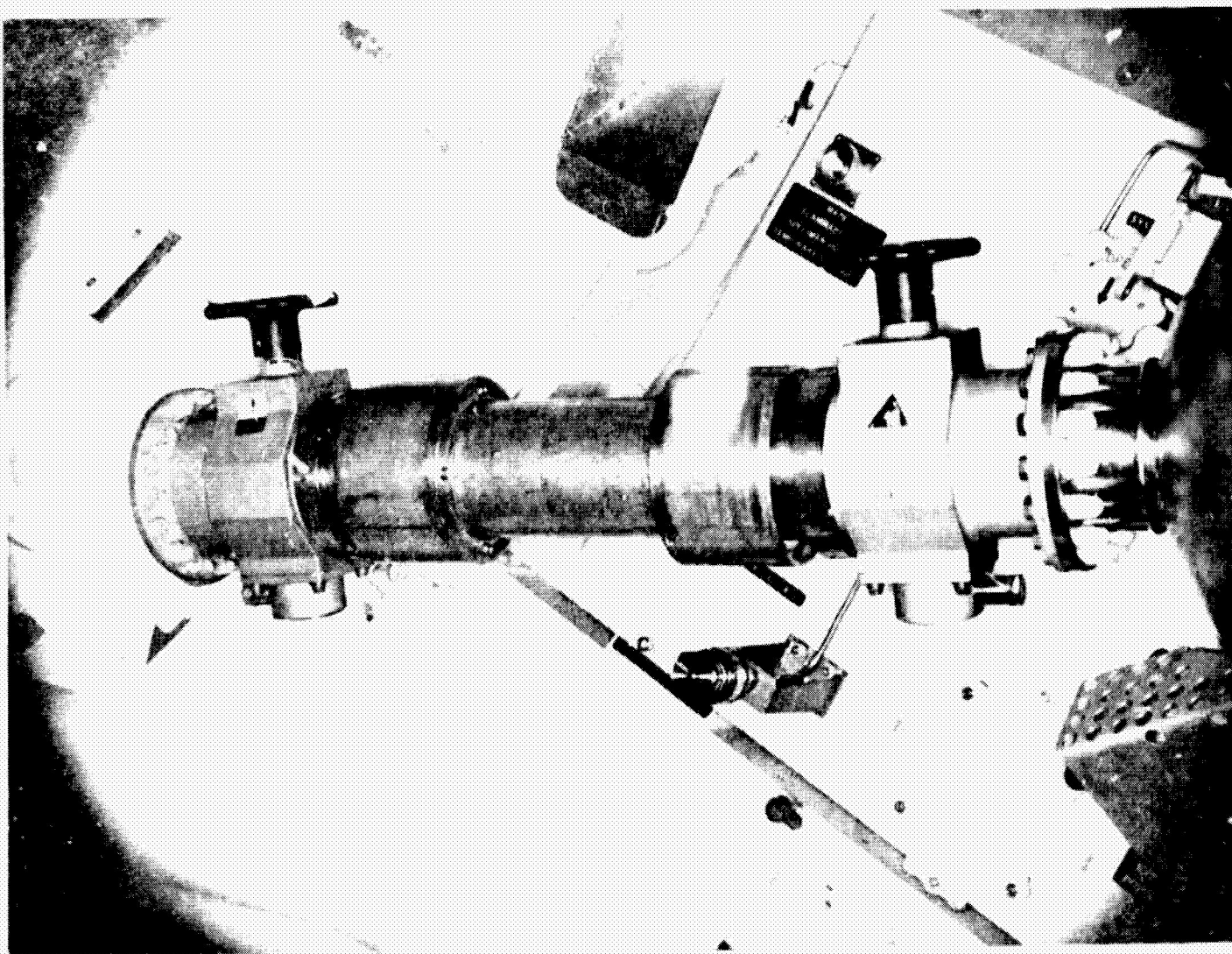


FIGURE 43. MDA VACUUM VENT SYSTEM

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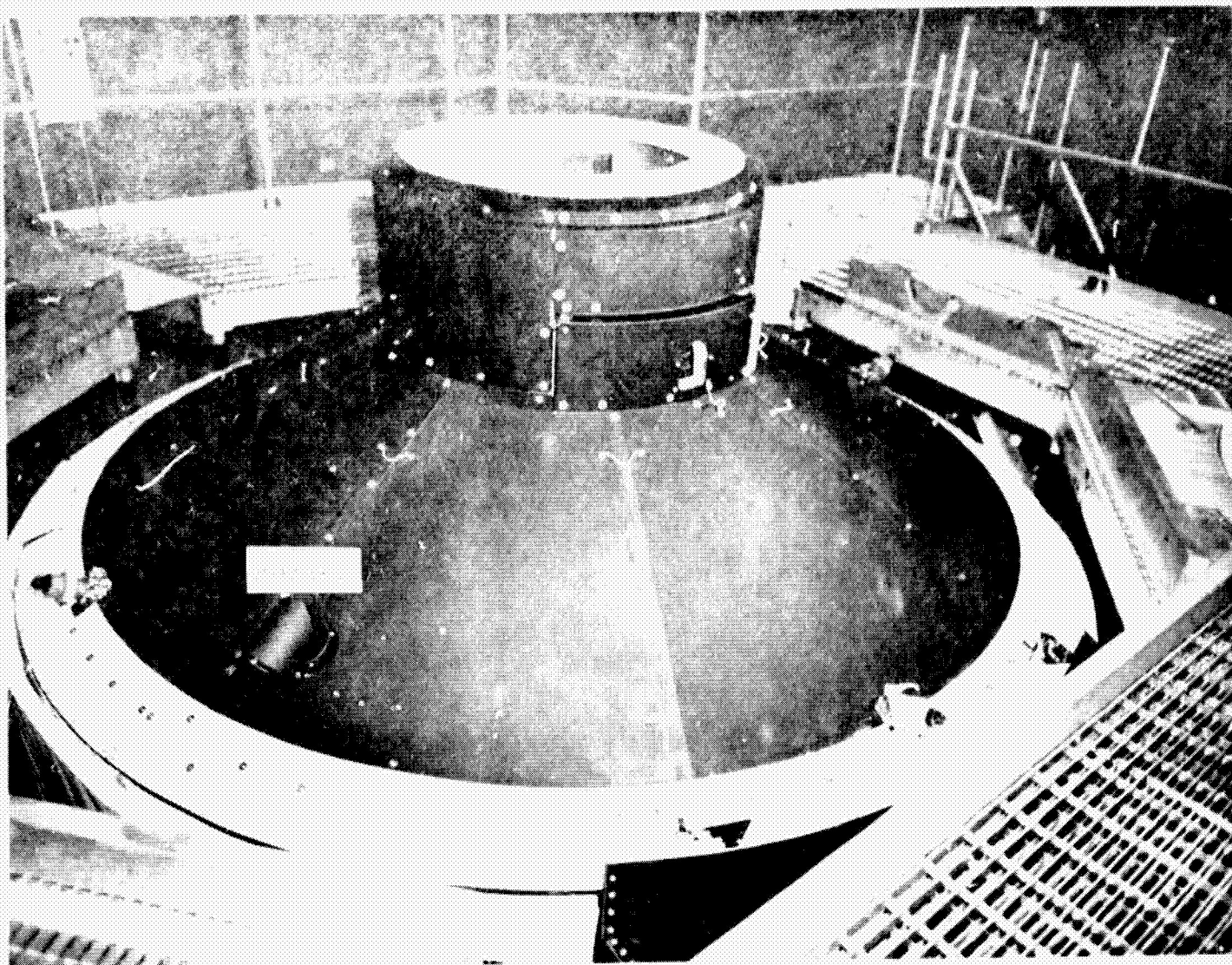


FIGURE 44. MDA VENT LINE (EXTERNAL)

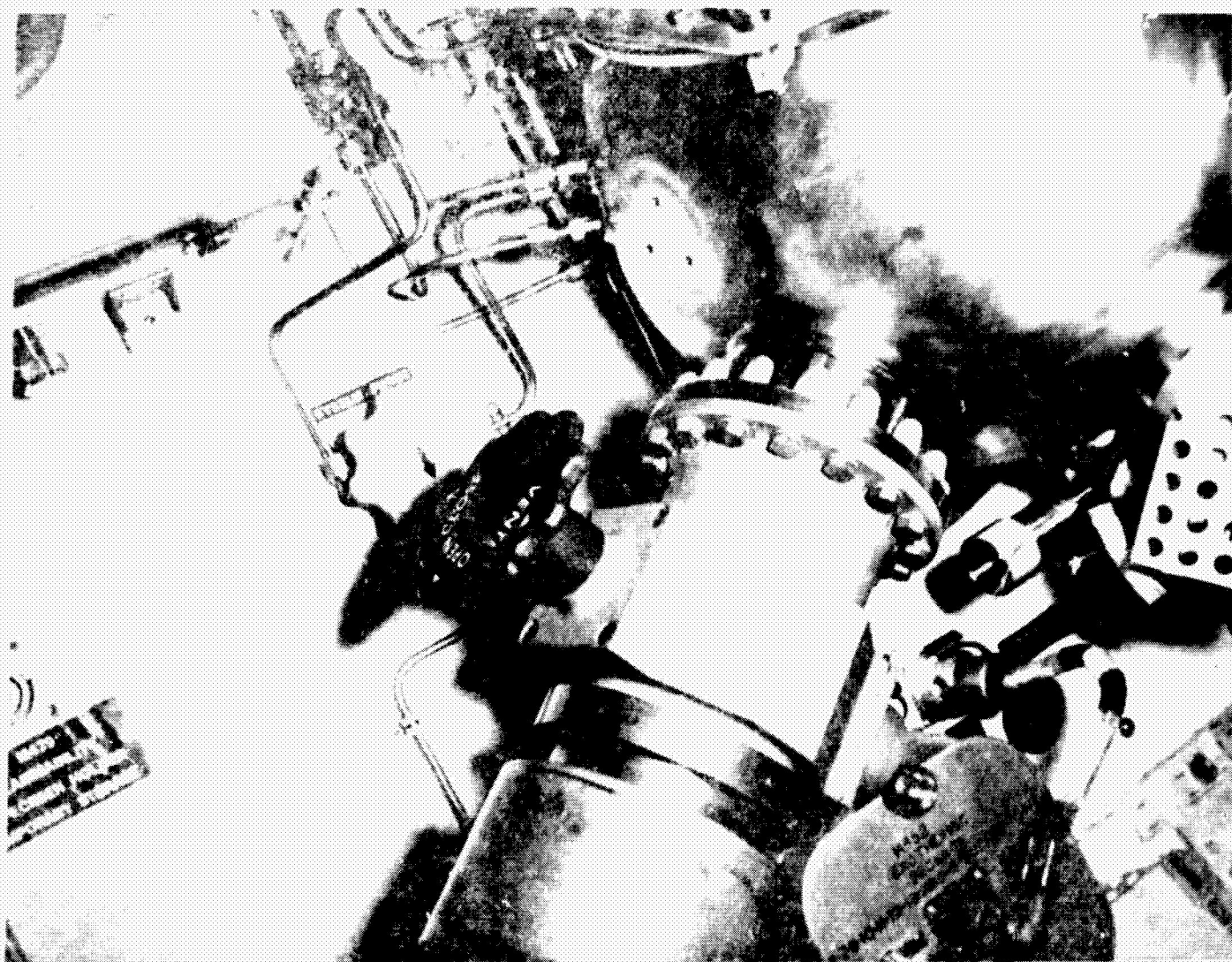


FIGURE 45. VACUUM VENT VALVE

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operations, the valves were placed in the CLOSED position in the same order. The VENT position was used only for M518 operations during crew sleep periods, when the work chamber valve was left fully OPEN and the bulkhead valve was placed in VENT as a safety precaution.

(b) Vent line filter number 1. Vent filter number 1 (figure 46) was installed in the vacuum vent line prior to experiment operations to trap contaminants from experiments performed in the M512 facility. The filter was constructed of an aluminum alloy frame containing a 1200 micron filter. The frame included three detent balls that secured the filter in the vent line near the chamber interface.

(c) Chamber repressurization subsystem. The chamber repressurization system consisted of a 0.6 centimeter (0.25 inch) line, a valve, and a 10 micron filter used to repressurize the work chamber with MDA atmosphere after experiment operations. The CHAMBER REPRESS valve was a two-position (OPEN and CLOSED) hand-operated valve as shown in figure 26. The entire system is illustrated in figure 47, with the repressurization line M512 work chamber interface shown in figure 48.

(6) Water quench subsystem. Experiment M479 required a system capable of dispensing 0.06 liters (2 fluid ounces) of water through spray nozzles inside the chamber within 4 seconds after activation of the spray valve. The spray nozzle assemblies were not permanently mounted in the chamber and are discussed as M479 hardware in subsection 6 following. The complete system is illustrated in figures 22 and 47. Water for the system was obtained from orbital workshop (OWS) water tank number 6 through an 18.3 meter (60 foot) OWS flexible water umbilical. Two water system lines interfaced the M512 work chamber as shown in figure 48. A water spray connection cover was provided in the equipment storage container to cover the water inlet line inside the chamber during all experiment operations prior to M479.

(a) SYSTEM PURGE valve. The SYSTEM PURGE valve was a hand-operated, two-position valve that was used to vent the air from the water lines prior to initial operation of the water quench system. Once the system had been evacuated, the PURGE valve was CLOSED and remained CLOSED.

(b) WATER SOURCE interface. Figures 43 and 49 show the connection between the M512 water quench system and the OWS water umbilical. The M512 water quench system was designed to operate with a  $30 \times 10^4$  newtons per square meter (42 pounds per square inch) differential input pressure from the OWS water supply.

(c) Water accumulator. The accumulator (figure 50) was a reservoir for the water required for each quench operation. When the WATER SPRAY valve was opened, the 0.06 liters of water was forced

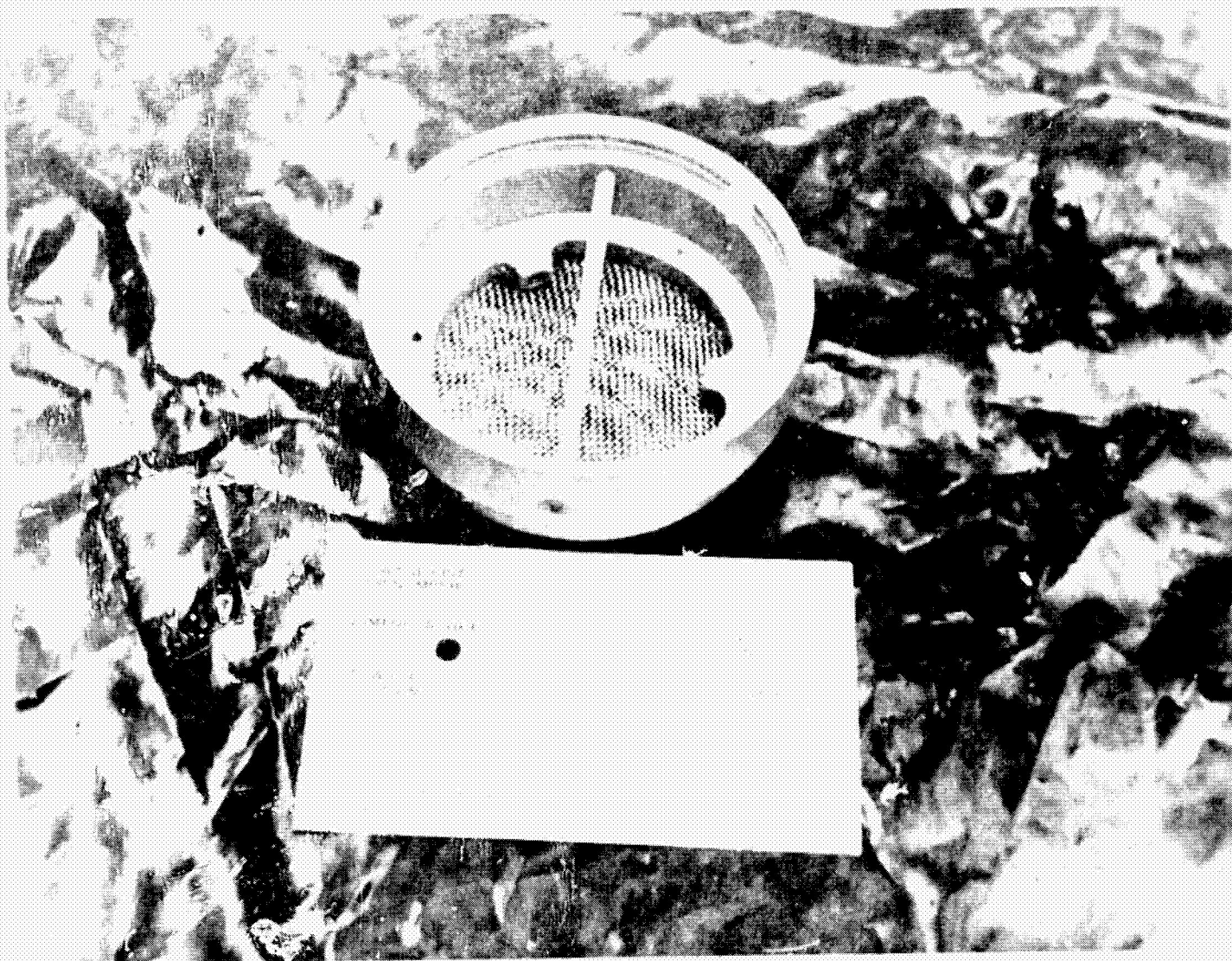


FIGURE 46. VENT LINE FILTER NUMBER 1

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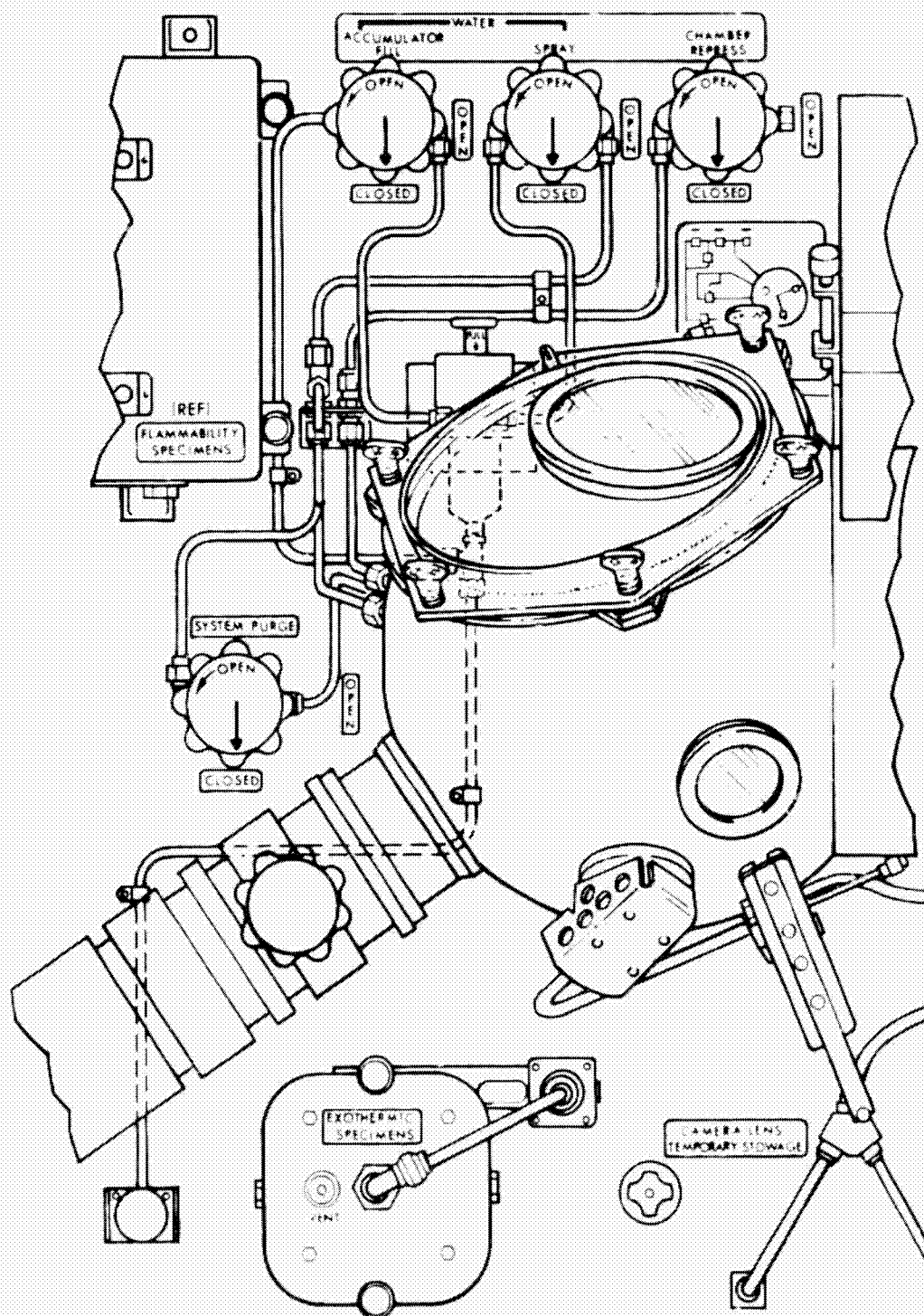


FIGURE 47. CHAMBER WATER AND REPRESSURIZATION SYSTEMS SCHEMATIC

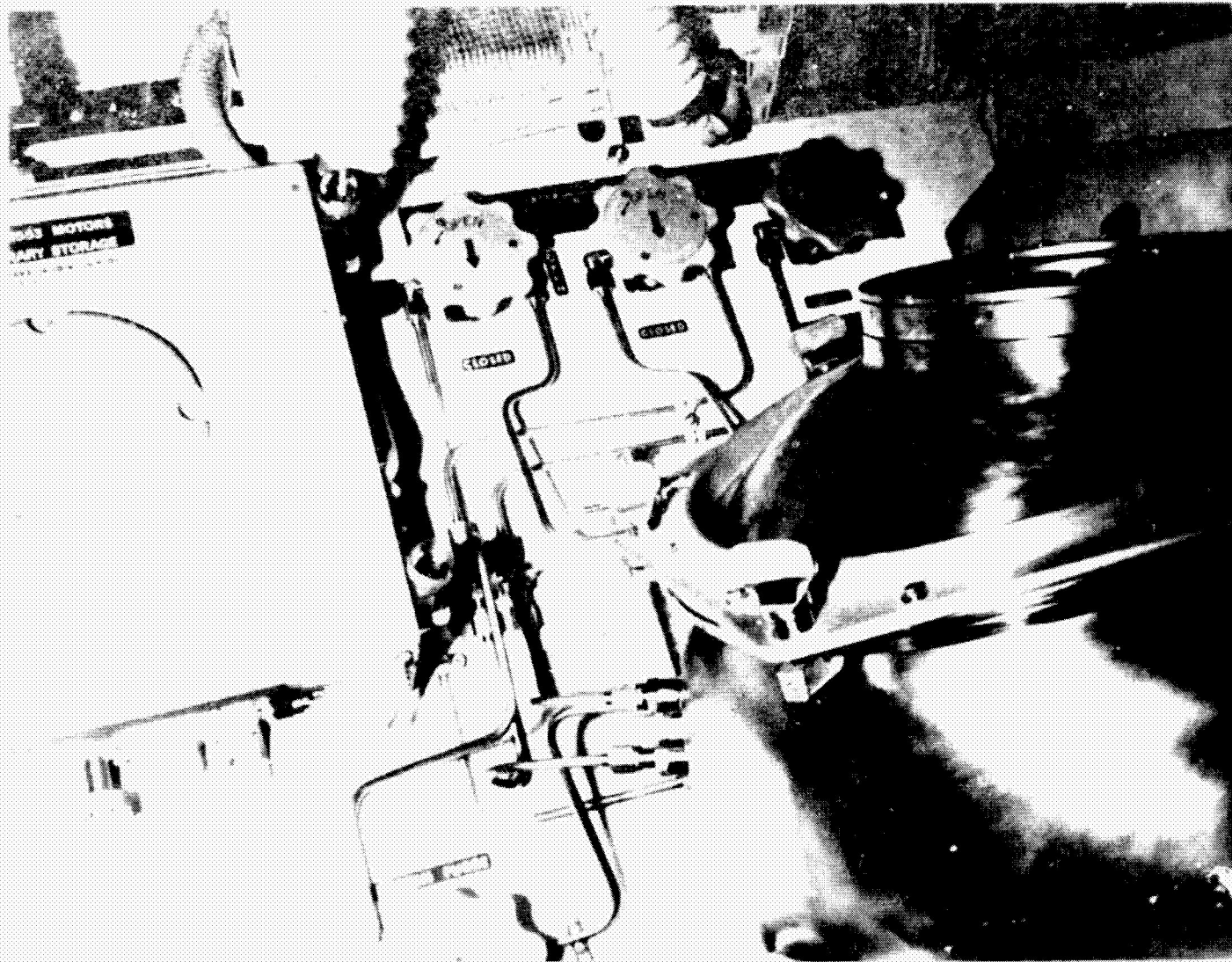


FIGURE 48. CHAMBER WATER AND REPRESSURIZATION SYSTEMS





108-KSC-73C-621 UNCL 2-26-73  
NASA SKYLAB NO F502-397  
SKYLAB I MDA SEQUENCE 57M512-H<sub>2</sub>O LINE  
FIT CHECK. FINAL CLOSEOUT

FIGURE 49. M512/WATER UMBILICAL INTERFACE

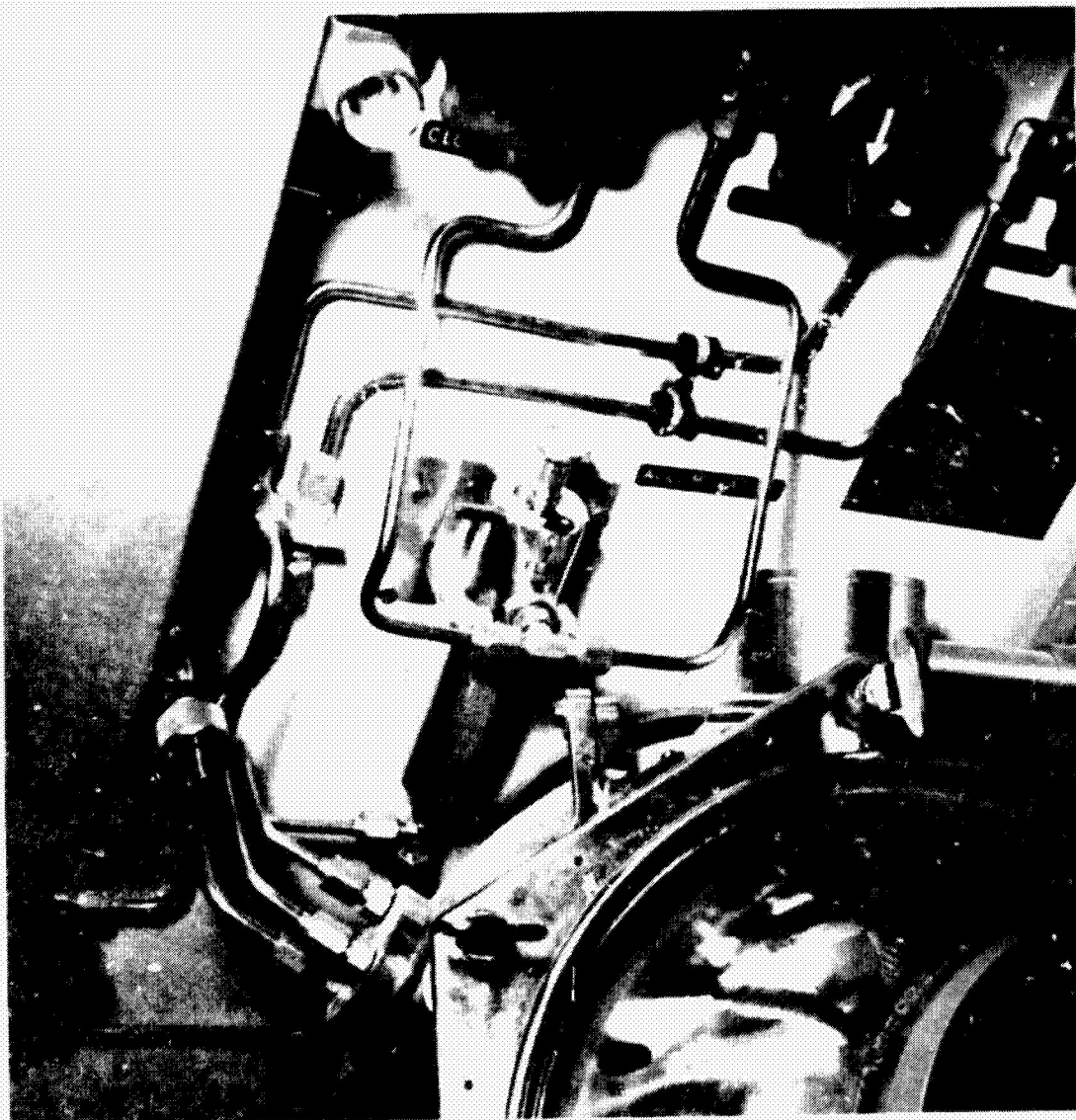


FIGURE 50. WATER QUENCH SYSTEM ACCUMULATOR

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into the spray nozzle assemblies in the vacuum chamber due to the pressure differential across the accumulator piston. Prior to refilling the accumulator, the piston was manually pushed to the bottom of the accumulator reservoir.

(d) WATER ACCUMULATOR FILL valve. This hand-operated, two-position valve allowed water to be transferred from the lower to the upper part of the water accumulator. After the accumulator reservoir was filled, the FILL valve was closed. In this condition, the water in the accumulator reservoir plus the lines from the FILL valve to the SPRAY valve to the reservoir equalled the desired 0.06 liters of water.

(e) WATER SPRAY valve. This valve was a hand-operated, two-position valve which, when opened, allowed the required amount of water to flow from the accumulator reservoir and lines to the spray nozzles in the vacuum chamber.

(7) Equipment storage. The M512 equipment storage container (figures 19 and 51) was a large, hinged aluminum box which contained experiment specimens for M551 and M553 and accessory hardware items required to conduct the associated M512 experiments. The container had dimensions of 58.4 centimeters (23 inches) wide by 73.7 centimeters (29 inches) high by 20.8 centimeters (8.2 inches) deep, with a weight of 34.1 kilograms (75 pounds) empty. Figure 52 shows the opened container and the numerous hardware items stored within. The door could be locked open with the bracket and fastener assembly at the top of the container. The individual experiment items shown will be discussed in later paragraphs of this section dealing with each experiment.

#### (8) Facility/experiment mounting assemblies.

(a) Facility mounting panels. The M512 facility and all associated experiment hardware stored in the MDA were mounted on one of the two aluminum-alloy-honeycomb facility mounting panels. The panels were installed side-by-side and shock mounted to MDA longerons 4 and 5, using a total of 12 shock isolators.

1 Upper mounting panel. The upper facility mounting panel had dimensions of 148.1 centimeters (58.3 inches) wide by 98.8 centimeters (38.9 inches) high by 3.5 centimeters (1.375 inches) deep, and supported the facility and all experiment hardware except the equipment storage container and the M518 furnace. This panel is shown installed in the MDA in figures 53 and 54. The large circular hole in the panel accommodated the heat sink as shown in the cutaway view, figure 24.

