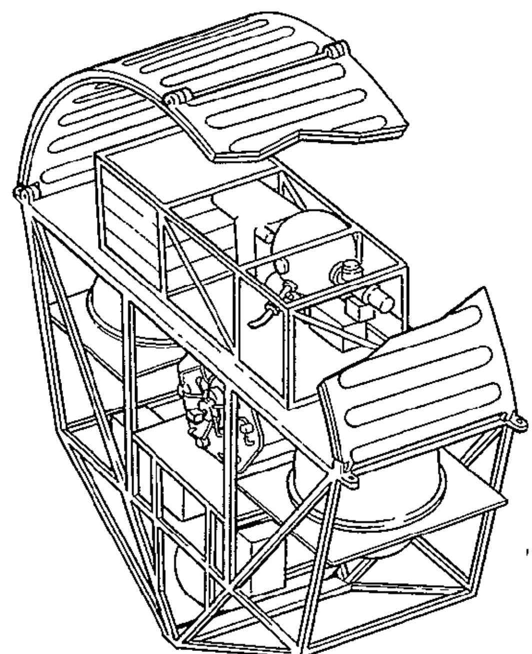
Automated Space Processing Payloads Study

(Contract NAS 8-30741)

Volume II Book 1
Technical Report

Final Report
BSR 4171

January 1975



Bendix Aerospace Systems Division

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Prepared for

George C. Marshall Space Flight Center
National Aeronautics and Space Administration
Marshall Space Flight Center, Alabama 35812

Prepared by:

The Bendix Corporation
Aerospace Systems Division
Ann Arbor, Michigan 48107

Bendix **Aerospace Systems Division**

CONTENTS

CONTENTS (CONT.)

CONTENTS (CONT.)

ILLUSTRATIONS

ILLUSTRATIONS (CONT.)

ILLUSTRATIONS (CONT.)

TABLES

TABLES (CONT.)

SECTION 1

INTRODUCTION

To date, the Space Processing Applications (SPA) Program has identified six major areas of material science research and technology that can be exploited in a weightless or low-gravity environment. These are metallurgy, electronic materials, glass technology, biological preparations, and physical and chemical processes in fluids. Work was performed by this and previous studies in system analyses and engineering areas to define an inventory of equipment to conduct the experiment program. Plans call for the pursuit of an aggressive program, taking advantage of a large number of potential Space Shuttle flight opportunities following the completion of a series of rocket experiments. Addition of automated space processing payload equipment will enable the SPA Program to participate in those Space Shuttle missions on which the only available resource is weight and volume capability, and to increase productivity on flights providing more extensive resources.

This study addresses the automated space processing payload equipment by examining the extent to which the experiment hardware and operational requirements can be met by automatic control and material handling devices and defines payload and system concepts that make extensive use of automation technology.

1.1 STUDY OBJECTIVES

Specific objectives satisfied by the study are to:

- Identify SPA experiments amenable to automation.
- Identify operations which may be more efficiently or economically performed by the flight crew.
- Define automated functions and equipment for space processing payloads.
- Determine the feasibility of automating SPA experiments for operation under STS mission conditions.
- Determine the extent to which existing commercial automation hardware, techniques, and measurement instrumentation can be applied to the SPA Program.
- Design space processing payloads which make optimum use of automation to a preliminary design level.

- Provide payload interface data for planning typical early Shuttle SPA missions.
- Provide estimates of development cost and schedules for automated SPA payloads.

1.2 OVERALL STUDY APPROACH

Seven tasks were undertaken to meet the objectives of the study. Figure 1-1 shows the interrelationships of these seven tasks. Task 1, Review and Compile Experiment Requirements and Hardware Data, and Task 2, Survey and Compile Data on Industrial Automation, were conducted in parallel, and provided the data base for the remainder of the study. Tasks 3, 4, and 5 resulted in the selection of representative experiment equipment and the preliminary design and definition of selected automated space processing concepts. Task 6 investigated the equipment combinations and resource requirements for the experiments to be flown on Shuttle flights in the 1979 to 1982 time-period. Task 7 defined the cost, schedule, and SR&T requirements for the major equipment items identified in the study.

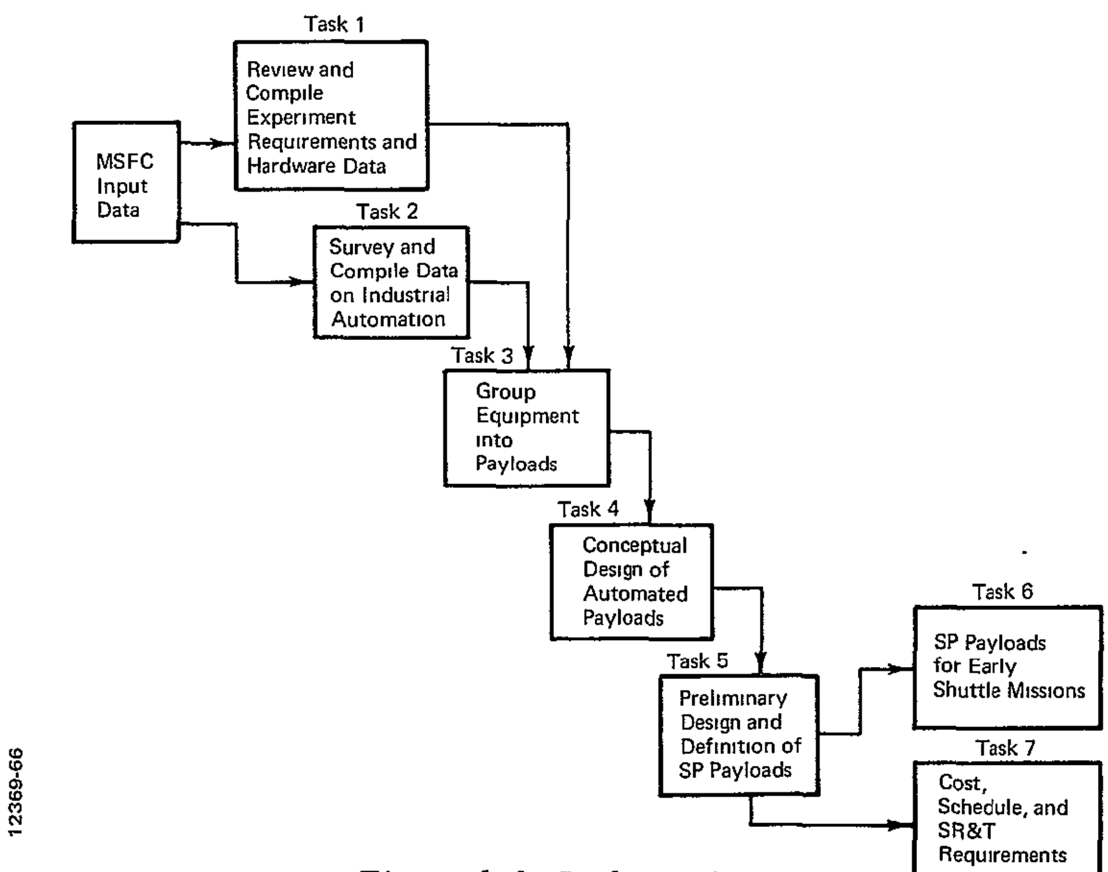

Figure 1-1 Study Logic

The study activities were integrated with inputs from related NASA in-house studies and data from other contractual sources, as provided by the COR.

1.3 SUMMARY

Volume I of the final report is an Executive Summary. Volume II, consisting of two books, contains a discussion of the technical results of the study. Volume II Book 1 is organized into six major sections corresponding to the study task activities. Volume II Book 2 contains the technical appendices. Volume III contains the programmatic data (cost, schedule, and SR&T) developed in the study. The following is a summary of Book I.

Section 2, Experiment Requirements and Hardware Data, contains the results of a review of more than 100 reports and documents. Hardware requirements for each experiment were established and tabulated. Investigations of applicable existing hardware were documented.

Section 3; Capabilities and Characteristics of Industrial Automation Equipment, Controls, and Techniques; contains a summary of applicable equipment characteristics in three basic mutually-supporting formats. The formats are applicable as follows: (1) where a number of manufacturers produce comparable equipment to implement a well-defined function, one representative hardware element is described in detail; (2) where a number of manufacturers produce comparable equipment to implement a well-defined function, a tabular comparison is made of the major characteristics of the equipment of different manufacturers; and (3) where specific hardware is not available to implement a function or where the available hardware is deemed to have undesirable characteristics, or alternative industrial automation techniques are discussed.

Section 4, Payload Grouping, presents the definition of facilities to perform groups of experiments. Four levitation groups, L-1 through L-4, and three furnace groups, F-1 through F-3, were defined, and the major hardware elements required to implement them were identified. These groupings or facilities formed the basis of the conceptual design effort.

Section 5, Space Processing Payloads Conceptual and Preliminary Design, consists of the conceptual design definition of ten different automated processing facilities. Specific equipment to implement each facility is identified, and design layouts of the different units are included.

Section 6, Automated Space Processing Payloads for Early Shuttle Missions, examines the constraints and the packaging, weight, and power requirements for six payloads postulated for Shuttle missions in the 1979 to 1982 time-period. The payloads are made up of various combinations of the facilities described in Section 5 or portions of them, depending on the flight mode to be used.

SECTION 2

EXPERIMENT REQUIREMENTS AND HARDWARE DATA

2.1 INTRODUCTION

The objectives of this effort were to identify "typical" process experiments and to define the procedures and hardware required to implement the experiments.

A review of existing documentation provided a list of potential experiments. Of these, several in each class were selected for further investigation. The requirements for each of these were then organized in order to identify areas of commonality and uniqueness. Procedures for each were examined in order to identify requirements for automation of the processes.

A total of 70 experiments was investigated. Of these, 42 were deemed to have sufficient merit to warrant further documentation. These have been documented on individual data sheets, as shown in Appendix A. Eighteen of these latter experiments were finally selected for further study.

2.2 DOCUMENT REVIEW

More than 100 reports, briefing handouts, and other similar documentation were screened. Most of the documents were provided by the COR; others were obtained from various NASA agencies and directly from the reporting contractors. The documentation covered studies funded by Shuttle, Skylab, ASTP, and various other programs.

Three major goals in the documentation review were:

- To provide a general familiarity with space processing experiment requirements.
- To identify typical material processes which hold promises of economic value.
- To identify hardware requirements for selected experiments.

2.3 EXPERIMENT DATA

Space processing experiments under consideration were categorized into the following groups:

- Biological.
- Crystal growth.
- Glass.
- Metallurgical.
- Physical and chemical processes.

Pertinent information for typical experiments in each group was extracted from the documents reviewed and was entered into individual experiment data sheets. Each data sheet is identified by an experiment designation consisting of a letter identifying the experiment category and an arbitrary sequential number. Letter designators B, C, G, M, and P correspond with the above list of experiment categories, respectively.

2.3.1 Experiments Identified

The experiments identified in each group are listed, together with identification of their applicable data sheets, in Tables 2-1 through 2-5.

Table 2-1

Biological Experiments

Experiment Title	Data Sheet
Bio-Growth of L-Phase Organisms	B-3
Dialysis/Fermentation	B-4
Electrophoretic and Dielectrophoretic Separation of Cells, Serums, and Proteins	B-1
Growth of Bacterial Cultures	B-2
Lyophilization	B-5
Protein Separation by Isoelectric Focusing	——

Table 2-2

Crystal Growth Experiments

Experiment Title	Data Sheet
Growth on Seed by Vapor Deposition (Skylab M536 and ASTP MA-085)	C-1
Whisker Growth from Vapor	——
Pulling from Containerless Melt	C-2
Growth in Aqueous Solutions and Flux	C-3
Pulling from Molten Zone	C-4
Growth on Molten Zone	——
Sphere Seeding (Skylab M560)	C-5
Mixed III-V Crystal Growth (Skylab M563)	C-6
Indium Antimonide Crystals (Skylab M562)	C-7
Epitaxial Growth of Magnetic Bubble Memory Crystal Films	——

Table 2-3

Glass Experiments

Experiment Title	Data Sheet
Containerless Preparation of Conventional Glass	G-1
Laser-Induced Damage to Glass Specimens	——
Production of Glass Fibers	G-2
Mixing of Conventional Glasses	G-3
Production of High-Melting-Point-Oxide Glasses	G-4 and G-8
Amorphous Solidification	G-5
Chalcogenide Glasses	G-6
Dispersion of Particles in Glass	G-9
Preparation of Conventional Glass by Furnace Method	G-7

Table 2-4

Metallurgical Experiments

Experiment Title	Data Sheet
Containerless Preparation of Ultra-Pure Metals and Alloys	M-1, M-17, and M-18
Directional Solidification of Eutectics	M-13 and M-15
Gas Phase Dispersion in Liquid Metals	——
Supercooling and Homogeneous Nucleation	M-4 and M-20
Purification by Containerless Distillation	——
Purification by Zone Refining	M-6
Solidification of Immiscible Materials	M-3 and M-8
Dispersion Strengthening (Composite Materials)	M-2, M-7, M-16 and M-19
Liquid State Forming (Membranes)	M-5
Metal Melting (M551 Skylab)	M-9
Sphere Forming (M553 Skylab)	M-10
Radioactive Tracer Diffusion (M558 Skylab)	M-11
Micro-segregation in Germanium (M559 Skylab)	M-12
Silver Grids Melting (M565 Skylab)	M-14

Table 2-5

Physical and Chemical Process Experiments

Dispersal of Particles in Liquid Phase
Flow Visualization of Suspended Particulate
Physical Property Measurements (Critical Points, Surface Tension, Free Volumes, and Flow Effects - See Data Sheet P-1 in Appendix B)
Instability in Containerless Liquid
Mass Transport by Diffusion
Contactless Heating of Containerless Liquids
Position Control of Containerless Liquids • Electromagnetic • Electrostatic • Gas jet • Acoustic
Heat and Mass Transport in Gases
Mixing of Containerless Fluids • Electromagnetic • Electrostatic • Gas jet • Acoustic
Thermal Gradient Mixing, Liquids
Thermocapillary Convection in Liquid-Solid Phase Change
Particle Manipulation by Small Forces
Precise Separation of Radioisotopes
Chain Reactions Affected by Convection
Surface Reactions and Electro-Synthesis
Electron-Spin Resonance of Free Radicals
Liquid-Solid and Gas-Solid Catalysis
Controlled Polymerization - Dynamics of Initiation, Extrusion, Optical Quality, and Dispersal of Particles
Chemical Kinetics - Free Radicals, Flow Systems, Excited Life Times, Heterogeneous Interface, and Wall Effects
Liquid Crystals
Synthesis of Compounds - Immiscible Liquids and Solid-Liquid Interaction.

2.3.2 Selection of Experiments for Further Study

Experiments were selected for further study based on a preliminary evaluation of their characteristics and the following selection criteria:

- The experiment should be typical; i.e., it should be of a type which might be flown on several Shuttle missions.
- The experiment should be amenable to automation. The process should be capable of operation essentially without human intervention.

In reviewing the five categories of experiments, we found that two of them, the biological and the physical and chemical process categories, are, in general, atypical. For example, they require a unique hardware installation, precise and complex monitoring, or special sample protection. Therefore, the concentration of this study was in the categories of crystal growth, glass, and metallurgy, although the biological separation experiment was also selected because of widespread interest in it and the fact that it may be flown on several missions.

It was found that the three main categories selected (outside of the biological separation category) have considerable commonality, notably in their requirements for the controlled application of heat and cooling, their adaptability to standardization of sample size, and their straightforward processes, definable in terms of time, temperature, gas pressure, etc. Further examination of these three categories showed that their respective experiments fall naturally into one of two subcategories, depending on whether they require containerless processing (levitation) or can be processed in a standardized line of furnaces.

The biological separation experiment uses the electrophoresis technique to obtain separation of cells, serums, and proteins. The experiment is described on Data Sheet B-1 of Appendix A.

Levitation Experiments. - The containerless processing or levitation experiments, designated for intensive investigation to establish protocol and hardware requirements, are listed in Table 2-6. The list includes representative experiments of the selected categories, with four metallurgical, four glass, and one cyrstal process designated.

Table 2-6

Levitation Experiments

Experiment Title	Suggested Material	Type of Levitation*	Data Sheet
Purification and Undercooled Solidification	Tungsten	EM	M-18
Dispersion Strengthening (Composite Materials)	Beryllia in beryllium	EM	M-19
Containerless Preparation of Ultra-Pure Alloys	Tungsten carbide	EM	M-1
High Melting-Point Oxide Glasses	Zirconia	EM or Ac	G-4
High-Resistivity-Oxide-Glasses	Alumina	Ac	G-8
Chalcogenide Glass	Germanium telluride	EM	G-6
Dispersion of Particles in Glass	Silver chloride in high silicate	Ac	G-9
Supercooling and Homogeneous Nucleation	Palladium-silicon	EM	M-20
Crystal Pulling from Containerless Melt	Silicon	EM or Ac	C-2
*EM - Electromagnetic Ac - Acoustic			

The processes span a wide range of requirements; hard vacuum (e.g., for tungsten carbide) or inert gas environment with or without partial pressures of oxygen, a temperature range from relatively low (800°C for germanium telluride) to relatively high (3,410°C for tungsten), and cooling methods which may include radiation (at a controlled or uncontrolled rate) or quenching with inert gas or water.

The low electrical conductivity of the glasses at ambient temperatures leads, naturally, to the evaluation of two alternative means of levitation. They are:

- Electromagnetic, with laser (for example) preheating to increase the sample's electrical conductivity to the level necessary to permit continued heating by the induced currents associated with levitation.

- Acoustic, with laser, thermal image, or resistance heating.

Furnace Experiments. - The furnace experiment sub-category includes all experiments requiring heating of the raw material without the added requirement of containerless processing. A list of the selected furnace experiments is shown in Table 2-7.

The tabulation includes representative experiments of the three selected categories; four metallurgical, three crystal, and one glass. The processes may employ hard vacuum or inert gas, with or without partial pressures of oxygen.

The eight experiments span a temperature range from relatively low (540°C) to moderately high (around 1,800°C for three experiments) temperatures. Cooling may be achieved through conduction or radiation (at a controlled or uncontrolled rate) or quenching in inert gas or water.

Table 2-7

Furnace Experiments

Experiment Title	Suggested Material	Data Sheet
Purification by Zone Refining	Silicon	M-6
Solidification of Composite Materials	Aluminum with aluminum oxide fibers	M-7
Solidification of Immiscible Materials	Copper and lead	M-8
Solidification of Eutectic Materials	Copper and aluminum	M-15
Crystal Growth by Vapor Transport	Cadmium selenide	C-1
Crystal Growth by Pulling from Molten Zone	Titanium dioxide	C-4
Crystal Growth from Solution	Yttrium iron garnet	C-3
Preparation of Conventional Glass by Furnace Method	Silicon dioxide	G-7

2.4 EXPERIMENT HARDWARE REQUIREMENTS

The hardware requirements for conducting the 18 "typical" experiments defined in Section 2.3 were identified and the status of each class of hardware required was defined. It should be noted that this section covers only the equipment directly related to the processes. Equipment required to automate the processes is discussed in Section 3 of this report.

2.4.1 Atmospheric Composition Equipment

The requirements for gas and vacuum system hardware for space processing are not unique. Components required to build up these systems are available in space-qualified form, having been used in numerous NASA programs through the years. Some of these readily available components are tanks, tubing, fittings, electrically-actuated valves, regulators, filters, and pressure monitors.

For most experiments, it is necessary to measure and identify the gases given off by the sample material. A residual gas analyzer is used for this purpose.

For other experiments, it is necessary to adjust the partial pressures of inert gas and oxygen. A gas chromatograph or specific gas detector is a suitable instrument for this application.

Both of the above requirements can probably be satisfied by minor adaptations of existing space-qualified hardware. Examples are:

- Upper Atmosphere Mass Spectrometer developed for the Viking Program.
- Omegatron Mass Spectrometer developed under GSFC contract by the University of Michigan for sounding rocket applications.
- Cabin Atmosphere Monitor built by Honeywell for NASA to measure gas partial pressures in space vehicle cabins. (Contract NAS8-30254).

The Beckman Model 6700 Gas Chromatograph is typical of commercial devices that could also be adapted for the space environment.

2.4.2 Contactless Position Control Systems (Levitation)

Both acoustic and electromagnetic position control systems will be required, depending on material characteristics.

Much developmental work remains to be done on both systems to qualify a flight unit. Intersonics, Inc. and JPL are studying acoustic position control under separately-funded NASA contracts and the rocket payloads program.

General Electric has studied the electromagnetic levitation requirements, and Pillar High Frequency Corporation has developed solid state electromagnetic systems for frequencies up to 100 kHz. Above this limit, vacuum tube amplifiers will be required unless considerable development work is undertaken.

2.4.3 Cooling Equipment

If a gas system is used, it can be adapted to expedite the cooling of samples after processing has been completed. This adaptation is expected to be straightforward.

Two other cooling requirements have been identified. The first is to provide an efficient heat-sink for directional solidification experiments. This will be an integral part of the furnace design for these experiments and will require an appropriate development effort. It may employ a pumped-liquid coolant to develop the reference cold temperature.

The second requirement is for a liquid (probably water) quench system for rapid cooling of sample specimens. The components required to assemble such a quench system are readily available in space-qualified form, and should pose no major problems once the required design is established.

2.4.4 Enclosures/Furnaces

The principal items required in this equipment group are:

- General-purpose enclosure.
- Tube furnaces.

The general purpose enclosure provides the physical structure and environmental facility for both levitation and furnace experiments. Important developmental work has already been done in this area. The concept of the M512 facility developed for Skylab can be readily adapted.

Tube furnaces will be used for experiments not requiring containerless processing. The M518 Skylab multipurpose furnace and the MA-010 furnace developed for ASTP are typical of the hardware previously developed. Several commercial devices are also adaptable to these needs and provide a more versatile capability. Among them are:

- Astro Industries, Inc. Model A200 (1,200°C at 1.1 kW); 5.08 cm ID by 28 cm (2 in. ID by 11 in.) long.
- Artcor (2,200°C); 12.7 cm ID by 40.6 cm (5 in. ID by 16 in.) long.
- Varian Marshall Model 1566 (1,700°C at 6.6 kW); 8.9 cm ID by 50.8 cm (3.5 in. ID by 20 in.) long.

2.4.5 Heating Units

Some of the required heating units are integral parts of other hardware elements described above; namely, resistance heaters in the tube furnaces and induction coils in the electromagnetic levitation equipment.

The remaining additional requirement involves a heater for use with acoustical levitation experiments and, possibly, a pre-heater for experiments employing electromagnetic levitation. No space-qualified hardware fully meeting the desired requirements has been defined. For example, lasers with average output power in the one-kilowatt region are excessively heavy, large, and inefficient. Typical are the following specifications for the GTE Sylvania Model 971:

- Weight:

Laser	1,364 kg	(3,000 lb)
Power supply	454 kg	(1,000 lb)
Total	1,818 kg	(4,000 lb)

- Size:

	Laser		Power Supply	
Height	1.22 m	(4 ft)	1.52 m	(5 ft)
Width	1.22 m	(4 ft)	1.22 m	(4 ft)
Length (depth)	1.52 m	(5 ft)	0.61 m	(2 ft)
Volume	2.26 m^3	(80 ft^3)	1.13 m^3	(40 ft^3)

- Power Input (to laser): 1,400V at 11A (15.4 kW)
- Efficiency (laser only): 6%

Some alternative approaches to permit the use of smaller and lower powered laser devices are:

- Restrict laser use to experiments involving materials with low melting points.
- Restrict sample size.
- Use laser in conjunction with hot-wall furnace to reduce heat radiation from sample.

Basic considerations for these approaches, assuming a CW laser output of 200 W, include:

- With a sample size of 2.54 cm (1 in.) diameter, materials with melting temperature up to 950°C can be processed.
- Assuming that materials with melting points of 2,700°C must be processed, sample size is restricted to 0.5 cm (0.2 in.) in diameter.
- To limit radiation sufficiently to raise a 2.54 cm (1-in.) diameter sample to 2,700°C, the furnace wall temperature would have to be raised to well over 2,600°C.

Another type of radiation heater investigated for this application is the thermal imaging furnace. Major developmental concerns are:

- Possible adverse interaction of the acoustic field with the light reflectors.
- The large size of the mirrors required to develop reasonable collection efficiency.
- The large heat rejection and cooling system (water) required for the xenon lamp and mirrors.

The feasibility of using an electron-beam (or an ion-beam) gun similar to the one used in the M512 facility on Skylab was investigated. Performance of the gun and of the levitation system at a compromise gas pressure level must be verified by suitable tests including, perhaps, a drop-tower or sounding-rocket verification of the combination.

2.4.6 Manipulation Units

Manipulation units are required to perform the following tasks:

- Introduce samples, in the correct sequence, to the furnace or levitation facility.
- Retrieve and stow samples in a manner permitting subsequent identification for analysis.
- Perform specific processing functions, such as (1) moving a sample at a controlled rate through the heater for zone refining or directional solidification and (2) pulling a crystal at controlled retraction and rotation rates.

All manipulation units must be governed by a programmable controller. It is probable that the mechanical portions of the manipulators can be designed as integral parts of the enclosure and furnaces.

2.4.7 Mixers

The mixers employed include acoustic, electromagnetic, and mechanical types.

Acoustic mixers will be employed only in those experiments using acoustic levitation. The mixer consists of a mechanical device which perturbs the acoustic standing wave, resulting in pressure differentials on the sample.

Electromagnetic stirring is a concomitant function of electromagnetic levitation. A variant will permit spinning the sample to facilitate degassing.

Mechanical mixers will be employed with furnace experiments. They will be of the general nature of shakers, rather than stirrers.

2.4.8 Temperature Measurement and Control

Techniques for measuring and controlling temperatures are well developed and much of the hardware is space-qualified. Furnace experiments will employ contact temperature measuring devices (resistance thermometers and thermocouples). These devices are an integral part of the furnace hardware. Their output can then be used in a servo loop to regulate furnace temperature in an experiment sequence requiring a single operating temperature. For more complex situations, the temperature sensor outputs will be read by a process controller, which will then regulate heater power to achieve the desired furnace temperature.

Levitation experiments will employ non-contacting temperature sensors of the general class known as pyrometers. A mirror or shutter arrangement will protect the sensor from destructive deposition. The pyrometer output will be read by the process controller and will be used to regulate the heater power (rf induction, laser, etc.) to achieve the desired sample temperature. Several commercial items appear to be promising candidates for fulfilling this requirement. Among them are Ircon Modline 2000 (400 to 3,000^{o}C) and Barnes Engineering Model EP-1 (700 to 3,000^{o}C).

2.4.9 Electrophoresis Apparatus

There are two basic electrophoresis techniques to be considered; the static column and the continuous flow. Experiments of both types have been developed for the Apollo Soyuz mission. In addition, static column experiments were developed for the Apollo 14 and 16 missions, and work was performed on a continuous flow unit for Skylab.

The Skylab experiment was carried to the prototype stage but was not flown. The equipment consisted of an electrophoretic separator, sample container assemblies, product storage containers, sample/product transporting containers, a mounting pallet, and a camera mounting bracket.

Two electrophoresis experiments have been devised for ASTP; one by a German experimenter and one by NASA-MSFC and other US investigators.

In the German experiment, electrophoretic separation of cells and particles is by continuous free-flow electrophoresis. The cells are separated by their differential movement in an electric field which is applied in an electrolyte perpendicular to the fluid-flow direction. The sample is added continuously at the upper end of the separation chamber and deflected, depending on flow-velocity, electric field, and electrophoretic mobility of the constituents. Other than sample unstowage and insertion, the instrument operation is automatic. The separated products are not collected but, instead, are detected by a diode array detection arrangement. The instrument weighs 17.5 kg (38.5 lb), has dimensions of 30 by 40 by 25 cm (12 by 16 by 10 in.), and requires 40 W of power.

The MSFC experiment is a self-contained apparatus with capability for storage of frozen samples and freezing of separated samples which have been separated by zonal electrophoresis and iso-electric focusing in static liquid media. For zonal electrophoresis, the sample materials, in the form of frozen discs, are inserted into a separation column filled with buffer solution through a sliding port and are allowed to melt before separation is initiated. For iso-electric focusing, the column is filled with a homogenous mixture of sample and ampholites. After the zonal run, the samples are immobilized in place by freezing the liquid in the column. After an iso-electric focusing run, the samples are collected by displacement of the liquid in the column into an array of capillary tubes. The equipment weighs 13.6 kg (30 lb), has dimensions of 15.2 by 22.9 by 30.5 cm (6 by 9 by 12 in.), and requires 100 W maximum and 10 W standby.