2 Lower mounting panel. The lower facility mounting panel had dimensions of 64.3 centimeters (25.3 inches) wide by



FIGURE 5-1. M512 EQUIPMENT STORAGE CONTAINER (CLOSED)



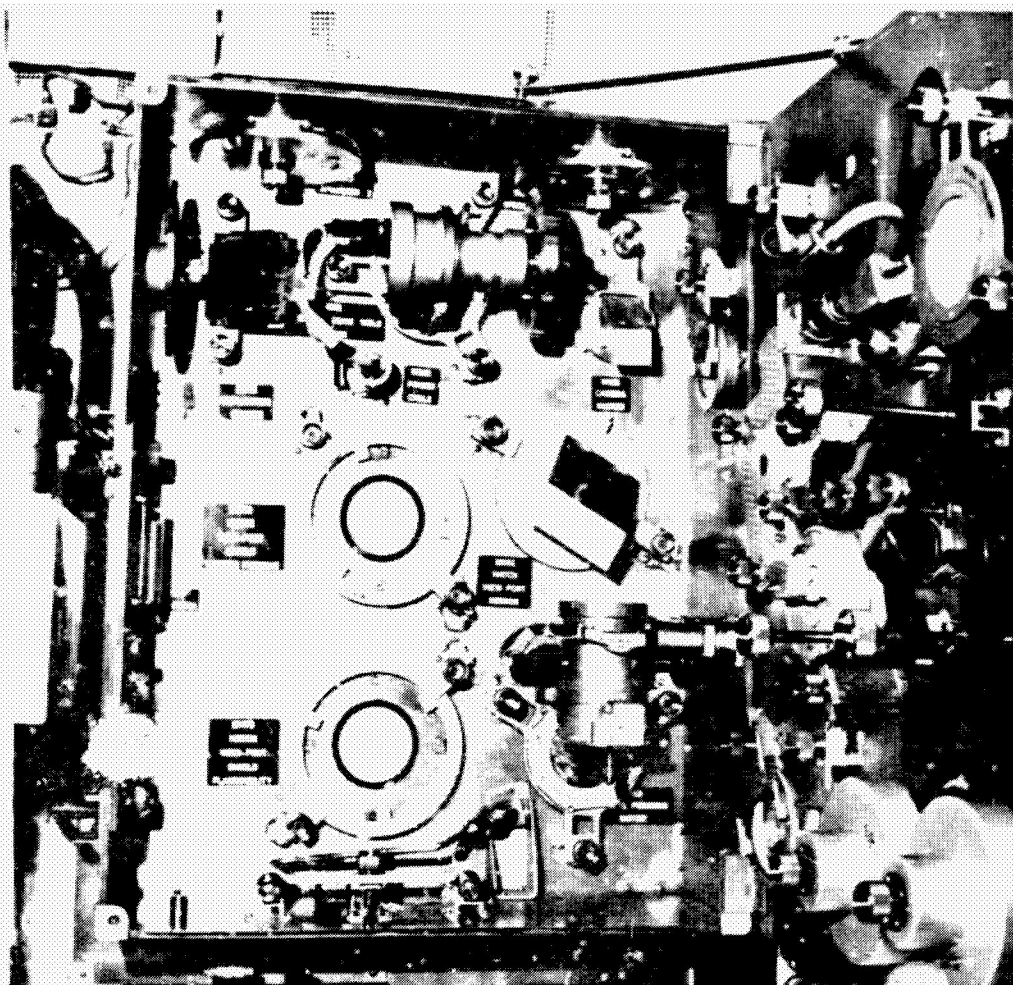


FIG. 52 M512 EQUIPMENT STORAGE CONTAINER

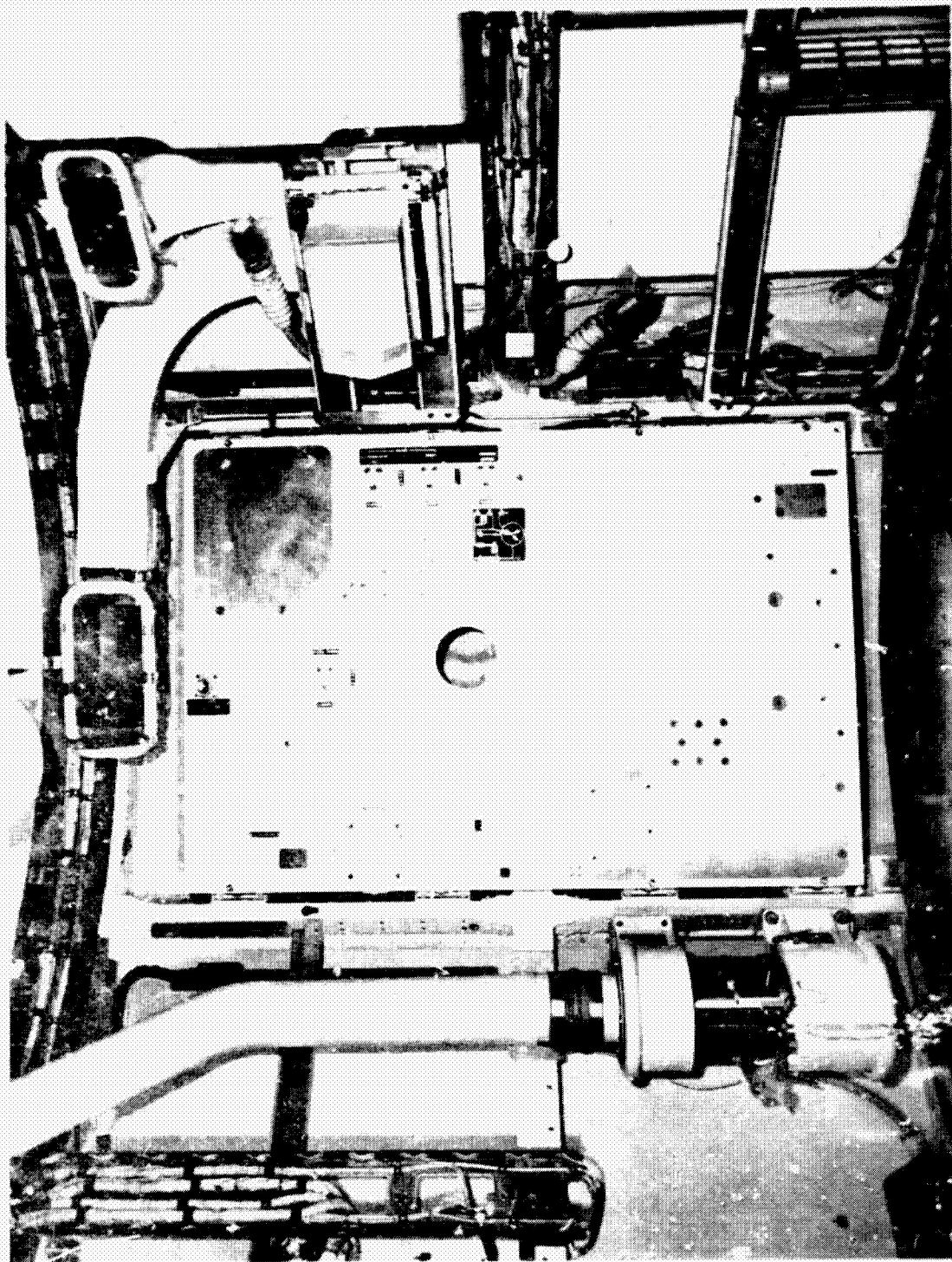


FIGURE 53. UPPER MOUNTING PANEL (FRONT VIEW)

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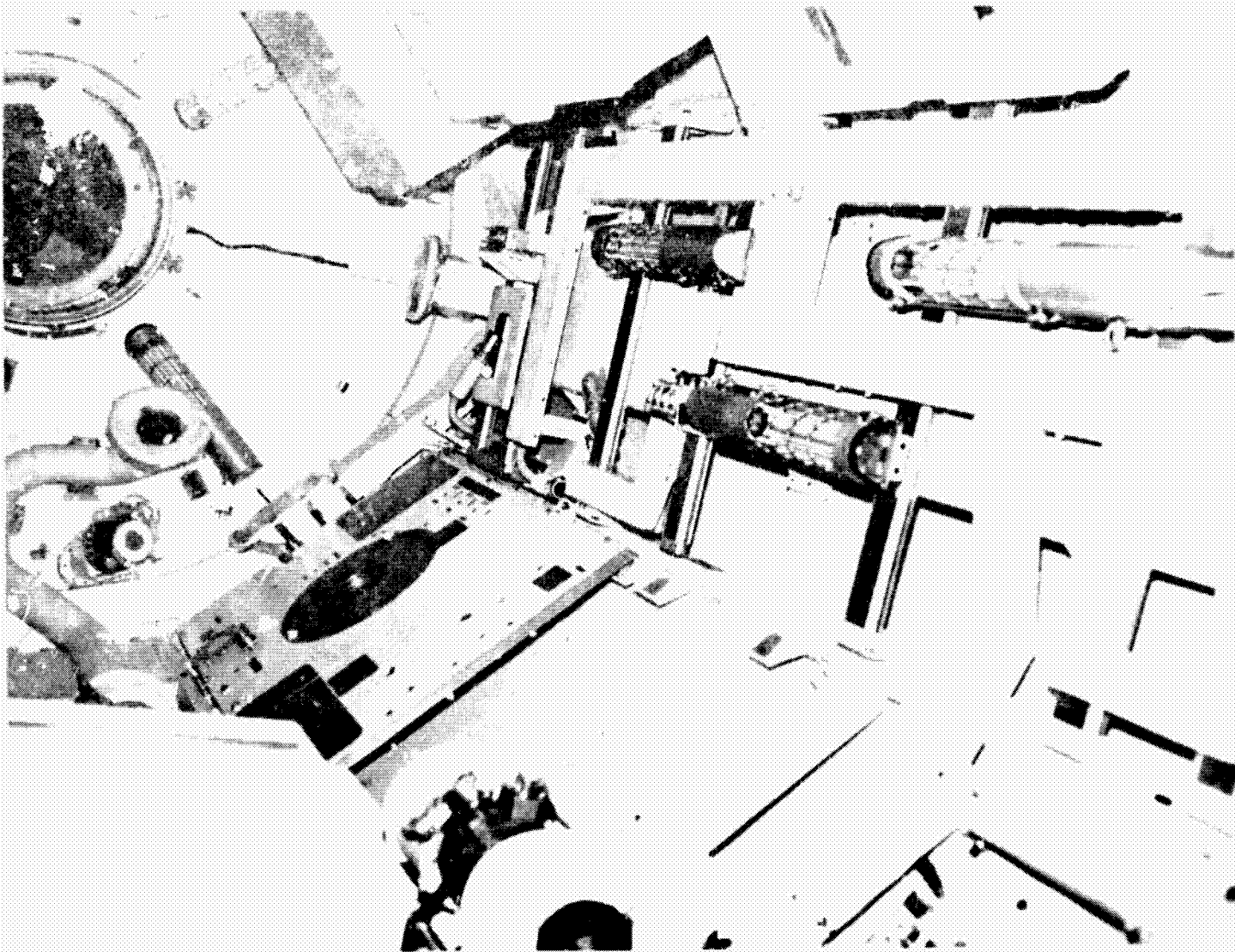


FIGURE 54. UPPER MOUNTING PANEL (SIDE VIEW)



98.8 centimeters (38.9 inches) high by 1.9 centimeters (0.75 inches) deep, and supported the equipment storage container and the M518 furnace, as can be seen in figure 51. Two of the shock isolators for the lower mounting panel are shown in figure 54.

(b) Experiment mounting provisions. The facility mounting panels provided storage locations for several items of experiment hardware that could not be stored inside the equipment storage container.

1 M479 provisions. The M479 flammability specimen storage container was an aluminum container with dimensions 31.4 centimeters (12.4 inches) wide by 31.4 centimeters (12.4 inches) high by 15.7 centimeters (4.75 inches) deep, located on the upper mounting panel adjacent to the water quench system valves, as shown in figure 55. The container had a hinged door that opened downward as shown in figure 56, and stored the 37 flammability specimen containers which are discussed in subsection 6 of this section. A vent port was installed in the bottom of the container (figure 55) for pressure equalization. The mounting ring (figure 55) on the storage container door was designed as a temporary storage location for the M551 and M553 motor assemblies, which are discussed in subsections 2 and 4 following. Also, the M518 console panel attached to this ring with a special M518 clamping assembly for M518 operations. Figure 43 shows the M479 FLAMMABILITY SPECIMEN HOLDER TEMPORARY STORAGE location, which was designed to temporarily secure the M479 specimen holder (see subsection 6) for specimen changeout.

2 M552 provisions. Mounting provisions were provided on the upper mounting panel for the M552 exothermic package and its associated cable. Figure 29 shows the two-hole mounting plate for the package and the adjacent dummy zero-g connector for the cable. Figure 45 shows the package and cable in the stored location.

3 M555 provisions. The M555 furnace was launched and stored in a heated launch container for which mounting provisions were provided on the upper mounting panel. The M555 support adapter was designed to support the M555 launch container (see figure 19). Figures 26 and 27 show the support adapter without the launch container and figures 20 and 42 show the launch container in the stowed position. Also, a dummy zero-g connector (figure 51) was provided on the lower mounting panel for temporary storage of the M555 power cable when required.

4 M518 provisions. Mounting provisions were provided on the lower mounting panel for storage of the M518 multipurpose furnace, as illustrated in figure 19 and shown in figures 20 and 51.

5 Camera lens temporary storage. Figure 29 shows the mounting provision on the upper mounting panel for temporarily

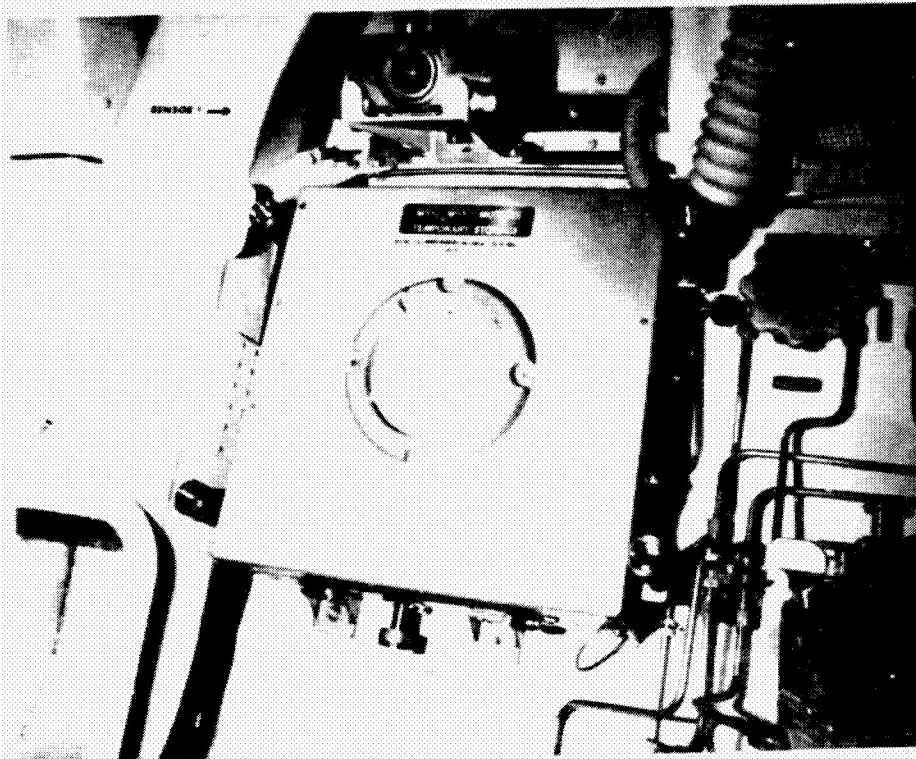


FIGURE 55. M479 FLAMMABILITY SPECIMEN STORAGE CONTAINER (CLOSED)

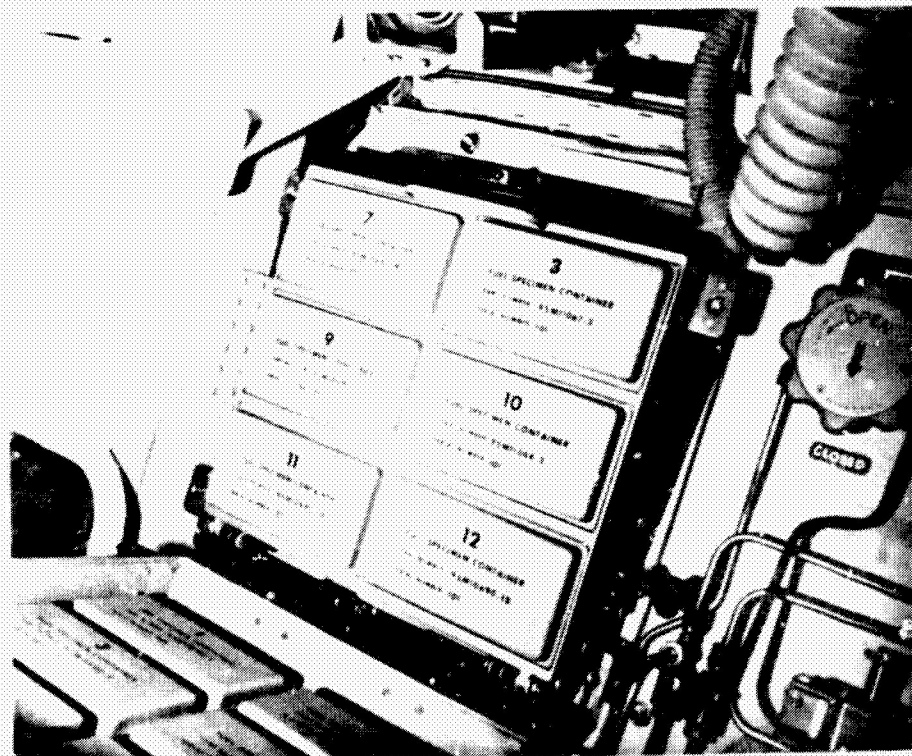


FIGURE 56. M479 FLAMMABILITY SPECIMEN STORAGE CONTAINER (OPEN)

securing the camera lens assemblies when required during experiment operations.

## **2. Experiment M551 - Metals Melting.**

a. Objectives. The objectives of M551 were to study the behavior of molten metals in free fall at low acceleration levels, to characterize the structures formed in metals melted and rapidly solidified in free fall, and to test the possibility of joining metals by electron beam welding in space.

b. Concept. The experimental concept was to heat metal to its melting point by rotating a metal sample through the path of an electron beam gun as depicted in figure 57, then allow the molten metal to resolidify under low-gravity conditions. Three metals (2219 aluminum alloy, type 304 stainless steel and pure tantalum) were selected as sample materials.

c. Hardware description. Figure 58 includes two views (photograph of mockup unit and cross-sectional drawing) of the operational configuration of the M551 hardware. Each required hardware item is discussed individually in the following paragraphs. Nomenclature used for the mirrors was changed late in the program to conform with astronaut preference; both names are given, where applicable.

(1) M551 weld specimens. The three sample weld specimens were stored in the equipment storage container as shown in figure 52. The cross-sectional thickness at the radius of beam impingement varied to accommodate different operational aspects; i.e., cutting, complete penetration, partial penetration and dwell. This sample design can be seen in the photograph of figure 58. The stainless steel and aluminum samples were 165 millimeter (6.5 inch) diameter disks, graduated in thickness from 0.6 millimeter (0.025 inch) to 6 millimeters (0.25 inch). The tantalum sample was a 165 millimeter (6.5 inch) diameter disk with a graduated thickness from 0.4 millimeter (0.017 inch) to 1.6 millimeters (0.062 inch). The typical M551 operational sequence can be seen on the returned flight sample in figure 59. The electron beam was initially aligned using a tungsten target embedded in the specimen disk shown at the 11 o'clock position in figure 59. The sample was then rotated 270 degrees through the electron beam, at which time the beam was terminated at a hole in the sample. The sample was rotated another 45 degrees, stopped and the beam reinitiated to dwell for a predetermined time period which differed for each material.

(2) M551 electron beam weld motor. The weld motor assembly, also known as the drive assembly (figure 60), was stored in the equipment storage container (figure 52) and consisted of the motor to drive the specimen disk, the provisions for mounting the specimen disk to the motor, tripod mounting base to interface with the heat sink

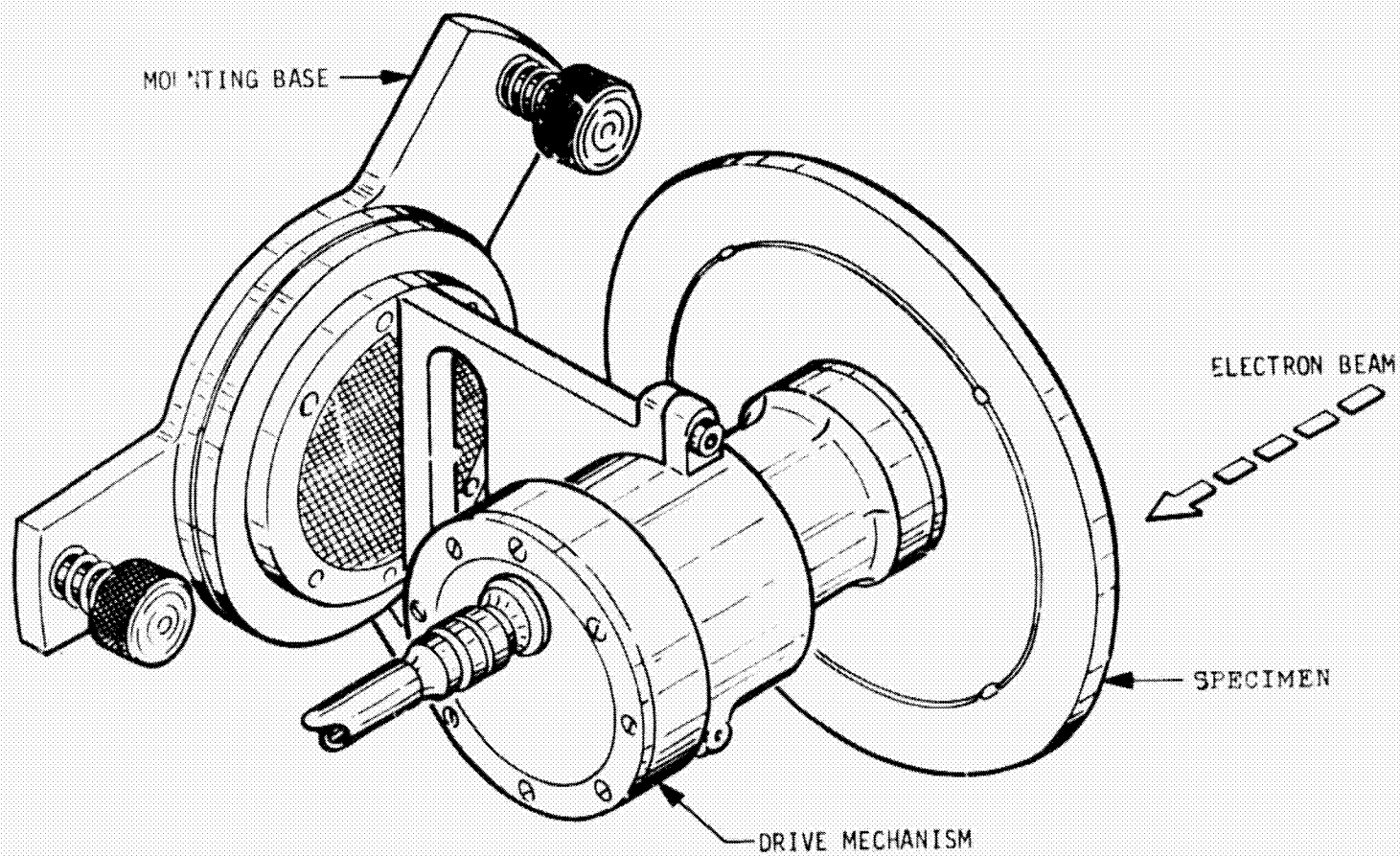


FIGURE 57. M551 HARDWARE SCHEMATIC

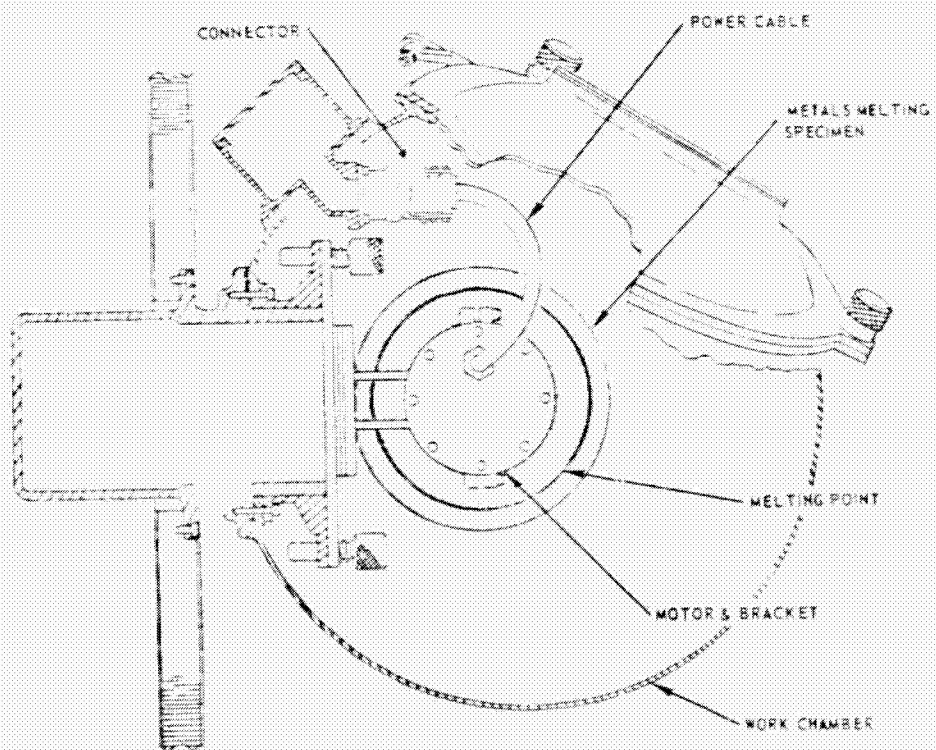
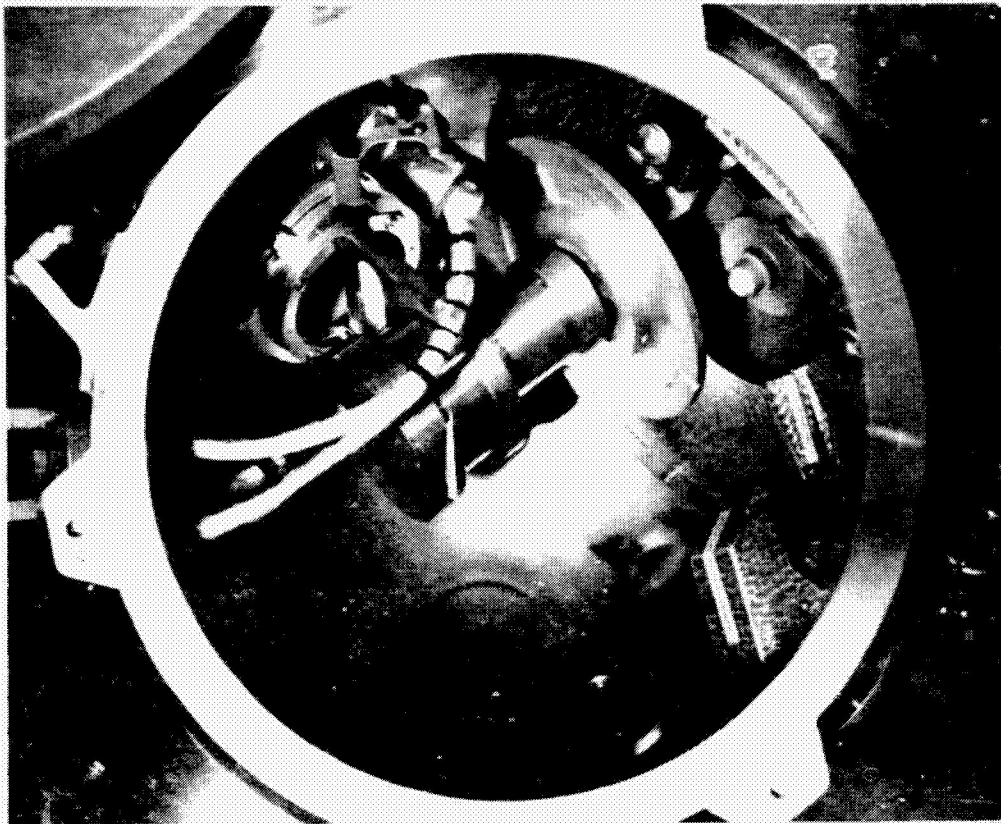


FIGURE 58. NOT INSTALLED IN CHAMBER





flange, and an electrical connector. The sample disk clamped to the drive assembly and, when the assembly was placed in the chamber, the sample disk position was such that the tungsten target was approximately on the electron beam axis. The drive assembly included a 28 Vdc, 1760 revolutions per minute (rpm) motor and gear-type speed reducer (300:1) to rotate the sample disk at a linear rate of approximately 89 centimeters per minute (35 inches per minute). To arrive at this output shaft speed of 2.6 rpm, the motor armature speed was reduced by running at an actual input voltage of only  $10 \pm 1$  Vdc. The motor received power from the M512 battery through the zero-g connector inside the work chamber and was controlled by a three-position switch on the control panel as discussed in subsection B. This assembly (motor with sample attached) was installed onto the work chamber heat sink by three Calfax fasteners as shown in figure 58.

(3) M551 optical mirror systems. Figure 61 illustrates the two mirror systems used during M551 operations. The point-of-view of the basic drawing (lower center) is looking at the EB gun from the beam absorber plate, with the four mirrors labelled. Three of the four mirrors can be seen in their operational configuration in figure 58 and their storage locations in figure 52.

(a) Camera mirror system. Section A-A of figure 61 (upper right) illustrates the camera mirror system, consisting of the M551 CAMERA MIRROR and the permanently-mounted camera deflection mirror which allowed photography of the beam impingement on the sample. As discussed earlier, the camera utilized a right-angle lens which is evidenced by the fact that the camera lens assembly centerline is perpendicular to the camera viewport centerline. This system can also be clearly seen in figure 58.

1 M551 CAMERA MIRROR. This assembly was also known as the CAMERA OPTICAL ADAPTER, as labelled in figure 58. The assembly consisted of a type 6061 aluminum alloy mounting base, containing a mirror, which was attached to the inside of the camera viewport. The base had three ball detents and two alignment pins for attachment and alignment. The mirror was fused silica 7940 with dimensions of 5.6 millimeters (0.22 inch) by 25 millimeters (0.98 inch) by 30 millimeters (1.4 inches).

2 Camera deflection mirror. This permanently-mounted mirror was previously discussed in subsection 1.

(b) View mirror system. Section B-B of figure 61 (upper left) illustrates this system, which allowed the astronaut to view the beam impingement point for alignment, focusing, and control of the beam during experiment operation. This system consisted of the M551 HATCH VIEWPORT MIRROR and the M551 DEFLECTION MIRROR, which were installed in the chamber by the astronaut. Figure 58 shows only the M551 DEFLECTION MIRROR, since the chamber hatch is opened.



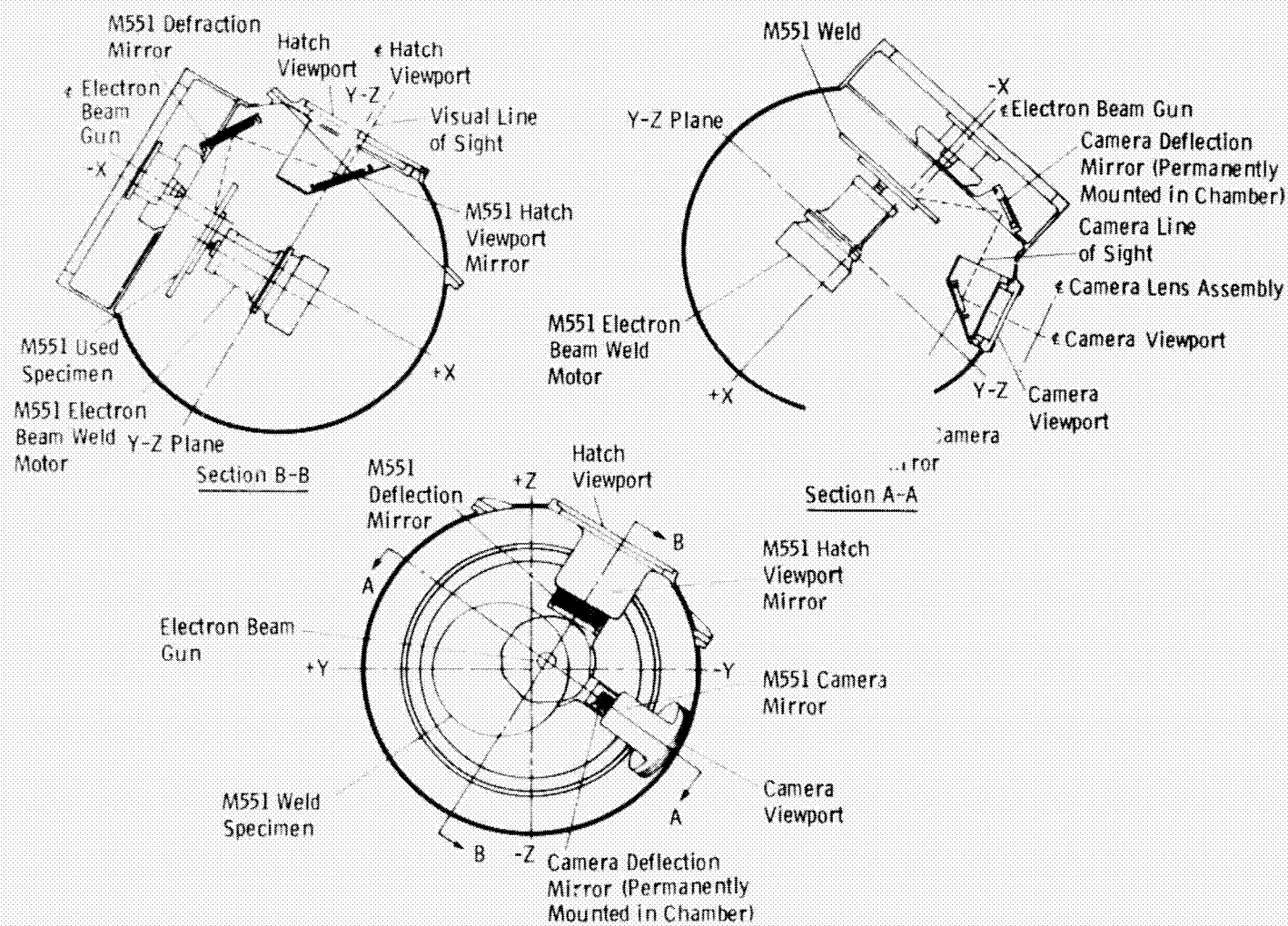


FIGURE 61. M551 MIRROR LAYOUT

1 M551 HATCH VIEWPORT MIRROR. This mirror assembly was also known as the VIEWPORT OPTICAL ADAPTER and is shown in figure 62. The red-striped metal clips shown in figure 62 are part of the protective covers used during ground handling and removed prior to launch. The 6061 aluminum base plate attached and aligned with the inside of the hatch viewport in the same manner as the CAMERA MIRROR previously discussed. Also the mirror used in this assembly was identical to the CAMERA MIRROR.

2 M551 DEFLECTION MIRROR. Figure 63 shows this mirror assembly, also known as the VIEW MIRROR, with its protective cover. The mirror was made of fused silica 7940, with dimensions of 4.8 millimeters (0.19 inch) by 66 millimeters (2.6 inches) by 83 millimeters (3.25 inches), and mounted in an aluminum bracket. The bracket included a recessed area at one end to avoid interference in the chamber with the conical electron beam housing. The bracket was attached by four screws to the aluminum mounting base, which included two Calfax fasteners for attachment to the interior chamber wall.

(c) Photographic equipment. The 16 millimeter data acquisition camera (DAC), a 100 millimeter lens, an extender, and a right-angle mirror for the 100 millimeter lens were used for photography of the M551 experiment. This equipment was furnished by the spacecraft and was not M512 hardware.