2.4.10 Hardware Status Summary

The availability status of the experiment hardware required for the 18 "typical" experiments is summarized in Table 2-8. Significantly, the hardware requirements for the typical experiments include no additional equipment types beyond those identified by TRW in their study under Contract NAS8-28938. Additional commercial vendors with applicable product lines have been identified, and the degree of space qualification of each equipment group has been assessed.

As shown in the table, the areas requiring the greatest developmental effort are those of sample handling (including positioning and mixing) and heating/cooling.

In the other equipment groups, most of the requirements can be satisfied with relatively minor modifications to existing commercial or space hardware.

Developmental problems are, generally, related to optimizing size, weight, power consumption, and heat dissipation and to tailoring known concepts and existing designs to the specific requirements of the selected experiments.

Table 2-8

Experiment Hardware Status Summary

Equipment Group	Units	Status: Space Qualified	Status: Commercial Item	Status: Developmental
1. Atmospheric Composition	a. Gas/Vacuum System (Components)	X		
	b. Gas Analyzer	X		
2. Position Control	a. Acoustic			X
	b. Electromagnetic			X
	c. Mechanical		X	
3. Cooling	a. Furnace Heat-Sink			X
	b. Gas Quench	X		
	c. Liquid (H_2O) Quench	X		
	d. Refrigeration	X		
4. Enclosures/Furnaces	a. General-Purpose Enclosure	X		
	b. Tube Furnaces		X	
5. Heating	a. Resistance	X		
	b. Induction		X	
	c. Radiation			X

Table 2-8 (Cont.)

Equipment Group	Units	Status		
		Space Qualified	Commercial Item	Developmental
6. Manipulation	a. Sample Insertion			X
	b. Sample Retrieval			X
	c. Sample Stowage			X
	d. Crystal Pulling		X	
7. Mixers	a. Acoustic			X
	b. Electromagnetic			X
	c. Mechanical			X
8. Temperature Measurement	a. Resistance Thermometers	X		
	b. Thermocouples	X		
	c. Pyrometers		X	
9. Biological Separation	a. Static Electrophoresis	X		
	b. Continuous-Flow Electrophoresis			X
	c. Isotaco-electro-phoresis			X

SECTION 3

CAPABILITIES AND CHARACTERISTICS OF INDUSTRIAL AUTOMATION EQUIPMENT, CONTROLS, AND TECHNIQUES

3.1 INTRODUCTION

In parallel with the experiment requirement effort, a survey of industrial automation equipment, controls, and techniques was undertaken. This survey was approached in five steps, designed to cover the broad range of industrial automation equipment in a manageable way, yet providing in-depth data on pertinent equipment.

- Development of a model of automated processes and identification of the automation functions and equipment classes found in space processing payloads.
- Identification of automation hardware types and general equipment characteristics for space processing automation.
- Definition of the Space Shuttle and Spacelab environments in which the space processing equipment must operate.
- Survey of industrial sources of process automation equipment and techniques for data applicable to space processing payloads.
- Organization and compilation of equipment and technique data.

3.2 SYSTEM MODELS AND ANALYSIS OF HARDWARE FUNCTIONAL REQUIREMENTS

3.2.1 Generalized Model

A totally automated process is one in which all functions are performed by machines, including control of the complete process. The role of a human operator in such a process is to ensure that there is a supply of raw material, to distribute the product to the users, and to turn the automated equipment on and off.

Figure 3-1 shows a generalized model of an automated process. In the model, the actuators operate directly on the raw material to convert it into the product. Typical actuators are mechanical positioning devices, furnaces, machine

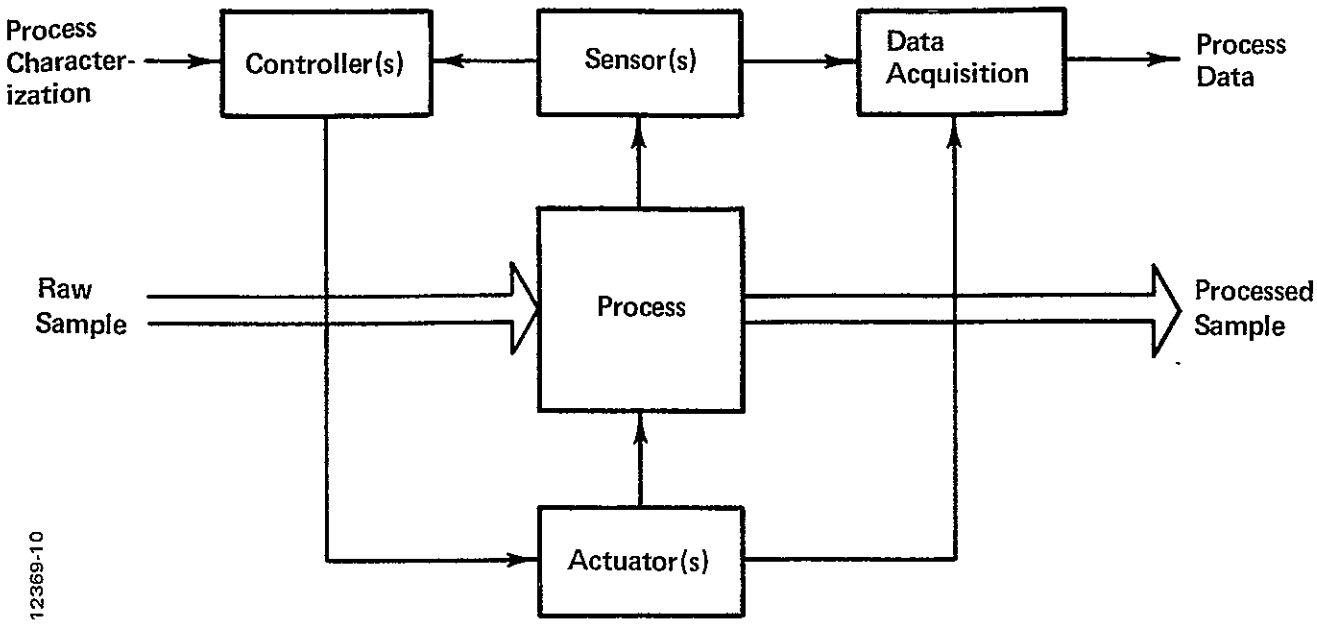

Figure 3-1 Automated Process Model

tools, and valves. Sensors in the model measure critical process parameters which provide information on the process performance. Typical sensors are gages, flowmeters, temperature sensors, pressure sensors, and pH meters. Controllers monitor the sensed process parameters and sequence and drive the actuators to force the process to follow a predetermined characterization. For example, the controller could provide the power level control required to cycle a furnace and, thereby, the process temperature, through a profile of rate of temperature rise, constant temperature duration, and rate of cooling. Typical controllers are sensor-dedicated controllers (e.g., temperature controllers), relay controllers, solid state programmable controllers, and minicomputers. The data acquisition element provides a record of the process procedure. Typical data acquisition equipments are data loggers, recorders, and cameras.

From consideration of the general model, it is clear that the main differences between the automated and non-automated processes are that the automated processes require controllers and, perhaps, some increase in data acquisition and actuator equipment. The increase in actuator equipment is largely a result of the need to store and handle raw materials, intermediate-process products, and output products.

The degree to which a process can be automated depends on how completely the process can be characterized. Processes can be typified as well-characterized, ill-characterized, and un-characterized. Well-characterized processes have either completely-defined relationships between process parameters and product output or, at least, definition of process parameters for some level of product output. An ill-characterized process has parameters or procedures that are not completely defined but depend on the subjective experience of the human operator. An example of such a process is that of growing a single crystal of gallium phosphide in a Czochralski system. Start of the crystal growth process depends on the skill of the operator and his ability to judge several process parameters. An un-characterized process is an experiment. Unlike the well-characterized and ill-characterized processes, whose objectives are to produce or maximize the end product, the objective of an un-characterized process is to define and quantify the process parameters which result in the product. Both the well-characterized and un-characterized processes can be completely automated; the ill-characterized processes can be only partially automated.

3.2.2 Space Processing Model

While space offers a unique environment that can be used advantageously, the space environment also places unique requirements on the processing system and equipment. In the space environment, new factors must be considered in process system design. The environment in which the space processing systems must operate is described in Section 3.4.

Figure 3-2 shows a functional model of an automated space processing system. In this model, each functional block can be subdivided into more specific space processing automation functions. Material handling functions are those of storage, transfer, and manipulation of the process raw materials, intermediate products, and final process products. Process and environment measurement and control functions are those of sensing and controlling such parameters as temperature, pressure, vacuum, and gas constituents. Command sequencing functions are the generation of on/off, timing, and time delay command signals. Typical data acquisition functions are sensor signal conditioning, multiplexing, analog-to-digital conversion, and film recording. Power conditioning functions are those of dc-to-ac conversion, frequency conversion, and voltage transformation. A preliminary listing of functions to be automated for selected experiments is given in Table 3-1.

3.3 ENVIRONMENT AND FLIGHT SYSTEM RESTRICTIONS

An investigation of the environmental and flight system restrictions was undertaken so that the available automation hardware and systems could be evaluated relative to this application. A summary of this study follows.

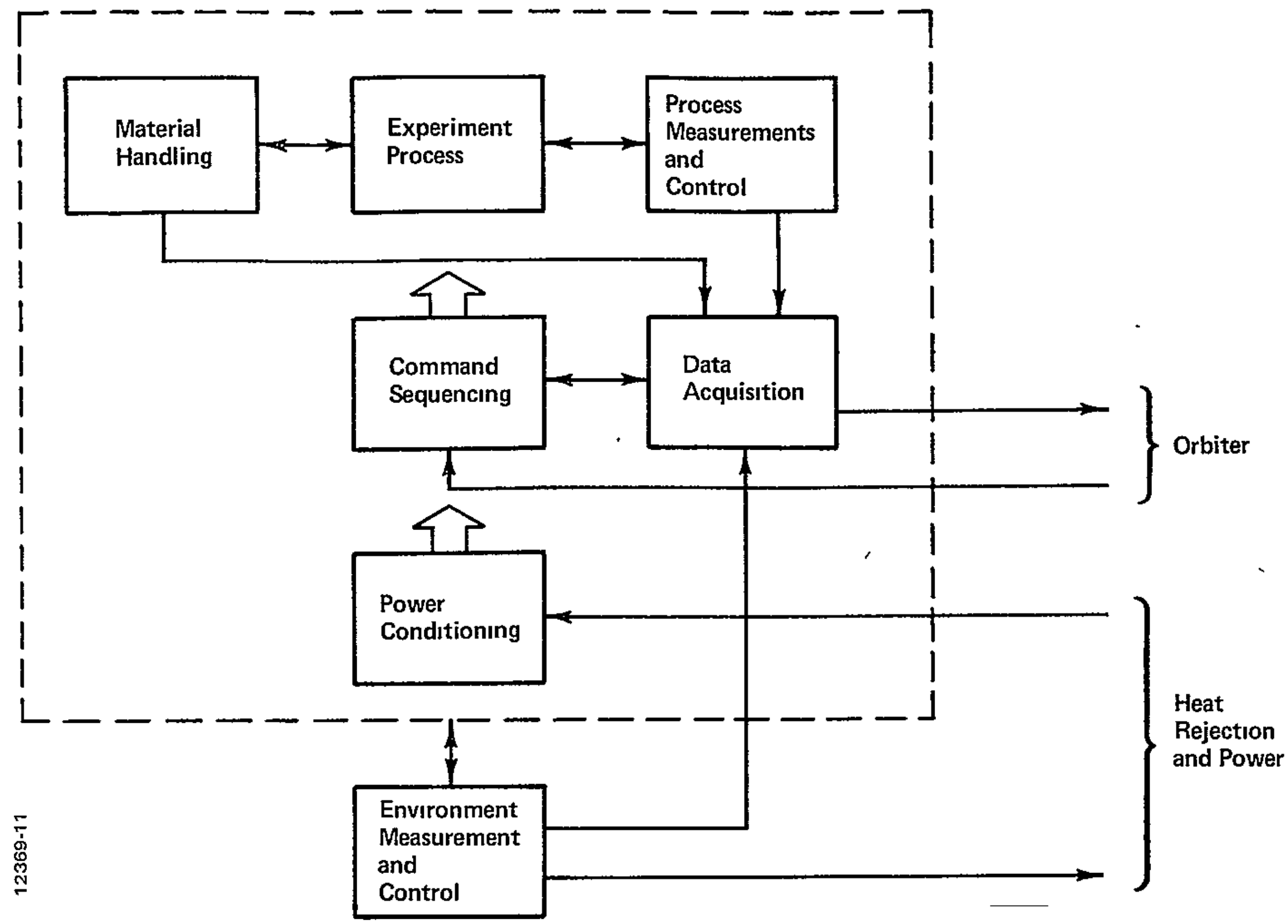

Figure 3-2 Automated Process Functions

3.3.1 Environmental Characteristics

The Shuttle Orbiter and Spacelab design characteristics are not firm. Therefore, the information presented here is based on the predicted or calculated performance. The orbiter payload bay environment has been selected as representative of what the space processing equipment will see.

Payload Bay Limit-Load Factors. - Table 3-2 summarizes the load factor in g's. Note that the factors do not include the dynamic response of the payload.

Table 3-1

Automated Functions for Selected Experiments

Electromagnetic levitation on/off
Sample injection
Temperature monitor
Temperature control
Time dwell at temperature
Cooling rate control
Sample retrieval
Sample stowage
Acoustic levitation on/off
Crystal pulling
Boat pulling (cartridge manipulation)
Gas/vacuum control
Quench control
Mixer on/off
Furnace heater on/off
Preheater on/off
16 mm movie camera on/off
TV camera on/off and focus control
Data system on/off
Caution and warning astronaut override
TV data acquisition
Film recording of process

Table 3-2

Payload Bay Load Factor Limits

Condition*	X_o (g)	Y_o (g)	Z_o (g)
Lift-off***	-1.7 ±0.6	±0.3	-0.8 -0.2
High-Q boost	-1.9	±0.2	+0.2 -0.5
Booster end burn	-3.0 ±0.3	±0.2	-0.4
Orbiter end burn	-3.0 ±0.3	±0.2	-0.5
Space operations	-0.2 +0.1	±0.1	±0.1
Entry	±0.25	±0.5	+3.0 -1.0
Subsonic maneuvering	±0.25	±0.5	+2.5 -1.0
Landing and braking	±1.5	±1.5	+2.5
Crash**	+9.0 -1.5	±1.5	+4.5 -2.0

*Positive X, Y, and Z directions equal aft, right, and up. Load factors carry sign of externally-applied load.

**Crash load factors are ultimate and only used to design payload support fittings and payload attachment fasteners. Crash load factors are for nominal payload of 65,000 lb. Longitudinal load factors are directed in forward azimuth within 20° of Orbiter longitudinal axis. Specified load factors operate separately.

***Factors include dynamic transient load factors at lift-off.

Vibration. - Calculated random vibration levels for the mid-fuselage section of the Orbiter are shown in Figure 3-3. The data are based on scaled data and do not include payload input impedance effects.

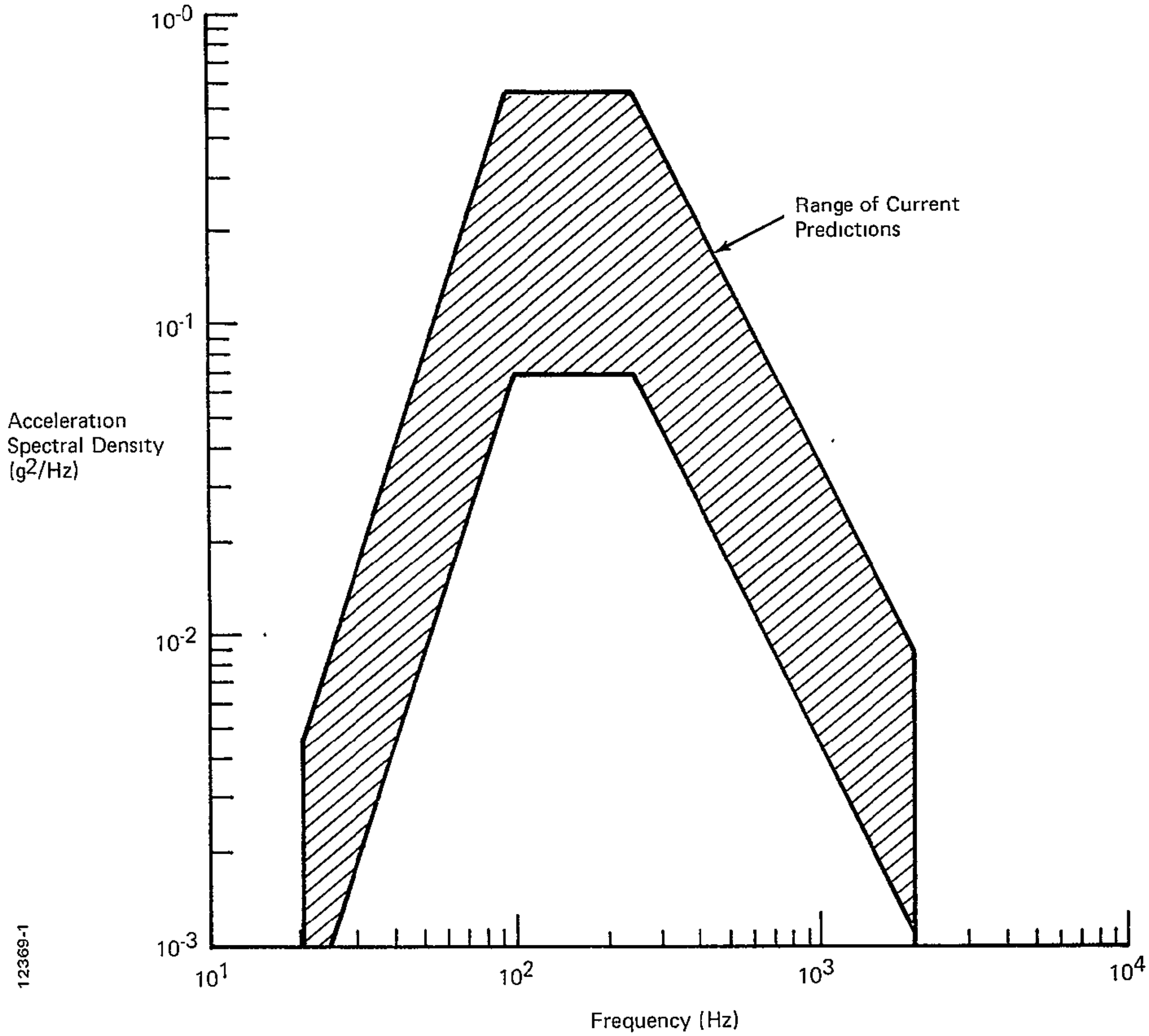

Figure 3-3 Analytical Predictions of the Orbiter Mid-Fuselage Primary Structure Vibration Spectra

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Acoustic. - Figures 3-4 and 3-5 give the analytical predictions of the Orbiter payload bay internal acoustic environment and acoustic spectra.

Payload Bay Atmosphere. - The Orbiter payload bay is vertical during the launch and entry phases and operates unpressurized during the orbital phase of the mission. For design purposes, it is assumed that the payload bay pressure level is 10^{-3} Torr. If a lower or higher pressure is required for payload operation, the environment must be supplied by the payload.

Thermal Environment and Control. - Throughout on-orbit operations, the radiator/payload doors will normally remain open. The payload will be exposed to the space environment and must provide for its own pressure and/or active thermal control.

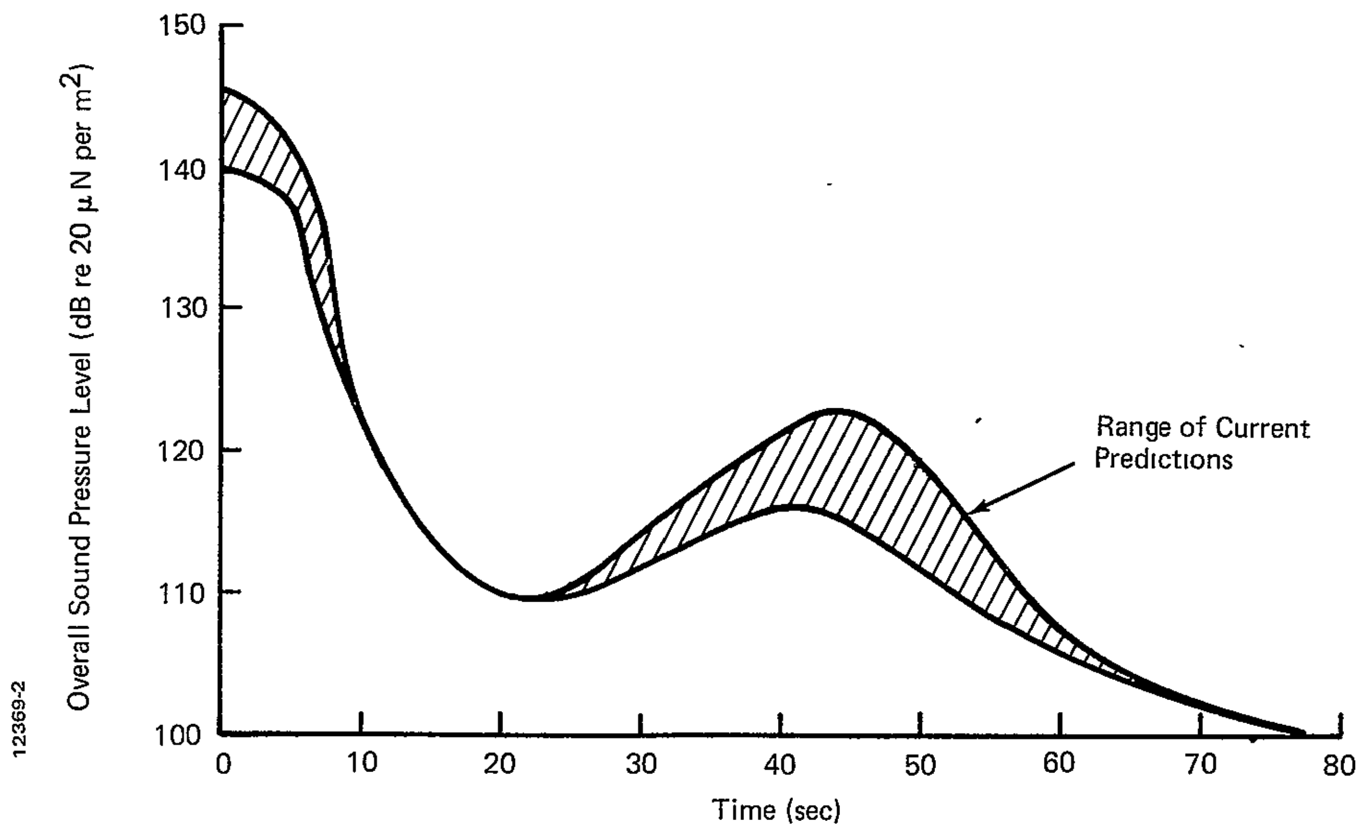

Figure 3-4 Analytical Predictions of the Orbiter Payload Bay Internal Acoustic Environment

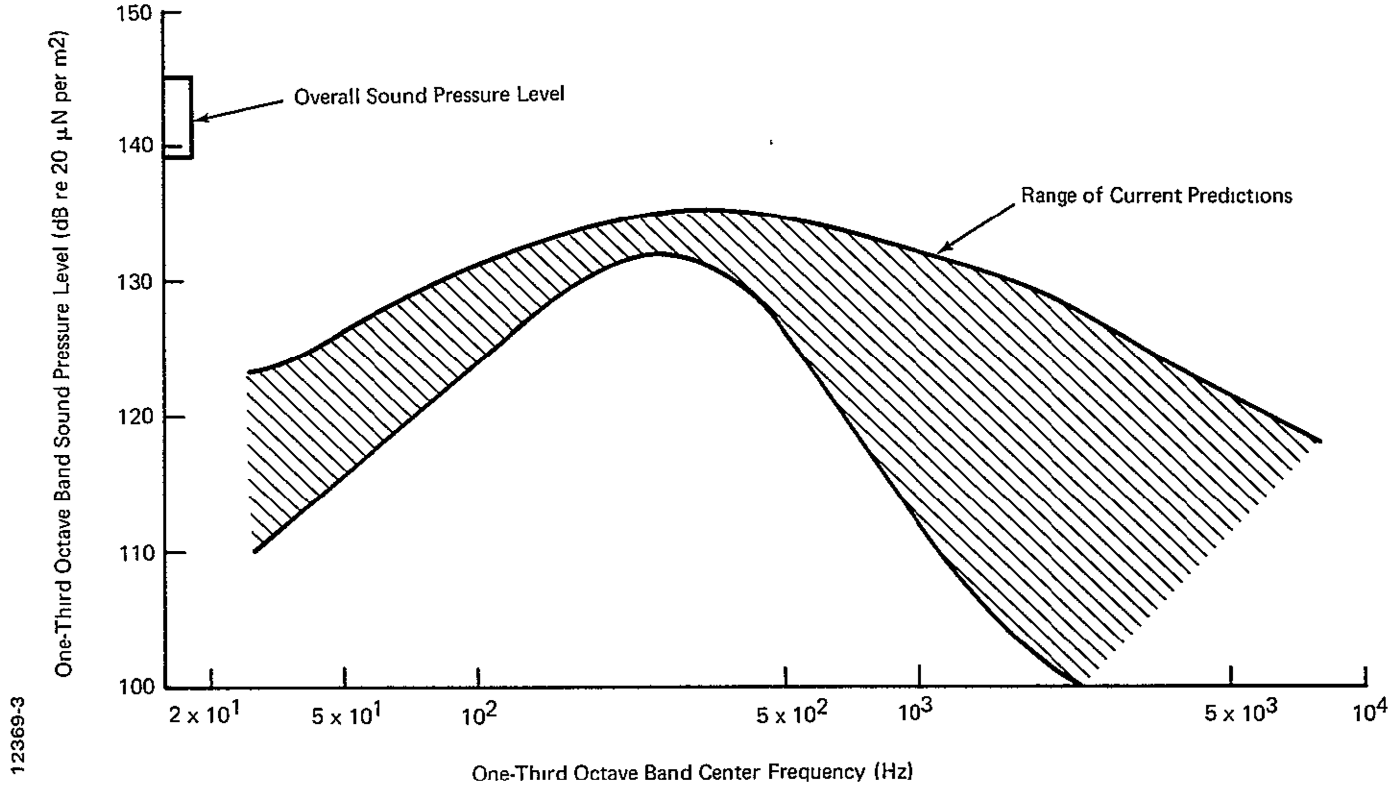

Figure 3-5 Analytical Predictions of the Orbiter
Payload Bay Internal Acoustic Spectra

Electromagnetic Compatibility. - Electromagnetic emissions shall not appear on power leads, control leads, signal leads, interconnecting cables, sources, or loads of an equipment in excess of the values shown on Figure 3-6 in the frequency range of 30 Hz to 20 KHz or shown on Figure 3-7 in the frequency range of 20 KHz to 50 MHz (a design goal margin of 6 dB shall be provided).

Narrowband E-field emissions in the frequency range of 14 kHz to 10 GHz shall not be generated and radiated in excess of the values shown in Figure 3-8.

Continuous or repetitive broadband E-field emissions shall not be generated and radiated in excess of the values shown in Figure 3-9.