### 3. Experiment M552 - Exothermic Brazing.

a. Objectives. The objectives of this experiment were to evaluate brazing as a tube-joining technique for the assembly and repair of hardware in space, and to study the spreading, mixing and capillary action of molten braze material in near-zero gravity.

b. Concept. The experiment was to produce four simulated joints by brazing a metal sleeve over a tube of similar material. The heat required to melt the braze alloy was to be supplied by exothermic (heat-producing) materials. The clearance (gap) between the sleeves and tubes was to be varied to produce optimum and extreme brazing conditions.

c. Hardware description. The M552 experiment consisted of only the M552 experiment package shown in figure 64. This package was an aluminum housing with dimensions of 17.1 centimeters (6.75 inches) wide by 19.3 centimeters (7.61 inches) high by 19.2 centimeters (7.56 inches) deep, containing four specimens (see figure 65) that were successively brazed. The package was attached to two of three heat sink tripod mounting holes, and electrically interfaced the J6 connector as shown in figure 66. The experiment package construction is discussed in the following paragraphs to aid understanding the experiment function. The M552 experiment operations involved package installation into the M512 work chamber

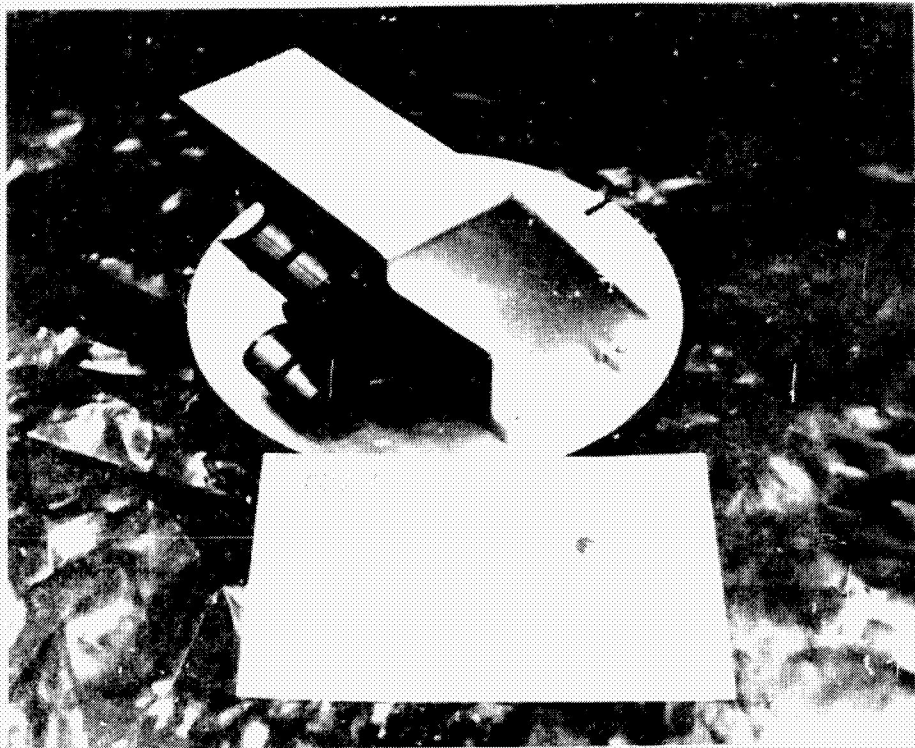


FIGURE 62. MS51 HATCH VIEWPORT MIRROR ASSEMBLY

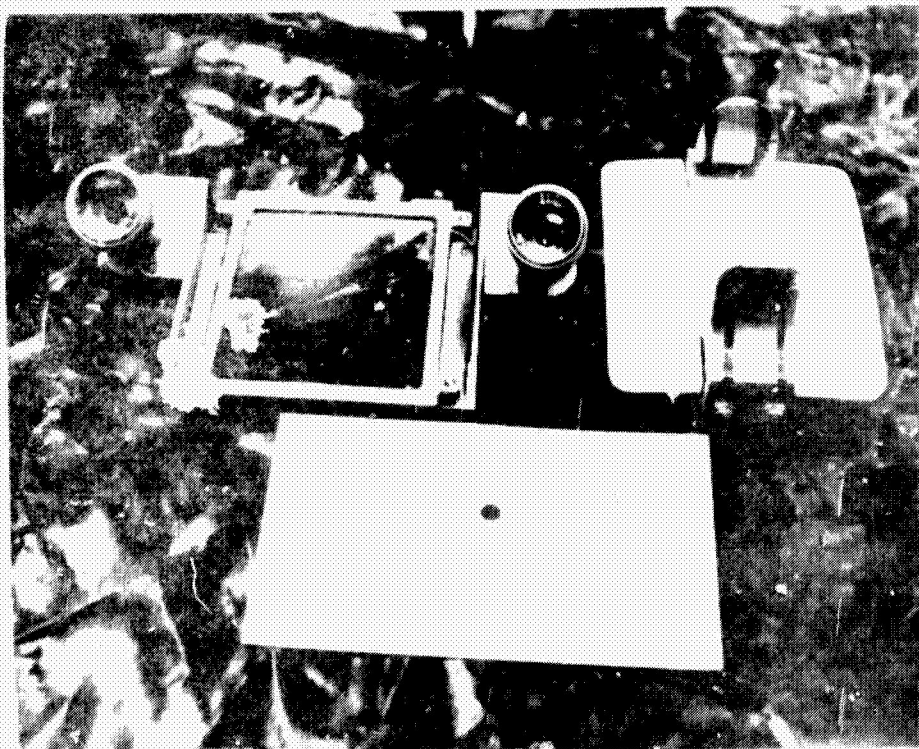


FIGURE 63. MS51 DEFLECTION MIRROR ASSEMBLY

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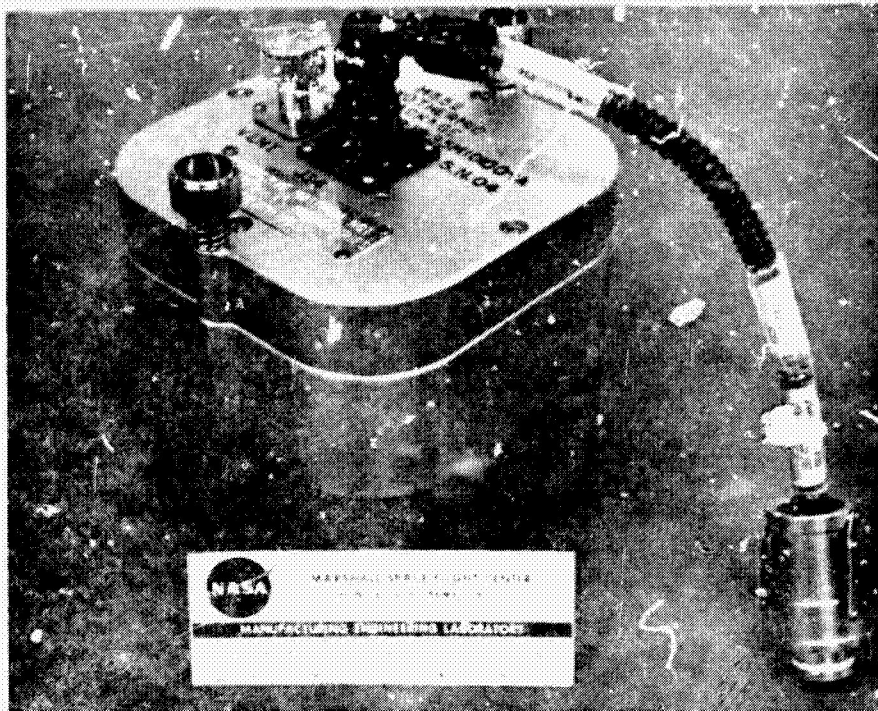


FIGURE 64. NRG EXOTHERMIC PACKAGE

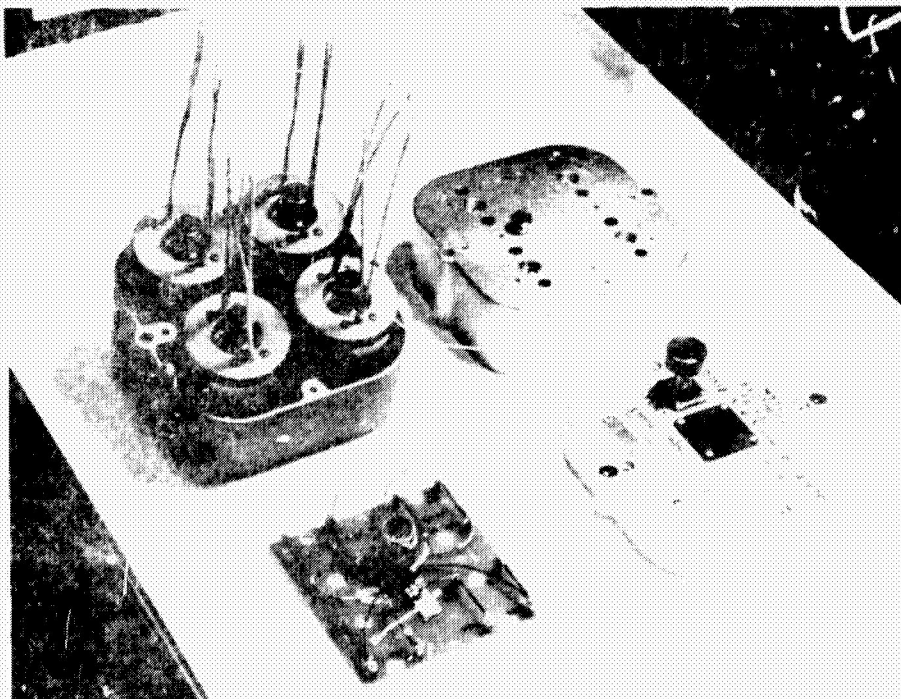


FIGURE 65. NRG PACKAGE COMPONENTS

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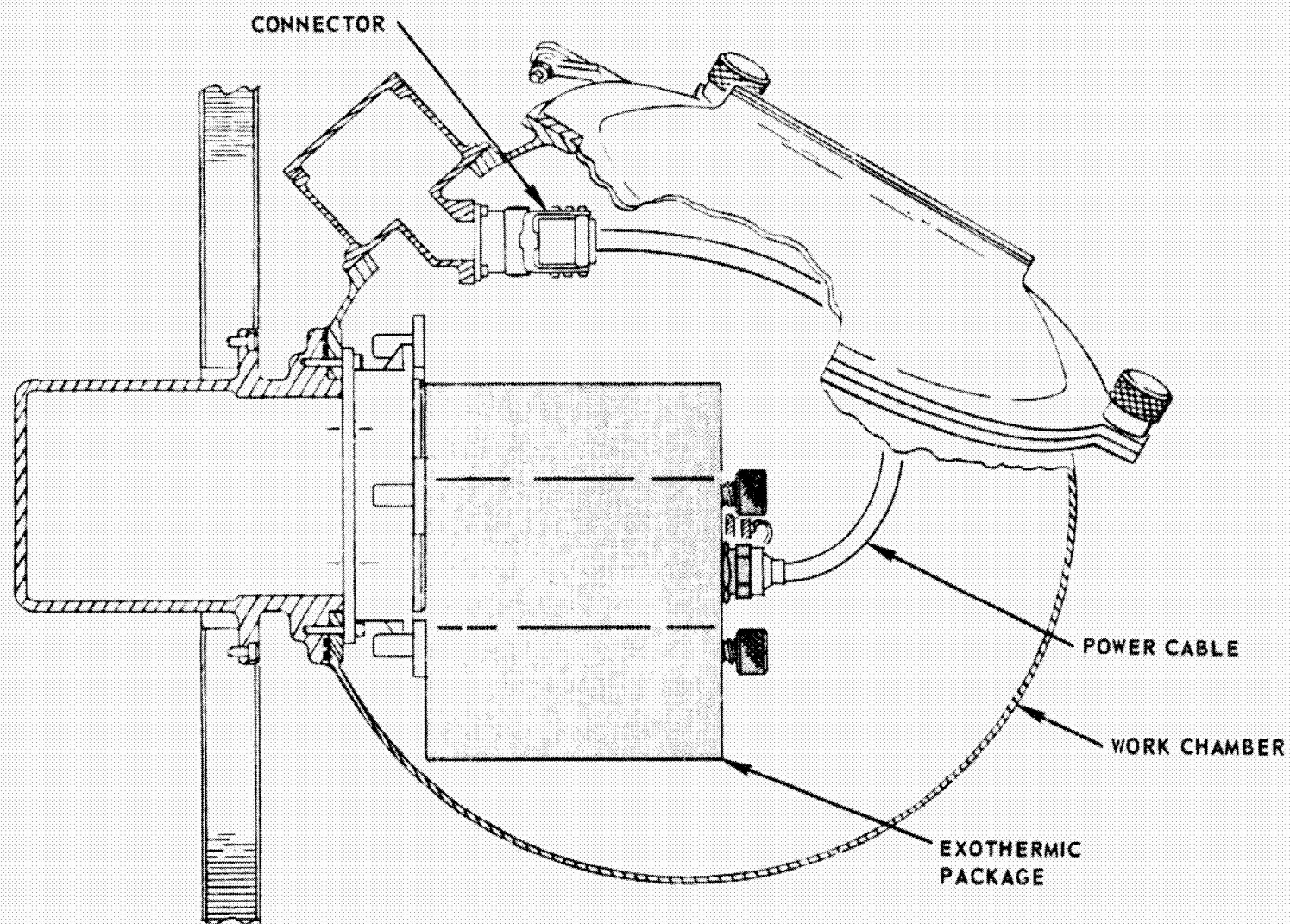


FIGURE 66. M552 EXOTHERMIC PACKAGE INSTALLATION

and chamber evacuation to space vacuum (zero pressure on the work chamber pressure gauge). The sample ignition was initiated by actuation of the control panel TRIGGER switch. Each ignition pulse was 120 amperes at 28 Vdc (battery power) for 5 milliseconds (14.4 joules per pulse). Approximately 90 seconds were required for the complete reaction, with approximately 2 hours and 45 minutes required for sample cooling. Each sample ignition and cooldown was a separate operation. The package temperature was monitored by a thermocouple sensor in the package that closed a circuit at approximately 43°C (110°F), lighting the EXP HOT light on the control panel.

(1) Exothermic brazing assembly. Each of the four braze specimens consisted of a tube, sleeve, inserts (spacers), and silver-copper-lithium braze rings. Each specimen, testing a different clearance gap between the tube and sleeve, was positioned in a separate canister containing the exothermic material, igniters and insulation. A cutaway of this assembly is shown in figure 67.

(a) Braze specimens. Two of the four specimens contained pure nickel tubes and sleeves. An isotope, 110-Silver with a half-life of 253 days, was added to a section of one braze ring in the nickel specimens to enhance analysis of capillary flow. The location of the isotope pellet prior to melting is shown in figure 68. The other two tubes and sleeves were type 304L stainless steel, with the tube partially slit through the center cross-section, but with some solid portions for support and to simulate a butt joint.

(b) Braze alloy ring. Each braze alloy ring weighed 1.95 grams (0.07 ounces) and was composed of 71.8 percent silver, 28.0 percent copper, and 0.2 - 0.4 percent lithium by weight. The alloy's melting temperature was 760°C (1410°F).

(c) Exotherm material. Three exotherm rings with a combined weight of 60 grams (2.1 ounces) were installed over the sleeve to provide the heat source required to produce a brazed tube and sleeve joint. Substantially all of the reaction products were solid, and no external oxygen supply was required for the reaction. The exotherm material ignited at 1104°C (2020°F) and produced 2721 joules per gram ( $1.84 \times 10^4$  calories per ounce). Approximately 90 seconds were required for the exotherm to complete its reaction. The exotherm used in the M552 experiment had the following percentage composition by weight:

|                    |              |
|--------------------|--------------|
| Aluminum           | 24.8 percent |
| Boron              | 5.0 percent  |
| Titanium Dioxide   | 55.2 percent |
| Vanadium Pentoxide | 15.0 percent |

(d) Igniters. Two igniters, positioned against the exotherm ring, were used to initiate the exotherm reaction. Although



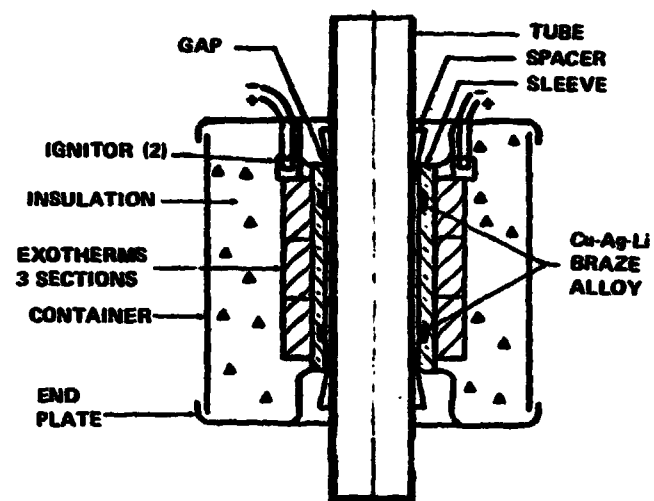


FIGURE 67. BRAZE ASSEMBLY

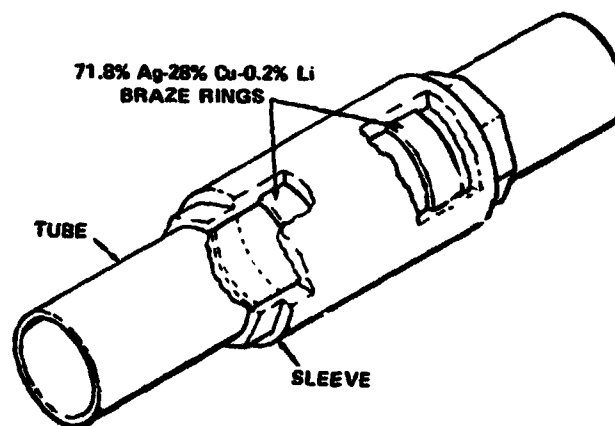


FIGURE 68. ISOTOPE LOCATION

one igniter is normally sufficient, the second one was added to provide redundancy to the system. This igniter exotherm material reacts at 510°C (950°F) and has the following percentage composition by weight:

|                    |              |
|--------------------|--------------|
| Aluminum           | 14.8 percent |
| Boron              | 7.7 percent  |
| Titanium           | 10.0 percent |
| Vanadium Pentoxide | 67.5 percent |

(e) Insulation. The exothermic material was surrounded with Fiberfrax (fibrous aluminum oxide) insulating material, which contained the heat generated for the brazing process and also protected the outside container from overheating.

(f) Container. Each braze assembly was housed in a thin-wall cylinder approximately 7 centimeters (2.75 inches) outside diameter by 5 centimeters (2 inches) long, made of type 321 CRES and fitted with two end covers.

(2) Package housing. The aluminum housing, figure 69, which held the four exothermic brazing assemblies, was made in two halves and after installation of the exothermic assemblies was bolted together along its median plane. A thermocouple temperature sensor was bolted onto the top-half portion of the housing, and electrical connections to this sensor and to the igniter wires in the exothermic packages were soldered to an insulated terminal board attached to the top half of the housing. All electrical connections terminated in the power connector on the cover. The cover also included a vent cap to vent gases generated by the experiment to the inside of the work chamber. It was capped during storage and was opened during the experiment operation.

#### 4. Experiment M553 - Sphere Forming.

a. Objective. The objective was to demonstrate zero-gravity and space vacuum effects upon solidification of: a pure nickel at under-cooling not possible on Earth; a nickel-tin alloy having a wide freezing range; a nickel-silver alloy having a narrow melting range which cores on solidification; and a nickel-copper alloy having a wide melting range, but little difference in density between the two elements.

b. Concept. The experimental concept was to successively melt small metal samples, using the electron beam gun as a heat source, and allow these samples to resolidify under zero-gravity conditions. The metal sample was to be released from its holder to free-float during resolidification, allowing examination of surface tension effects on the solidification processes. Theoretically, the surface tension forces should cause the molten metal to take a spherical shape when solidified.

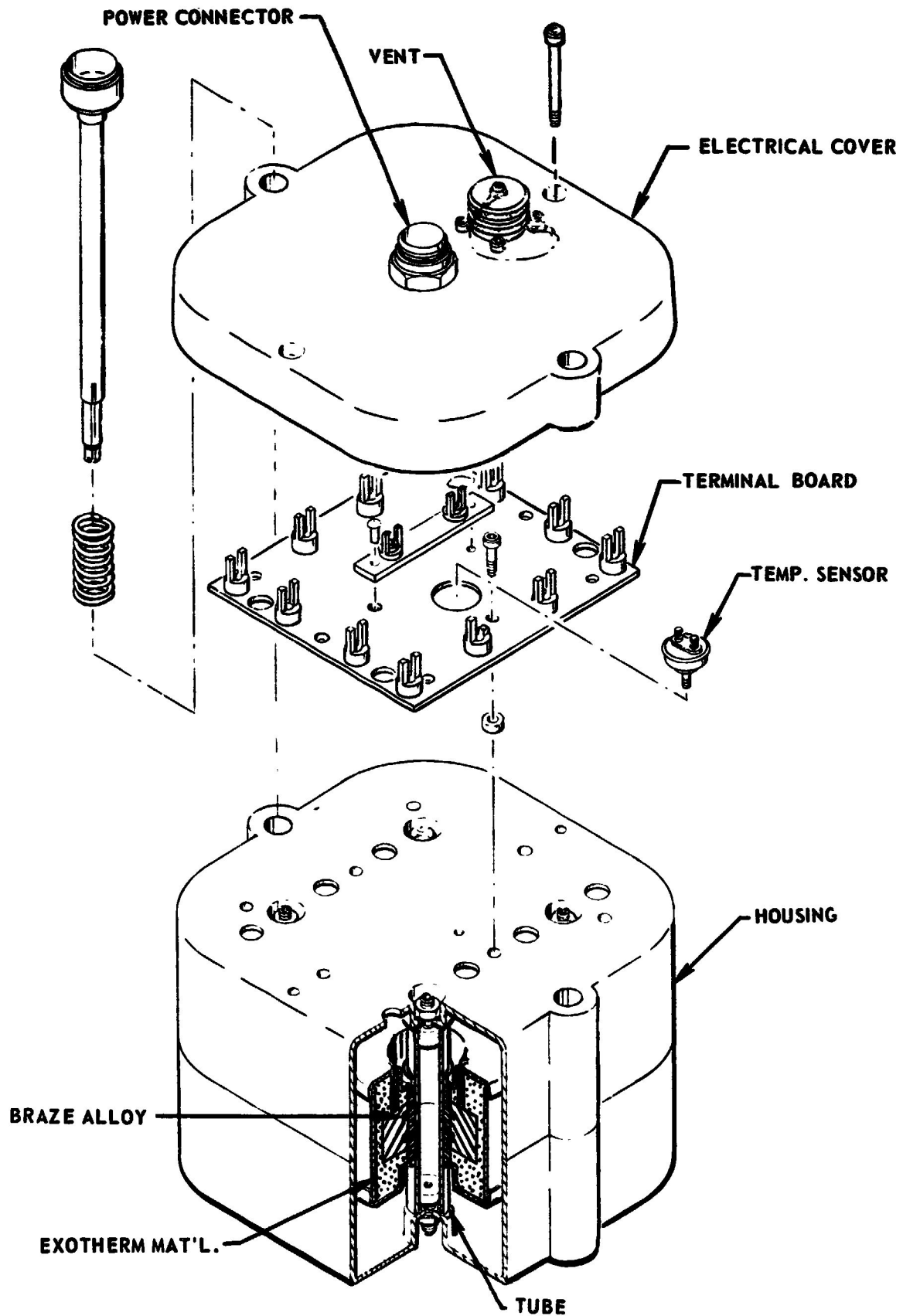


FIGURE 69. M552 PACKAGING CONCEPT

c. Hardware description. The individual hardware items from the equipment storage container (figure 52) required for the M553 operations are discussed in the following paragraphs.

Figure 70 is a photograph of the M553 mockup unit that shows the positioning of the experiment equipment in the chamber; however, this photograph of the mockup did not include all the auxiliary equipment used with M553. The sketches shown in figure 71 provide other views of the M553 installation.

(1) M553 sphere forming motor. The sphere forming motor, also known as the M553 drive assembly, is shown in figure 72. The assembly positioned and indexed the specimen wheel as required to place each specimen in the path of the electron beam for melting. The assembly consisted of the tripod mounting base that attached to the heat sink flange and an indexing electric motor. The indexing motor was a 28 Vdc electric motor with a gear-type speed reducer (100:1). A cam arrangement on the output motor shaft operated a ratchet mechanism which advanced the specimen wheel 24 degrees  $\pm$  20 minutes rotation per index cycle. The motor operation was controlled by a three-position switch on the M512 control panel, operating at 28 Vdc for the switch manual reset position and 10  $\pm$  1 Vdc for automatic operation.

(2) Specimen wheel assembly. The experiment samples were contained on two specimen wheels (one of which is shown in figure 73). Each M553 specimen wheel was a pinwheel having 15 spokes or positions for samples. Each sample wheel contained four pure nickel samples, four nickel/12 percent tin alloy samples, four nickel/1 percent silver alloy samples, and two nickel/30 percent copper alloy samples. The first position contained the tungsten target, located in the figure at the 3 o'clock position, which was used for the electron beam gun alignment. The next three positions contained small cylindrical samples attached to the wheel by thin cylindrical metal rods located at the four, five and six o'clock positions. These samples remained mounted after resolidification until cut from the wheel by the crewman. The third sample is shown removed in the figure to illustrate the mounting rod. The remaining 11 positions contained samples, each mounted to a ceramic post by a small metal rod called a sting, as shown in the cross-section in figure 74. The sting was retracted from the molten sample by a spring, allowing the sample to resolidify in a free-floating state. Also, this sting retraction opened switch contacts inside the ceramic pedestal that automatically removed power from the electron beam gun regulator and deflection coils and stopped camera operation. The specimen wheel assembly included a tapered hole in the center of the hub that interlocked with the drive cone.

(3) Sphere catcher. The sphere catchers were small metal cups 3.8 centimeters (1.5 inches) in diameter and 5 centimeters (2 inches) long, with 144 small holes drilled in the side and bottom.

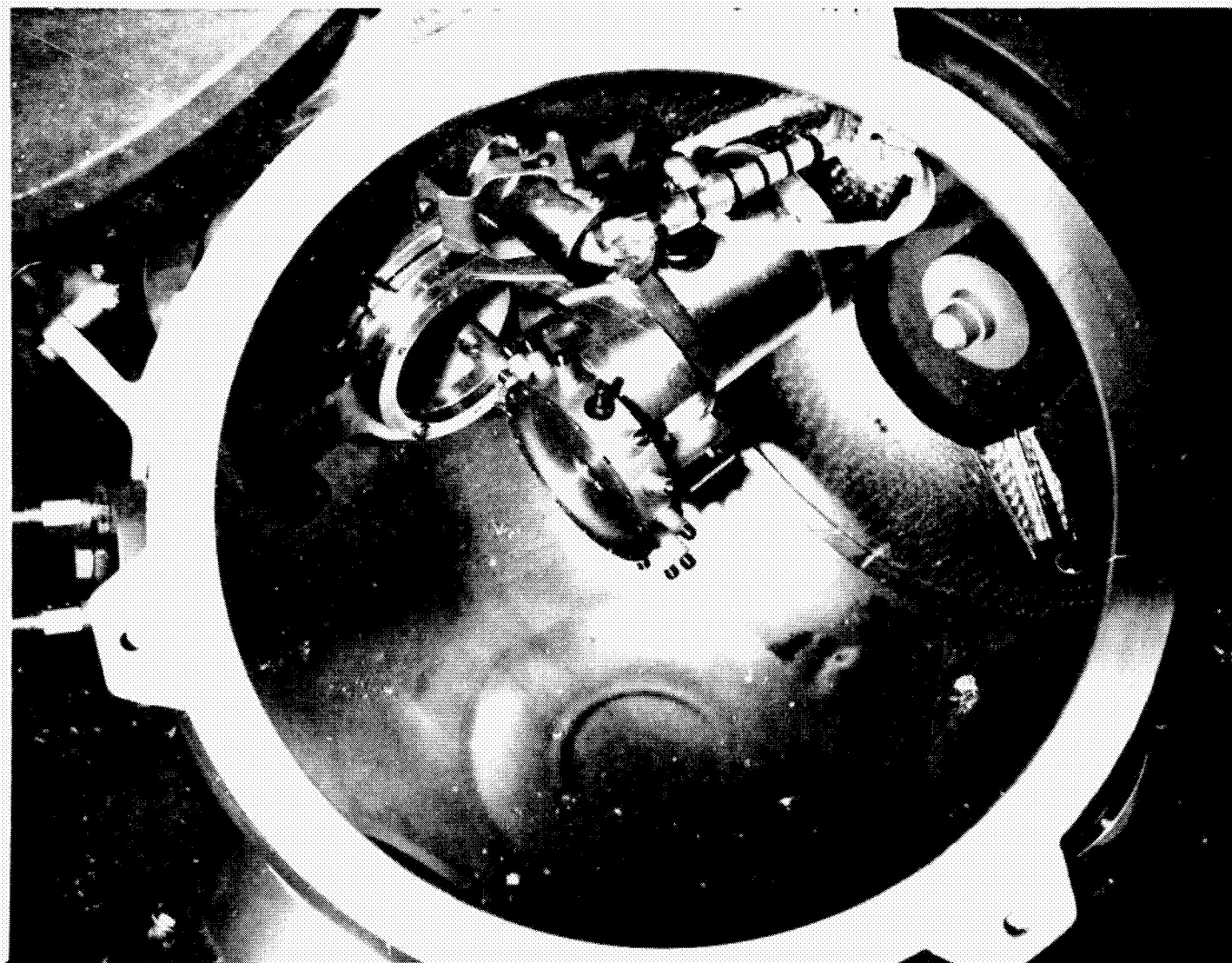


FIGURE 70. M553 HARDWARE INSTALLED IN CHAMBER

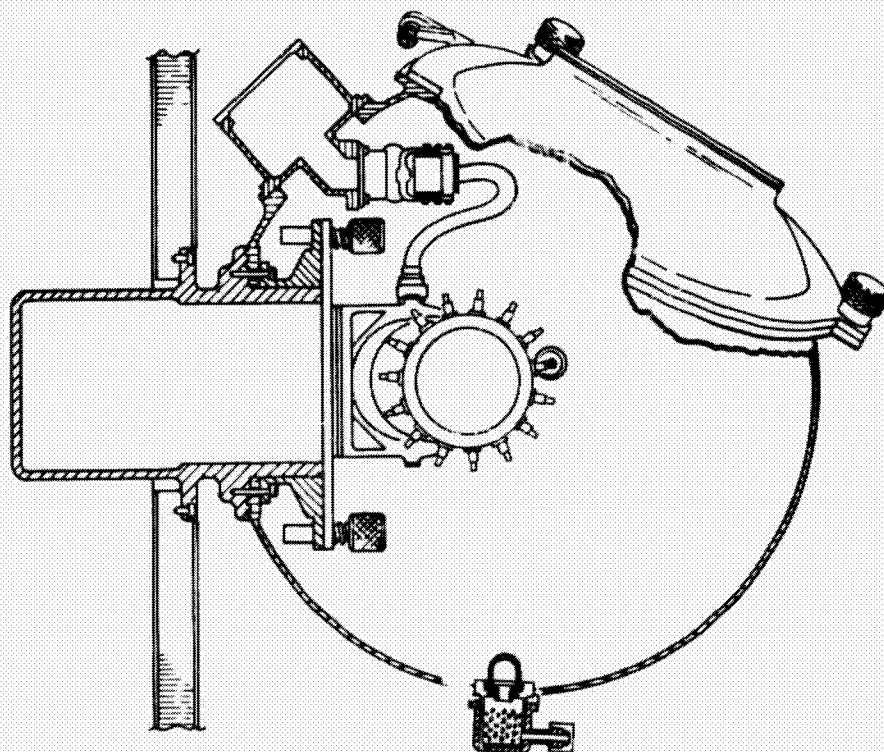
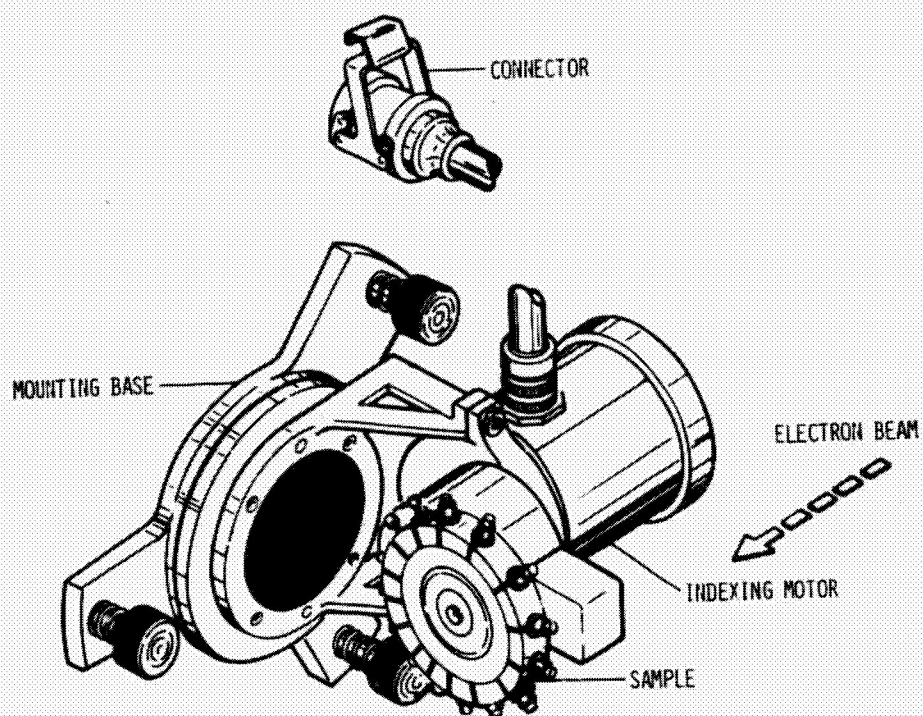


FIGURE 71. M553 HARDWARE SCHEMATIC



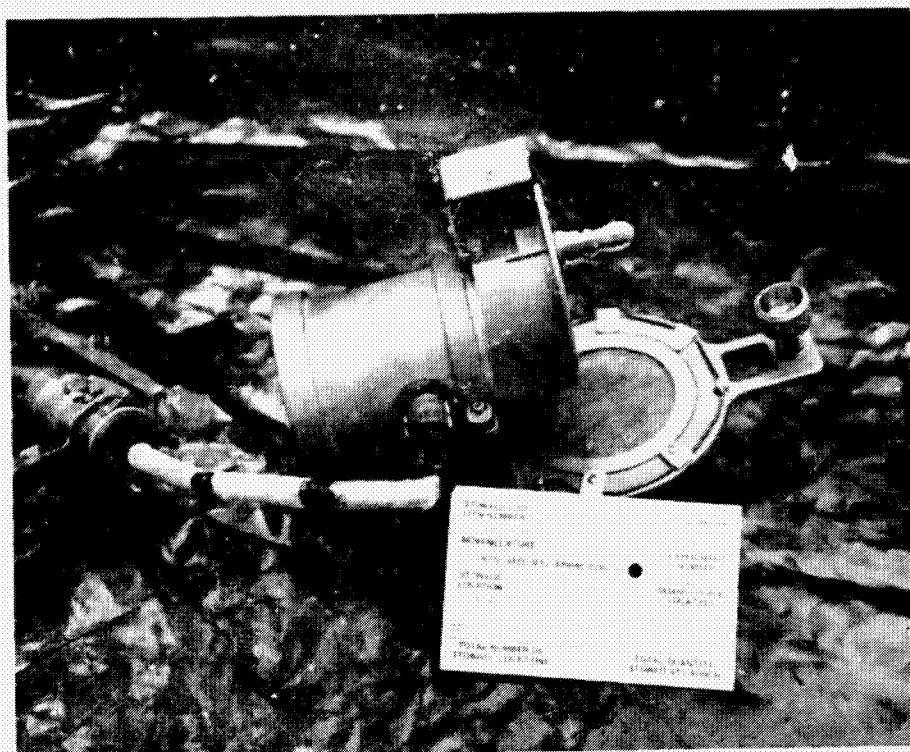
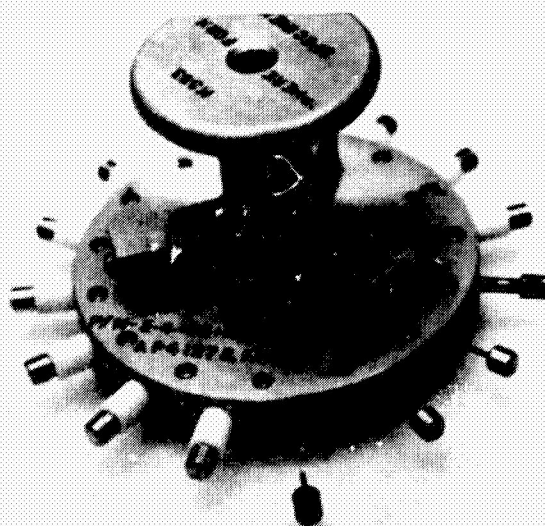


FIGURE 72. M553 INDEXING MOTOR



STORAGE LIST  
ITEM NUMBER

NOMENCLATURE

SUPPLIER

EXPERIMENT  
NUMBER

FIGURE 73. M553 SPECIMEN ASSEMBLY

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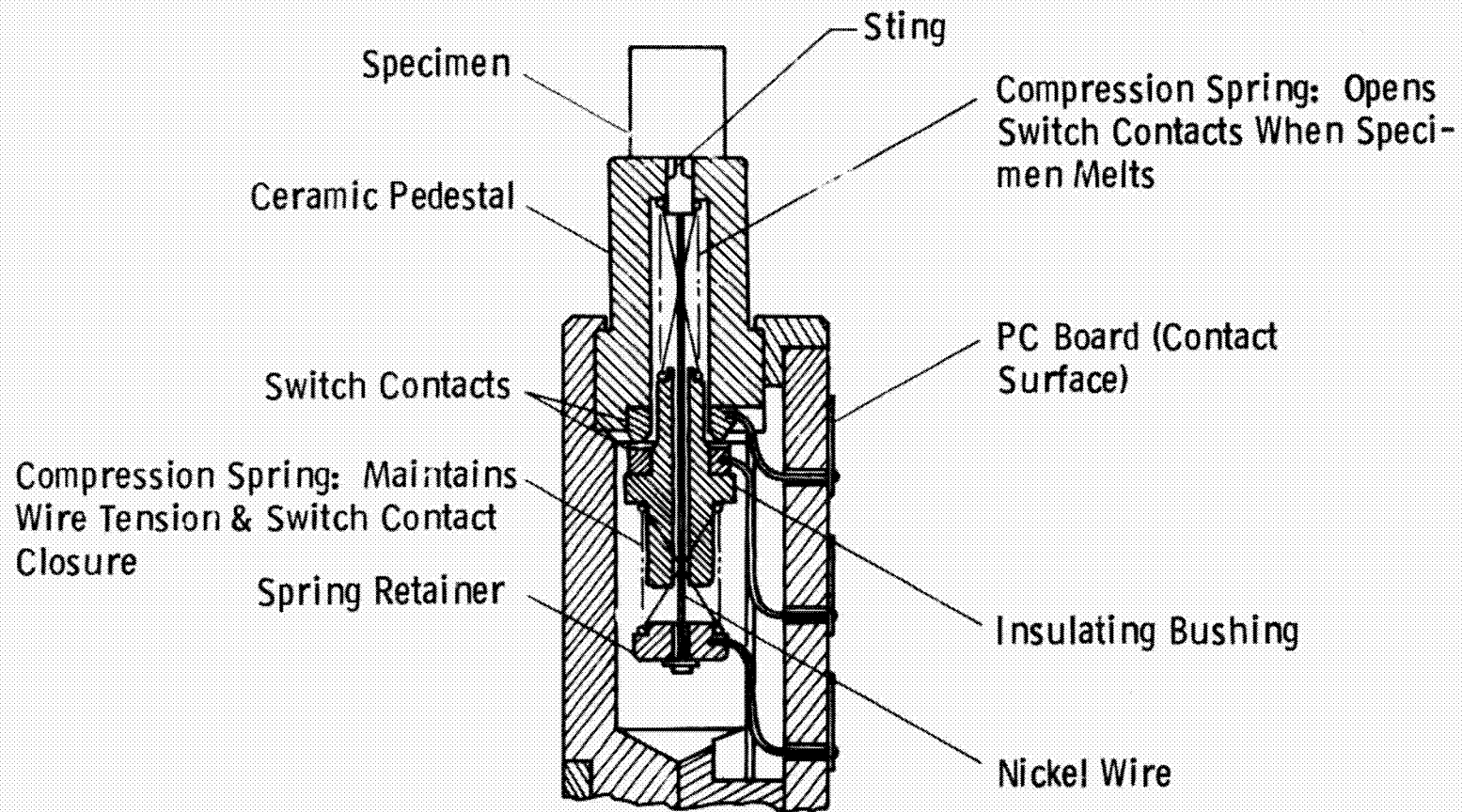


FIGURE 74. M553 SPECIMEN SWITCH/RELEASE MECHANISM

Figure 75 illustrates the operation of the sphere catchers. The cup assemblies were installed in the vacuum cleaner port located at the chamber bottom prior to the experiment operation. The vacuum cleaner was attached to the port after the operation was completed and the chamber had been repressurized. The hatch was "cracked" and the vacuum cleaner started, resulting in an airflow from the chamber top to bottom. Theoretically, this airflow would pull the small floating spheres to the vacuum cleaner port, where they would accumulate in the sphere catcher cups.