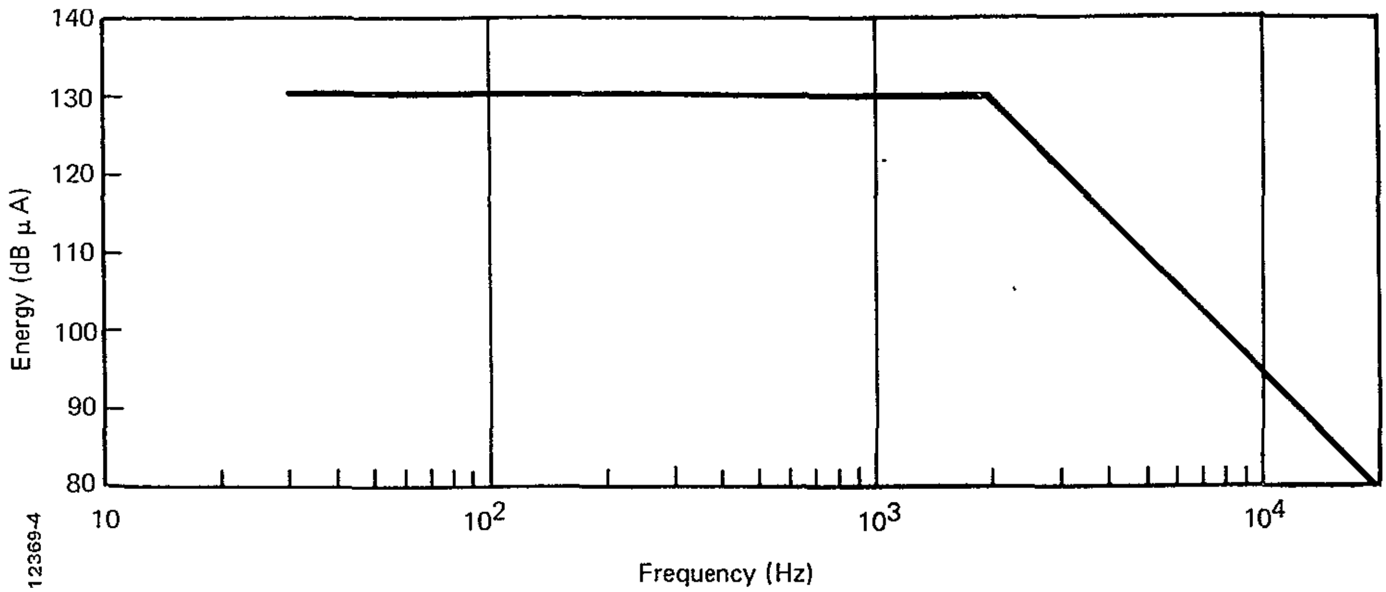

Figure 3-6 MIL-STD-461A Shuttle Amendment Limits for CE-01 and CE-02 Narrowband Emissions

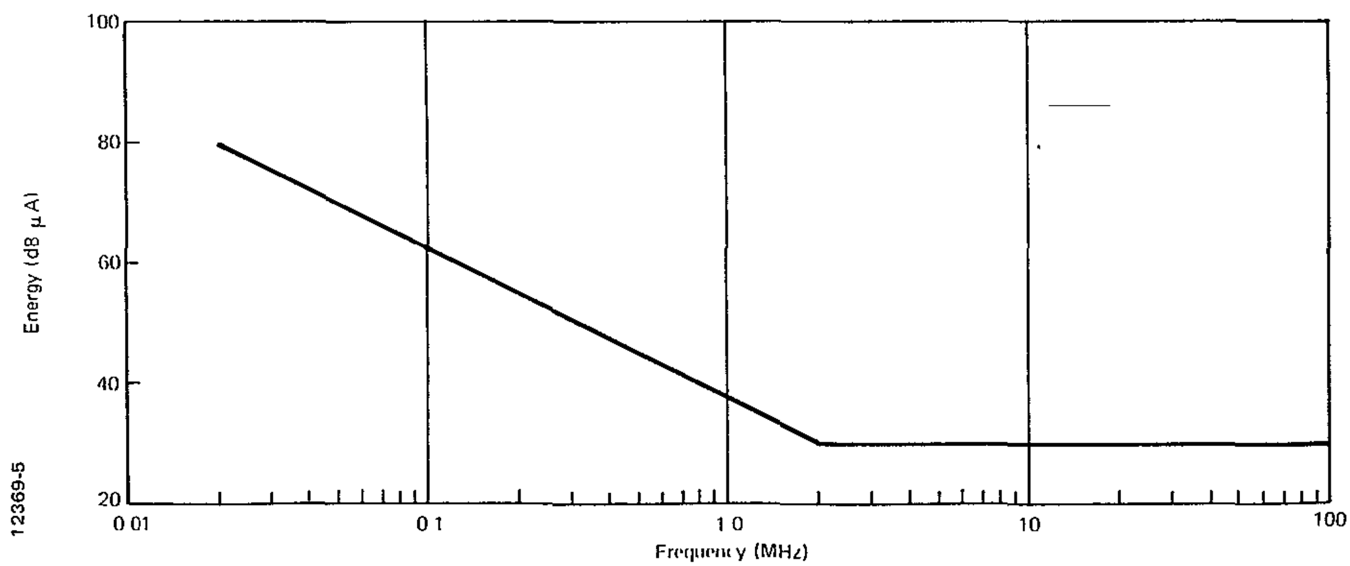

Figure 3-7 MIL-STD-461A Shuttle Amendment Limits for CE-03 and CE-04 Narrowband Emissions

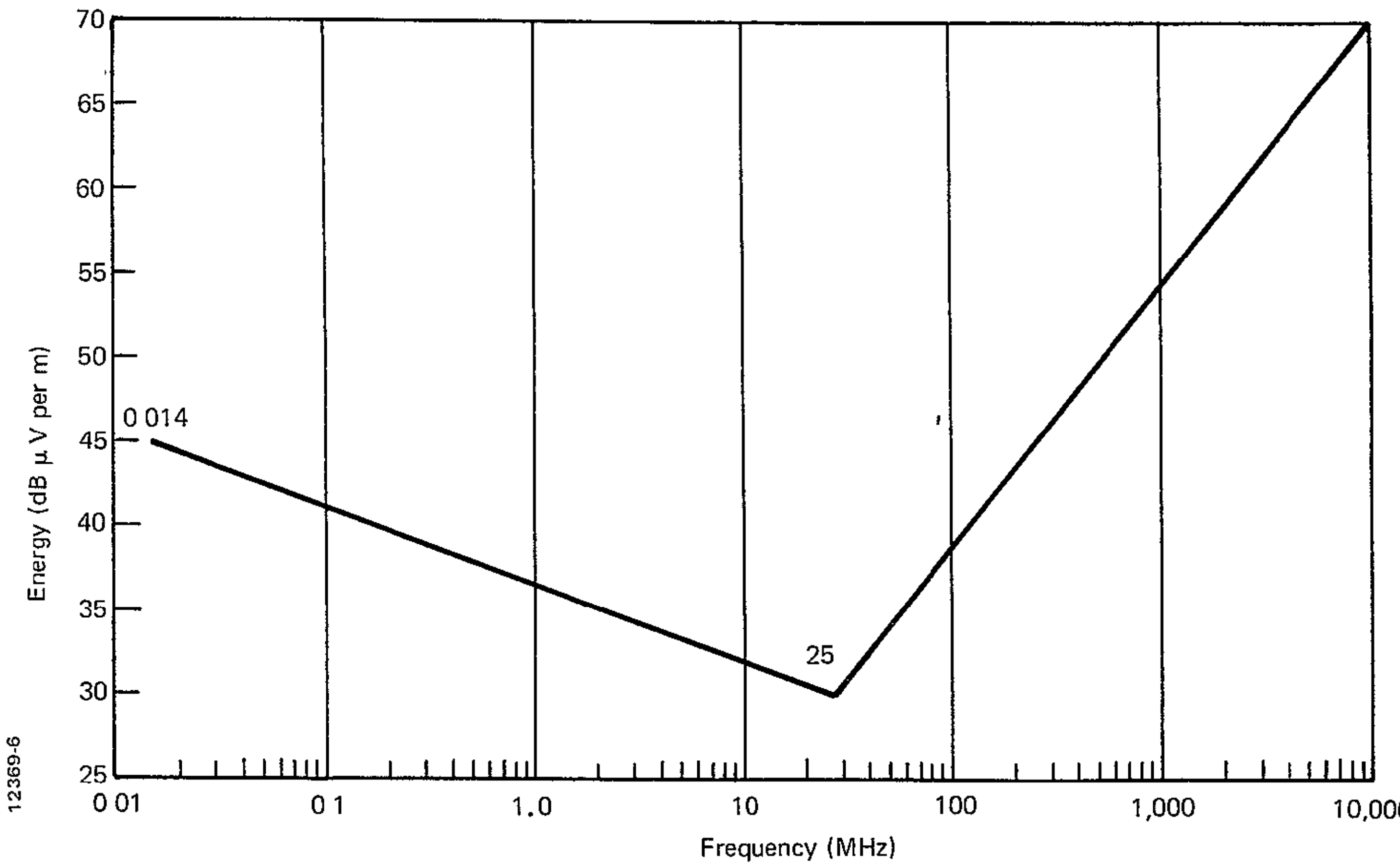

Figure 3-8 MIL-STD-461A Shuttle Amendment Limits for RE-02 Narrowband Emissions

Acceleration (On-Orbit). - Nominal acceleration during experiment operations shall be less than 10^{-4}g. Effects of atmospheric drag are given in Figure 3-10.

Venting and Purging. - No special requirements exist. However, contamination must be minimized. Therefore, anticipated contaminants from equipment or processes must be specified so control can be exercised.

3.3.2 Operational Characteristics

The most significant operating characteristics affecting the choice of equipment to be used are presented here.

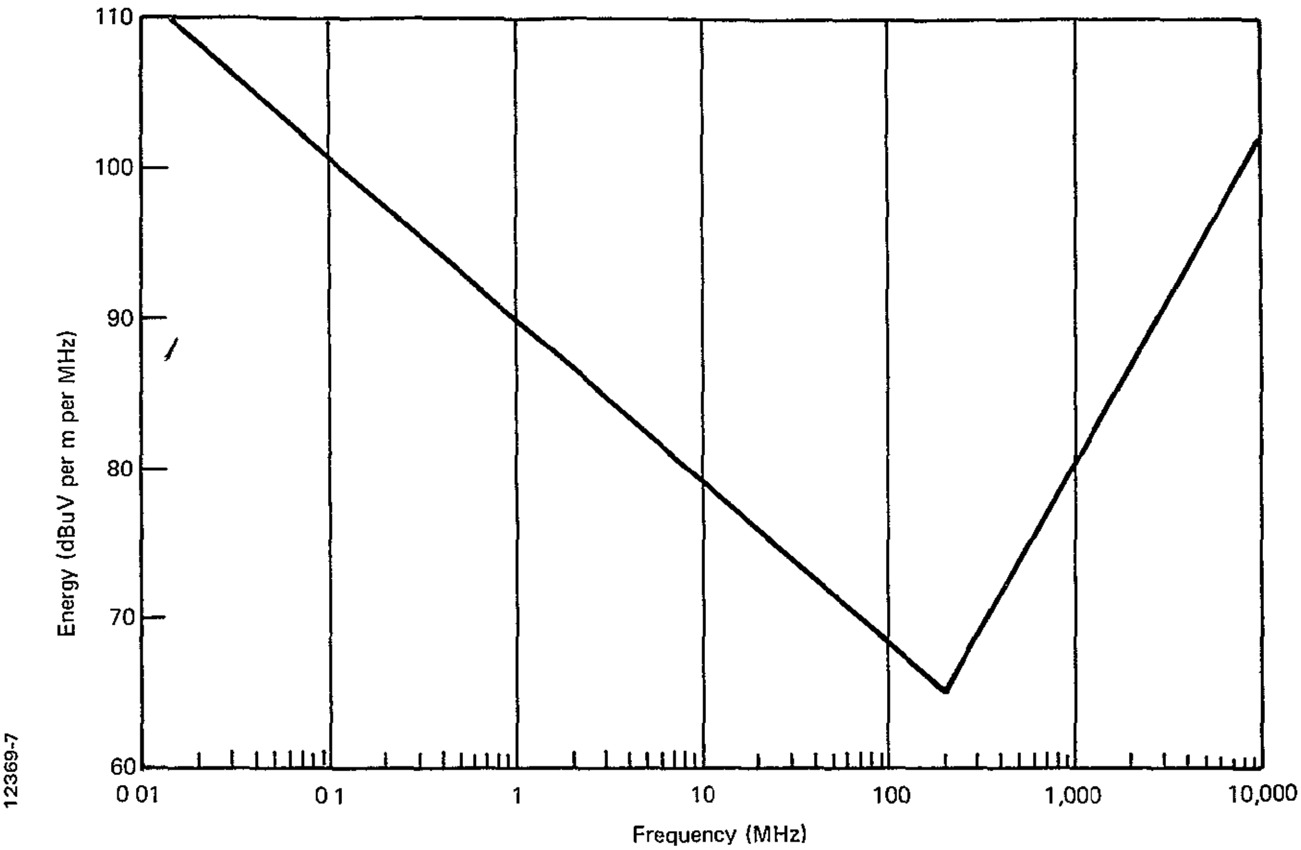

Figure 3-9 MIL-STD-461A Shuttle Amendment Limits for RE-02 and RE-05 Broadband Emissions

Power. - Operating power will usually be supplied at dc, 400 Hz, or 1,800 Hz. The nominal voltage output of the dc power supply is 25.5 to 32 V.

Communications and Data (Through Orbiter Links). -

Command link - 2 kbps.

Data link - 25 kbps real-time.

TV and high data - 3 MHz TV and 256 kbps time-shared with Orbiter.

Data storage - Spacelab recorder.

Digital - 30×10^6 bps.
Video - 5 MHz.
Analog - 2.5 MHz.

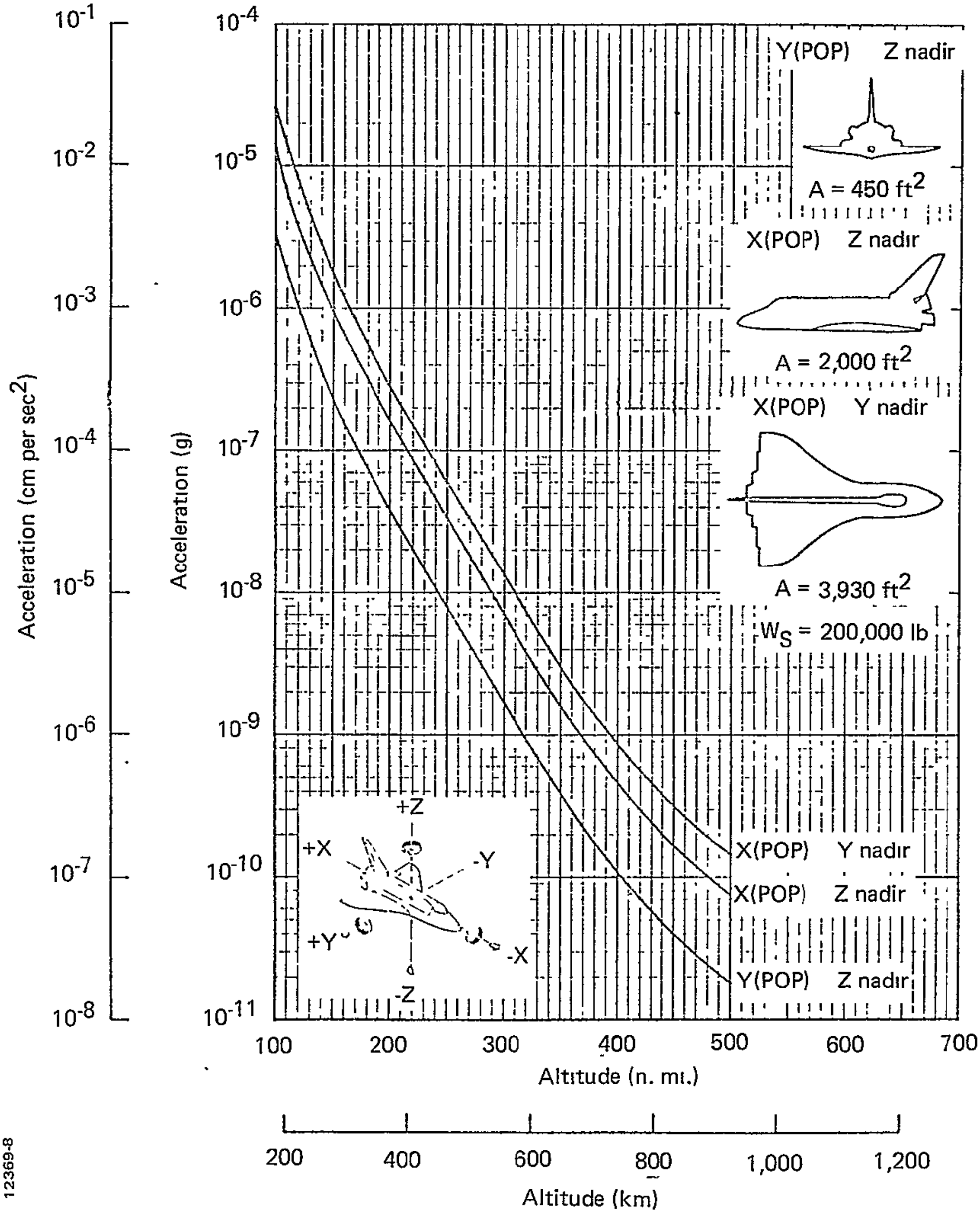

Figure 3-10 Effects of Atmospheric Drag on the Orbiter

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Operating Time. - 120 hours on-orbit operations. Equipment to be good for 60 re-uses.

Orbiter Cabin Interface. - Caution and warning annunciators. Safing/override controls for critical functions.

Thermal Control. - Thermal control will usually be by means of a closed-loop cooling system consisting of fluid loops and heat exchangers. Forced-air or convection-cooling will only be available for equipment mounted in the Spacelab or Orbiter cabin.

3.4 APPLICABLE INDUSTRIAL AUTOMATION EQUIPMENT

Industrial automation equipment to implement the space processing automation functions described in Section 3.2 are described in Appendix E. Table 3-3 lists the automation hardware types included, organized by basic automation functions

Equipment characteristics were compiled in three basic mutually-supporting formats:

- Format in which a number of manufacturers produce comparable equipment to implement a well-defined function. One representative hardware element is described in detail. An example of such an element is a thermocouple temperature sensor which is produced by a multitude of companies. The data sheet format used follows that developed in the "Requirements and Concepts for Material Science and Manufacturing in Space Study", Contract NAS 8-28938.
- Format in which a number of manufacturers produce comparable equipment to implement a well-defined function. A tabular comparison is made of the major characteristics of equipment of different manufacturers. This supplements the representative element data sheet described by showing the variation in the ranges of the major characteristics for the equipment of different manufacturers.
- Format in which specific hardware is not available to implement a function or in which the available hardware is deemed to have undesirable characteristics. Some alternative industrial automation techniques are discussed. An example of this is material transfer, in which industrial equipment depends largely on gravity and devices such as conveyors or unwieldly robots. In this case, typical material transfer techniques are described.

Table 3-3

Automation Hardware

- Material Handling
  - Raw material storage
  - Product storage
  - Material transfer
  - Process support
- Process and Environment Measurements
  - Temperature
    - Pyrometer
    - Thermocouple
    - Resistance sensor
    - Thermistor sensor
  - Pressure
    - Solid state sensor
    - Strain gage sensor
    - Variable reluctance sensor
  - Vacuum
    - Ion gage
    - Thermocouple gage
  - Gas constituents
    - Mass spectrometer
    - Gas chromatograph
    - Specific gas analyzers
- Process and Environment Controllers
  - Sensor-dedicated
  - Programmable controllers
  - Relay controllers
  - Minicomputers
- Command Sequencing
  - Programmable controllers
  - Relay controllers
  - Minicomputers
- Data Acquisition
  - Data acquisition systems
  - Magnetic tape recorders
  - Television cameras
  - Film cameras
- Process Control Actuators
  - Relays
  - Valves
  - Motors

Table 3-4 summarizes the availability and the modifications required to be completed on industrial automation hardware in order to make it applicable to the automation of space processing functions.

Table 3-4

Automation Hardware Availability Summary

Automation Hardware	Applicable Commercial Unit Available	Modifications Required
MATERIAL HANDLING		
• Raw material storage	Custom	New design.
• Product storage	Custom	New design.
• Material transfer	Custom	New design.
• Sample levitation	Custom	New design.
• Crystal puller	Yes	Brushless motors and computer control.
• Boat puller	Yes	Brushless motor, computer control, and repackage electronics.
PROCESS AND ENVIRONMENT MEASUREMENTS		
• Temperature		
Pyrometer	Yes	Repackage electronics.
Thermocouple	Yes	None.
Resistance sensor	Yes	None.
Thermistor sensor	Yes	None.
• Pressure		
Solid state sensor	Yes	None.
Strain-gage sensor	Yes	None.
Variable reluctance sensor	Yes	None.
• Vacuum		
Ion gage	Yes	
Thermocouple gage	Yes	Repackage electronics.

Table 3-4

Automation Hardware Availability Summary (Cont.)

Automation Hardware	Applicable Commercial Unit Available	Modifications Required
• Gas constituents		
Mass spectrometer	Yes	None.
Gas chromatograph	Yes	None.
Gas analyzers	Yes	Repackage electronics.
PROCESS AND ENVIRONMENT CONTROLLERS		
• Sensor-dedicated	Yes	Repackage electronics.
• Programmable controllers	Yes	Repackage electronics.
• Relay controllers	Yes	
• Minicomputers	Yes	None.
COMMAND SEQUENCING		
• Programmable controllers	Yes	Repackage electronics.
• Relay controllers	Yes	
• Minicomputers	Yes	None.
DATA ACQUISITION		
• Data acquisition systems	Yes	Repackage electronics.
• Magnetic tape recorders	Yes	None.
• Television cameras	Yes	Repackage electronics.
• Film cameras	Yes	None.
PROCESS CONTROL ACTUATORS		
• Relays	Yes	None.
• Valves	Yes	None.
• Motors	Yes	None.

SECTION 4

PAYLOAD GROUPING

4.1 INTRODUCTION

The objective of the payload grouping effort was to form experiment sets or groupings for the conceptual design investigation.

The specific approach followed was:

- Set up criteria by which experiments and equipment were grouped.
- Define potential experiment sets compatible with the payload constraints and grouping criteria.
- Prepare preliminary hardware identification for each group.

Specific groupings were selected for concept design analysis.

4.2 GROUPING CRITERIA

The three major classes of experiment equipment groupings are the levitation (or containerless processing) experiments, the furnace (or closed container) experiments, and the biological separation experiment.

To further group the experiments into payload equipment groups, four criteria were defined as follows:

- Material compatibility.
- Material handling commonality.
- Supporting function requirements.
- Resource requirements (Shuttle payload accommodation).

Material compatibility includes the following considerations:

- Melting temperature within the same equipment range capability.
- Heating method applicable to the materials, necessity for preheating, and heating power required.

- Heating profile required.
- Waste produced (including gases, solids, or heat) and the possibility of contaminating the facility.
- Required cooling rates.
- Comparable size sample requirements or those within the same equipment range.

Material handling commonality includes the following considerations:

- Methods of sample storage or isolation before and after processing.
- Method of sample insertion into the processing facility.
- Necessity for stirring or agitating the melt during processing and necessity to move the molten zone through the sample.
- Requirements for crystal pulling.
- Method of product recovery.

Supporting function requirements are associated with the design definition of control equipment and gas and vacuum handling requirements. Grouping considerations include the following:

- Number of input/output functions to a programmable controller, computer, or other control center.
- Number of process steps or sequences required.
- Rate at which steps are executed.
- Firmness of requirements or process variables and range to be accommodated.
- Gas requirements, including type, pressure, flow rate, and measurements required.
- Vacuum requirements, including pumpdown times and outgassing potential.
- Fluids required for quenching or coolant loops.

4.3 EXPERIMENT GROUPING

The 18 experiments identified in Section 2 for further study have equipment requirements which divide them naturally into three subcategories; levitation, furnace, and electrophoresis experiments. Within these major groupings, the experiments have been further classified in accordance with their hardware implementation, as described in the following paragraphs.

4.3.1 Levitation Experiments

Several of the selected experiments require containerless processing in order to preserve sample purity and to achieve uniform solidification. These groupings of levitation experiments are identified in Table 4-1 as L-1 through L-4. It should be noted that several of the experiment classes are adaptable to more than one grouping. Determination of the optimum facility for the process then depends on the selection of the specific material. Materials shown in the table should be considered as typical. Each grouping is further described below.

Group L-1. - This group consists of a broad set of experiments in processing of materials which require (or can tolerate) a vacuum environment and which have low-to-medium resistivity. The latter characteristic permits levitation of sample specimens electromagnetically, with only a few watts of power at a relatively low frequency, e.g., about 35 kHz.

The vacuum environment makes feasible the use of an electron-beam gun for sample heating. This is a highly-efficient method of heating small samples of the types of materials included in this group. Secondary and thermionic emission maintain an electrical charge balance on the free-floating sample.

Table 4-1

Levitation Experiment Groups

L-1	L-2	L-3	L-4
Chalcogenide Glass (GeTe) Ultrapure Alloys (WC) Purification and Under-Cooled Solidification (W) Amorphous Solidification (PdSi)	Dispersion Composites (Beryllia in Be)	High Melting Point Oxide Glass (Zirconia)	Crystal Pulling from Melt (Si) High-Resistivity-Oxide-Glass (Alumina) Striking Glass (AgCl in High Silicate)

Typical time-lines and other pertinent parameters for this group are summarized in Table 4-2. The materials shown in the table are representative and were selected to permit quantification of the other parameters. It will be noted that processing temperatures range from 800 to 3,410°C (1,073 to 3,683°K) and that diameters of the spherical specimens range from 1 to 4 cm (0.4 to 1.6 in.). Specimen processing times run from 13 to 41 minutes, and average power required for the total facility ranges from 1.0 to 2.0 kW.

The hardware requirements for the L-1 facility are listed in Figure 4-1. The list does not include power generation and conversion equipment, radiators, or thermal storage and heat exchangers.

Group L-2. - This "group" comprises a single experiment class, shown in Table 4-1 as "Dispersion Composites", with beryllia in beryllium as a typical material. The resistivity of this group permits efficient heating by electromagnetic radiation at a relatively low frequency, e.g., 100 kHz. Thus, the same generator and coils used for levitating the specimen can be used also for heating. No electron-beam gun or auxiliary heater is required. Processing can be accomplished in a vacuum or inert-gas environment.

In a typical process, a spherical sample 2 cm (0.8 in.) in diameter is heated to melt in two stages, with dwells of 5 minutes at 1,000°C (1,273°K) and 2 minutes at the melting point of 1,284°C (1,557°K). Total heating time of 9.8 minutes and cooling time of 10.2 minutes comprise the time-line. Peak power required is 3.3 kW, and average power is 1.5 kW.

Table 4-2

Group L-1 Typical Process Parameters

Material	Maximum Temperature (°C)	Sample Diameter (in)	Dwell Temperature (°C)	Time to Dwell (min)	Time at Dwell (min)	Time to Melt (min)	Time at Melt (min)	Time to Cool (min)	Total Time (min)*	Average Run Power (kW)
GeTe	800	0 8	600	1	1	3	4	4	13	1 0
WC	2,900	0 4	2,200	4	20	2	5	10	41	1.3
Tungsten	3,410	0 4	2,400	0 4	10	0 9	2	10 7	24	2 0
PdSi	960	1.6				5	5	5	15	1 9

Notes 1 3 kW peak power available from electron-beam gun Total peak power is 4 5 kW, independent of material. Power includes core equipment and conversion losses

*First process run requires a few additional minutes for facility checkout and chamber evaluation Each sequence also requires about two additional minutes for sample insertion and retrieval

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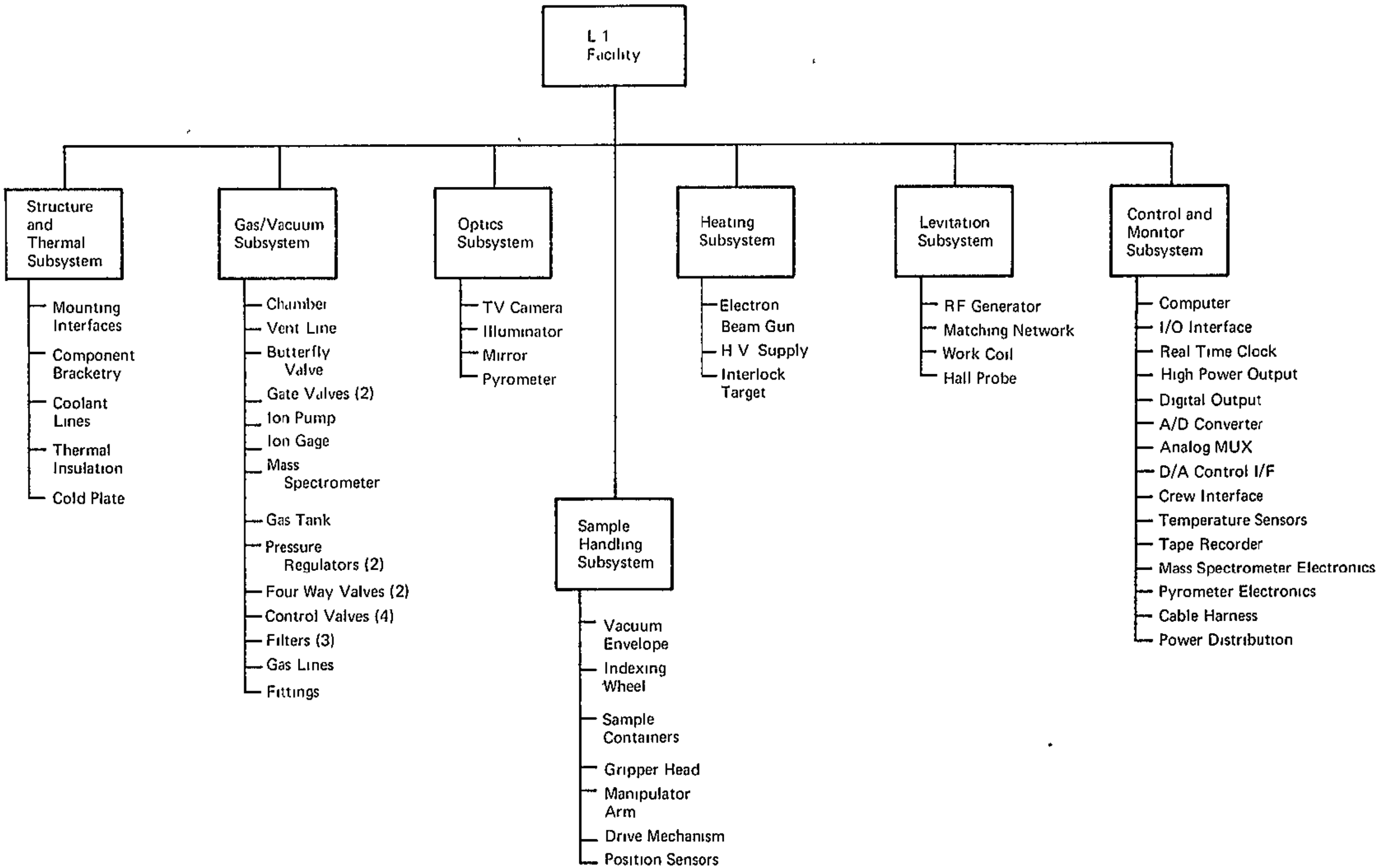

Figure 4-1 L-1 Hardware Tree

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Figure 4-2 lists the facility hardware requirements for this class of experiments.