(4) Sphere catcher installation tool. The sphere catcher installation tool was a machined insert that attached to the sphere catcher assembly for handling purposes.

(5) M553 CAMERA PORT SHIELD. This shield was one of the two identical shields shown in figure 76 and was installed over the camera port inside the chamber to prevent metal deposition on and splatter damage to the camera port window during M553 operations. The shield assembly was constructed of Vicor 7913 glass for thermal shock and mounted in an aluminum alloy frame. The frame had three ball detents for attachment to the camera port.

(6) M553 HATCH VIEWPORT SHIELD. This shield is one of the two identical shields shown in figure 77. The shield's purpose, construction, and mounting was the same as the camera port shield.

(7) M512 ELECTRON BEAM COVER. The cover was originally designed for the M479 operations, but was redesigned to be installed prior to the M553 operations. Therefore, after M551 was completed, the cover was installed for M553 and remained in place for all subsequent operations (M552, M555, M479, M518). The cover was designed to prevent contamination, residue or floating spheres (in the case of M553) from entering the electron beam gun port area adjacent to the work chamber. The original cover is shown in figure 78 and was constructed of an aluminum alloy with three Calfax fasteners that mated to the interior chamber wall. The cover redesign replaced the center screen with a small orifice to allow passage of the electron beam for M553 operation, and is shown on the inside of the equipment storage container door in figure 79.

(8) Photographic equipment. The 16 millimeter data acquisition camera (DAC), a 75 millimeter lens, an extender, and a right-angle mirror for the 75 millimeter lens were used for photography of the M553 experiment.

5. Experiment M555 - GaAs Crystal Growth. The M555 experiment hardware was designed and developed for the Skylab Program; however, in order to provide launch space in the Command Module for repair equipment, the M555 launch container was not launched and the experiment were not performed on the Skylab Program. The hardware system descriptions are included since the M555 development is within the scope of this report.

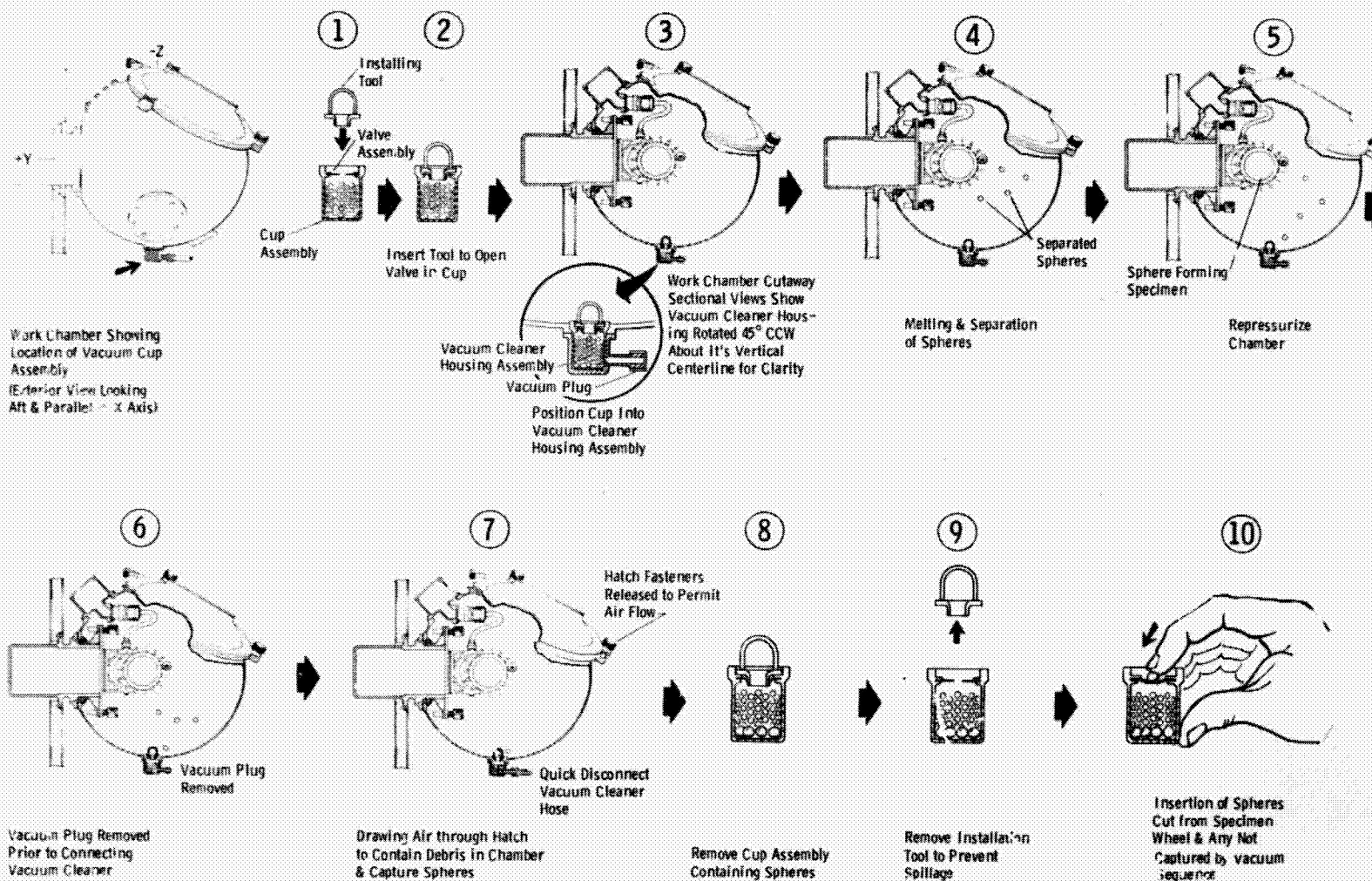


FIGURE 75. M553 SPECIMEN RECOVERY PROCEDURE

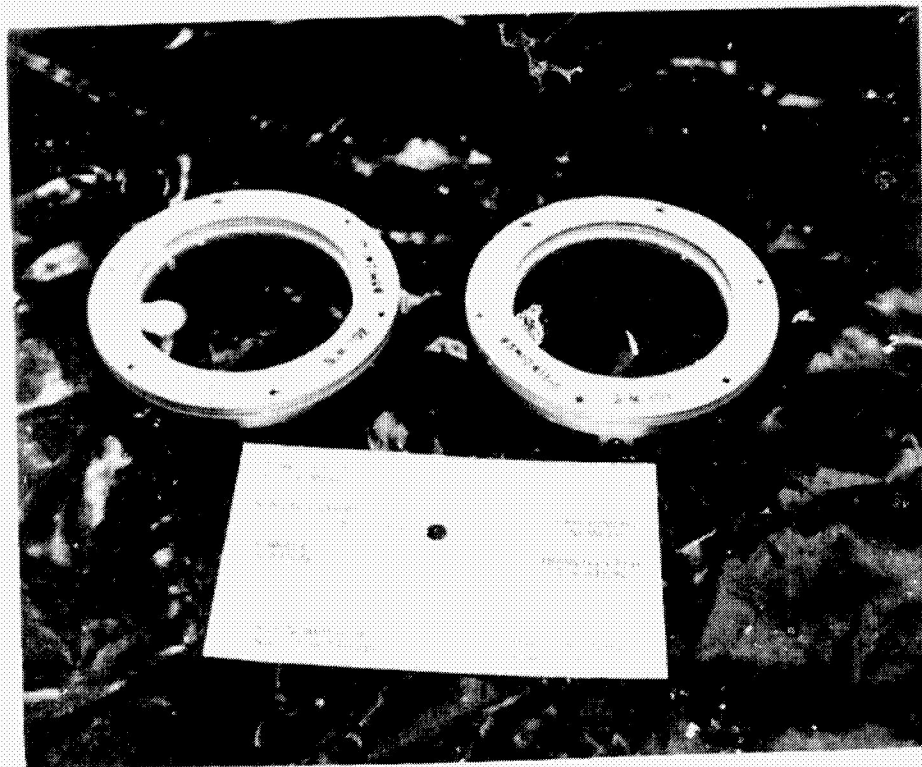


FIGURE 76. CAMERA PORT SHIELDS

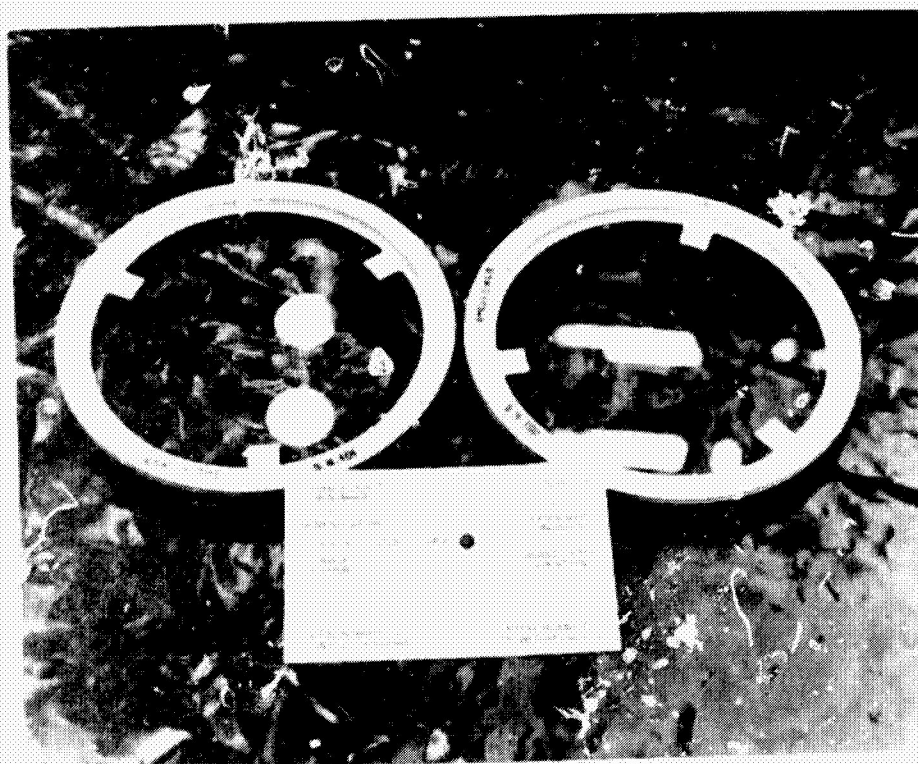


FIGURE 77. HATCH VIEWPORT SHIELDS





FIGURE 78. EB GUN COVER

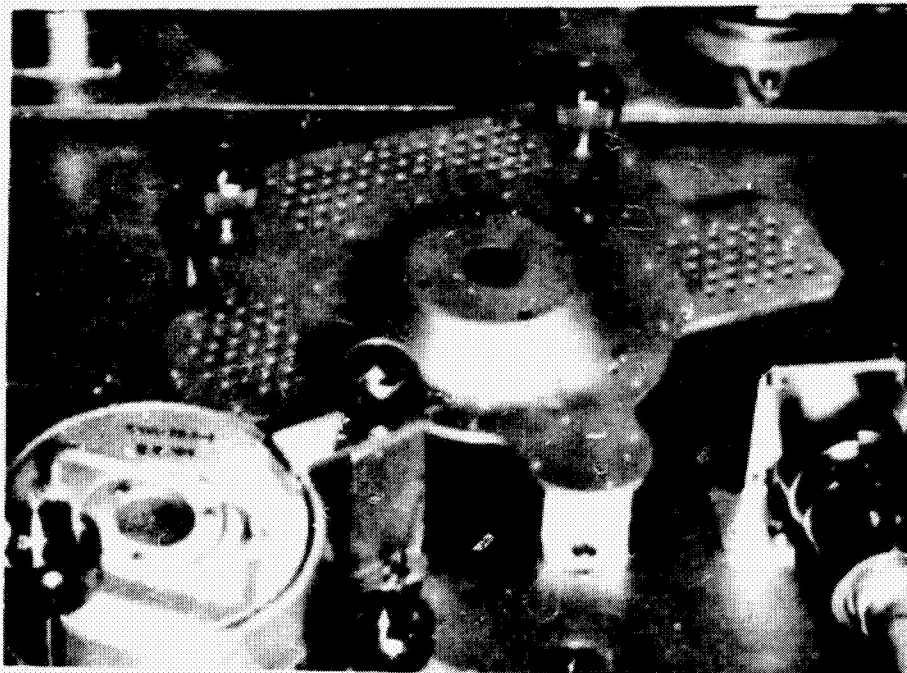


FIGURE 79. REDESIGNED EB GUN COVER



a. Objective. The objective was to grow single crystals of gallium arsenide from solution in near-zero gravity, in anticipation of producing material of exceptionally high chemical and crystalline perfection.

b. Concept. The heart of the experiment was the growth ampoule, a fused quartz tube containing the source, solvent, silicon dopant, and seed. In general, the source material, chunks of high-purity gallium arsenide (GaAs), was to be dissolved in liquid gallium metal at the hot end of the elongated ampoule, then transported by diffusion down the ampoule, and finally deposited on a seed at the colder end of the ampoule. The experiment consisted of a pure GaAs layer grown on a pure seed (ampoule 1), a pure GaAs layer grown on a doped seed (ampoule 2), and a doped GaAs layer on a pure seed (ampoule 3).

c. Hardware description.

(1) M555 crystal growth package. The three experiment ampoules were inserted into the three cavities of a cylindrical furnace 10 centimeters (4 inches) in diameter by 29 centimeters (11.5 inches) in length, as shown in figure 80. The furnace, developed and built by the Westinghouse Electric Company, provided an insulated housing for the ampoules and a separate instrumentation compartment for the protective thermostats and the six thermocouple reference junctions. The entire furnace, including the electrical receptacle was sealed, but was vented to vacuum conditions inside the work chamber through a manual vent valve on the side of the furnace. The furnace was installed inside the heat sink recessed cavity (figure 81), and secured by the M555/M518 CRYSTAL GROWTH/MULTIPURPOSE FURNACE CLAMPING RING shown in figure 82. The clamp ring fit over the furnace flange area and was attached to the tripod mounting flange of the heat sink with three Calfax fasteners as shown in figure 83, thus establishing a heat conduction path to the M512 heat sink. A special thermal coating was used on the furnace flange to maximize the contact for better conduction. The furnace was connected to the work chamber power receptacle (J6) by the M555 power cable, thereby creating the interface for power and data circuits.

(2) M555 launch container. The M555 furnace was to be launched and stored in the heated container developed and built at MSFC shown in figure 84. The launch container had dimensions of 46 centimeters (18 inches) by 20 centimeters (8 inches) by 28 centimeters (11 inches), and weighed 9.1 kilograms (20 pounds) with the furnace installed. The furnace was wrapped in a heater blanket to ensure that the temperature of the furnace did not drop below 29°C (85°F). Below this temperature the liquid gallium in the ampoules could freeze, degrading the experiment data, and possibly rupturing the sample ampoules. The blanket was constructed of 33 gauge nichrome wire (inside heat-reactive tubing), sealed between

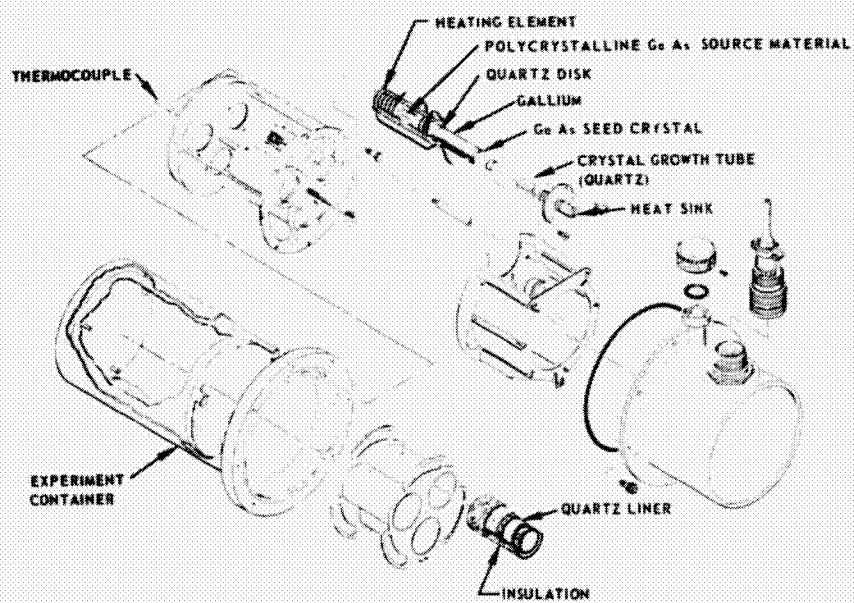
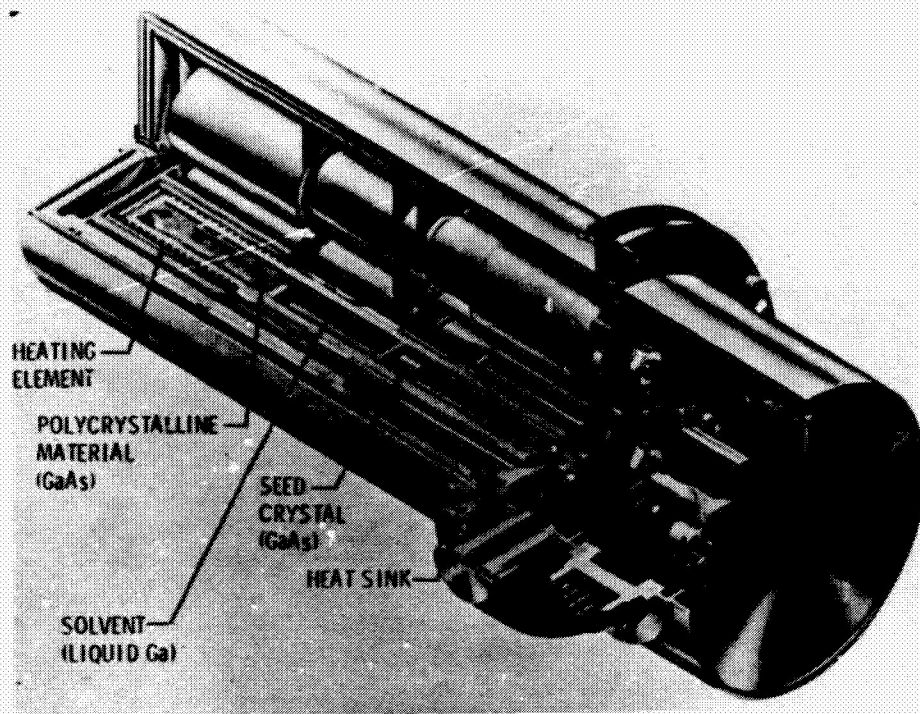


FIGURE 80. M555 GaAs CRYSTAL GROWTH FURNACE

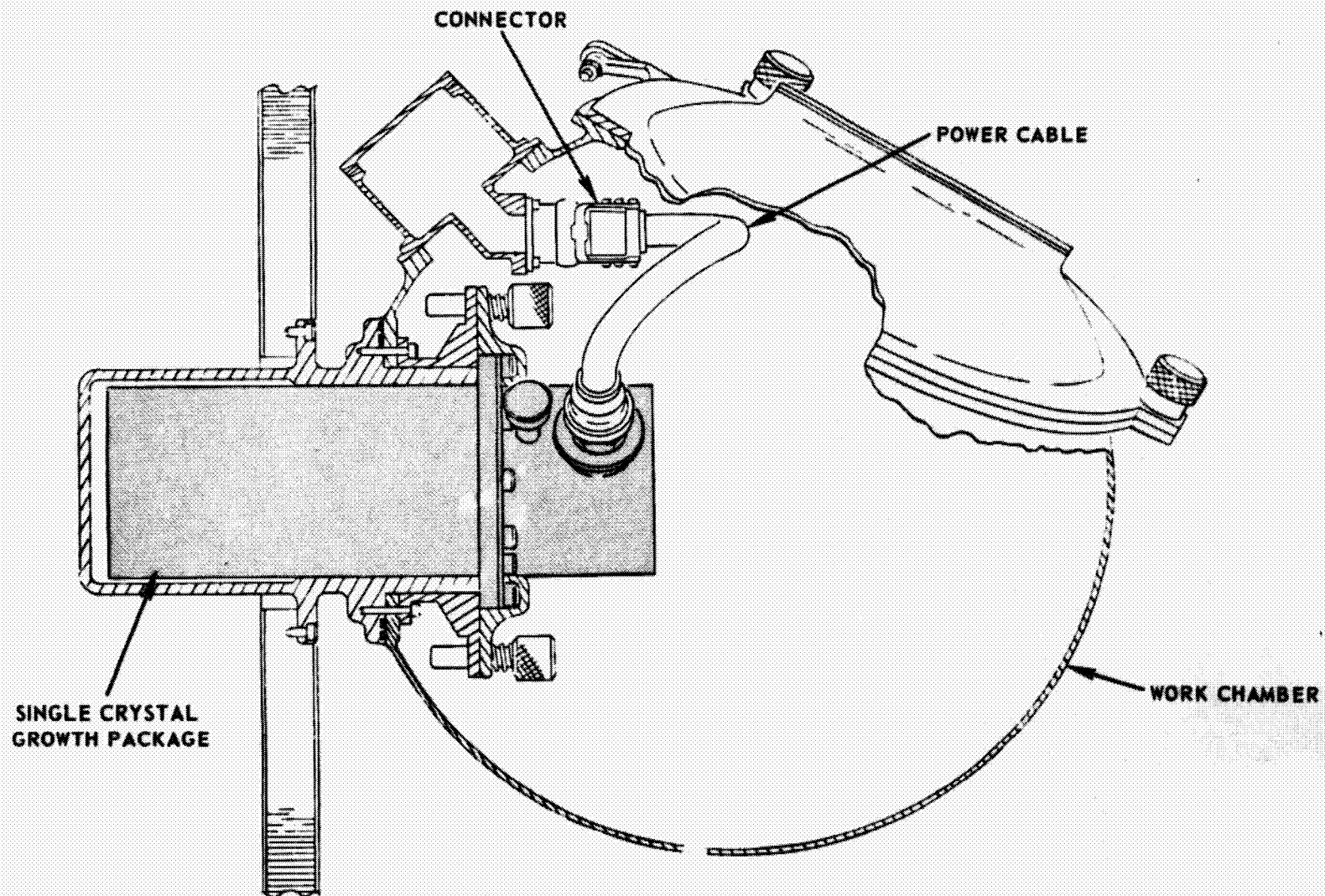


FIGURE 81. M555 CRYSTAL GROWTH FURNACE INSTALLATION SCHEMATIC



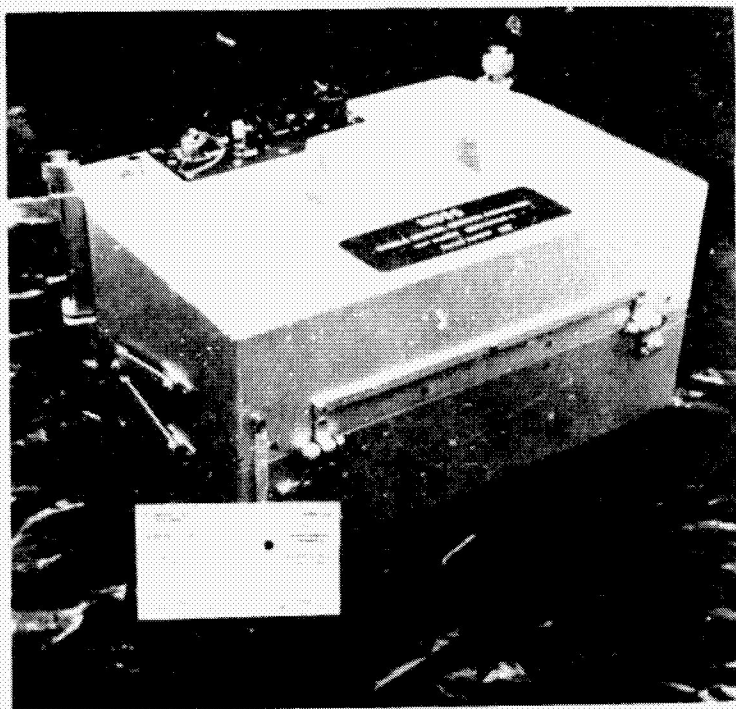


FIGURE 84. M555 LAUNCH/STORAGE CONTAINER

two sheets of rubber. The blanket received AM Bus 1 spacecraft power through the M555 launch container power cable (see figure 42) when in the M512 storage location, and CM power when in the Command Module. The electrical power was converted to heat by the nichrome wire and transferred to the package by conduction and radiation. The blanket dissipated 6.5 watts maximum.

#### 6. Experiment M479 - Zero-Gravity Flammability.

a. Objective. The experiment objective was to ignite various materials in a  $3.45 \times 10^4$  newtons per square meter (5 pounds per square inch) absolute spacecraft atmosphere (nominally 70 percent oxygen - 30 percent nitrogen) under zero-gravity conditions to observe the following:

- (1) Extent of surface propagation flash-over to adjacent materials
- (2) Rates of surface and bulk flame propagation under zero convection
- (3) Extinguishment by vacuum or water spray and self-extinguishment

b. Concept. Material samples were electrically ignited in the pressurized chamber (using cabin atmosphere). Individual flammability test durations were from a minimum of 3 seconds to a maximum of over a minute.

The flammability process was recorded on 16 millimeter film in the visible (color) and infrared regions. Additional data were obtained from the recorded crewman's voice comments while performing the experiment. The crewman was invaluable in observing several test aspects that could be missed by photography, such as drift rates of detached fuel specimens, sublimation products, overall energy profiles, environmental changes in the chamber, and water-spray patterns. A detailed crew observation log form for each test was included in the MDA Experiment Crew Procedures and Log.

#### c. Hardware description.

(1) Flammability sample. A typical flammability sample is shown in its storage configuration in figure 85. The sample material was supported by a metallic frame and the sample identified by a numbered tab (number 7 in the figure). The sample was ignited by an electrically heated nichrome filament which was powered through the connector on the right side of the photograph. Power was 28 Vdc from AM Bus 1, through the flammability subpanel of the M512 control panel. In all, 37 flammability specimens were tested. Six different substances were used as



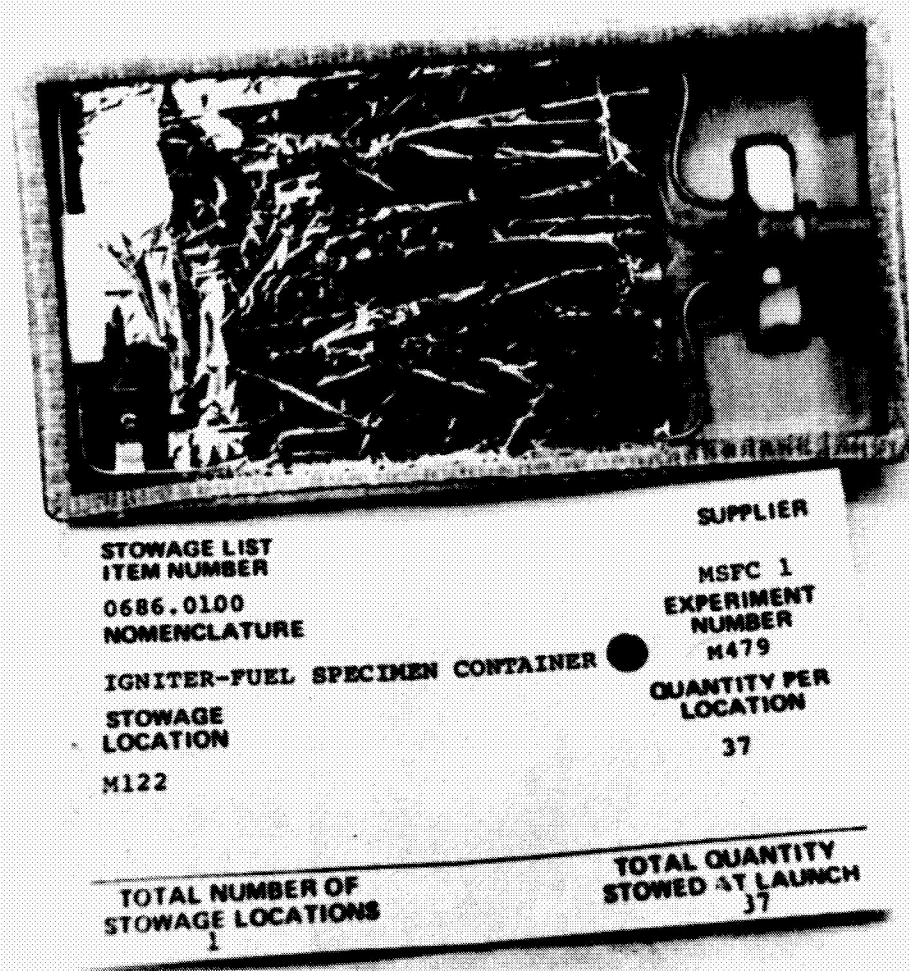


FIGURE 85. TYPICAL M479 FLAMMABILITY SPECIMEN

sample materials: aluminized Mylar film, 6.7 centimeters by 9.2 centimeters (2 5/8 inches by 3 5/8 inches); nylon sheet, 2.5 centimeters by 2.5 centimeters (1 inch by 1 inch); neoprene-coated nylon fabric, 6.7 centimeters by 9.2 centimeters (2 5/8 inches by 3 5/8 inches); polyurethane foam, 0.6 centimeter by 0.6 centimeter by 5 centimeters (0.25 inch by 0.25 inch by 2 inches); bleached cellulose paper, 6.7 centimeters by 9.2 centimeters (2 5/8 inches by 3 5/8 inches); and Teflon fabric, 6.7 centimeters by 9.2 centimeters (2 5/8 inches by 3 5/8 inches).

(2) **FLAMMABILITY SPECIMEN HOLDER.** The **FLAMMABILITY SPECIMEN HOLDER** (figure 86) was the mechanical and electrical interface between the flammability sample and the zero-g connector in the work chamber. The correct hardware configuration is shown in the sketch of figure 86. The line filter (small box) was added late in the program for M512 circuit protection, therefore it is not shown in all hardware photographs. The holder configuration positioned the specimen in the approximate center of the chamber, in the 16 millimeter DAC field-of-view as shown in figure 87.

(3) **Flammability specimen container.** Each of 37 specimens was stored in a two-piece container. The sample was snapped into one half of the container (figure 85) and the other half was attached by Velcro. The 37 sample containers were stored in the flammability specimen storage container, as discussed in subsection A.1 and shown in figure 56.

(4) **Water quench spray nozzle assembly.** Figure 88 shows this assembly, which was installed in the work chamber for the six water quench sample operations. The assembly connected to the water line from the accumulator, which penetrated the chamber wall. The nozzles were oriented to spray both sides of the sample. Each nozzle contained a check valve which operated with a cracking pressure of  $13.8 \pm 0.3 \times 10^4$  newtons per square meter ( $20 \pm 0.5$  pounds per square inch) differential.

(5) **Heat sink cover.** The M479 **HEAT SINK COVER** (figure 89) was installed over the work chamber heat sink during M479 operations to prevent any combustion debris from entering the heat sink. The cover was constructed of an aluminum alloy frame containing a wire cloth fiber. The three Calfax fasteners that interfaced with the tripod mounting holes in the heat sink flange are shown in figure 87.

(6) **Vent line filter number 2.** Figure 90 shows this filter, which was installed into vent line filter number 1 (see subsection A.1.c of this section) for the M479 operations. Filter number 2 was constructed of an aluminum alloy frame containing a 220 micron filter to prevent fine combustion particles from being vented to space. The frame had three detent balls that secured filter number 2 to filter number 1. The filter also acted as a 2.54 centimeter (1 inch) diameter orifice to restrict air flow through the vacuum vent line during the M479 vacuum quench tests.