Group L-3. - This "group" comprises a single experiment class and is shown in Table 4-1 as High-Melting-Point Oxide Glass. The characteristics of this group include a requirement for processing in an oxygen environment. Another characteristic is high electrical resistivity.

The high resistivity leads to a requirement for high power dissipation in electromagnetic levitation at a relatively high frequency, e.g., 15 MHz. As the resistivity is an inverse function of temperature near the melting point, a requirement also exists for a pre-heater to bring the sample into a conductive state.

The oxygen environment precludes the use of an electron-beam gun for heating, so the required heating power is applied to the induction coils used for levitation.

Typical materials for this experiment are the oxides of zirconium, cerium, thorium, and yttrium. For purposes of quantification, zirconia has been selected. A total heating time of eight minutes and a cooling time of 100 minutes comprise a representative time-line. Peak power of 3.4 kW to melt at 2,715°C (2,992°K) and controlled cooling of the 1-cm (0.4-in.) diameter specimen result in an average power expenditure of 1.0 kW for the 108-minute cycle.

The hardware requirements for the L-3 facility are listed in Figure 4-3.

Group L-4. - This group consists of a number of experiments which require levitation of materials, crystals and glasses whose resistivities are not electrically compatible with the electromagnetic technique. Therefore, an acoustical levitation facility will be required to process this group. All of the selected experiments in this group can tolerate a moderate-pressure gas environment, which is essential for acoustic levitation. Heating will be accomplished by a resistance furnace or an arc image heater.

Parameters for the selected experiments are listed in Table 4-3. Both oxygen and inert-gas environments are represented. Processing temperatures range from 1,410 to 2,050°C (1,683 to 2,323°K) and sample diameters range from 1 to 4 cm (0.4 to 1.5 in.). Processing times vary from one to several hours, and average powers are about 3 to 4 kW.

The hardware requirements for the L-4 facility are shown in Figure 4-4.

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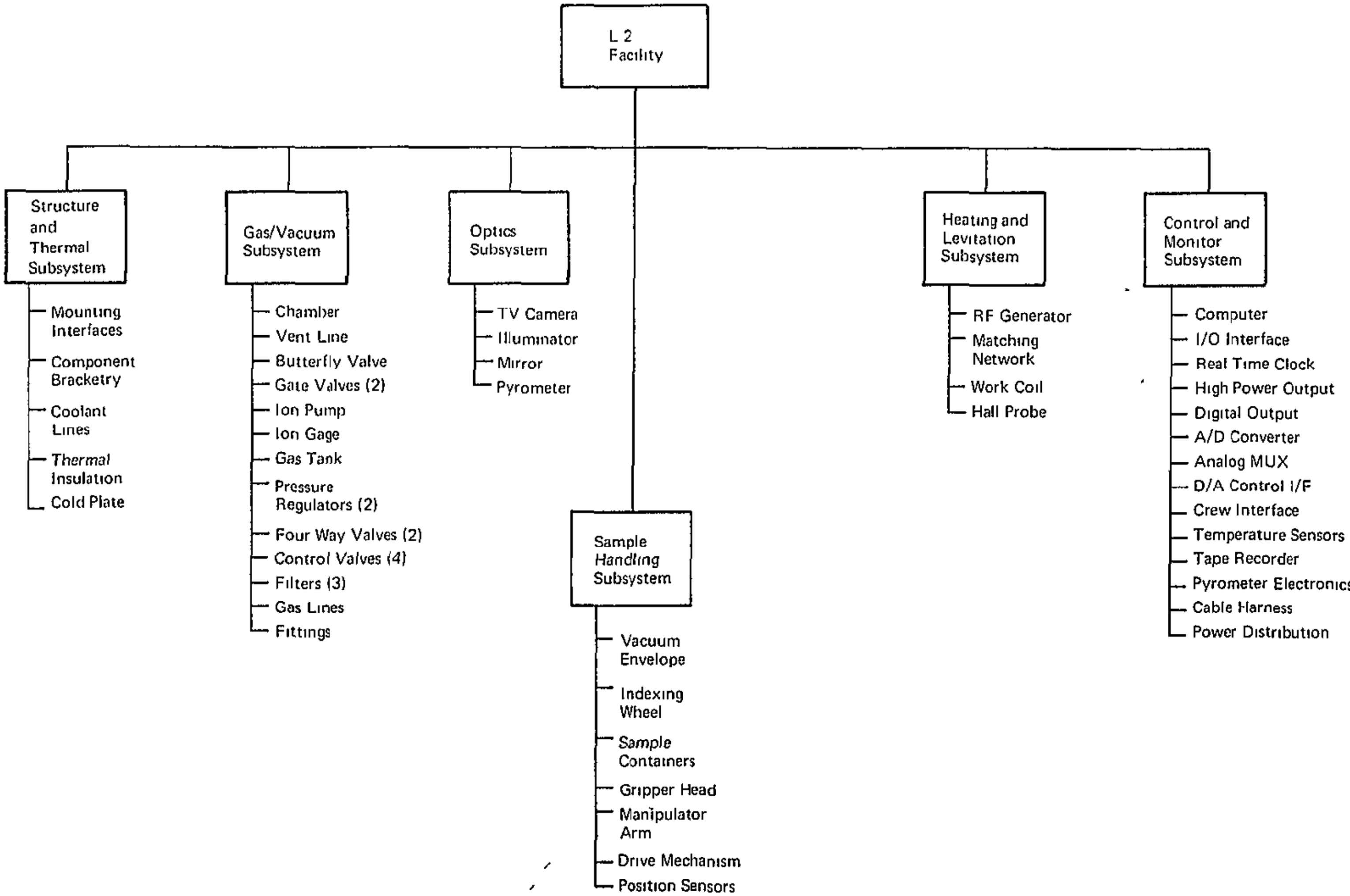

Figure 4-2 L-2 Hardware Tree

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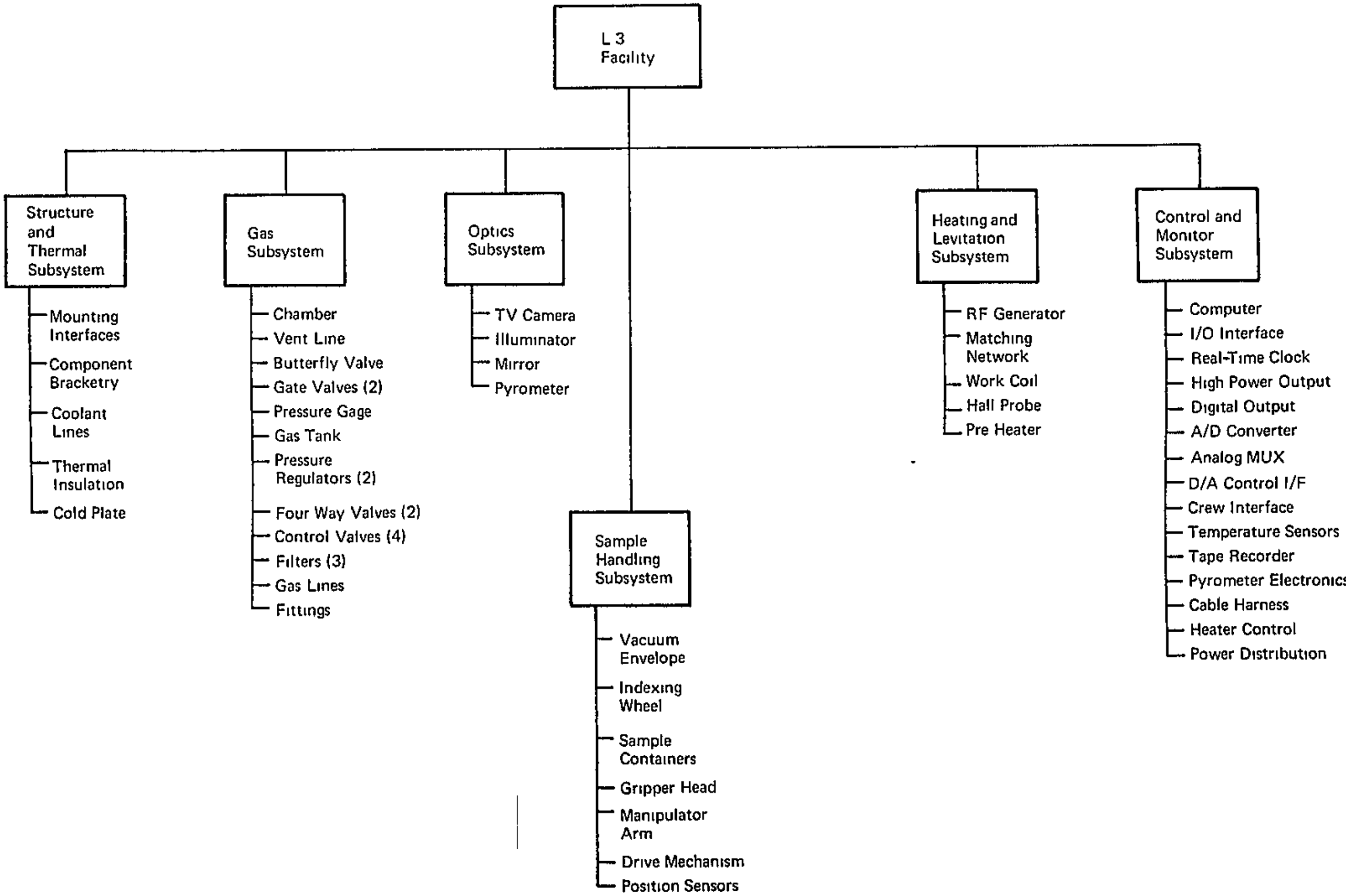

Figure 4-3 L-3 Hardware Tree

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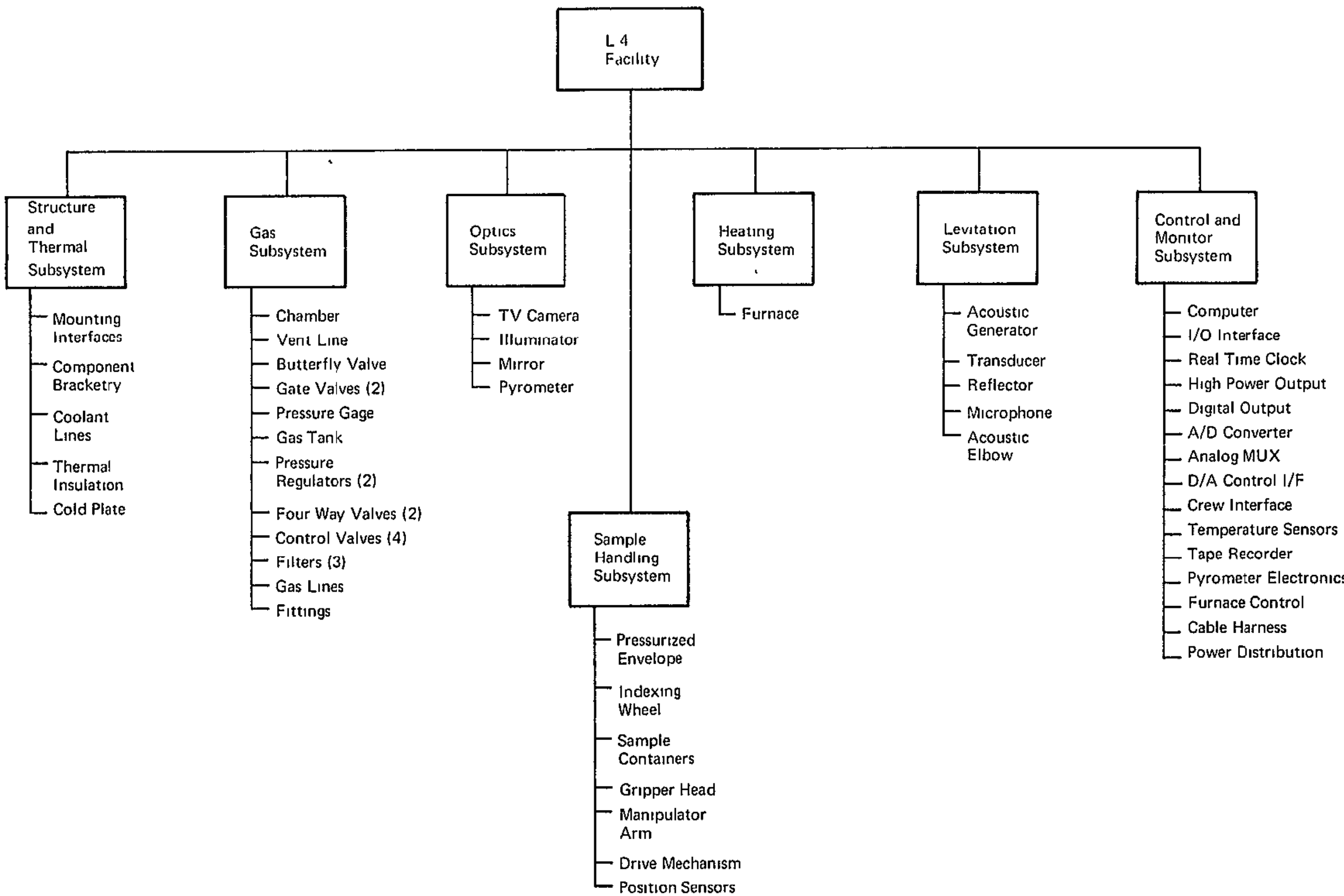

Figure 4-4 L-4 Hardware Tree

Table 4-3

Group L-4 Typical Process Parameters

Material	Maximum Temperature (°C)	Gas Environment	Sample Diameter (in.)	Heating Time (Min)				Cooling Time (min)	Total Time (min)	Average Power (kW)	Peak Power (kW)
				To Dwell	At Dwell	To Temperature Maximum	At Temperature Maximum				
Silicon	1,410	Inert	1 5			101	190	120	411	2 7	3 3
Alumina	2,050	O_2	0.4	94 (1,827°C)	5	7	5	100	211	3 6	6.0
AgCl in High Silicate	1,500	Inert	1 5			101	15	20	136	3 2	3 6

Notes Maximum furnace power of 4 1 kW
Power values include conversion losses and core equipment
Time includes 60 minutes furnace warm-up

4.3.2 Furnace Experiments

Those of the selected experiments which do not require containerless processing can be implemented with electrically-heated furnaces. Three groupings of furnace experiments have been identified as F-1 through F-3 in Table 4-4.