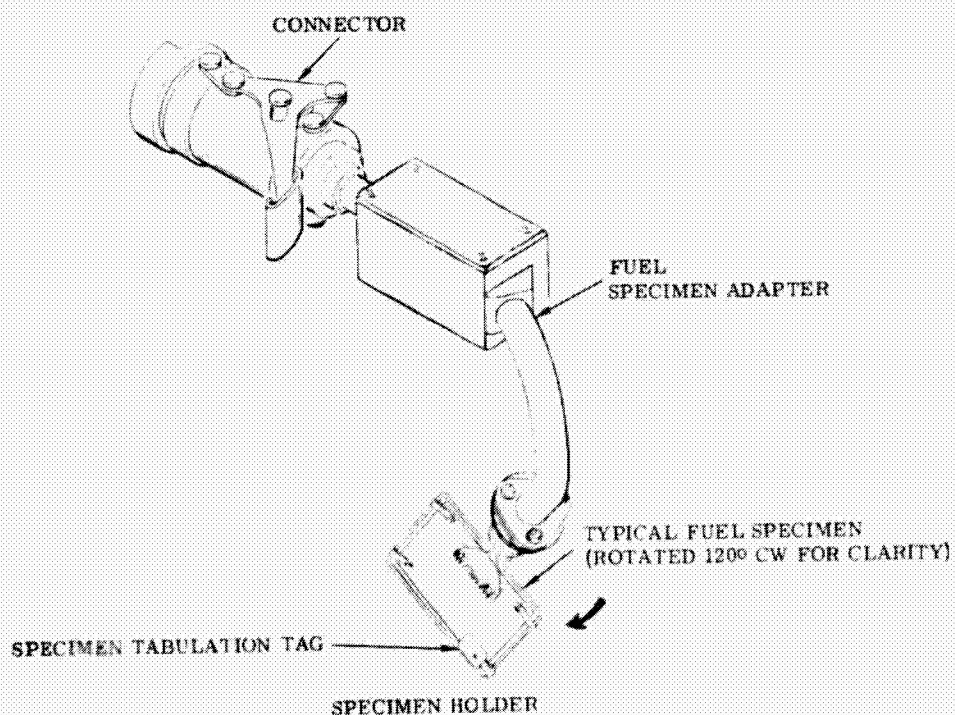
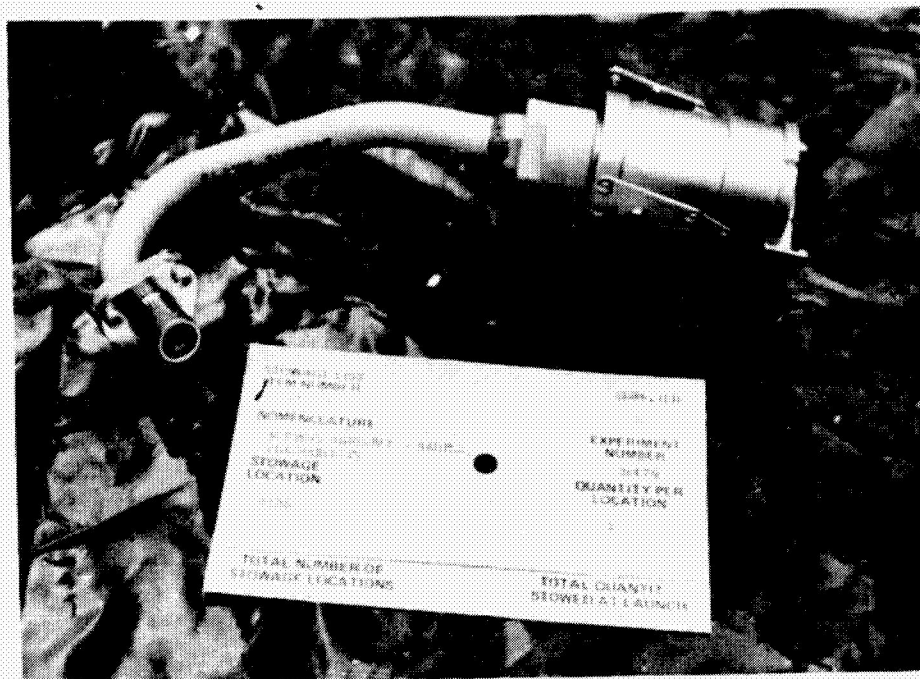


FIGURE 86. M479 FLAMMABILITY SPECIMEN HOLDER

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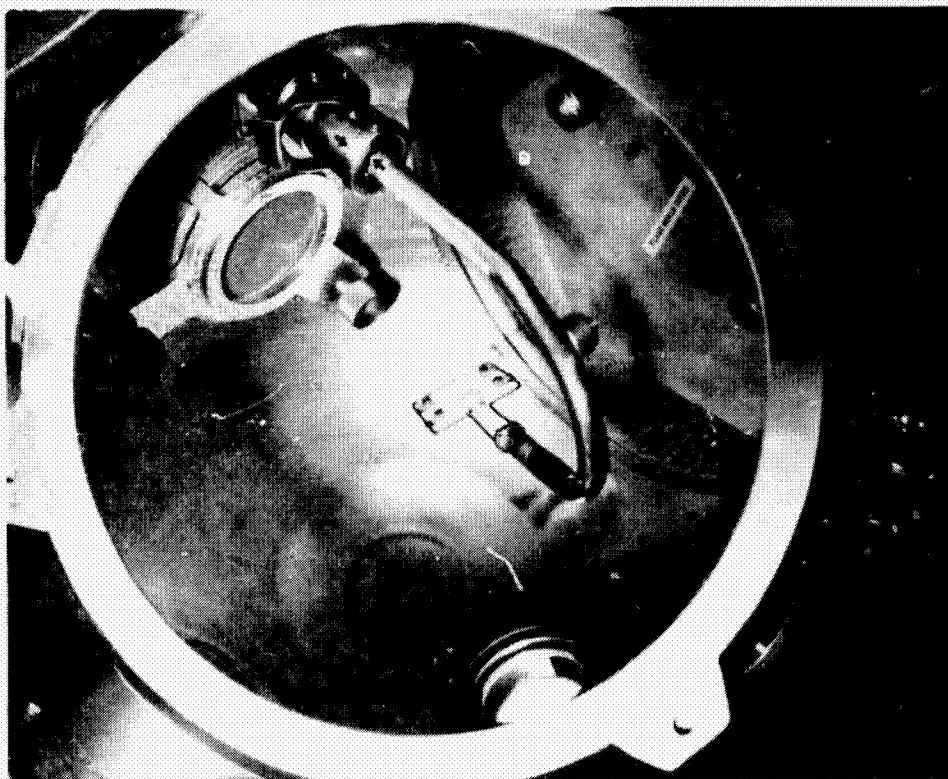
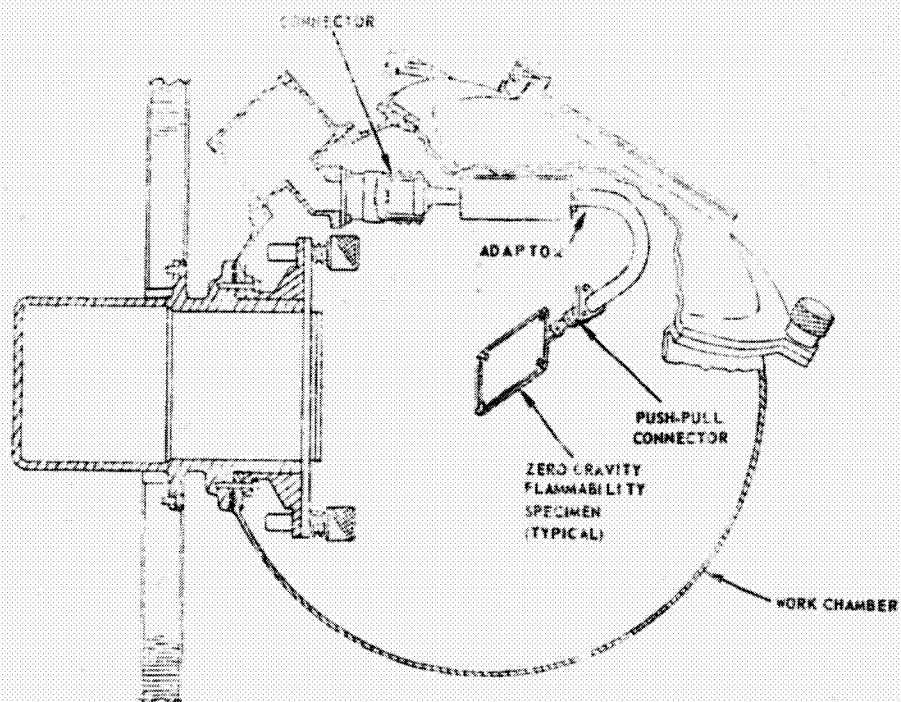


FIGURE 87. INSTALLATION OF M479 SPECIMEN IN WORK CHAMBER

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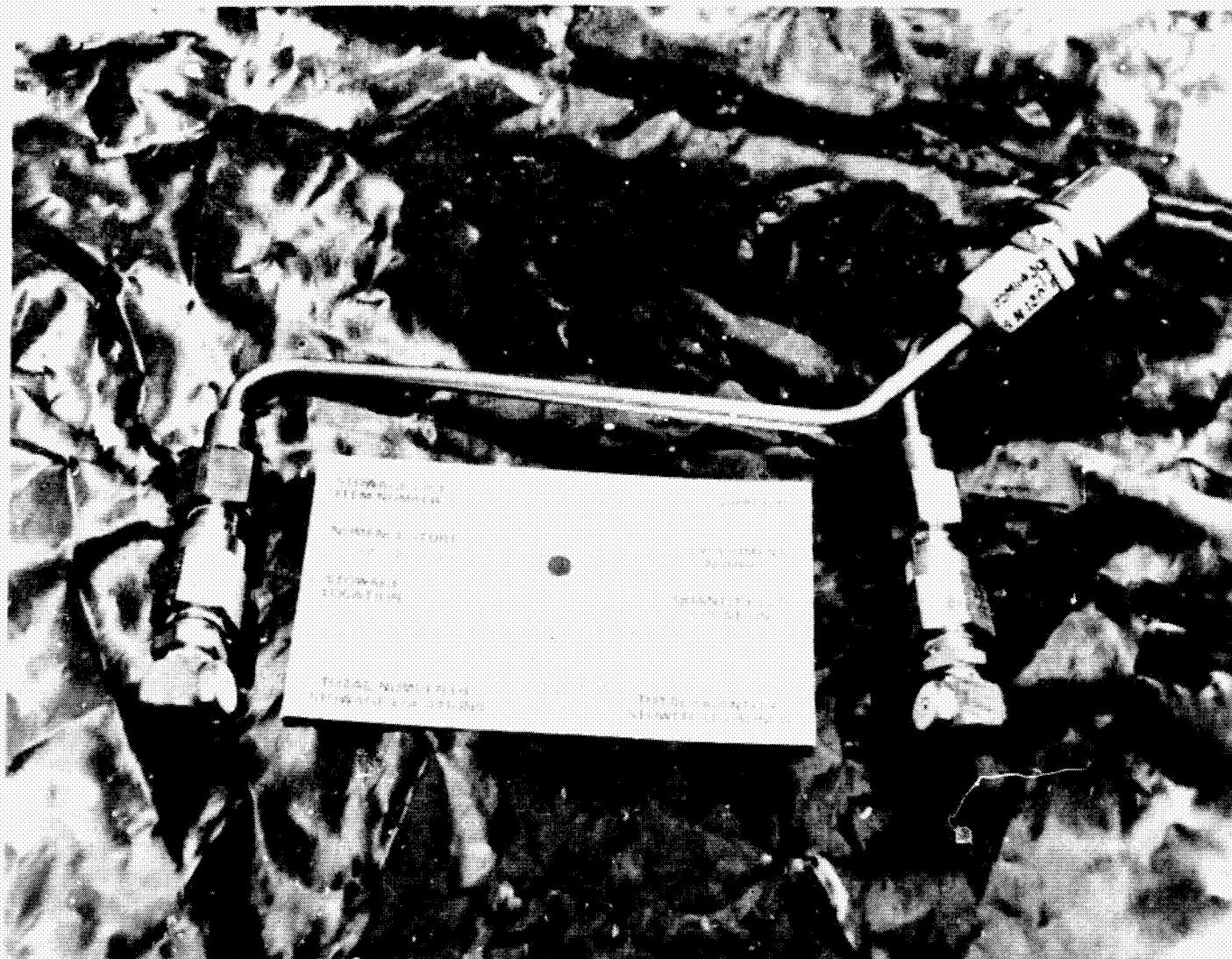


FIGURE 88. WATER QUENCH SPRAY NOZZLE ASSEMBLY





FIGURE 89. M479 HEAT SINK COVER

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FIGURE 96. VENT LINE FILTER NUMBER 2

(7) Work chamber port shields. Glass shields similar to those provided for M553 operations were also used during the M479 operations.

(a) M479 CAMERA PORT SHIELD. This camera port shield shown with the M553 shield in figure 76 had the same purpose and is identical with the M553 camera port shield.

(b) M479 HATCH VIEWPORT SHIELD. This viewport shield is shown with the M553 shield in figure 77. The construction and installation is the same as the M553 shield, the separate shield being required due to possible metal deposition on the M553 shield limiting light transmission.

(8) Photographic equipment. The 16 millimeter DAC, a 18 millimeter lens, and a right-angle mirror for the 18 millimeter lens were used for photography of the M479 experiments.

#### B. Electrical System

The description of the electrical system is presented to give a comprehensive view of the circuit theory and operational procedures pertinent to the electrical/electronic sections of the M512/M479 facility and specimen containers. The circuits are described as they were used by the individual experiments.

i. Metals Melting and Sphere Forming (Experiments M551 and M553). Because both the metals melting and sphere forming experiments used the same circuitry, data for both have been placed together in this paragraph. This circuitry was required for the electron beam gun.

##### a. Functional description.

(1) Metals melting. The metals melting experiment was carried out like a conventional EB welding test. A sample disk of varying thickness was installed on the drive motor in the vacuum work chamber. The electron beam was initiated and focused on the tungsten target in the sample, and sample rotation started, causing the beam to melt the metal to some depth along its track. After 270 degrees of rotation the beam was terminated, the sample was advanced approximately 45 degrees and the beam reinitiated to form a molten metal. After a prescribed period of time, the beam was terminated and the sample removed.

(2) Sphere forming. The samples for the sphere forming experiment were mounted on a rotating holder such that the samples formed the spokes of a wheel, the hub of which was connected to a rotation and positioning mechanism installed in the M512 chamber. The samples were positioned sequentially in the electron beam and melted. Some of the samples were resolidified while supported on stings; these required

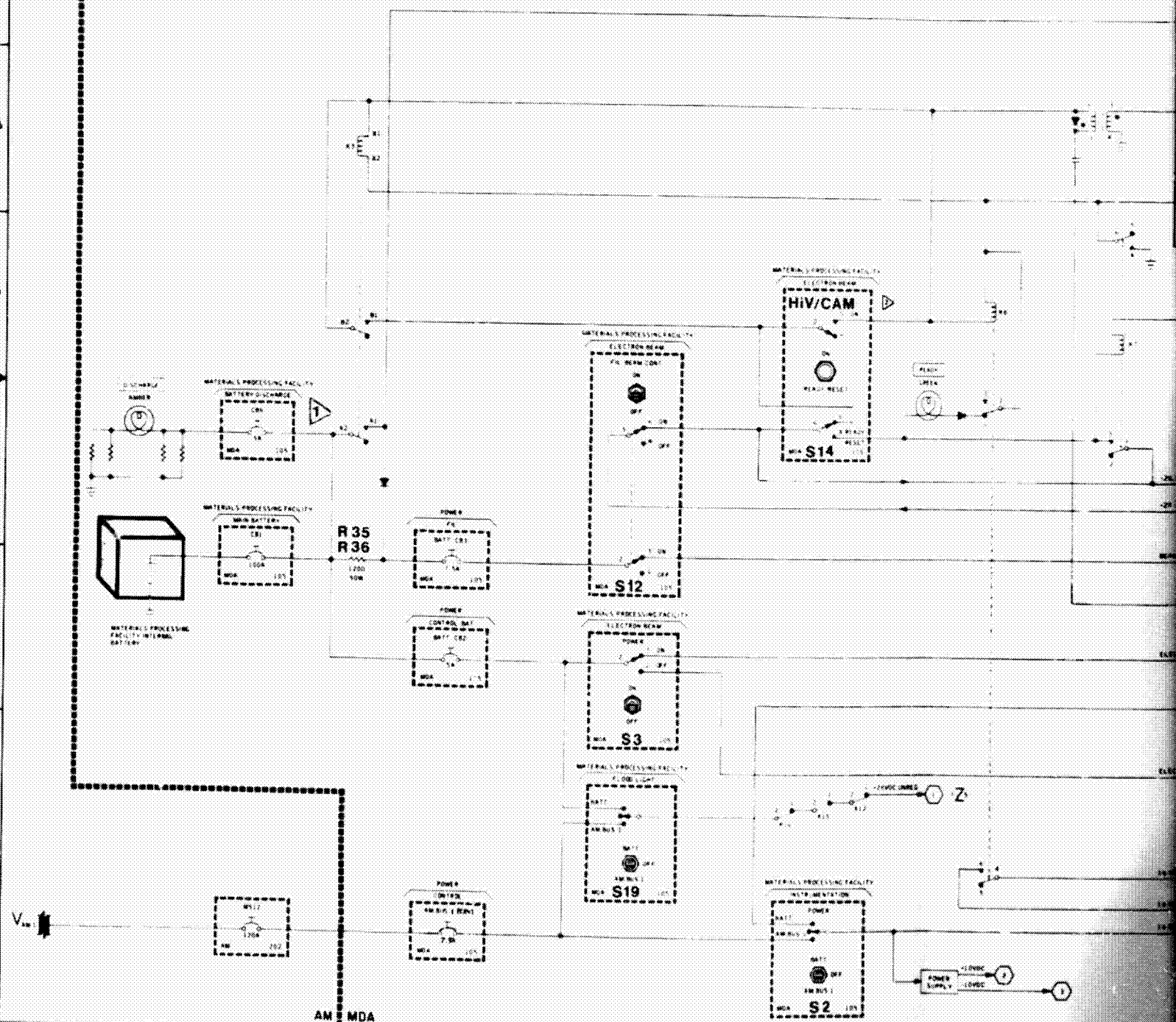
manual termination of the electron beam. Others were automatically released from their stings when melted, resulting in automatic termination of the beam.

b. Theory of circuit operation. Prior to operation of the electron beam circuitry, three constraints had to be met. First, the metals melting motor or the sphere forming motor with specimen wheel attached had to be installed in the chamber and electrically connected. Second, the FILAMENT CHAMBER VENT valve had to be opened, since the valve was interlocked with the high voltage in such a way that the high voltage could not be turned on unless the valve was in the open position. Third, the pressure in the vacuum work chamber had to be lower than  $1.33 \times 10^{-2}$  newtons per square meter ( $1 \times 10^{-4}$  torr); this was to prevent arcing of the electron beam gun and oxidation of the filament when high voltage was applied. With these constraints met, the following discussion presents the theory of operation of the M512 facility to perform the metals melting and sphere forming experiments. Refer to figure 91 for a simplified electrical schematic.

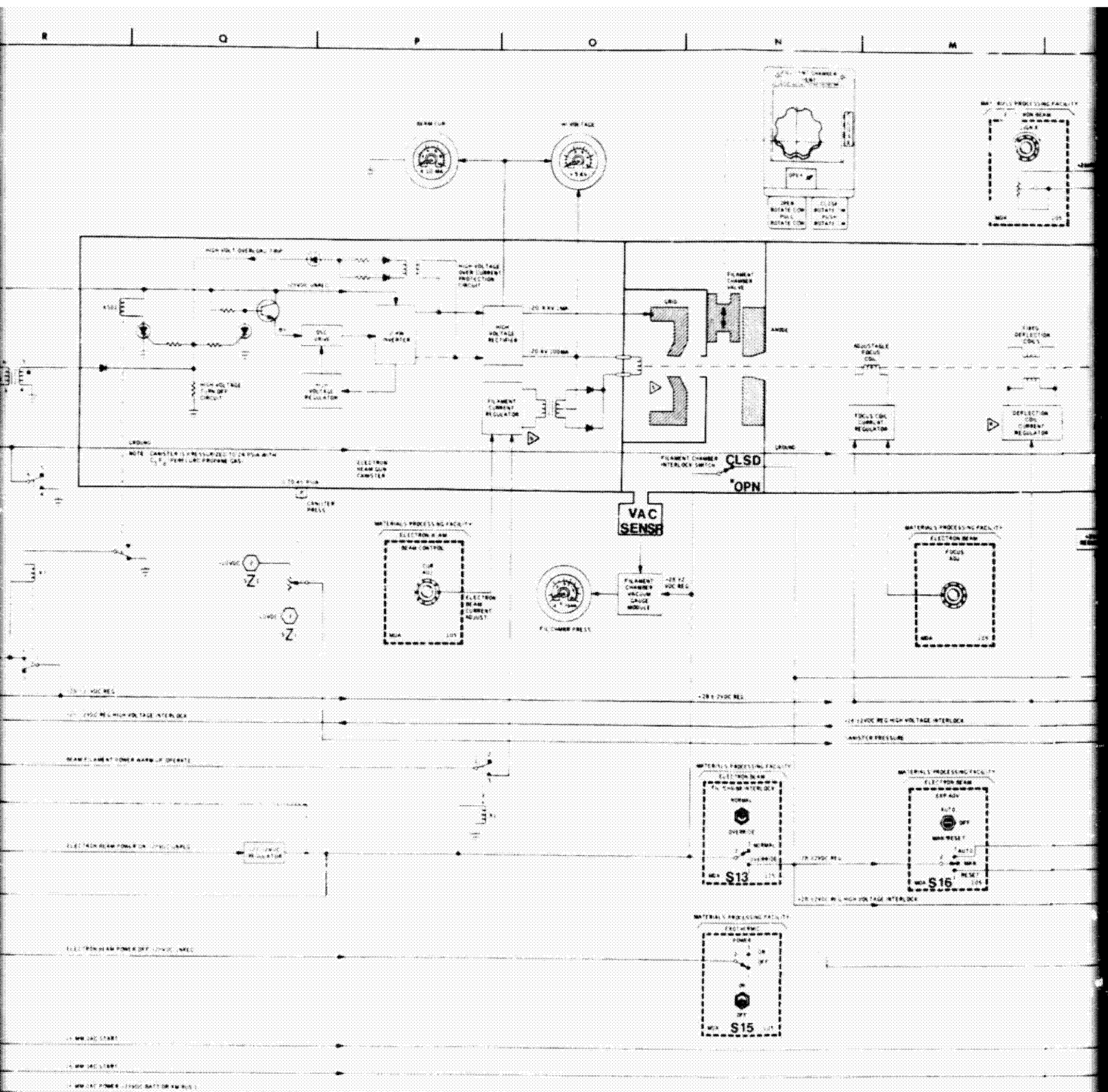
The MAIN BATTERY circuit breaker (CB1), when placed in the ON position, applies a nominal 36 Vdc to one terminal of the BATTERY DISCHARGE circuit breaker (CB6), to one terminal of the POWER CONTROL BATT circuit breaker (CB2), and to one side of power resistors R35 and R36. R35 and R36, in parallel, drop the battery voltage going to the POWER FIL BATT circuit breaker (CB3) to approximately 30-32 volts when the EB gun filament is drawing current and the high voltage is not on. When the EB welder is welding, R35 and R36 are bypassed by a set of relay contacts of relay K3. These resistors compensate for the increased battery voltage when the EB welder is not welding, and this same set of contacts on K3 applies battery voltage to the EB welder control circuits and to the high voltage power supply.

Closing the POWER FIL BATT breaker completes the circuit to the toggle of the ELECTRON BEAM FIL/BEAM CONT switch (S12). Placing the switch in the ON position applies battery voltage to the electron beam filament current regulator through two normally-open sets of contacts of relay K1. The other pole (6) of switch S12, when placed in the ON position, applies regulated voltage to the focus and deflection coil current regulators. The toggle (5) of this half of S12 gets power through a jumper wire in the metals melting package (J6-E to J6-D) or the sting switching mechanism of the sphere forming package, which connects through normally-closed contacts of relay K6 (not energized) to the toggle of the ELECTRON BEAM EXP ADV switch (S16). This half of switch S12 (in the ON position) also applies power to the toggle of the ELECTRON BEAM HI VOLT/CAM switch (S14), to the lens deflection section of the welder through a 26 Vdc regulator, and to the coil of relay K7 through a normally-open set of contacts of K7. The ELECTRON BEAM HI VOLT/CAM switch, when placed in the READY/RESET position, applies the voltage at the toggle (5) to one side of the coil of relay K7. The

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## FOLDOUT FRAME









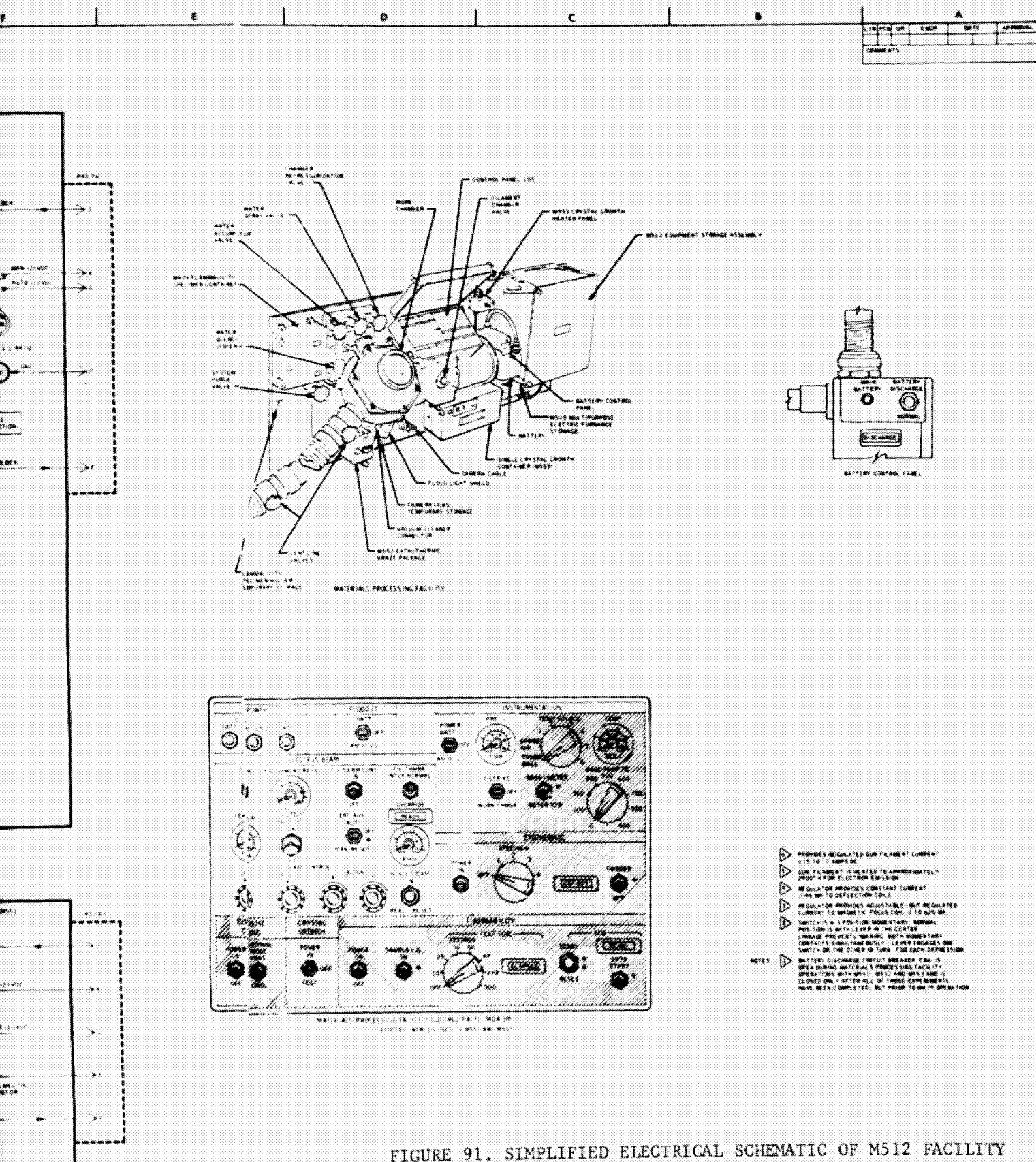


FIGURE 91. SIMPLIFIED ELECTRICAL SCHEMATIC OF M512 FACILITY FOR OPERATION OF EXPERIMENTS M551 AND M553

other side of the coil goes through normally-closed contacts of K501 in the welder to the negative terminal of the battery. When K7 closes, the voltage at the toggle (5) of the ELECTRON BEAM HI VOLT/CAM switch is fed to one side of the coil of K7 through a normally-open set of contacts of K7. This set of contacts and the READY/RESET position of the switch give relay K7 a self-latching feature. When in the READY/RESET position, toggle voltage is also applied to one side of the ELECTRON BEAM READY light. When relay K7 closes, a normally-open set of contacts applies (if the ELECTRON BEAM POWER switch is in the ON position) the battery negative terminal to one side of the coil of relay K3, to one side of the coil of relay K8, to the "X" and "Y" deflection coil circuits, and to one side of the ELECTRON BEAM READY light through a normally-closed set of contacts of relay K8.

After K7 is energized, placing the ELECTRON BEAM HI VOLT/CAM switch (S14) in the ON position places the toggle voltage to one side of relay K8, to one side of relay K3, and to the EB high voltage turn-off circuitry. One of the normally-open set of contacts of K3 is between the toggle of S14 and the coil of K3. This makes the relay self-latching. Energizing K3 activates the electron beam gun circuitry by applying unregulated battery voltage directly to the 2 kW inverter. Energizing K8 turns off the ELECTRON BEAM READY light and starts the 16 millimeter camera.

The POWER CONTROL BATT circuit breaker (CB2), when placed in the ON position, applies 36 volts to the toggle (2) of the ELECTRON BEAM POWER switch (S3) (if CB1 is ON) and to the BATT terminal of the FLOOD LT switch (S19). With the ELECTRON BEAM POWER switch (S3) OFF (and CB1 ON and CB2 ON), 36 volts is applied to the toggle of the EXOTHERMIC POWER switch (S15). If S3 is placed in the ON position, power is removed from S15. This arrangement is an interlock so both experiments cannot be activated at the same time.

Placing the ELECTRON BEAM POWER switch in the ON position (with CB1 ON and CB2 ON) puts 36 volts from the battery to the input of a 26-30 volt series voltage regulator. The output of the regulator goes to the welder high voltage turn-off circuitry, to one side of the coil relay K1, to the power input of the vacuum module, to the BATT terminal of the INSTRUMENTATION POWER switch (S2), to the toggle of the ELECTRON BEAM FIL CHMBR switch (S13), and to the toggle of the Filament Chamber Interlock switch (S27).

The second pole of the ELECTRON BEAM POWER switch, when in the ON position, connects all circuitry to battery negative terminal.

The INSTRUMENTATION POWER switch, when placed in the BATT position, applies power to the instrumentation power supply module and to the camera. This switch also applies the ground to the power supply and the camera.

One output of the power supply module is connected to the canister pressure transducer. The output of the transducer goes to the CSTR X3 terminal of the INSTRUMENTATION PRESS switch (S1). When this switch is placed in the CSTR X3 position, the transducer output is monitored by the INSTRUMENTATION PRESS meter. When the switch is placed in the WORK CHMBR position, the meter will monitor the output of the chamber pressure transducer which also receives power from the power supply module.

The ELECTRON BEAM FIL CHMBR PRESS meter monitors the pressure in the filament chamber accurately in the range of  $1.33 \times 10^{-1}$  to  $1.33 \times 10^{-3}$  newtons per square meter ( $1 \times 10^{-3}$  to  $1 \times 10^{-5}$  torr).

The ELECTRON BEAM BEAM CONTROL CUR ADJ control is a three-turn potentiometer which goes to the filament section of the EB welder, used to adjust the beam current.

The Filament Chamber Interlock switch (S27) is activated by opening the FILAMENT CHAMBER VENT valve, and is an interlock for the ELECTRON BEAM PHOTO LT switch. When the chamber interlock switch is closed, the output of the 30 volt regulator is applied to the toggle of the ELECTRON BEAM PHOTO LT switch (S4), which when placed in the ON position applies voltage to the photo light located inside the spherical work chamber. The chamber interlock switch also applies voltage to the toggle of the ELECTRON BEAM EXP ADV switch (S16).

The ELECTRON BEAM FIL CHMBR switch (S13) is an interlock switch and is wired in parallel with the Filament Chamber Interlock switch. The ELECTRON BEAM FIL CHMBR switch is open in the INTLK NORMAL position and closed when in the OVERRIDE position.

When the ELECTRON BEAM EXP ADV switch has power to the toggle, placing the switch in the MAN/RESET position applies full regulated 28 Vdc to the metals melting package drive motor or sphere-forming package indexing motor. If the switch is placed in the AUTO position, the voltage on the toggle is applied to either drive motor through the motor control regulator.

The ELECTRON BEAM BEAM CONTROL FOCUS ADJ is a three-turn potentiometer which acts as a voltage divider and controls the focus coil current regulator located inside the EB gun canister.

The ELECTRON BEAM BEAM CUR meter and the ELECTRON BEAM X5KV meter monitor the current and voltage of the welder when the beam is on.

The ELECTRON BEAM BEAM CONTROL ALIGN X and ALIGN Y potentiometers are three-turn potentiometers which are part of two identical deflection circuits. These circuits work such that the potentiometers

control both the polarity and the magnitude of the voltage applied across the deflection coils. The align Y network is connected to the "Y" deflection coil and the align X network is connected to the "X" deflection coil. Power is supplied to the deflection circuits from the deflection coil regulator.

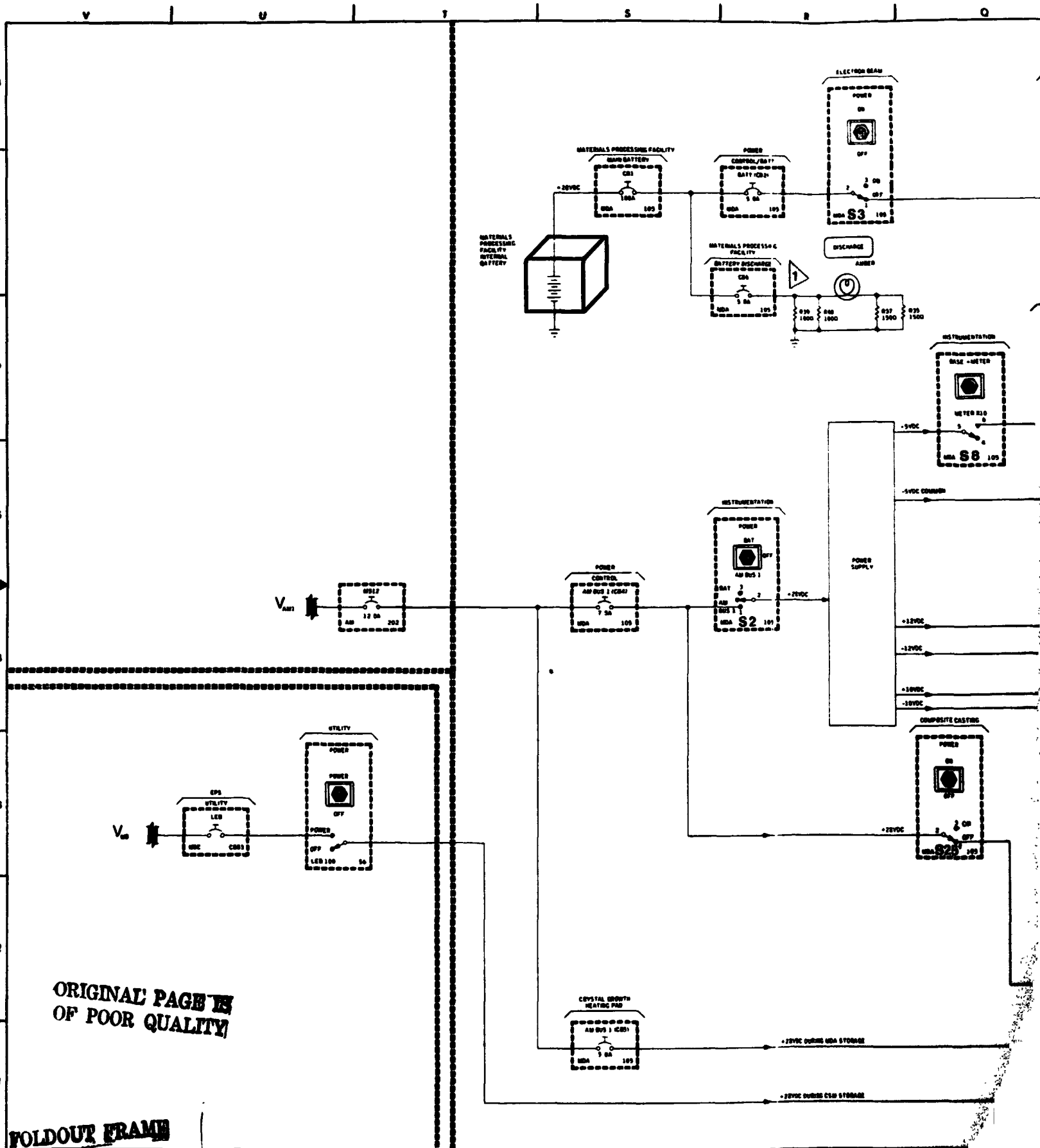
## 2. Exothermic Brazing (Experiment M552).

a. Functional description. The exothermic package container was mounted in the M512 work chamber and consisted of four exothermic braze units. Each exothermic braze unit consisted of a tube, sleeve, two tapered inserts (for concentric positioning of tube and sleeve), two braze alloy rings (copper, silver and lithium), exothermic material, insulation, two igniters, outside housing, and two end plates. The metals joining (brazed sleeve joint) was accomplished when the igniter was energized by an electric current from a 28 volt battery power source. The filament in the igniter, when electrically energized, heated up sufficiently to activate the igniter material, which in turn fired  $[510^{\circ}\text{C} \pm 10^{\circ}\text{C} (950^{\circ}\text{F} \pm 50^{\circ}\text{F})]$  the exothermic material. The exothermic material developed heat  $[1104^{\circ}\text{C} \pm 10^{\circ}\text{C} (2020^{\circ}\text{F} \pm 50^{\circ}\text{F})]$  sufficient to melt the braze alloy rings that were contained within two grooves (one on each side of the joint) in the sleeve. The braze alloy flowed by capillary action between the parts to be joined (tube and sleeve) which were heated sufficiently to form a metallurgical bond with the braze alloy.

b. Theory of circuit operation. The astronaut will place the exothermic package, consisting of the four braze units, in the M512 chamber, close the hatch, evacuate the chamber and operate the switches on the exothermic control panel according to the sequence specified in the following paragraphs. Refer to figure 92 for a simplified electrical schematic.

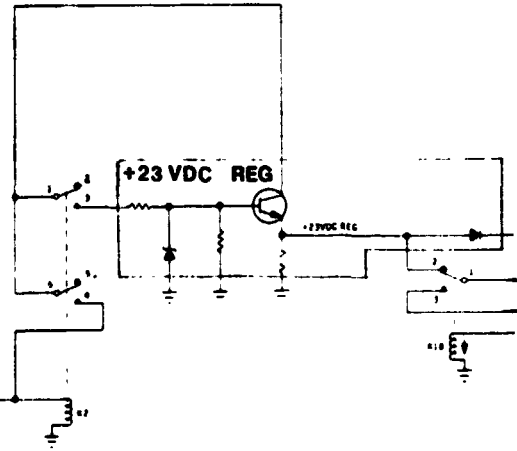
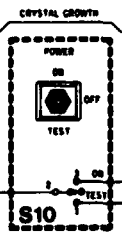
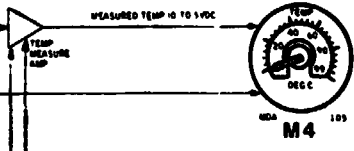
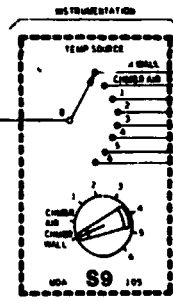
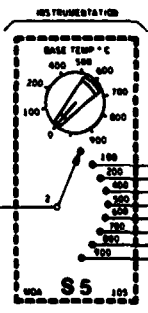
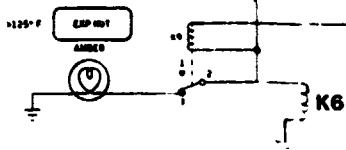
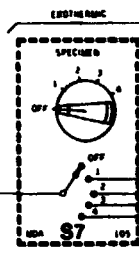
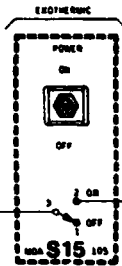
With the MAIN BATTERY (CB1) and POWER CONTROL BATT (CB2) circuit breakers closed and the ELECTRON BEAM POWER switch OFF, the first step is to place the EXOTHERMIC POWER switch (S15) to the ON position. This action applies a voltage across the coils of relays K6 and K9 and causes their contacts to pick up. Opening K6 contacts prevents energizing the electron beam circuitry. (Note that the current path for K9 is completed through the exothermic package thermostat). Since contact K9 (1-2) is now open, the EXP HOT light remains OFF until the temperature of the exothermic package reaches  $52^{\circ}\text{C} (125^{\circ}\text{F})$  causing the thermostat contact to open and thereby de-energizing K9.

The second step is to place the SPECIMEN select switch (S7) to position 1 and then place the TRIGGER switch (S6) to the momentary ON position. Subsequently, a current path is completed through switches S6 and S7 to igniter EXO-1. This current fires the igniter and starts the exothermic experiment. The astronaut monitors the EXP HOT light to

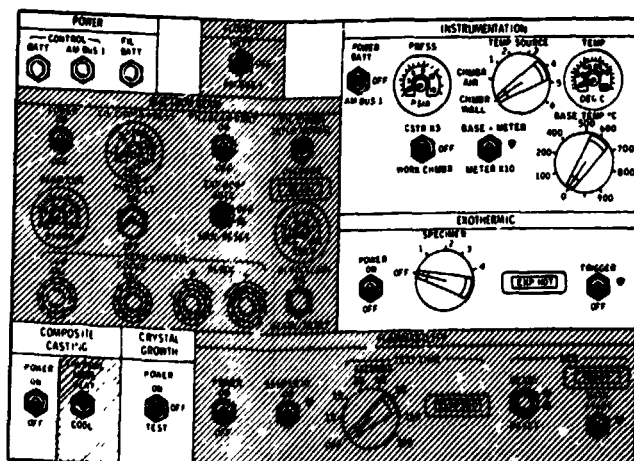
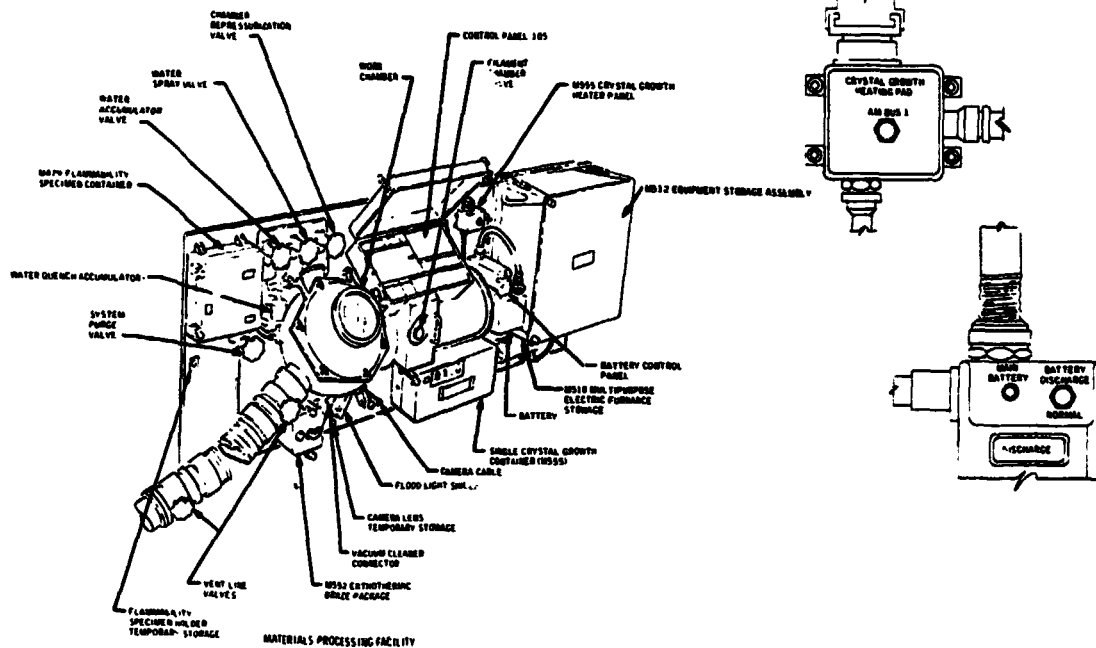




P O N M L







MATERIALS PROCESSING FACILITY CONTROL PANEL MDA 105  
EXPERIMENT CONTROL USED BY M552 - M555

FIGURE 92. SIMPLIFIED ELECTRICAL SCHEMATIC OF M512 FACILITY  
FOR OPERATION OF EXPERIMENTS M552 AND M555

- THE CRYSTAL GROWTH PACKAGE M555 IS STORED INSIDE THE CRYSTAL GROWTH STORAGE CONTAINER WITH P41/P40 CONNECTED TO J41/J40. DURING THE EXPERIMENT OPERATION THE CONNECTOR IS DISCONNECTED. THE CRYSTAL GROWTH PACKAGE REMOVED FROM THE STORAGE CONTAINER AND IS TAPPED IN THE WORK CHAMBER. P41/P40 IS THEN CONNECTED TO J41 INSIDE THE WORK CHAMBER.
- VARIABLE 3 VOLTS APPROX: WHEN M555 IS IN THE PREOPERATION STORAGE MODE TO 100 WATT APPROX: DURING M555 OPERATION.
- R110 RELAY IS MECHANICALLY LOCKED IN POSITION WHEN INITIATED AND CAN ONLY BE RESET ON THE GROUND. POWER WILL STILL BE AVAILABLE TO THE HEATERS ALTHOUGH THE "LO TEMP" LIGHT WILL COME ON WHENEVER TESTED.
- NOTES: BATTERY IS DISCHARGED BY CLOSING OF CB 6.

assure that the exothermic unit actually ignited. The remaining exothermic units (EXO-2, 3 and 4) are fired individually in the same manner as EXO-1, except that the SPECIMEN select switch (S7) is placed to positions 2, 3, and 4, respectively. Between firings, the unit is given sufficient time lapse (about 2 hours) to cool the test container down to approximately 43°C (110°F) (EXP HOT light goes OFF) before the next unit is fired.

3. GaAs Crystal Growth (Experiment M555). The operation of the crystal growth experiment required two individual circuits. The crystal growth launch and stowage container was used to maintain the crystal growth furnace's temperature above 29°C (85°F) to prevent the liquid gallium in the furnace from freezing. The circuitry to accomplish this was contained in the launch stowage container. The circuitry in the M512 facility was used for actual experiment performance.

a. M555 crystal growth storage container.

(1) Functional description. The purpose of this container was to maintain the temperature of the crystal growth furnace above 29°C (85°F) prior to experiment performance. This was accomplished by supplying electrical power to both the furnace heating coils and a heating blanket in the container. A visual display was provided if the furnace temperature dropped below 29°C (85°F).

(2) Theory of circuit operation. Refer to figure 92 for a simplified electrical schematic. The subsequent discussion is based upon the assumption that AM-Bus-1 power or CM utility power is present, and switches and breakers are in the following positions:

LO-TEMP TEST/LAMP TEST switch S28: OFF  
AM-BUS-1 breaker CB5: OFF

The system is energized by closing circuit breaker CB5. When switch S28 (LO-TEMP TEST/LAMP TEST) is placed in the LAMP TEST position, the LO TEMP lamp will be illuminated. This is simply a functional check for the LO-TEMP lamp. With power applied to the circuit the contacts of relay K17 will be arranged and latched in the positions shown in figure 92; also switch S28 will be in the position shown in this schematic.

Depending upon the temperature level of the experiment furnace and the storage container, thermostats S30, S29, S37 and the furnace thermostat (105-120°F) will be either closed or opened, thereby delivering or interrupting power to the heater elements inside the experiment furnace as well as to the heating blanket which is wired in series with the furnace heaters. In the event that the furnace temperature ever drops below 29°C (85°F), the contacts of another furnace thermostat (85-100°F) will close, causing the relay contacts of K17A to be latched into a new position. The LO TEMP lamp will now illuminate when switch S28 (LO-TEMP

TEST/LAMP TEST) is placed in LO-TEMP TEST position. A positive voltage (+28 Vdc) is required at K17B to reset relay K17. This reset capability requires ground support equipment.

b. M555 crystal growth furnace operation.

(1) Functional description. The crystal growth furnace contained three like crystal growth ampoules. Source material (gallium arsenide polycrystals) was dissolved in liquid gallium solvent at the hot end of the ampoule, transported by diffusion down the length of the ampoule, and finally deposited on a seed crystal at the cold end of the ampoule. The furnace was heated electrically after being installed into the heat sink of the M512 vacuum chamber. The furnace required heating for approximately 100 hours to complete the crystal growth process.

(2) Theory of circuit operation. Refer to figure 92 for a simplified electrical schematic. The subsequent discussion is based upon the assumption that AM-Bus-1 power is present to INSTRUMENTATION POWER switch (S2) and the toggle of COMPOSITE CASTING POWER switch (S25) and all switches are in the following positions:

|  |              |
|--|--------------|
| COMPOSITE CASTING POWER, S25               | = OFF        |
| CRYSTAL GROWTH POWER, S10                  | = OFF        |
| INSTRUMENTATION BASE + METER/METER X10, S8 | = METER X10  |
| INSTRUMENTATION TEMP SOURCE, S9            | = CHMBR WALL |
| INSTRUMENTATION BASE TEMP °C, S5           | = 0          |
| INSTRUMENTATION POWER, S2                  | = AM BUS 1   |

With switch S8 in the METER X10 position, a coarse meter range is de-energized and no power is applied to the input of the 23 volt regulator circuit. Therefore no power is applied to the crystal growth furnace heaters. A regulated voltage of  $\pm 10$  volts, however, is being constantly supplied by the power supply module to operate reference junctions RJ1 and RJ2, all thermocouple reference junctions mounted inside the crystal growth package and the work chamber pressure transducer. These reference junctions provide an output signal in millivolts which is reference to 0°C.

With switch S8 in the meter X10 position, a coarse meter range of from 0-1000°C is displayed on the INSTRUMENTATION TEMP meter (M4). With switch S8 in BASE + METER position, a negative bucking voltage of -5 volts from the power supply module is applied to the temperature measurement amplifier (depending upon the particular position of the INSTRUMENTATION BASE TEMP °C switch S5), causing an attenuation of the scale on meter M4 in steps of 100°C from 0-900°C.

The INSTRUMENTATION TEMP SOURCE switch (S9) and INSTRUMENTATION BASE TEMP °C switch (S5) being in the fully CCW position, the thermocouple

output signal from reference junction RJ1 is being switched across contacts of S9 and applied to the temperature amplifier. INSTRUMENTATION TEMP meter (M4), which is connected to the amplifier module, will now indicate the wall temperature of the work chamber in °C. The meter is calibrated to read in the following ranges: 0-100-200-400-500-600-700-800-900-1000°C.

Having switched the INSTRUMENTATION TEMP SOURCE switch one step clockwise, the thermocouple output from reference junction RJ2 is now being switched across different contacts of S9 and applied to the amplifier module. INSTRUMENTATION TEMP meter (M4) will now indicate the temperature of the ambient air inside the work chamber in °C.

All other clockwise steps of INSTRUMENTATION TEMP SOURCE switch (S9) will successively switch all remaining six thermocouple readouts coming from inside the crystal growth furnace to input terminals of the amplifier. The processed and amplified signal will then be displayed by meter M4 via output terminals of the amplifier.

To apply power to the crystal growth furnace, CRYSTAL GROWTH POWER switch (S10) must be either in the TEST or in the ON position. If this switch is in the TEST position, with COMPOSITE CASTING POWER OFF the positive side of AM-Bus-1 is being directly supplied to relay K18 coil and through K18 contacts to the crystal growth furnace. The negative side of AM-Bus-1 is being supplied through contact of S10 (CRYSTAL GROWTH POWER switch) to K18 and the crystal growth furnace. The heater inside the furnace is now energized.

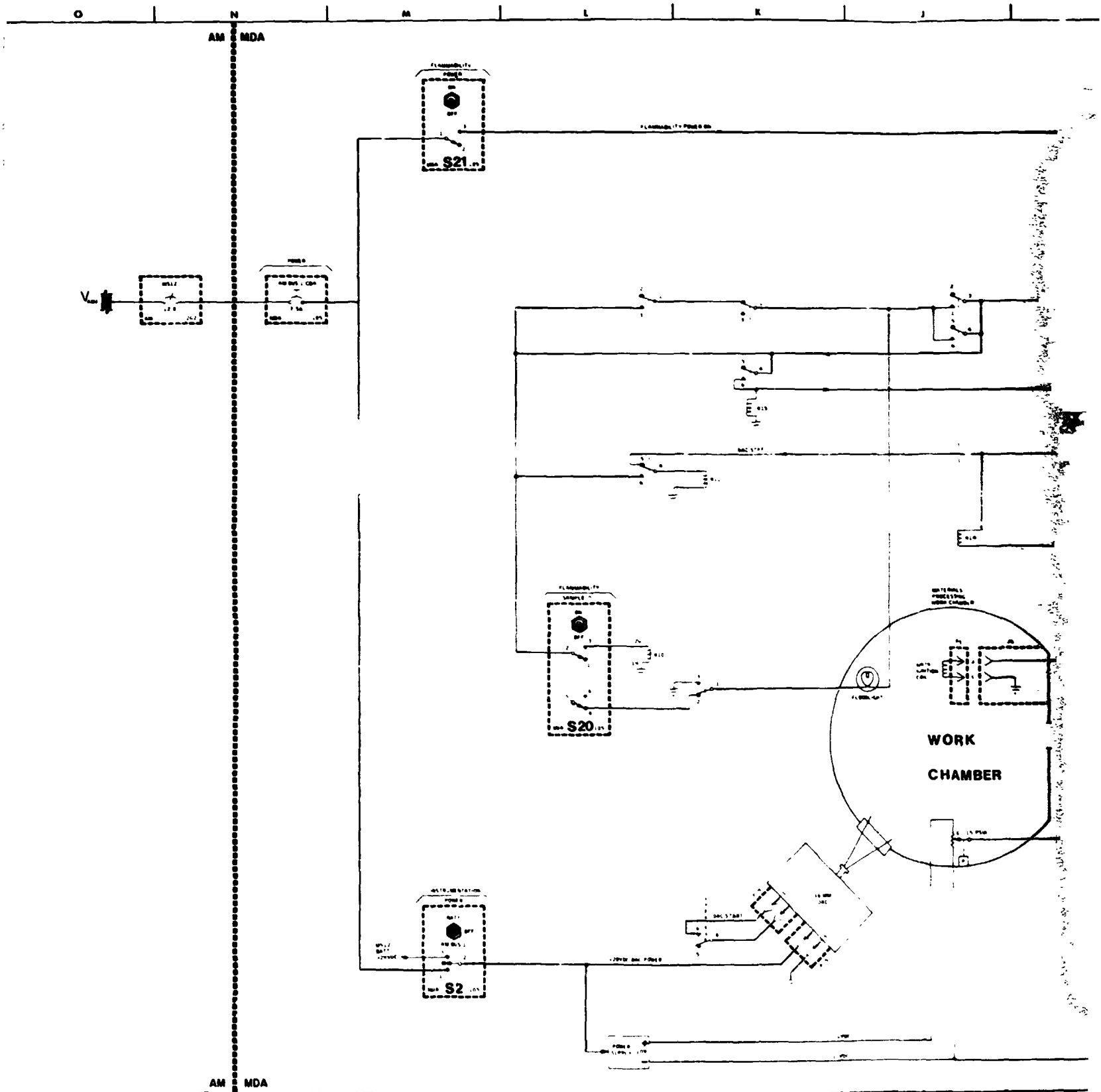
Turning the CRYSTAL GROWTH POWER switch (S10) to the ON position (with COMPOSITE CASTING POWER switch (S25) in OFF) will apply the positive side of AM-Bus-1 to relay coil K2. The negative side of the AM-Bus-1 is supplied through S25 and S10 (CRYSTAL GROWTH POWER switch) to relay coil K2. This will energize relay K2 and supply the positive side of AM-Bus-1 through its now-closed contacts 4 and 6, and 1 and 3, to the input of the 23 Vdc regulator circuit.

The negative side of the supply voltage is connected to the negative side of the regulator. The 23 volt regulator now will supply an output voltage to the positive side of the crystal growth furnace.

#### 4. Zero-Gravity Flammability (Experiment M479).

a. Functional description. The objective of the flammability experiment was to electrically ignite fuel samples in an ambient spacecraft environment and study flame propagation under zero-gravity conditions and the effects of water and vacuum extinguishment. The function of the M512 facility flammability circuit (see figure 93) was to: (1) turn on and off the floodlight located inside the combustion





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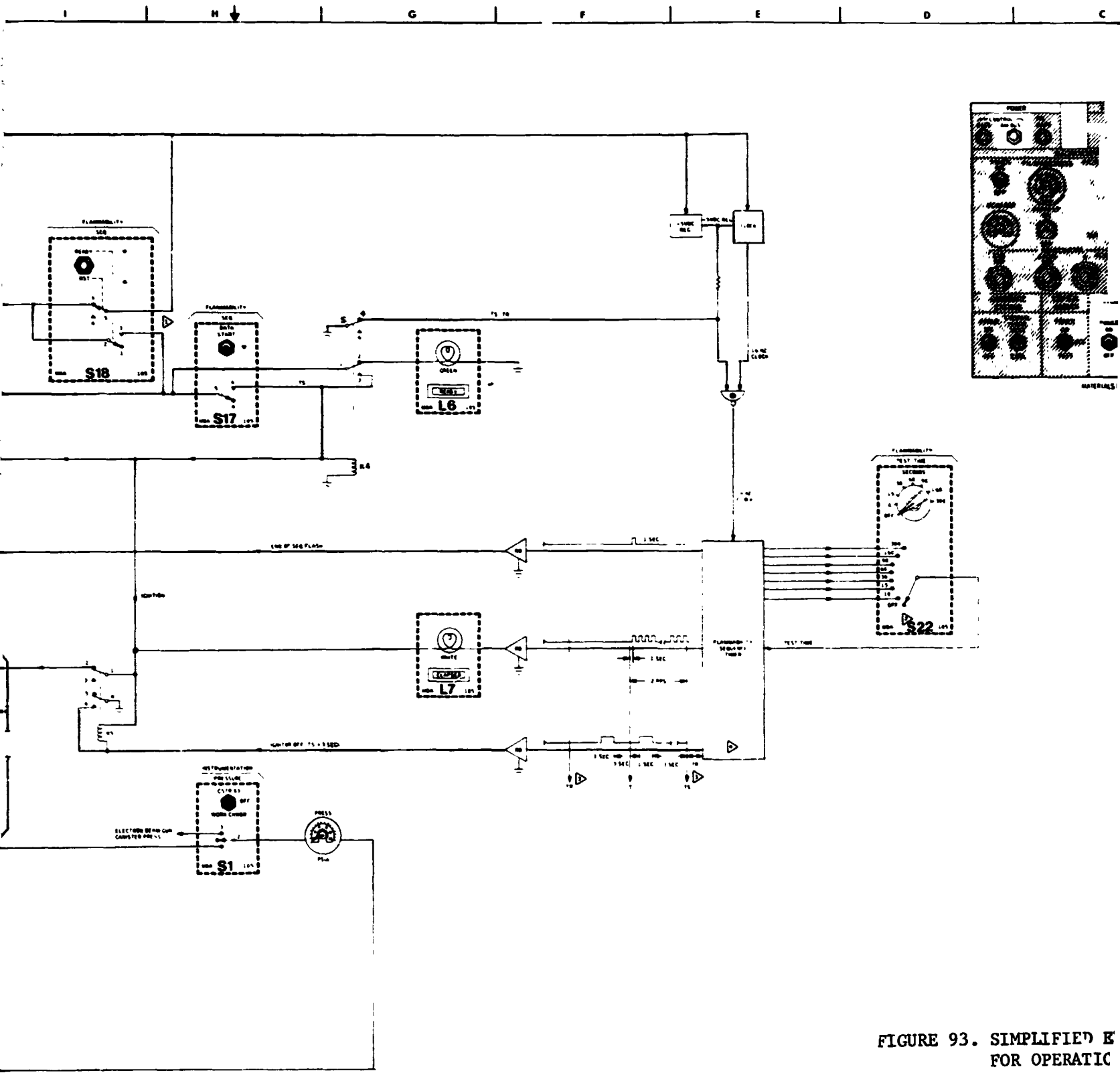
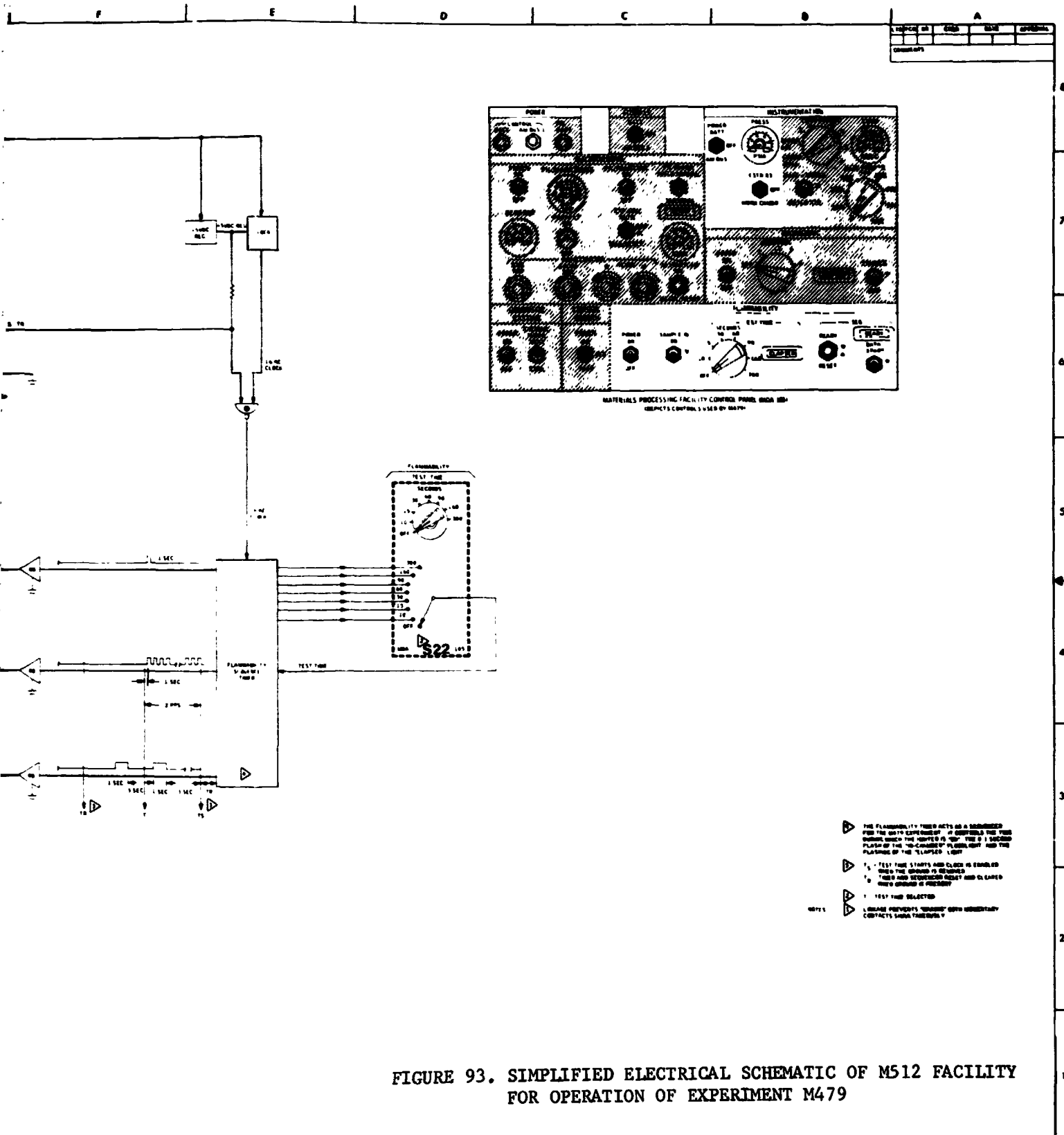


FIGURE 93. SIMPLIFIED E  
FOR OPERATIC

FRAME 2



**FOLDOUT FRAME**

chamber, (2) turn on and off the SEQ READY light located on the control panel, (3) turn the camera on and off at the proper time, (4) turn the sample igniter on and off and (5) indicate to the astronaut that the experiment was completed by means of an electronic timer. The mode of operation for this circuit was keyed in accordance with the sequence required to conduct the flammability experiment.

There were six relays, labeled K4, K5, K10, K12, K14 and K15. The contacts of these devices were used to sequence the voltage used to operate the other components. Also included in this circuit were three lamps. The floodlight illuminated the test specimen located in the combustion chamber, before testing, for the purpose of photo identification. The SEQ READY light illuminated when the flammability circuit had been sequenced to the step where the experiment was ready to initiate. Energizing the DATA START switch turned on the igniter and camera. The TEST TIME ELAPSED light flashed on and off at the end of the experiment. Time for the experiment was preset by the TEST TIME switch.

The 16 millimeter data acquisition camera was mounted on the M512 materials processing facility and was used to photograph the experiment operation. The camera, for the flammability experiment, was controlled (on or off) by contacts from relay K12. Photography was done at 24 frames per second.

Each igniter-fuel assembly consisted of: a specimen, a plug, and an igniter enclosed in a case with socket. The igniter filament was made of nichrome wire, type V, having a resistance of 0.85 ohms per inch. The igniter-fuel assemblies were used as fuel samples and ignited in the M512 chamber.

b. Theory of circuit operation. The first observation to be made when studying this circuit is to note that its power source is from AM-Bus-1 28 Vdc supply. This power source is controlled by the ON/OFF FLAMMABILITY POWER switch (S21). Placing the switch to the ON position is the first step in the operation of this circuit. Subsequently, this voltage activates the 16 hertz oscillator located on the flammability timing module and the 5 Vdc regulator. Positive voltage passes through the closed terminals 5 and 6 of the FLAMMABILITY SEQ READY/RESET switch to terminal 2 of the FLAMMABILITY SEQ READY/RESET and FLAMMABILITY SAMPLE ID switches, to terminals 3 and 6 of relay K10, to terminals 3 and 4 of K14, and to terminal 4 of K15. The other pole of S21 supplies negative AM Bus voltage to the coils of K4, K10, K12, and K15; to J6-L; to terminal 4 of K5; to terminal 5 of K4; to terminal 3 of K12; to the timing module; and to the FLAMMABILITY SEQ READY light.

The second step in operating the flammability circuit is to place the FLAMMABILITY SAMPLE ID switch (S20) (spring return) to the ON position. This action completes the circuit to the coil of relay

K10, causing K10 to be energized and its contact to pick up. Contact K10 (4-6) closes and completes the circuit to the coil of K12. With the coil of K12 energized, contacts K12 (1-3) and K10 (1-3) complete the circuit to the floodlight. Note that contact K10 (4-5) opens to prevent voltage feedback to terminal 6 of the FLAMMABILITY SEQ DATA START switch (S17). Contact K12 (4-6) closes and turns on the 16 millimeter data acquisition camera. When enough data have been taken to identify the test specimen, the FLAMMABILITY SAMPLE ID switch (S20) is released and the coil of K10 is de-energized, contact K10 (1-3) opens the floodlight circuit (the light goes off), and contact K10 (4-6) opens the circuit for the coil of K12, de-energizing the relay and subsequently turning off the data acquisition camera.

The third step is to select the desired time interval of the experiment by using the FLAMMABILITY TEST TIME switch (S22).

The fourth step in operating this circuit is to place the FLAMMABILITY SEQ READY/RESET switch (S18) (spring return) to the READY position. This action completes the circuit to the FLAMMABILITY SEQ READY light and causes it to illuminate. A circuit is also completed to the coil of K15, energizing the relay, causing contact K15 (4-6) to bypass switch S18 to the +28 volt supply.

The fifth and final step in the operation of this circuit is to place the FLAMMABILITY SEQ DATA START switch (S17) to the DATA START position. When this occurs, a current path is completed through contact K5 (1-2) and the igniter is turned ON. In addition, a voltage is present across the coil of K4, causing contact K4 (1-3) to close, thus bypassing switch S17; contact K4 (1-2) to open, thus turning the FLAMMABILITY SEQ READY light off; and contact K4 (4-5) to open, thereby resetting the flammability timing module to zero. Placing S17 to the DATA START position also energizes K12 through closed contacts 4 and 5 of K10, starting the camera and presenting negative AM-Bus voltage to the floodlight, and presents +28 Vdc to the coil of K14 and the FLAMMABILITY TEST TIME ELAPSED light. Three seconds after resetting the timer, a signal from the timer energizes relay K5, causing contact K5 (1-2) to open the igniter's circuit and contact K5 (4-6) to close, thus causing K5 to become self-latched. When the experiment time (chosen by the FLAMMABILITY TEST TIME switch) elapses, a 0.1 second signal from the timer turns relay K14 ON and contact K14 (1-3) closes, causing a 0.1 second flash of the floodlight in the chamber. After 0.5 seconds have elapsed from the end of the experiment, an on/off signal from the timer flashes the FLAMMABILITY TEST TIME ELAPSED light at intervals of 0.5 seconds.

This ends the sequence of operation for the flammability circuit; the circuit is returned to its original state by placing switches S17, S22, and S21 in the OFF position.

## 5. Supporting Electrical Systems.

### a. Battery discharge circuit.

(1) Functional description. The purpose of this circuit was to discharge the battery that supplied power to the M512 electrical/electronic circuits when the M551, M552 and M553 experiments were completed or when the astronauts left Skylab.

(2) Theory of circuit operation. The circuit is shown in figure 94 and consists of a BATTERY DISCHARGE circuit breaker (CB6), a light, and discharge and current-limiting resistors. With MAIN BATTERY circuit breaker CB1 closed, the discharge operation is initiated when CB6 is closed. The battery is mostly discharged through parallel resistors R39 and R40. Resistors R37 and R38 dissipate some of the battery power, but in this circuit are used to limit the current through DISCHARGE light L8. L8 consists of two redundant bulbs and remains illuminated until the battery is virtually discharged. When the battery is discharged, circuit breakers CB1 and CB6 are then opened.

b. Line filter assembly. The purpose of this unit was for filtering any unwanted line transients or ripple which otherwise might appear at the power inputs of the various experiment and control modules of M512. It was also designed to provide ample protection against any expected radio frequency interference which could possibly upset and disturb other experiments feeding from the same 28 volt bus, since it was proven that while operating the M551/M553 specimen motors, a considerable amount of interference was generated and appeared at various power inputs. On the other hand, this filter also protected the M512 experiments from radio frequency interference being picked up and conducted into the system from some outside source. The line filter consisted of chokes and capacitors designed to filter conducted, common mode, and line-to-ground noise and transients.

### C. Experiment Interfaces

The Skylab interfaces and services required to operate the M512 facility and perform the associated experiments are described, and an assessment of the performance of the interface or service is included in this subsection.

#### 1. Interfaces.

a. Stowage. The launch stowage location for all M512 facility hardware was in the MDA. Table I summarizes the pre-mission environmental requirements (Cluster Requirements Specification) and compares them with the actual measured values. All requirements were met with one minor exception. The slightly lower pre-habitation pressure reflected in the table did not affect the M512 hardware.



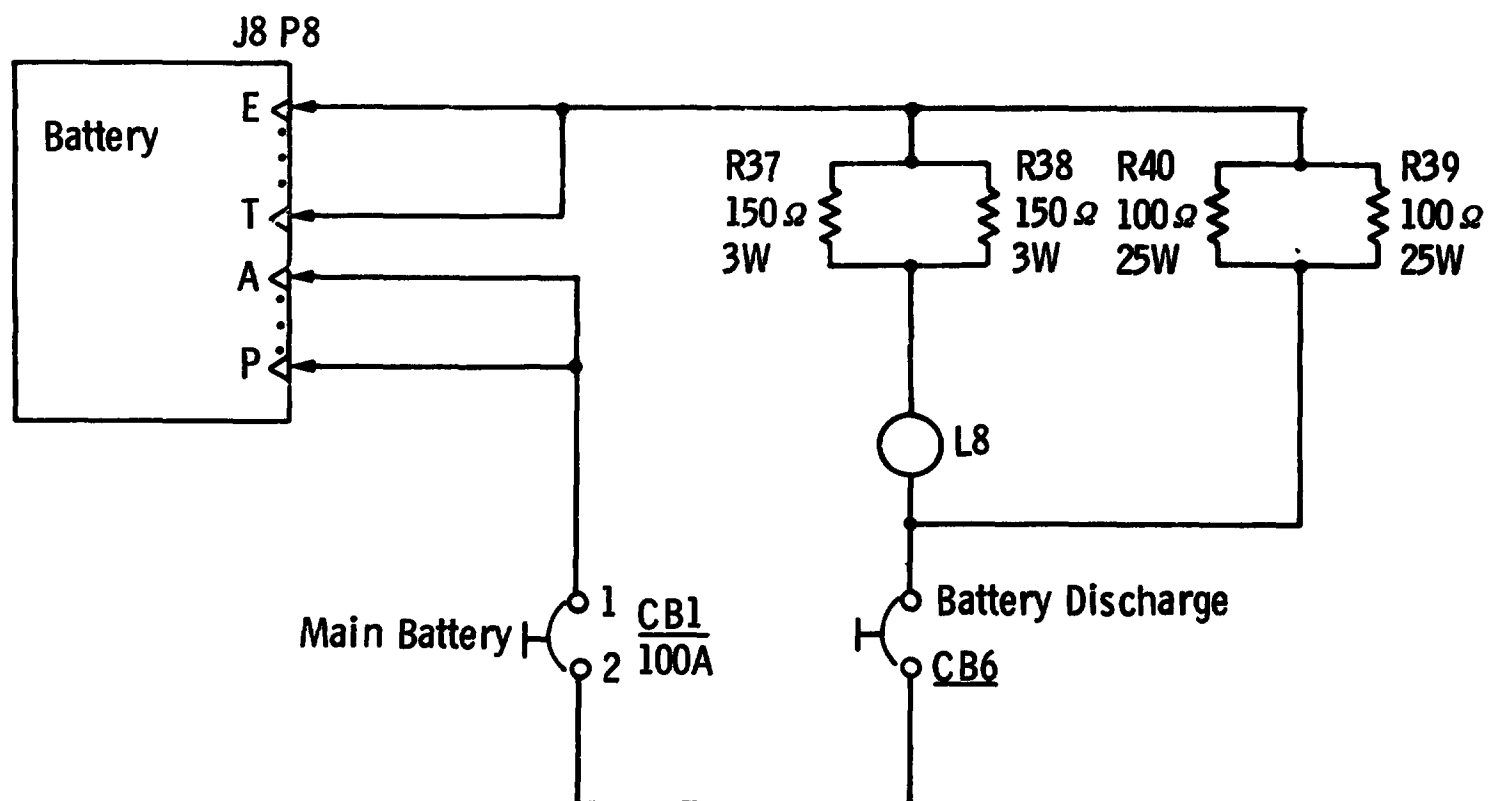


FIGURE 94. M512 FACILITY BATTERY DISCHARGE CIRCUIT

TABLE I COMPARISON OF SKYLAB MEASURED ENVIRONMENTAL  
EXTREMES WITH CLUSTER REQUIREMENTS  
SPECIFICATION (CRS) REQUIREMENTS  
FOR EXPERIMENT HARDWARE

| MISSION<br>PHASE<br>ENVIRONMENT | LAUNCH & ASCENT                          |  | PRE-HABITATION                                   |   | HABITATION  |  |
|---------------------------------|--|--|--|---|---|--|
|                                 | CRS REQ'T                                | MEASURED<br>VALUES                       | CRS REQ'T  | MEASURED<br>VALUES  | CRS REQ'T   | MEASURED<br>VALUES   |
| Temperature<br>Int. MDA         | 40-90°F                                  | 50-75°F                                  | 40-90°F  | 45-70°F   | Wall: 50-90°F<br>Atmos: 60-90°F<br>(Orb. Stor.: 40-90°F)          | Manned: 52-72°F<br>Orb. Stor.: 46-71°F   |
| Relative<br>Humidity            | 5%                                       | Estimated<br>5%                          | 5%   | 5%  | 30-85%  | 36-81%   |
| Pressure                        | 14.7 psia to<br>0.5 psia                 | 14.7 psia<br>to 0.5<br>psia              | 0.5-6.0<br>psia                                  | 0.3 psia-<br>5.0 psia   | 5.0-6.0 psia  | Manned: 4.8-5.4 psia<br>Orb. Stor.:<br>0.3-5.1 psia  |
| Atmosphere<br>Comp.             | 80% N <sub>2</sub><br>20% O <sub>2</sub> | 80% N <sub>2</sub><br>20% O <sub>2</sub> | 100% N <sub>2</sub><br>to<br>100% O <sub>2</sub> | 100% N <sub>2</sub><br>to<br>74% O <sub>2</sub> ,<br>26% N <sub>2</sub> | 70% O <sub>2</sub> , 30% N <sub>2</sub> to<br>100% O <sub>2</sub> | 60% O <sub>2</sub> , 40% N <sub>2</sub> to<br>79% O <sub>2</sub> , 21% N <sub>2</sub> by<br>Vol. |
| Vibration                       | Ref:<br>IN-ASTN-AD-70-1                  | Less than<br>IN-ASTN-<br>AD-70-1         | N/A  | N/A   | N/A   | N/A  |
| Shock                           | N/A                                      | N/A                                      | IN-ASTN-<br>AD-70-1                              | Not<br>Measured   | N/A   | N/A  |
| Acceleration                    | 4.7 g                                    | 4.7 g                                    | N/A  | N/A   | N/A   | N/A  |
| Radiation                       | N/A                                      | N/A                                      | 0.5 rads/<br>day                                 | 0.2 rads/<br>day  | 0.5 rads/day  | 0.2 rads/day   |

All hardware for experiments M551, M552, M553 and M479 was launched either in the M512 accessory container or on one of the M512 mounting panels. There were no stowage interface control documents (ICD) for the launch of this hardware.

The three M551 sample disks, the M552 exothermic package, and the two M553 sphere catchers containing the experiment specimens were returned to Earth in Command Module (CM) 116 (SL-2). These stowage interfaces, controlled by ICD 13M13507, were successfully met.

Although the M555 experiment was not performed on Skylab, ICD 13M13507 also controlled the launch of the experiment storage container and the return of the furnace in CM116.

b. Mechanical. The M512 facility mechanical interfaces with the MDA were controlled by ICD 13M12161A. These interfaces included:

- M512 honeycomb panels to MDA longerons 4 and 5
- M512 vacuum vent to MDA vacuum vent system
- M512 battery vent line to MDA vacuum vent manifold system
- M512 line filter junction box to AM power system cable

The data acquisition camera mechanical interface with the M512 facility was controlled by ICD 13M13546.

The interfaces of the individual experiments with the M512 facility are described elsewhere in Section III. ICDs were not applicable because the interfaces were with the M512 facility and not the MDA; for interface documentation, the M512-related experiments were considered part of the M512 facility.

Based on the crew voice comments and the experiment crew debriefing, all mechanical interfaces were successfully met with the exception of the M551 deflection mirror interference with the electron beam housing, discussed in Section VI, which did not adversely affect the experiment performance.

c. Electrical. The M512 facility electrical interface with the AM power bus was through a single connector and was controlled by ICD 40M35625. Electrical power (7.15 amperes at nominal +28 Vdc) was supplied by AM-Bus-1 for operation of M479 and instrumentation during M518 operations. Power to operate M551, M552, and M553 was supplied by the M512 battery. The electrical interface for the data acquisition camera was controlled by ICD 40M35681.

All electrical interfaces were successfully met.

Although not launched, the electrical interface between the M555 storage container and CM116 was controlled by ICD 40M35753. This interface was required to maintain the furnace above 29°C (85°F) prior to experiment operation. M555 would also have received electrical power from AM Bus 1 during both the storage and operational modes.

d. Instrumentation and communications. The M512 facility and related experiments did not utilize telemetry.

2. Services. The M512 facility required two special services beyond the normal environmental factors such as lighting, temperatures, etc. The facility required vacuum from two separate sources. A vacuum of  $1.33 \times 10^{-2}$  newtons per square meter ( $1 \times 10^{-4}$  torr) through the 10 centimeter (4 inch) MDA vacuum system was required for the electron beam gun operation and  $6.7 \times 10^{-2}$  newtons per square meter ( $5 \times 10^{-4}$  torr) was required for the M518 experiment operations. Experiment M552 required only a zero pressure reading on the work chamber pressure gauge and M479 required only the vacuum line valves be momentarily opened for vacuum extinguishment and venting the products of combustion. Secondly, the spacecraft vacuum cleaner was used to initiate and maintain an air flow through the work chamber for retrieval of the M553 spheres. The desired vacuum levels were met prior to all experiment operations and the vacuum cleaner operated properly during M553, although the M553 spheres were not affected by the air flow as expected, mainly due to residual magnetism in the sphere forming indexing motor.

The second service required by the M512 facility was spacecraft water. The OWS water system was connected to the M512 water quench system for M479 operations. The water servicing unit umbilical mechanical interface to the facility was controlled by ICD 13M13543. The water umbilical mechanical interface was successfully met although the hand pump on the water accumulator had to be used during the actual experiment performance to spray water on the samples. This is discussed further in Section VI.

## SECTION IV. VERIFICATION SUMMARY

### A. Qualification Verification

The M512 qualification facility, AAP-2V, and all associated experiments underwent qualification testing, according to test specification 95M01900, from November 1971 through September 1972. Verification tests were conducted at the beginning of the qualification program, after unplanned events, following major hardware changes or repairs, and after the completion of the qualification tests. The results of the M512 and associated experiment qualification tests are documented in qualification test report 70 TR1-95M10500-1.

1. Qualification by Test. The experiment hardware was physically subjected to, and passed, the following qualification tests:

- a. Vibration
- b. Acoustic Noise
- c. High Temperature
- d. Low Temperature
- e. Humidity
- f. Electromagnetic Interference
- g. Corona Discharge

No shock testing was required because the M512 hardware was installed in the spacecraft with shock isolators.

2. Qualification by Analysis. Analyses were performed to verify that the M512 facility and associated experiments met the qualification limits for:\*

- a. Oxygen compatibility
- b. Fungus resistance
- c. Outgassing
- d. Stress Corrosion
- e. Flammability
- f. Odor-offgassing
- g. Acceleration

3. Hardware Failures. The experiment hardware successfully met all qualification criteria. A few component parts were upgraded as a result of the tests and two hardware redesigns were required. The first modification added power input line electrical filters to allow

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\*Note reference to many tests conducted throughout development of experiment system, page 2 of this report.

the M512 facility to pass the electromagnetic interference tests. The second modification involved redesigning the M555 storage container's heating blanket to allow the M555 experiment to pass its low temperature test.

One problem that kept recurring throughout the qualification tests involved the electron beam gun high voltage power supply. This problem manifested itself by repeated arc-outs of the gun when first turned on, causing damage to resistors, capacitors, diodes and transformers in the high voltage supply. Although the damaged hardware was repaired after each failure, the cause of the failure could not be diagnosed. It was thought that the filament of the gun (at -20,000 volts) was arcing to the anode (ground potential), but even installing higher rated components did not solve the problem.

It was not until December 1972 that it was found that the cause of the problem was a grid-to-anode arc-out. A modified circuit was designed, tested and found to eliminate the problem. This circuit modification was installed in all M512 hardware.

#### B. Reliability Verification

All M512 hardware was designed so that its probability of performing as intended was 0.997 or better. Based on the failure modes and effects analyses, single failure point summaries, and the failure modes and criticality effects analyses performed on the facility and experiments, the confidence level probability of the facility and experiments performing the required functions under the defined conditions at the designated time for the specified operating period was as follows:

1. M512 - 0.9974
2. M551 - 0.999511
3. M552 - 0.999963
4. M553 - 0.999509
5. M554 - 0.999901
6. M555 - 0.998648
7. M479 - 0.999

#### C. Acceptance Verification

Prior to hardware delivery, the flight unit was subjected to acceptance testing. The procedures used to perform these tests were:

1. 70TP1-95M10500      Materials Processing in Space  
Experiment M512 Verification  
Test Procedure
2. 83TP1-95M10001-900      M512 Vacuum and Pressure Test Procedure
3. 95M10900      M512 Facility and Hardware Electrical  
and Optical Functional, Acceptance,  
and Systems Checkout Procedures

Two hardware modifications were required as a result of the acceptance tests. One involved the addition of three sealing clamps to the work chamber hatch; it was found that six clamps were required to prevent leakage between the hatch and work chamber. The second modification required redesign of the water quench metering system. The original bellows design of the water quench system was replaced with a cylinder-plunger type water dispenser to improve the reliability of the system. These redesigns allowed successful completion of the acceptance test program.

#### D. Ground Support Equipment

Numerous items of specially designed ground support equipment (GSE) were required for M512 assembly checkout, acceptance tests, and user site testing. The following list identifies the major pieces of M512 GSE.

|          |   |
|----------|---|
| 95M10810 | M512 Shipping Container                             |
| 95M10820 | M555 Shipping Container                             |
| 95M10850 | M512 Vacuum System for KSC Operations               |
| 95M10870 | M512 Honeycomb Panels Shipping Container            |
| 95M10875 | M512 Vacuum System for McDonnell Douglas Operations |
| 95M10877 | Flight Sample Shipping Container                    |
| 95M10901 | M512 Optical Alignment Fixture                      |
| 95M10930 | M512 Electrical Checkout Box                        |
| 95M10980 | M512 Orbital Welder EB Gun Container Assembly       |
| 95M10985 | M512 EB Welder Filament Calibration Unit            |
| 95M11520 | M512/M555 Thermocouple Simulator                    |
| 95M11530 | M555 Container Checkout Unit                        |
| 95M11830 | M512 Power Housing Purge System                     |
| 95M11940 | M512/M555/M479 Electrical Checkout Box              |
| ---      | M479 Sequence Timer Checkout Box                    |
| HT15287  | M512 Hoisting Tool                                  |
| 253C372  | EB Gun Removal Tool                                 |



## SECTION V. MAN/MACHINE INTERFACES

A major consideration in the design and development of the M512 facility was the man/machine interface requirements. Man was a major element in the success of the Skylab Program, and in particular of the materials processing experimentation. The presence of the astronaut enhanced the system hardware performance and guaranteed achievement of nearly 100 percent of the planned experiment objectives. The flight crews provided design inputs throughout the development program to increase the "workability" of the M512 facility systems, to save time in task performances, and most importantly to become personally involved in the materials science research program and thereby aware of the importance of the M512 experimentation. The significance of this last statement became apparent in the first Skylab mission when it appeared that scheduling priorities might preclude the performance of M512 experiments. An interest in the program and a desire to operate the facility prompted Commander Conrad to request permission to perform the M512 experiments, even if it required that these experiment be done on his own "free time". A similar situation occurred on the last Skylab mission, when Commander Carr worked on his own time and late into his scheduled sleep periods to complete the M479 performances prior to the scheduled deadline for experimentation during final Skylab deactivation. These actions were the major impetus to the ultimate completion of all the M512 experimentation on Skylab.

The following paragraphs outline the man/machine requirements and crew involvement in the facility design and development phases.

### A. Design Requirements

Concurrent with establishment of the Skylab dry workshop concept in 1969, a concerted effort was initiated to firmly define the man/machine interfaces. Prior to this time, there was no definition of astronaut design requirements. Specific crew system documentation was included in the following documents that established mandatory development criteria:

- |                            |   |
|----------------------------|---|
| 1. MSFC RS003M00003        | Cluster Requirements Specification  |
| 2. MSFC 10M32447A          | Human Engineering Design Requirements for AAP Experiments   |
| 3. MSFC 10M32158A          | Man/System Design Requirements for Orbital Workshop, Multiple Docking Adapter, Airlock Module, and Apollo Telescope Mount |
| 4. MSFC-STD-267A           | Human Engineering Design Criteria   |
| 5. MIL-STD-1472 (DOD)      | Human Engineering Design Criteria for Military Systems, Equipment, and Facilities   |
| 6. End Item Specifications |   |

## B. Design Verification

In addition to documented requirements, specific requirements evolved and were recognized as a result of active participation by flight crew members in reviewing and monitoring the M512 design progress. Frequent formal crew reviews were held at MSFC and contractor facilities and included at least one prime crew member. Crew participation occurred both as designated crew review meetings and as crew review portions of system design reviews.

The accumulative inputs from the crew increased the effectiveness of the facility from a human factors standpoint and gave the astronauts the interior arrangement and man/machine interfaces they desired. The crew participated in the following M512 reviews:

- |                  |  |
|------------------|--|
| 1. June 1967     | Astronaut Critique of Electron Beam Gun  |
| 2. June 1968     | M492/M493 Preliminary Design Review (PDR)  |
| 3. March 1970    | M512 Crew Station Review (CSR)   |
| 4. April 1970    | M512 PDR   |
| 5. December 1970 | M512 Critical Design Review  |
| 6. December 1971 | MDA Crew Compartment Fit and Function<br>Reviews (C <sup>2</sup> F <sup>2</sup> ) at Martin Marietta, Denver<br>Division |
| 7. March 1972    | M512 CSR <sub>2</sub> and C <sup>2</sup> F <sup>2</sup> at MSFC  |
| 8. May 1972      | AM/MDA C <sup>2</sup> F <sup>2</sup> at McDonnell Douglas, St. Louis   |
| 9. March 1973    | Skylab C <sup>2</sup> F <sup>2</sup> at KSC  |

Also, three operational and two mockup systems were built for crew training and procedures verification. The development laboratory at MSFC used the operational qualification unit for establishment of crew procedures and a mockup unit was provided for MSFC crew system personnel. An operational system and a mockup system for the MDA trainer were delivered to JSC to be used for crew training. In addition, an operational system was developed and used on KC-135 zero-gravity simulation flights for procedural and design verification.

## SECTION VI. OPERATIONS ANALYSIS

### A. Flight Operations Summary

This summary presents discussions of facility and experiment operations and an evaluation of the hardware performance for each Skylab mission during which they were operated.

#### 1. M512 Materials Processing Facility.

a. Facility operations. One crewman was required for facility and experiment operations. Operation of three experiments (M551, M553 and M479) required continuous crew participation; however, the other experiments' operations were essentially automatic after initial setup. A detailed discussion of each experiment's performance is included in individual experiment paragraphs of this section. Crew procedures for the facility verification and all experiment sequences were included in the MDA Experiment Checklist and Log. The typical operational sequences for an experiment utilizing the facility are summarized in the following paragraphs.

The experiment preparation sequence was essentially the experiment equipment installation and preparation of the facility for experiment operation. The procedure involved experiment hardware transfer and installation in the work chamber with the required facility accessory hardware (e.g., mirrors, filters, etc.). During experiment preparation, the data acquisition camera was attached to the camera mount on the work chamber exterior face for those experiment operations involving photography. The control and display panel switches were properly configured for the particular experiment operation and the chamber repressurization valve was closed.

The experiment operational sequence included the crew procedures required to operate that particular experiment. The vacuum work chamber was vented to space vacuum and after the desired vacuum level was obtained, the crewman initiated the experiment performance. Following the experiment performance, the chamber was repressurized by closing the two vacuum vent valves and then opening and closing the repressurization valve.

The experiment termination sequence was the removal and stowage of the experiment and facility hardware. The experiment samples and film were stowed for return. The facility controls and valves were

returned to pre-operational positions. The work chamber hatch was closed and latched.

(1) SL-1/2 operations. The facility verification was performed at 1353 GMT, June 11, 1973, before any experiment performances. The facility verification was performed once during a mission and was essentially a post-launch inspection of the facility condition and switch configuration.

The first experiment performed was M551 (Metals Melting) on June 12 and 13. Experiment M553 (Sphere Forming) performances were accomplished on June 13 through 15. Experiment M552 (Exothermic Brazing) was performed on June 15 and 16. Following the M552 operations, the M512 battery discharge was initiated on June 16. More detailed experiment timeline information is presented in the following individual experiment discussions.

Experiment M555 (GaAs Crystal Growth) was planned to be performed during SL-1/2. However, the experiment was first postponed and eventually cancelled from the Skylab Program due to mission-level constraints (see subsection A.5 following).

(2) SL-3 operations. The facility was not originally planned for use during the SL-3 mission. However, late in that mission, crew time became available and the M518 experiments, scheduled for SL-4, were performed on SL-3. The M518 multipurpose electric furnace and its associated experiments utilized the M512 facility.

(3) SL-4 operations. Experiment M479 (Zero-Gravity Flammability) was performed on February 4, 5 and 7, 1974. For details on the M479 operational sequence, refer to subsection A.6. Several M518 experiments were resupplied and performed again on SL-4.

b. Hardware performance. This paragraph includes the performance of facility subsystems and facility hardware items that were used during the operations of more than one experiment. As an example, the electron beam subsystem was used for M551 and M553 experiment operations and is therefore evaluated in the M512 facility section.

(1) SL-1/2 performance. Experiment operations (M551, M552, M553) during the first mission required the most extensive use of the M512 facility subsystems and hardware during the Skylab Program. This operation of experiments M551 and M553 constituted the only electron beam subsystem used during the Skylab Program. On SL-1/2, the M512 battery was utilized as the power source. Essentially all the hardware items (except the M479 items) stored in the equipment storage container were used at least once during this mission.

The facility performed as designed with two exceptions:

(a) Time-to-vacuum. Pre-mission time estimates were basically analytical in nature, since actual time-to-vacuum data had never been obtained during a manned mission. An estimate of 30 minutes to reach the desired pressure level of  $1.33 \times 10^{-2}$  newtons per square meter ( $1 \times 10^{-4}$  torr) was used to establish pre-mission experiment timelines. During the first chamber evacuation for performance of M551, approximately 2.5 hours were required to obtain this vacuum level. A substantial amount of outgassing was expected during the initial chamber evacuation; however, the increased time may indicate that the space vacuum pumping ability of the immediate Skylab environment was not as efficient as predicted. The situation did not affect the performance of M551 and is not considered a facility anomaly.

At 1500 GMT on June 12, the crew stated that they were "not getting any reading on the filament chamber pressure meter", but the work chamber pressure gauge showed a zero reading. The work chamber pressure gauge registered from  $1 \times 10^5$  to zero newtons per square meter (15 to zero pounds per square inch) pressure, and the crew later related that this gauge went to zero immediately after the vacuum vent valves were opened. The filament chamber pressure gauge (vacuum gauge) registered from  $6.7 \times 10^{-1}$  to  $1.33 \times 10^{-3}$  newtons per square meter ( $5 \times 10^{-3}$  to  $1 \times 10^{-5}$  torr), utilizing a sensor located in the electron beam filament chamber, while the work chamber pressure sensor was located in the work chamber itself. The vacuum gauge sensor was located in that position because the vacuum level was more critical in the filament chamber for the electron beam gun activation/operation than to experiment operations in the work chamber.

The filament and work chambers were connected by a 1.9 centimeter (0.75 inch) diameter line with a valve (filament chamber vent valve). As a result of this configuration, a time lag was expected between a zero pressure reading on the work chamber pressure gauge and the activation of the filament chamber pressure gauge. This proved to be the case in this situation because, at 1744 GMT on June 12, the crew stated that the filament chamber pressure gauge "was just very slow coming on line", but that the proper pressure level was obtained and M551 operations had begun.

Each of the two subsequent pump-downs for the remaining M551 samples required approximately 1 hour. The first M553 specimen wheel was installed in the work chamber prior to the June 13 sleep period. The work chamber was evacuated during the sleep period to establish a good vacuum for the first M553 operation early in the next crew workday. As a safety precaution, the vent valve configuration during sleep periods was one valve in the fully OPEN position and the other valve in the VENT position (90 percent closed). On June 14, the crew stated that the vacuum gauge reading was  $1.33 \times 10^{-3}$  newtons per

square meter ( $1 \times 10^{-5}$  torr), which was the best vacuum obtained in the chamber during the Skylab missions.

During the M553 operations, the vacuum problem continued, with extra evacuations in excess of 1 hour required after melting only one or two M553 samples. Crew checklists and timelines had been formulated with the assumption that the pressure increase that occurred during sample melting would be easily removed between sample operations. However, it appeared that the pressure continued to increase to a point where the crewman had to interrupt operations after only a few samples to allow the chamber vacuum to be reestablished before continuation. These longer and more frequent delays to reestablish the desired vacuum impacted the mission timelines, and ultimately led to an early termination of the second M553 specimen wheel to assure sufficient time for the performance of M552.

(b) Electron beam gun operation. The M512 electron beam gun failed to turn off when the READY/RESET switch was operated to terminate operations after the third and last M551 sample on June 13. This anomaly also occurred intermittently during the M553 performances. The situation was continuously monitored, malfunction isolation analysis performed, and several work-around procedures formulated. These procedures enabled successful completion of all M553 samples, except those not processed due to the time-to-vacuum constraints just discussed. See subsection B for a discussion of the EB gun anomaly.

(2) SL-3 performance. The M518 multipurpose electric furnace system utilized the M512 facility during this mission. The M518 system is not evaluated in this report; however, the M512 facility involvement in the M518 operations will be discussed at this time.

The M518 system operated essentially independently of the M512 facility after installation, with the only requirements on the facility being establishment of a proper vacuum and activation of the facility vacuum gauge for pressure verification.

There was no requirement for the crew to record the time-to-vacuum for the M512 or M518 experiments. However, to obtain a second data point, the crew was asked to record the time-to-vacuum for experiment M562 (the second experiment in the M518 series). The crew reported that only 9 minutes were required to reach  $6.7 \times 10^{-2}$  newtons per square meter ( $5 \times 10^{-4}$  torr) as compared to a premission estimate of approximately 30 minutes. It should be noted that the greater amount of hardware outgassing would have occurred during the initial chamber evacuation (after the installation of the M518 furnace) rather than between experiment operations (when this data point was taken), but the initial evacuation times were not recorded.

(3) SL-4 performance. The M512 facility support of M518 operations was the same on this mission as on SL-3, and all support requirements were met. It is interesting to note that when time-to-vacuum was recorded on this mission, 45 to 90 minutes were required.

The last experiment operation performed was M479, zero-gravity flammability, and the facility performed satisfactorily during these operations. The problems associated with the water quench nozzle are discussed with the M479 experiment in subsection A.6.

## 2. M551 Metals Melting.

a. Experiment operations. Each experiment operation involved mounting a sample disk to the M551 drive assembly and installing this in the M512 work chamber.

Physically, the M551 experiment was performed in a conventional welding test manner. The melting process was accomplished by utilizing the electron beam as a heat source and rotating the metal disk through the beam path. The beam power was about 1.6 kilowatts and the sample disk was approximately 4 centimeters (1.5 inches) from the electron beam port.

The beam was initially aligned on a target which was a small piece of tungsten embedded in the sample. The disk was then rotated and the metal melted to some depth along the beam's track. The molten metal at the track center became superheated with a steep temperature gradient from the center to the edge of the molten metal pool. As the disk moved through the beam, the melted metal left behind solidified very rapidly since the rest of the plate served as an effective heat sink.

Following this welding operation, the sample disk was advanced to a prescribed position and the beam allowed to impinge on one spot (dwell) without sample rotation, for a predetermined time period. Motion pictures were taken of the entire melting process.

The M551 functional objective (FO) performances are summarized below:

F01 (Stainless Steel) - June 12, 1973, at 1740 GMT  
F02 (Aluminum) - June 12 at 2223 GMT  
F03 (Tantalum) - June 13 at 0030 GMT

These times are approximate, based upon crew real-time comments, voice recorded data and the published flight plan.

b. Hardware performance. The M551 hardware operated as designed with one exception. As the crewman prepared the chamber for



the first M551 operation, he made the following report:

"I can't account for this because I know that it was fit about ten times, but the mirror (M551 deflection mirror) over the electron beam gun would not fit today because the electron beam must have shifted during launch, that is the only thing that I can think of. Now is there any way that thing can move around in there or move in its adjustments, because the mirror, I got the mirror on it and you can see through it OK by just using one screw (Calfax fastener), but it lacks fitting by a good one-eighth of an inch to the other screw because it interferes with the electron gun . . . I welded the plate OK, it's all right . . . we took photographs of it."

Malfunction analysis was immediately performed on the qualification unit at MSFC. It was concluded that the problem did not involve any movement in the electron beam gun, but rather that the flight unit deflection mirror frame was improperly assembled. This assumption was proved correct by examination of the photograph (see figure 95) taken by the crew to record this situation. The photograph shows that the upper Calfax fastener is aligned as evidenced by the black alignment marks; however, the lower Calfax fastener did not align with its mounting hole, as described by the crew. The reason for this clearance problem is that the left edge of the mirror frame assembly is resting against the electron beam housing (center of photograph); therefore, the lower Calfax fastener cannot be positioned far enough to the left to align with the hole. The notch machined into the right edge of the mirror frame was designed to fit over the electron beam housing to avoid this interference problem.

The crew was correct when they stated that several fit checks had been performed; however, after the final M512 checkout at KSC, test mirrors were replaced by the flight mirrors. The deflection mirror frame had to be disassembled to accomplish this replacement, and the frame was reassembled upside-down, or with the notch facing opposite the electron beam gun housing. This situation was not considered an anomaly, since all M551 operations were completed with no problems.

Crew observations of the experiment performance were voice-recorded during the mission. In addition, crew comments on the experiment were made during the SL-1/2 Crew Debriefing (July 6, 1973).

### 3. M552 Exothermic Brazing.

a. Experiment operations. The M552 experiment operations involved package installation into the M512 work chamber and chamber evacuation to space vacuum (zero pressure on the work chamber

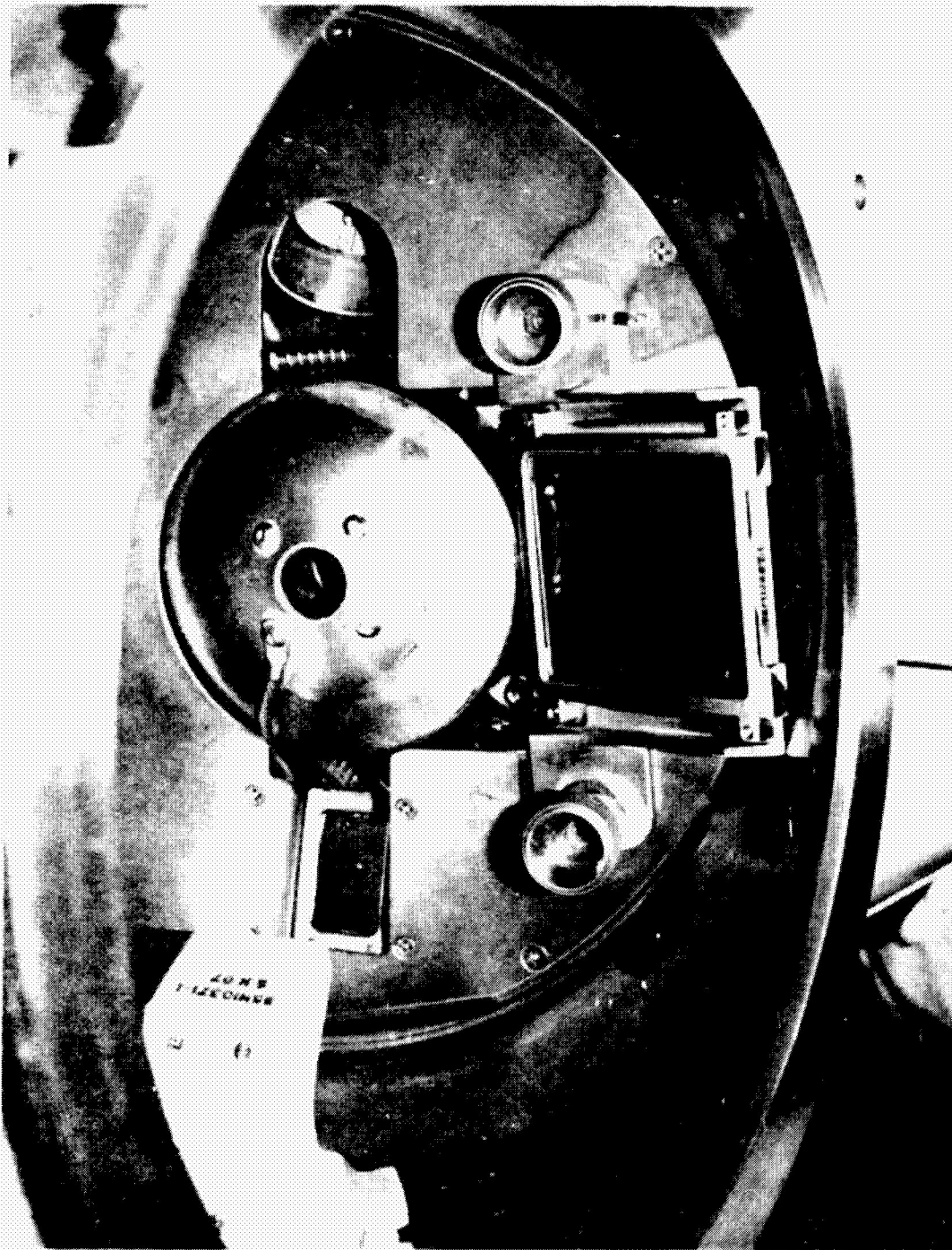


FIGURE 95. M551 DEFLECTION MIRROR INSTALLATION DURING SL-1/2

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vacuum gauge). The sample ignition was initiated by actuation of the control panel TRIGGER switch. Approximately 90 seconds were required for the complete reaction, with approximately 2 hours and 45 minutes required for sample cooling. Each sample ignition and cooldown was a separate functional objective. After package installation and sample 1 initiation, the crewman was only required to return at pre-determined times to initiate the remaining samples.

The M552 experiment operation was performed by the SL-2 crew as a shopping list item and not scheduled into the SL-2 timeline. All four M552 samples were completed. The approximate completion times were as follows:

F01 - June 15, 1973 at 1745 GMT  
F02 - June 16, 1973 at 0300 GMT  
F03 - June 16, 1973 at 0900 GMT  
F04 - June 16, 1973 at 1200 GMT

(Times noted above are approximate, based upon crew real-time voice comments.) The crew stated that the M552 terminate checklist was complete and the M512 battery discharge initiated at 2010 GMT on June 16.

b. Hardware performance. The M552 exothermic package performed as designed with no discrepancies.

#### 4. M553 Sphere Forming.

a. Experiment operations. The first specimen wheel (F01) was installed in the work chamber prior to the June 13, 1973 sleep period. The work chamber was evacuated to space vacuum during the sleep period to establish a proper vacuum for the first operation.

At 1500 GMT, June 13, the crewman reported that he had performed the initial electron beam gun alignment for operation. He stated that the vacuum had reached  $1.33 \times 10^{-5}$  newtons per square meter ( $1 \times 10^{-5}$  torr) in the work chamber, but that he had experienced difficulty in performing proper alignment and that outgassing was causing the vacuum level to degrade. The possible outgassing cause was discussed and it was concluded to be a normal situation due to the tungsten target outgassing level. In addition, any contamination ionization on the sphere forming assembly could also have caused vacuum degradation.

The 16 millimeter film coverage of the operation began with the third permanently mounted sample and it is not clear why there was no film coverage of the tungsten target alignment and the first two sample melting operations. However, a film review of the first specimen wheel did indicate that the electron beam was aimed too close to the sample mounting sting interface.

F01 operations were started at 1615 GMT, June 13. The crew, reporting (1701 GMT) on the first specimen wheel operation, described the successful completion of the first three samples and stated that the electron beam gun automatically turned off after 1 second of the normally 5 second melt time on the fourth sample. The flight films revealed that the electron beam struck the ceramic post, which could have melted the nichrome wire inside the post, resulting in automatic electron beam cutoff. The crew reiterated that the vacuum level continued to degrade during electron beam gun operation. They stated that whenever the filament chamber pressure gauge reading approached  $1.33 \times 10^{-2}$  newtons per square meter ( $1 \times 10^{-4}$  torr), they would terminate electron beam gun operation in accordance with the checklist and wait for the pressure level to decrease.

Experiment operations on specimen wheel 1 were completed at approximately 1300 GMT, June 14, and specimen wheel 2 operations were begun at approximately 1749 GMT, June 14. After completion of seven samples, F02 operations were terminated at 0022 GMT June 15 to allow time for experiment M552 to be performed.

b. Hardware performance. The hardware operated essentially as expected, with two minor exceptions. The first exception involved the sample release and early beam cutoff already discussed in paragraph 4.a. The second exception concerned the sample retrieval method. The crew reported during the crew debriefing that the samples that did release from the wheel were found attached to the motor housing instead of in the sphere catcher. The vacuum cleaner retrieval method did not pull any samples into the sphere catchers. The crew had to manually retrieve all the samples and place them into the sphere catchers. The most likely cause is that the motor created enough magnetism to attract the floating metal spheres.

##### 5. M555 GaAs Crystal Growth.

NOTE: Experiment M555 was not performed during the Skylab Program. This discussion is included for information pertaining to the experiment and documents the reasons why it was not launched.

a. Experiment operations. The operational sequence would have involved the furnace removal from the launch container and insertion into the M512 chamber heat sink cavity. The furnace was to be connected using the zero-g connector, and experiment operation initiated by activation of a control panel switch. The subsequent operation time (115 hours) would not have required crew participation.

(1) SL-1/2 operations. The hardware was scheduled to be launched in the SL-2 Command Module and performed in the M512 chamber during this mission. However, due to the SL-1 launch anomaly, the launch

container was removed from the SL-2 CM to provide additional launch space for the contingency equipment.

(2) SL-3 operations. Approval was obtained for launch and performance of M555 on the SL-3 mission, and the launch container was stowed in the CM. However, at the SL-3 Flight Readiness Review on July 24, 1973, the container was deleted to allow easier stowage of the contingency rate gyro "six-pack" hardware.

(3) SL-4 operations. The hardware was included on a priority list for launch in the SL-4 CM; however, the hardware was not launched on SL-4. The experiment hardware is currently stored at MSFC in the event that a future program may provide an opportunity for performance.

#### 6. M479 Zero-Gravity Flammability.

a. Experiment operations. A typical M479 experiment operation involved the installation of a sample on the sample holder and connection of this assembly to the zero-g connector in the work chamber. The work chamber had been filled with cabin air and the chamber repressurization valve was closed. The sample identification (ID) number was recorded on the film by activation of the SAMPLE ID switch. Sample ignition occurred when the DATA START switch was activated and the camera automatically ran for the time period preset on the control panel.

Sample extinguishment was accomplished by one of three methods: self-extinguishment or sample burnout by itself; vacuum quench or opening of the vent line to space vacuum; or water quench (i.e., spraying) of the sample with 0.06 liter (2 ounces) of water. An additional photograph of the sample was taken after the burnout or extinguishment was completed.

The M479 operations began on Mission SL-4, February 4, 1974, at 1340 GMT. All 37 operations were scheduled during one crew day; however, due to other priority operations, the crew was able to finish only samples 1 through 30 during this time.

Samples 1 through 12 consisted of two samples of each material that were allowed to burn undisturbed to test for self-extinguishment. Samples 13 through 18 consisted of one sample of each material that tested the vacuum mode of extinguishment. Samples 19 through 24 tested the water quench extinguishment mode and the effects of water impingement on the sample. It was during sample 21 operations that the crew made the following report:

"Okay, I'm trying to do it right now. I've done samples 19 and 20, and the water-quench system is not working properly . . . the lower nozzle appears to be completely

plugged. And I just don't have time to mess with it to try to unplug it. The upper nozzle just sends out a dribble rather than a nice spray. So what I've done is I've gone back and completely reserviced the system again, and we'll try it over again."

That report was made at 0119 GMT, February 5, and was the last scheduled conversation with the crew that day.

It was concluded from data given that air may have been present in the water system or umbilical and reservicing should correct this situation. No malfunction analysis was performed since there was no crew contact after this report was made.

However, the recorded tapes received the following morning related that the crew continued to experience this problem with the water system. The crewman reported that he finished water-quench samples 19 through 24 and samples 25 through 30 before retiring at approximately 0300 GMT, February 5. Samples 25 through 30 were only partially supported by the mounts, to observe the paths and rates of float as the sample material burned away from the specimen mount.

There were no plans to complete testing the remaining seven samples; however, on February 7, the crewman finished testing the last samples on his own time. These samples (samples 31 through 37) tested "flashover" between two sample material strips that were separated by gaps of various dimensions; 0.3, 0.6, and 1.3 centimeters (1/8, 1/4 and 1/2 inches).

The following list summarizes the sample operation times:

Sample 1 - 1340 GMT, February 4, 1974  
2 - 1409 GMT, February 4, 1974  
3 - 1447 GMT, February 4, 1974  
4 - 1502 GMT, February 4, 1974  
5 - 1516 GMT, February 4, 1974  
6 - 1527 GMT, February 4, 1974  
7 - 1545 GMT, February 4, 1974  
8 - 1552 GMT, February 4, 1974  
9 - 1600 GMT, February 4, 1974  
10 - 1927 GMT, February 4, 1974  
11 - 1942 GMT, February 4, 1974  
12 - 1952 GMT, February 4, 1974  
13 - 2021 GMT, February 4, 1974  
14 - 2028 GMT, February 4, 1974  
15 - 2035 GMT, February 4, 1974  
16 - 2051 GMT, February 4, 1974  
17 - 2117 GMT, February 4, 1974  
18 - 2126 GMT, February 4, 1974

19 - 0055 GMT, February 5, 1974  
 20 - 0114 GMT, February 5, 1974  
 21 - 0134 GMT, February 5, 1974  
 22 - 0142 GMT, February 5, 1974  
 23 - 0155 GMT, February 5, 1974  
 24 - 0214 GMT, February 5, 1974  
 25 - 0230 GMT, February 5, 1974  
 26 - 0236 GMT, February 5, 1974  
 27 - 0240 GMT, February 5, 1974  
 28 - 0258 GMT, February 5, 1974  
 29 - 0301 GMT, February 5, 1974  
 30 - 0306 GMT, February 5, 1974  
 31 - 0258 GMT, February 7, 1974  
 32 - 0303 GMT, February 7, 1974  
 33 - 0306 GMT, February 7, 1974  
 34 - 0310 GMT, February 7, 1974  
 35 - 0314 GMT, February 7, 1974  
 36 - 0319 GMT, February 7, 1974  
 37 - 0323 GMT, February 7, 1974

b. Hardware performance. All M479 hardware performed as designed, with the exception of the water quench system. There was no opportunity to perform any water-quench malfunction isolation. However, the following morning, the problem was discussed with the Skylab water management personnel. They stated that the records indicated that the water tank to which the umbilical was attached had not been pressurized (with nitrogen) since the SL-1/2 mission. The SL-4 crew procedures did not require a check of this system because pre-mission planning was based upon that tank being pressurized. Therefore, it was concluded that insufficient tank pressure caused the water-quench problem.

The crew was able to work around the problem to some extent by utilizing the accumulator hand pump located on the water-quench accumulator top. This accumulator pump was designed to assure that the accumulator contained sufficient water prior to the first water-quench operation. The crewman's hand pump use provided sufficient water pressure to obtain some water-quench data on at least two samples. This problem was not considered a hardware anomaly.

#### B. Hardware Anomalies

The M512 electron beam anomaly was first reported at 0038 GMT on June 13, 1973, after the "dwell" sequence (electron beam fixed on one point) on the third M551 sample, when Skylab Commander Conrad made the following voice transmission (with some terminology corrections):

"On the third plate, when I got to the cross and was doing the pooling (dwell), at the end of the amount of time for the electron beam gun to be on, I hit the ready/reset switch



to turn it off and it would not turn off. So I reached up and turned off the fil/beam power switch. This shut the beam off, but I could hear something clicking away back by the battery; the X5KV meter was still on for some reason. The only way I could get this shut off was to pull the main batt cb. Went through malfunction procedures - zero. Plugged main batt cb back on and sure enough the X5KV was still on. Turn on the fil/beam power switch and that turned the X5KV meter off. About that time, the electron beam came on by itself; so I decided a relay was sticking or something. I pulled the fil bat cb this time and reset it, and that action reset everything that was wrong in there. I finished the specimen."

Malfunction isolation to one component could not be completed with the data available from this voice communication. A work-around procedure and a malfunction isolation procedure were developed at MSFC for uplink to the crew after their sleep period on June 13. Assuming that the third M551 specimen remained in the chamber (per flight plan), it was concluded that the electron beam gun condition could be determined on June 13 for M551 termination and stowage. The following recommendations were made concerning implementation of the procedures:

1. Perform the procedures on the M551 specimen still in the chambers.
2. If the electron beam gun operates normally, proceed with M553 operations per crew checklist.
3. If the electron beam gun malfunctions, proceed with malfunction isolation procedures. It should be performed to obtain the information required to support a proper decision on further operations of the M553 and M552 experiments.

However, when the crew was contacted, Commander Conrad reported that he had already removed the M551 sample and installed the first M553 sample. The procedures were revised for implementation during the M553 operation.

Commander Conrad stated that he had already begun with M553 alignment. The electron beam gun operated normally and the crew was informed that M553 operations should be continued using the normal crew checklist. The electron beam gun operated normally for the first five M553 samples on specimen wheel 1. The malfunction reoccurred at this time and malfunction procedures were again formulated. Commander Conrad continued to perform the M553 operations, completing the first specimen wheel and seven of the 14 samples on the second wheel. The malfunction occurred intermittently and Conrad used alternate procedures to shut off the beam at these times.

1. Discussion of Electron Beam Circuit Operation. There are three means of de-energizing the electron beam welder dc to dc power supply, see figures 96 and 97: (a) the fast cutoff circuit, (b) relay K3, and (c) the MAIN BATTERY circuit breaker. Upon initiation of an "off" signal, the fast cutoff circuit should normally switch off +28 Vdc battery power to the power transistor driver transformer and stop current flow to the main power transistor bases. This action is initiated in about 10 to 20 microseconds after the de-energization signal (READY/RESET) is generated, and the -20 kV output voltage will start to decay. Input current from the 28 Vdc battery is switched off in about 1 millisecond except for the basic oscillator which draws 1.5 to 2 amperes. The fast cutoff circuit also operates relay K501 which de-energizes relay K7 to open-circuit the control circuit, de-energize the coil of relay K3, and completely remove all power from the basic orbital welder 28 to 20 kV dc to dc converter. The exception is the electron beam gun filament supply which is switched off manually via the FIL/BEAM CONT switch. Relay K3 removes all current to the 28 to 20 kV dc to dc converter in 10 to 20 milliseconds to completely turn off the power supply and oscillator. Of course, opening the MAIN BATTERY circuit breaker removes all battery power from the controls, EB power supply, oscillator, and the EB gun filament supply. The high voltage 28 to 20 kV dc to dc converter electronic components can be damaged due to a large rise in output voltage (greater than -40 kV) if the filament power is removed and the dc to dc converter power is left on. The worst case is if the high volt power supply is turned on without having first heated up the EB gun filament for at least a few seconds. In this case, arcing will almost certainly take place within the high voltage power supply. In the past, this mode of operation has caused permanent damage to high voltage components and could create arcing paths from high to low voltage surfaces or terminals.

a. Fast cutoff circuit operation. Action of the fast cutoff circuit is as follows, refer to figure 96. If the EB power supply is operating and the READY/RESET switch, FIL/BEAM CONT switch, Filament Chamber Valve Interlock switch, or the M553 sting interlock switch (see figure 96) are opened, a pulse is generated on the secondary of transformer T501 and a pulse is transmitted to the gates of silicon controlled rectifiers (SCR's) Q506 and Q108. Q108 shorts the base of Q109 to ground to switch off power to the power transistor driver, and reduces the current through the main relay K3 contacts from approximately 90 amperes to approximately 2 amperes. In the meantime, SCR Q506 has triggered and initiated energization of relay K501 to de-energize relays K7 and K3.

b. Backup cutoff circuit operation. Should the fast cutoff circuit malfunction and fail to initiate fast cutoff K3 opens and breaks about 100 amperes rather than the desired 2 amperes. Also, if the fast cutoff and K3 fail to operate properly, the MAIN BATTERY circuit breaker must be opened to shut off the EB power supply.

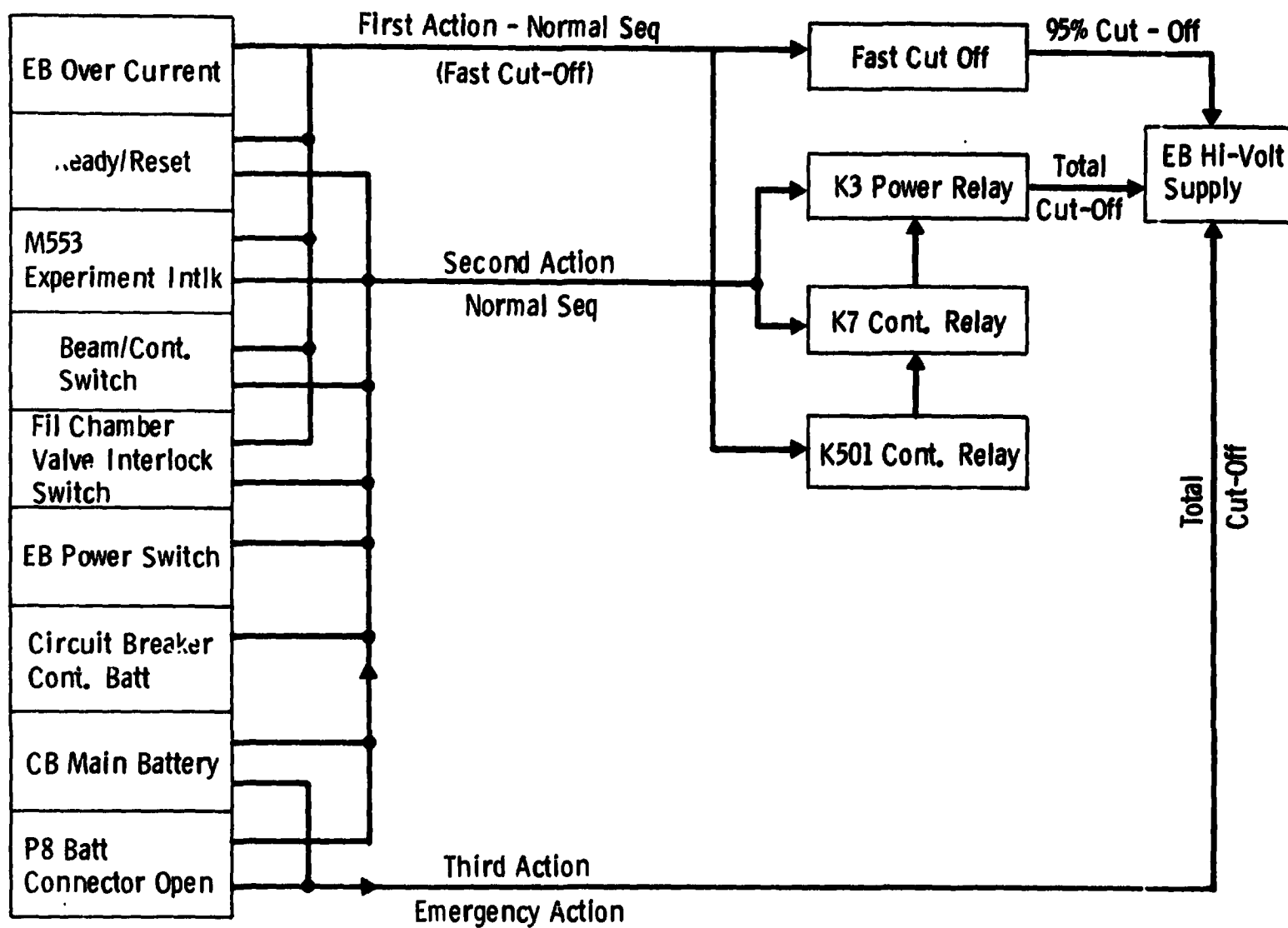


FIGURE 96. CONTROLS TO SWITCH OFF ELECTRON BEAM HIGH VOLTAGE SUPPLY

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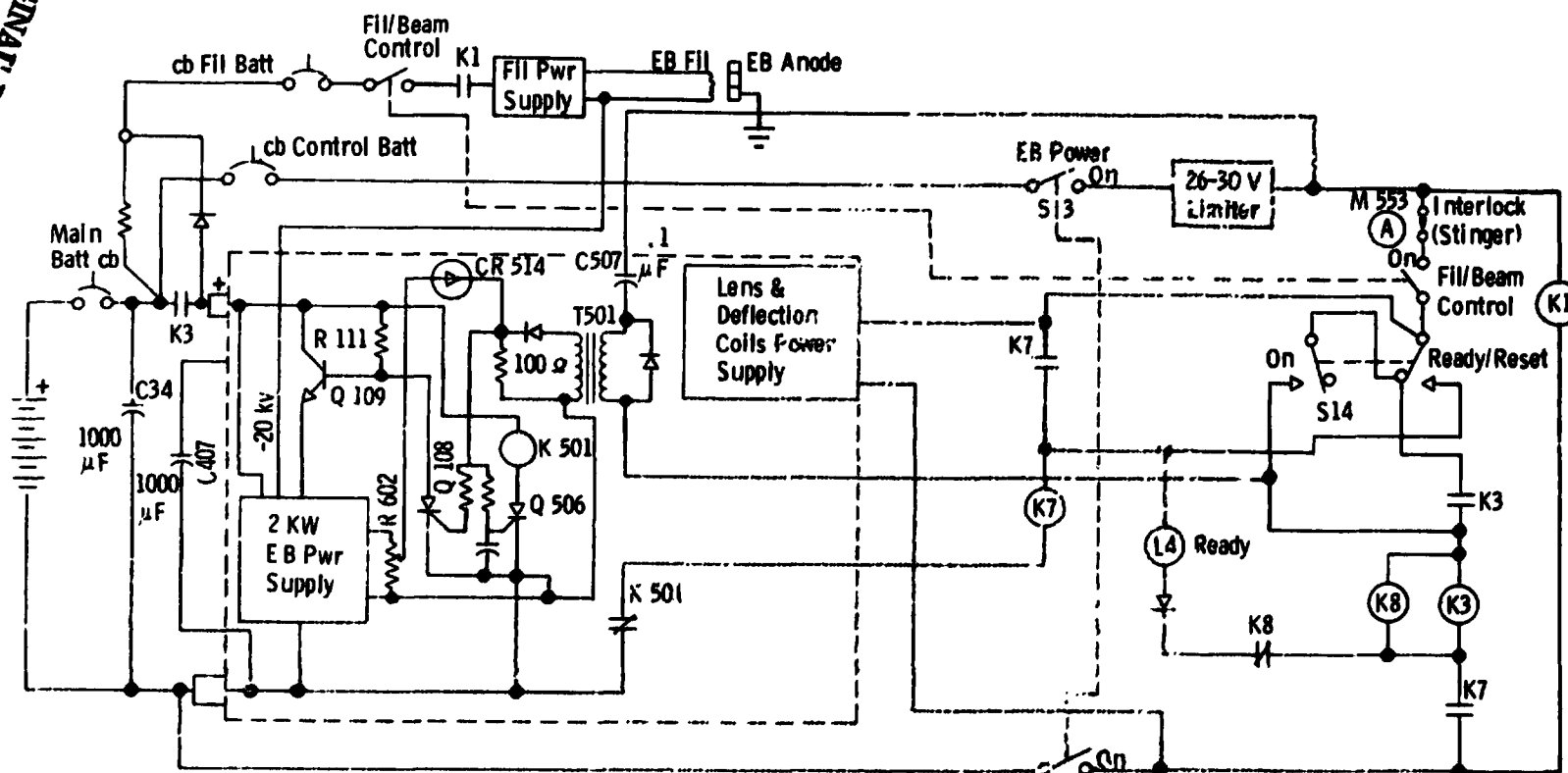


FIGURE 97. SIMPLIFIED ELECTRON BEAM SCHEMATIC

2. Problem on Skylab. With this basic understanding of the EB cutoff circuit operation, a review was made to ascertain the equipment malfunctions from Commander Conrad's malfunction report of June 12, along with his answers to questions posed at the SL-1/2 debriefing held July 6, 1973. Commander Conrad initially reported that the READY/RESET switch did not turn off the EB power supply, and the electron beam continued. A review of figure 97 indicates the following most likely candidates which could cause failure of the EB power supply and beam to cut off normally:

- 1.a. No fast cutoff initiation.
- 1.b. Relay K3 stuck closed.
- 1.c. Possible READY/RESET switch malfunction
- 1.d. K7 relay stuck closed.
- 1.e. K501 relay stuck closed.
- 1.f. Shorted capacitor C507.

Next, Commander Conrad reported that he turned off the FIL/BEAM CONT switch. The electron beam switched off since the EB filament was turned off, but the EB power supply continued to operate as evidenced by a reading on the high-voltage meter (Conrad called it X5kV meter). Had relay K7 been stuck closed or had the READY/RESET switch contacts been stuck closed, opening the FIL/BEAM CONT switch would have removed power to the K3 relay coil and de-energized the EB power supply. This series of events reduces the more probable malfunction causes to:

- 2.a. No fast cutoff initiation.
- 2.b. Relay K3 sticking closed (mechanical bind or contacts welded).
- 2.c. No fast cutoff and capacitor C507 simultaneously shorted but relay K3 OK.

It is almost certain that fast cutoff was intermittent, as will be explained later. Relay K3 could have been stuck, but neither failure of the fast cutoff circuit nor a sticking relay would necessarily be the source of the clicking sound Conrad reported. The clicking sound near the battery could have been relay K3, but only condition 2.c., above, could even begin to explain the clicking unless a loose or shorted wire entered into the picture. A loose wire seemed unlikely based on later events. With the FIL/BEAM CONT switch open, the only logical source of control power to the coil of relay K3 is through a shorted 0.1  $\mu$ F blocking capacitor C507 and transformer T501. Both components are located in the Westinghouse EB power supply. In

this case, relay K7 would be energized via the normally open contact of K3, the READY/RESET switch, K7's own normally open contact, and K501. This condition could cause K3 relay to oscillate under precisely the correct amount of shorted resistance of capacitor C507. In fact, this theory was tested on a breadboard EB unit, but it appeared to be too critical in terms of the necessary resistive value of C507 to be considered. Besides, the next event almost eliminates this malfunction as a candidate altogether.

The more probable source of the reported clicking sound was either noise generated by main transformer T201 or high-voltage arcing inside the electron beam canister. This noise, or arcing, would be due to the high-voltage supply output becoming open-circuited when the FIL/BEAM CONT switch was turned off. Next, Commander Conrad opened the MAIN BATTERY circuit breaker. This event turned off everything. However, upon reclosing the MAIN BATTERY circuit breaker, the high-voltage supply came back on as indicated by the high-voltage meter. With the FIL/BEAM CONT switch open, there is no way to re-energize K7 or K3 without repeating the normal start-up routine. Yet, the -20 kV power supply restarted. The high voltage output was then open-circuited. This restart virtually eliminates possible cause 2.c because relay K7 would not be de-energized following complete power shutoff and a normally operating K3 would be blocked from energizing the EB power supply. This leaves causes 2.a. and 2.b. as prime suspects.

In the next event, Commander Conrad turned on the FIL/BEAM CONT switch with the -20 kV power supply already on. He reported the -20 kV meter then went to zero, but soon the electron beam came on (and the meter had to return to -20 kV). It is theorized that the unheated EB gun arced (shorted) to the anode when heating power was applied (FIL/BEAM CONT switch closed) to the EB filament, causing the output voltage to approach zero. However, due to an inactive fast cutoff protective circuit, the electron beam was finally established when the EB filament reached operating temperature. This time, Conrad pulled and reset the FIL BATT circuit breaker and the EB power supply turned off. If relay K3 had remained stuck, this FIL BATT circuit breaker cycling would not have turned off the -20 kV supply. Therefore, either noise or signal due to the high-voltage electrical transient created by cycling the FIL BATT circuit breaker must have finally activated the fast cutoff circuit. Relay K501 probably energized this time, causing sticking relay K3 to open normally. Later, during the operation of M553, Commander Conrad stated that the EB sometimes turned off normally and sometimes required opening the MAIN BATTERY circuit breaker. It was evident from the returned data acquisition 16 millimeter film that the M553 interlock switches located in the M553 pinwheel were working properly to cut off the electron beam when the specimens melted. However, those times relay K3 stuck closed, the electron beam impingement point was being transferred from the specimen to a tungsten protective plate behind the electron beam lens coil. This transfer took place from

the moment the specimen interlock switch (circle A in figure 97) released until the MAIN BATTERY circuit breaker was opened. This condition occurred because release of the interlock switch normally (1) turns off the EB gun, and (2) turns off the beam zig-zag and focus coils. This abnormal condition was verified on the M512 qualification unit, and would undoubtedly result in considerable tungsten outgassing near the EB gun filament and the vacuum gauge sensor. Therefore, heating of the tungsten plate in back of the lens coil would account for some of the vacuum problems reported during M553 operations. This M553 report from Conrad and the above analysis indicates that the most probable cause(s) of the erratic turnoff circuit were:

3.a. Erratic fast cutoff circuit activation.

3.b. Soft sticking or mechanical binding of K3 relay main contacts.

### 3. Circuit and Component Tests.

a. Breadboard tests. MSFC has tested its EB power supply breadboard to subject the K3 relay, a Hartman Company Model N419 per MSFC Specifications 95M10111-1 and 40M38626, to the conditions imposed by a non-active fast cutoff circuit (i.e., the relay breaking 100 amperes, inductive). This condition has been tested for 2000 on-off cycles, at least 10 times the number of operations of the flight unit relay, with no failure. Meetings have been held with personnel who were instrumental in the initial development of this family of relays for MSFC, and of course, with the Hartman Company. But no one has been able to pin-point the failure mode. This relay failure was random in nature and cannot always be duplicated on the bench even if the relay were available for test and analysis. There has been only one other such Hartman N419 relay failure on this program and that was during initial EB power supply testing at Westinghouse. That failure was traced to the use of iron washers on the main relay terminals, creating overheating and finally contact sticking. Of course, the proper hardware was installed in the flight hardware. This failure at Westinghouse occurred during maximum duration testing, and was ultimately responsible for the vendor adding the fast cutoff circuit to turn off the power transistors prior to relay K3 opening. Significantly, it was also found that the EB breadboard fast cutoff circuit failed to function about a third of the time due to marginal signal levels to silicon controlled rectifiers (SCRs) Q506 and Q108. On several occasions, it was recommended that the fast cutoff circuit needed improvement. But unavailability of electron beam power supply hardware at the time prevented the necessary testing to define the proper modification. Testing of the newly completed EB breadboard led to the belief that the electronics fix is not complex, but would require a few additional components. This modification was investigated in the event it was needed for the M512 flight backup unit.



b. M512 flight backup unit tests. All of the above events and testing occurred prior to Martin Marietta MDA-OCP-S-30002 testing of the M512 backup unit in July, 1973. Since verification of the fast cutoff circuit operation had been by bench tests in prior checkout operations, it was decided to add a fast cutoff operational verification test to the OCP-S-30002 test procedure. The test was accomplished by connecting a memory oscilloscope across the battery (B+ to B-) and one-shot triggering the scope with the turnoff signal pulse.

Test results of the backup unit EB gun and power supply were completely normal. Five "On-Off" footprint cycles were performed, six "On-Off" weld cycles on M551 were normal, and six "On-Off" M553 cycles were satisfactory. Fast cutoff worked every time and the EB equipment functioned flawlessly. As far as the test procedure was concerned, it was a perfect success. However, it was noted on two or three occasions there was K3 relay bounce about 3.5 to 4 milliseconds after initial K3 opening. A high current was sometimes drawn during bounce, mainly due to re-charge of 1000  $\mu$ F capacitor C407 (see figure 97). Relay bounce unfortunately is normal, but it points up the possibility that capacitor C407 should be moved to the same connection point as capacitor C34; namely, upstream of relay K3. Initial charging current of C407 is in the neighborhood of 580 amperes. This high current, which is within relay specification limits, can cause relay K3 contact arcing and pitting which could eventually result in contact sticking. It is further suggested that this condition could have been responsible for the soft sticking of the flight unit K3 relay contacts. To explain, soft sticking of relay contacts can be created when the contacts experience heavy arcing during initial closure (or opening) and bounce. There is an extra heavy current drawn for a short period of time in the case of charging a 1000  $\mu$ F capacitor through a low resistance circuit. In the specific case of the M512 circuit, the charging current of C407 through relay K3 main contacts is about 580 amperes peak (2.9 Vdc battery short circuit voltage) divided by (0.002 ohms Batt + 0.003 ohms wiring, connectors, and relay). Time constant for the charging is  $(5 \times 10^{-3} \text{ ohms}) \times (1.0 \times 10^{-3} \text{ farads})$  equals  $5 \times 10^{-6}$  seconds for 2/3 full charge. So transient currents in excess of 100 amperes last at least 5 microseconds, but the relay has a 600 ampere current breaking rating of 50 times, minimum, with no life degradation. However, if high currents persist, this energy level can be sufficient to cause noticeable pitting of the contacts due to metal transfer. During normal EB operations, the contacts warm up from heat dissipation. Then, when the contacts must open 100 amperes inductive, as in the event fast cutoff fails, the arcing situation is aggravated and becomes more critical on ensuing bounce(s) when the battery attempts to recharge capacitor C407. It is on contact bounce(s) that soft sticking may have actually occurred. When the MAIN BATTERY circuit breaker was opened by Conrad, current through relay K3 went to zero. The contacts could then

cool, allowing the metal binding them to change strength characteristics and finally break loose. Bench tests, qualification tests, and development tests of flight configuration hardware simply never surfaced EB gun K3 relay as a significant potential problem. Still, it is known that relay closure on a highly capacitive load is not the ideal design, due to relay arcing during opening and closing bounce. In the interest of possible radio frequency interference problems, the existing circuit was finalized as the best compromise. It was desirable, for radio frequency interference suppression purposes, to keep capacitor C407 located as close as possible to the EB power transistor bases. But since qualification testing later surfaced no marginal radio frequency interference levels due to EB equipment operations, capacitor C407 could be moved, if physically possible, to the same location as 1000  $\mu$ F capacitor C34.

It is also likely that relay K3 may have been binding mechanically. In fact, the prototype model 95M10111-1 relay did bind mechanically if not mounted on a flat surface. However, to compensate for this problem, the return mechanism magnets were strengthened and the mounting surface flatness was specified as a requirement. These two corrective actions seemed to have been a satisfactory solution, and no mechanical binding malfunctions of the Hartman 95M10111-1 relay had been experienced since the prototype model. Whether the actual cause of relay K3 sticking closed was electrical or mechanical will probably remain unknown. About the best that can be determined without an exhaustive study is definition of the probable causes. Specific causes of hardware deficiencies are nearly impossible to positively define without having the malfunctioning hardware on hand to analyze. The alternative would be a rather large-scale test program. Neither solution seems practical.

4. Conclusions. It is concluded that the reason for intermittent cutoff of M512 electron beam power supply during SL-1/2 was an intermittent fast cutoff circuit in combination with a sticking Hartman, type N419, 100 ampere relay per 95M10111-1. It has been determined on a circuit breadboard that the initiating signal for fast cutoff is marginal in pulse power when wired according to Westinghouse drawings. There is no doubt that relay K3 was sticking or binding. Whether the relay malfunction was due to contact sticking (welding) or mechanical binding has not been determined. Tests of the M512 flight backup unit indicated that location of the capacitor C407 to the battery side of relay K3 main contact would reduce arc currents bridging K3 contacts during relay opening and closing operations. On the other hand, the identical breadboard of the troubled circuit has been cycled "on-off" approximately 2000 times with no malfunctions. Fifty percent of these cycles were under the worst conditions, wherein the fast cutoff was purposely bypassed so the relay contacts would be subjected to maximum arcing conditions. It is therefore concluded, based on all prior testing, that the flight unit relay malfunction was a one-time anomaly, aggravated by an intermittent fast cutoff circuit. Relay operational

specifications, though pushed to near limits, are not exceeded during C407 charging or during operation of the EB welder. This relay has a 600 ampere interruption rating of 50 times without contact damage and a 150 ampere rating for 10 minutes; therefore it should be sufficiently rugged for its job. If the EB welder fast cutoff circuit is reliable, there is no need to be overly concerned about the K3 Hartman relay.

### C. Experiment Data

This subsection identifies the data and hardware returned to Earth from Skylab for the M512 facility and associated experiments. No attempt will be made to interpret the significance of the data.

#### 1. M512 Materials Processing Facility.

a. SL-1/2. All physical hardware, relative to the M512 facility, returned on this mission was associated with individual experiments. However, the crew evaluation of the facility design was voice-recorded during the mission and was further discussed during the SL-1/2 crew debriefing on July 6, 1973. The M512 facility was shown during two television episodes, once during the M551 operations and again during the MDA crew "tour".

b. SL-3. No M512 hardware was planned for return on SL-3; however, as a result of crew comments made during the SL-2 crew debriefings, three M512 items were approved for return on SL-3. The SL-2 crew had discussed the metal deposition or plating that occurred on hardware items installed in the chamber during performance of experiments M551 and M553. The following M512 accessory items were therefore returned for evaluation:

(1) M553 camera port shield.

(2) M553 hatch viewport shield.

c. SL-4. All physical data returned on SL-4 pertained to experiment M479.

#### 2. M551 Metals Melting. The following M551 data were returned on SL-1/2:

a. Three M551 sample disks.

b. Approximately 200 feet of 16 millimeter type S0168 color film of the M551 operations (portions of magazines CI01 and CI03).

c. One 35 millimeter photograph of the M551 deflection mirror installation.

3. M552 Exothermic Brazing. The only physical data returned was the M552 exothermic package. Crew observations and comments were made during the mission and at the SL-1/2 Crew Debriefing.

4. M553 Sphere Forming.

a. SL-1/2. All 14 samples from specimen wheel 1 were returned for evaluation. The 14 samples (7 processed, 7 unprocessed) including specimen wheel 2 were returned for evaluation. Approximately 200 feet of 16 millimeter type S0168 color film of the M553 operations were returned (portions of magazines CI01, CI03, and CI07). Crew observations were voice recorded during the mission and some crew comments were made during the SL-1/2 Crew Debriefing.

b. SL-3. Specimen wheel 1 was returned for evaluation.

5. M479 Zero-Gravity Flammability. The following M479 data was returned on SL-4 for evaluation.

- a. Four rolls of 16 millimeter film data (one infrared, three visible-color).
- b. The remains of fuel specimens 2 (nylon), 8 (nylon), 11 (paper), and 26 (nylon).
- c. Television coverage of sample 2 before and after ignition and samples 16 and 17 test sequences.
- d. Extensive crew observations (voice-recorded during the mission) and the crew comments made at the SL-4 Crew Debriefing held on March 4, 1974.

## SECTION VII. CONCLUSIONS AND RECOMMENDATIONS

The most significant conclusions and recommendations drawn from the development and inflight operations of the M512 Materials Processing in Space facility and associated experiments are presented in the following paragraphs. These observations relate only to hardware performance, interfaces and operational procedures; scientific results of the experiments are not within the scope of this report.

### A. M512 Design Considerations

It is concluded that the M512 facility and associated experiment hardware successfully met their objectives. There are, however, certain design considerations and recommendations to be made.

#### 1. Vacuum Measuring Techniques

Conclusion - The vacuum measuring technique employed in the M512 facility was considered marginal, at best. Repeated problems during ground operations and the inconsistency in the reported time-to-vacuum by the Skylab crews verify this conclusion. The M512 vacuum measuring system provided an indication of the quality of the vacuum in the filament chamber by a meter located on the control panel. The meter was scaled to indicate from atmospheric pressure to  $1.33 \times 10^{-3}$  newtons per square meter ( $1 \times 10^{-5}$  torr). A voltage was applied to a small heating element in the filament chamber which heated a nearby thermocouple by convection. The amount of heat received by the thermocouple depended upon the vacuum in the chamber. Therefore, the vacuum in the chamber was proportional to the output voltage of the thermocouple. This small voltage was amplified to drive the meter on the control panel.

Recommendation - Future designs of vacuum measuring systems should consider the use of other measuring techniques, such as an ionization gauge. This type of reliable device was considered for application in the M512 facility, but could not be incorporated because of size limitation.

#### 2. Location of Electron Beam Gun.

Conclusion - The location of the electron beam gun in its separate filament chamber was not conducive to maintenance of an adequate vacuum level at the gun. The M512 facility utilized a separate vacuum work chamber and the gun's filament chamber, connected by only a 1.9 centimeter (0.75 inch) diameter opening. The electron beam gun

was designed to operate at a maximum pressure of  $1.33 \times 10^{-2}$  newtons per square meter ( $1 \times 10^{-4}$  torr). Pressure significantly higher than this level could cause gun arc-out or shorting, eventually resulting in failure of the high-voltage electronics.

**Recommendations** - Future apparatus utilizing an electron beam gun should locate the gun as close to its vacuum source as possible. All air flow restrictions should be eliminated. The selected location should also consider the prevention of contamination on the gun's filament.

### 3. Troubleshooting and Maintainability.

**Conclusion** - Skylab demonstrated the ability of astronauts to perform inflight maintenance. Several experiment repairs were made during the Skylab mission although specific ground rules established early in the program mandated inflight maintenance as a design consideration. Experiment troubleshooting was made difficult by lack of telemetry or crew displays that directly indicated the desired function.

**Recommendations** - Design manned space flight hardware to facilitate inflight maintenance.

Provide telemetry channels or crew status indicators which give direct readout of specific parameters desired to aid in troubleshooting hardware malfunctions and verifying proper operation.

### 4. Electron Beam Alignment.

**Conclusions** - The astronaut view angle, control location, and actual beam movement axes made it extremely difficult to align the electron beam on a target. This proved especially true during the beam alignment on the first M553 specimen wheel where, on numerous occasions, the beam struck the specimen's ceramic supporting pedestal.

**Recommendations** - A simplified method of beam alignment is required, especially if alignment is critical. M553 required alignment while viewing perpendicularly to the beam's axis. A method of alignment using a line-of-sight parallel to the beam is recommended.

### 5. Optics and Photography.

**Conclusion** - The photographic mirror system used to allow photography of the M551 welding sequences limited the field-of-view of the camera to a significant degree.

**Recommendation** - The use of mirrors should be avoided where an unrestricted field-of-view is desired. Mirrors also represent additional surfaces which can become contaminated by metal deposition or other foreign sources.

## B. Spacecraft Interfaces

### 1. Vacuum Measurements.

Conclusion - The quality of vacuum surrounding an orbiting spacecraft is still an unknown quantity. The large variation in the time-to vacuum as determined during the three Skylab missions raises the question as to whether "space vacuum" will be adequate for future manufacturing in space or material science investigations.

Recommendation - External vacuum sensors should be incorporated into future spacecraft to accurately determine the quality of vacuum available. The detrimental effect of the "contamination cloud" surrounding an orbiting spacecraft could then be evaluated for its impact on future manufacturing in space or material science investigations.

### 2. Telemetry.

Conclusion - The lack of available spacecraft telemetry prevented ground monitoring of the operation of the M512 facility. Numerous attempts were made to obtain telemetry data channels to monitor the performance of the facility. Each request was rejected based on the unavailability of data channels. Troubleshooting and malfunction analyses of the electron beam anomaly would have been easier and definitely more conclusive if facility performance indicators had been available on the ground.

Recommendation - Provide telemetry channels to give direct read-out of required hardware parameters.

### 3. Spacecraft Electrical Power.

Conclusion - The use of a battery to power the electron beam welder severely constrained the operational lifetime of this hardware. The capacity of the battery (30 ampere-hours after a 90 day wet-stand) limited the number of scientific investigations that could be conducted.

Recommendation - The use of spacecraft electrical power to operate the welder would have allowed operational flexibility, permitting the use of the welder on all three Skylab missions rather than being constrained to just the first mission. Additionally, a considerable weight saving and simplified electronic circuits would have been realized.

## C. Mission Interfaces

### 1. Crew Training.

Conclusion - The time allowed for crew training using the M512 hardware was not adequate. The M512 facility and associated experiments



were extremely complex. Crew training sessions dealt mainly with the mechanical actions of the crew to perform the experiments, sufficient training time was available for hardware operational theory.

Recommendation - Provide sufficient time for crew training; particular emphasis should be placed on the theory of hardware operation.

## 2. Real-Time Mission Support.

Conclusion - The procedures utilized to obtain information from the flight crew or provide information to the flight crew during the missions was extremely cumbersome. A timely interface with the Skylab crews from the Huntsville Operations Support Center (HOSC) was nonexistent; the paperwork involved and the approvals required to request or relay information were overwhelming. Attempts to obtain additional information during the M512 anomaly met with no success. Even troubleshooting procedures prepared at MSFC were not relayed to the crew.

Recommendation - Mission support personnel operating from a hardware development center must have direct access to the flight controllers at the mission control center. The intermediaries involved in the Skylab mission support operations only bogged down the system.

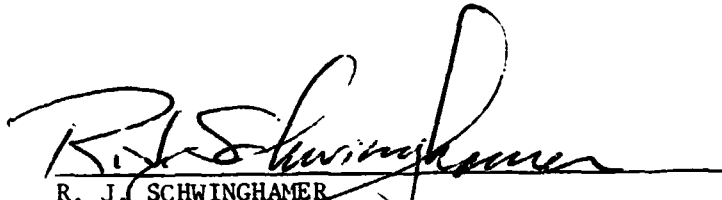
APPROVAL

SKYLAB MATERIALS PROCESSING FACILITY  
EXPERIMENT DEVELOPER's REPORT

By  
P. G. Parks

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.



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