Table 4-4

Furnace Experiment Groups

F-1	F-2	F-3
Crystal Growth in Flux (YIG)	Crystal Growth from Vapor (CdSe)	Zone Refining (Si)
Crystal Pulling from Molten Zone (TiO_2)		
Conventional Glass (SiO_2)	Composite Materials (Al_2O_3 fibers in Al)	Eutectic Materials (CuAl)
	Immiscible Materials (Cu-Pb)	

Group F-1. - This group is characterized by the high melting-point of the associated materials, over 1,200°C (1,473°K).

Process parameters for the selected experiments in this group are shown in Table 4-5. Sample sizes in the range of 3.8 to 10.4 cm (1.5 to 4.1 in.) equivalent diameter (specimens need not be spherical) require an average power of 2.4 to 3.8 kW. For these glass and crystal experiments, process times run from several hours to several days.

Table 4-5

Group F-1 Typical Process Parameters

Material	Maximum Temperature (°C)	Sample Equivalent Diameter (in.)	Time to Maximum Temperature (min)	Time at Maximum Temperature (min)	Time to Cool (min)	Total Time (min)	Average Power (kW)	Peak Power (kW)
YIG	1,300	4.1	161	240	7,380	7,781 (about 5.4 days)	1.9	3.0
TiO_2	1,850	1.5	98	408	720	1,226 (about 20 hours)	3.4	5.1
SiO_2	1,715	2.9	113	60	1,824	1,997 (about 33 hours)	2.3	4.5

Notes: Heating power is 3.3 kW maximum.
Time includes 60-minute furnace warm-up.
Power values include conversion losses.

The hardware required to implement this group of experiments is listed in Figure 4-5. It should be noted that a multiple-furnace facility is practical on missions with adequate power and thermal dissipation.

Group F-2. - This group consists of those experiments with low or moderate processing temperatures, below 1,200°C (1,473°K), which do not require containerless processing.

Process parameters for the selected experiments in this group are shown in Table 4-6. Processing temperatures range from 800 to 1,100°C (1,073 to 1,373°K) and sample sizes range from 1 to 2 cm (0.4 to 0.8 in.) in diameter. Average power ranges from 1.6 to 2.0 kW. Process times for the metallurgical experiments are typically about an hour, whereas the crystal experiments will run for several hours.

These experiments will, typically, require a moderate-pressure gas environment. This environment will be provided by a sealed capsule.

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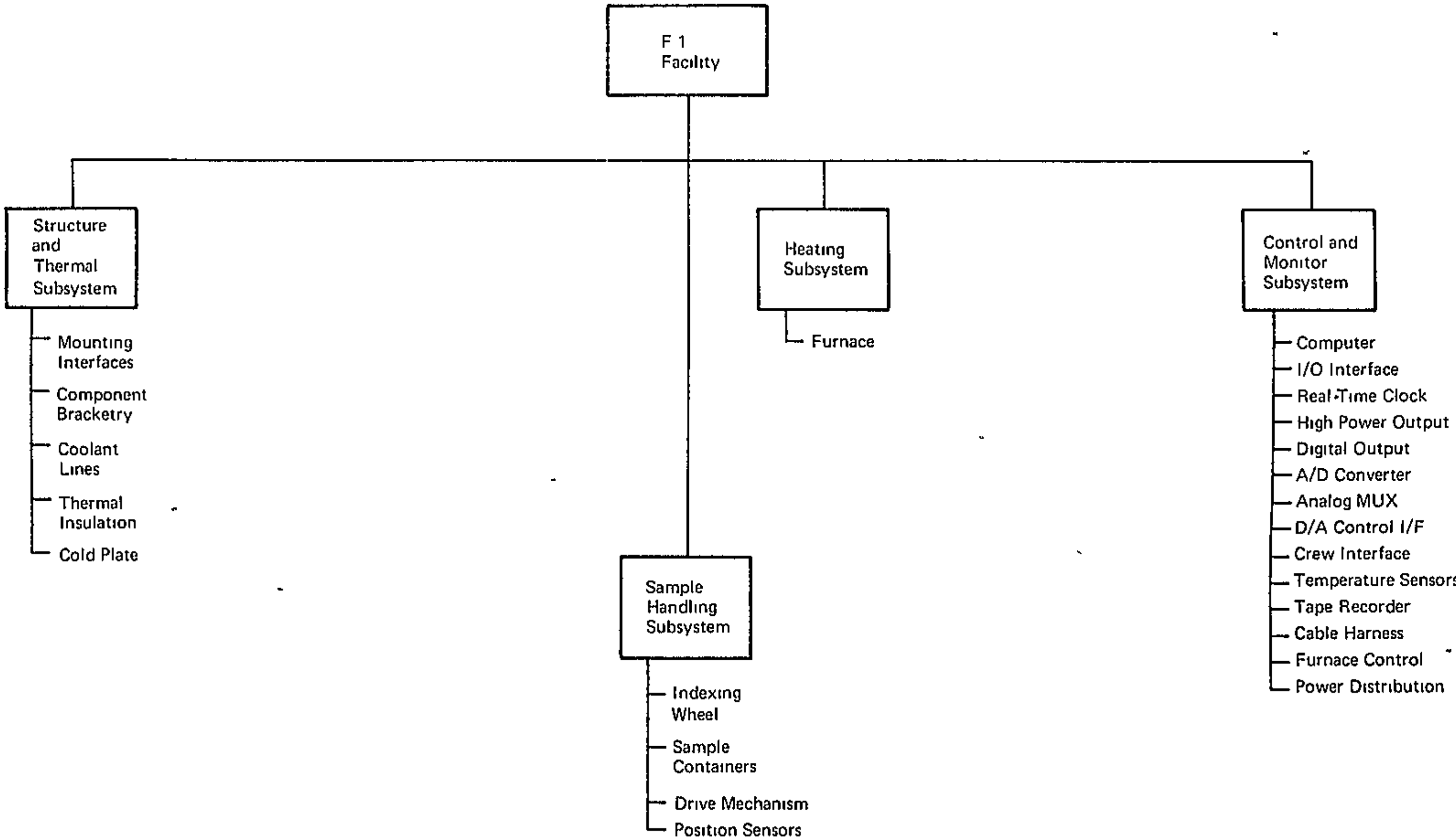

Figure 4-5 F-1 Hardware Tree

Table 4-6

Group F-2 Typical Process Parameters

Material	Maximum Temperature (°C)	Gas Environment	Sample Diameter (in.)	Time to Maximum Temperature (min)	Time at Maximum Temperature (min)	Time to Cool (min)	Total Time (min)	Average Power (kW)	Peak Power (kW)
Cu-Pb	1,100	Inert	0.4*	45	15	10	70	2.8	3.9
Al_2O_3 fibers in Al	700	Inert	0.8*	45	15	4	64	1.9	2.0
CdSe	800	Iodine	0.5	45	469	120	634 (about 10 hours)	1.8	2.1

Notes: Heating power is 2.2 kW maximum

*Rod - shaped sample, assumed 15 cm (6 inches) long
Time includes 30 minute furnace warm-up.
Power values include conversion losses

The hardware required to implement the selected experiments of this group is listed in Figure 4-6. As was the case with the F-1 facility, multiple furnaces can be accommodated on missions not limited by power and thermal dissipation.

Group F-3. - This group consists of those experiments requiring precisely-controlled temperature gradients and means for transporting the sample through the gradient.

Process parameters for the selected experiments in this group are shown in Table 4-7.

Processing temperatures range from 300 to 1,100°C (573 to 1,373°K) and sample diameters will be, typically, 1 to 2 cm (0.4 to 0.8 in.). Processing times will be, typically, about 1 or 2 hours. Average power required is about 2 kW.

The hardware required to implement this group of experiments is shown in Figure 4-7. Multiple furnaces can be accommodated on missions not limited by power and thermal dissipation.

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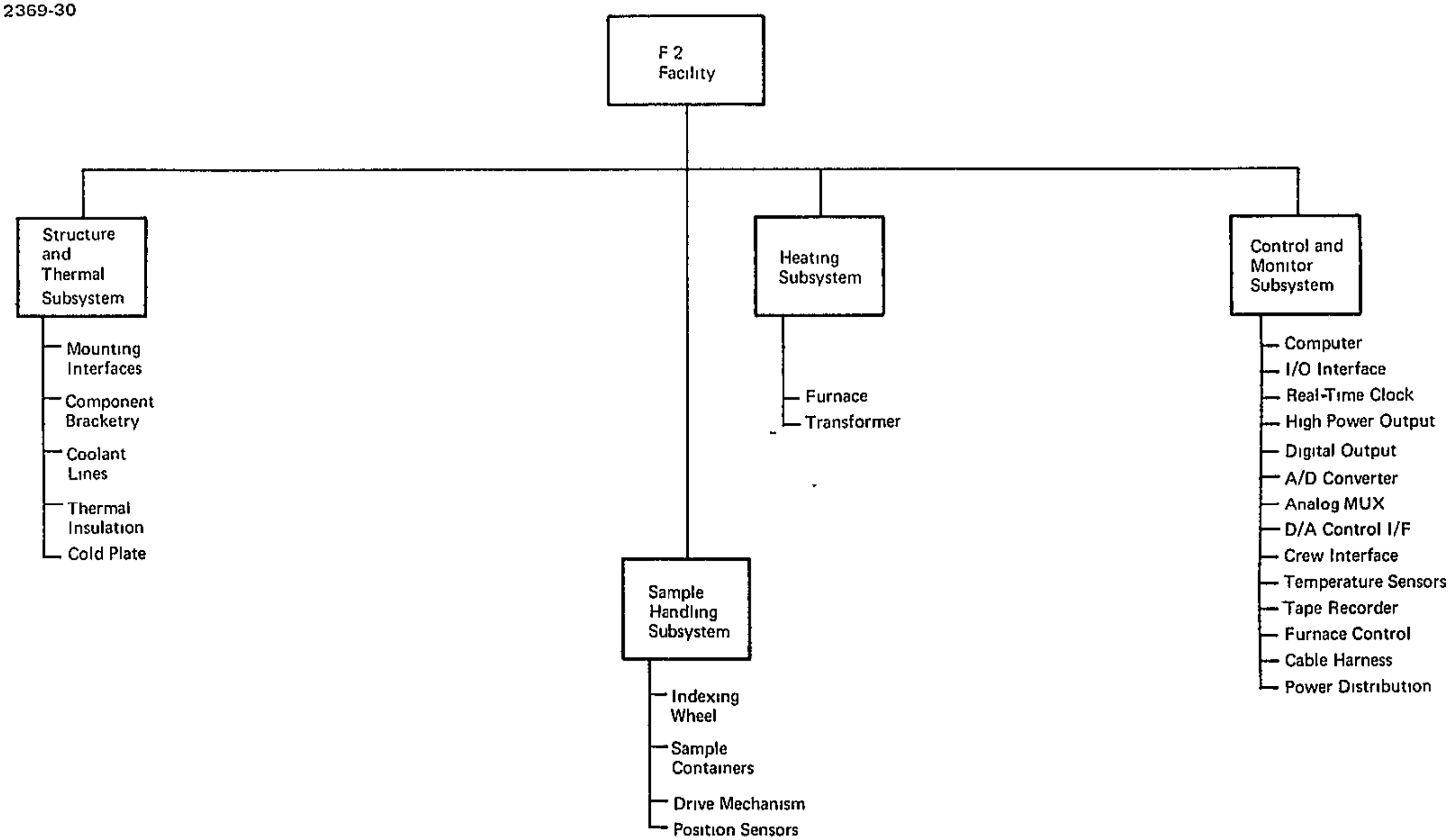

Figure 4-6 F-2 Hardware Tree

Table 4-7

Group F-3 Typical Process Parameters

Material	Maximum Temperature (°C)	Gas Environment	Sample Diameter (in)	Time to Maximum Temperature (min)	Time at Maximum Temperature (min)	Time to Retrace and Skip (min)	Total Time (min)	Facility: Average Run Power (kW)	Facility: Peak Power (kW)	Facility: Configuration
Cu-Al	540	Vacuum	0.4	3	504	2	509	3 3	3 7	F-3A
Si	1,410	Vacuum	0.8	30	1,404	24	1,458	3 0	4 1	F-3B

Notes Heating power is about 2.1 kilowatts
Rod-shaped samples, assumed 50 8 cm (20 in.) long.
For F-3B, time includes a 30-minute furnace warm-up and three passes through the furnace.
Power values include conversion losses.

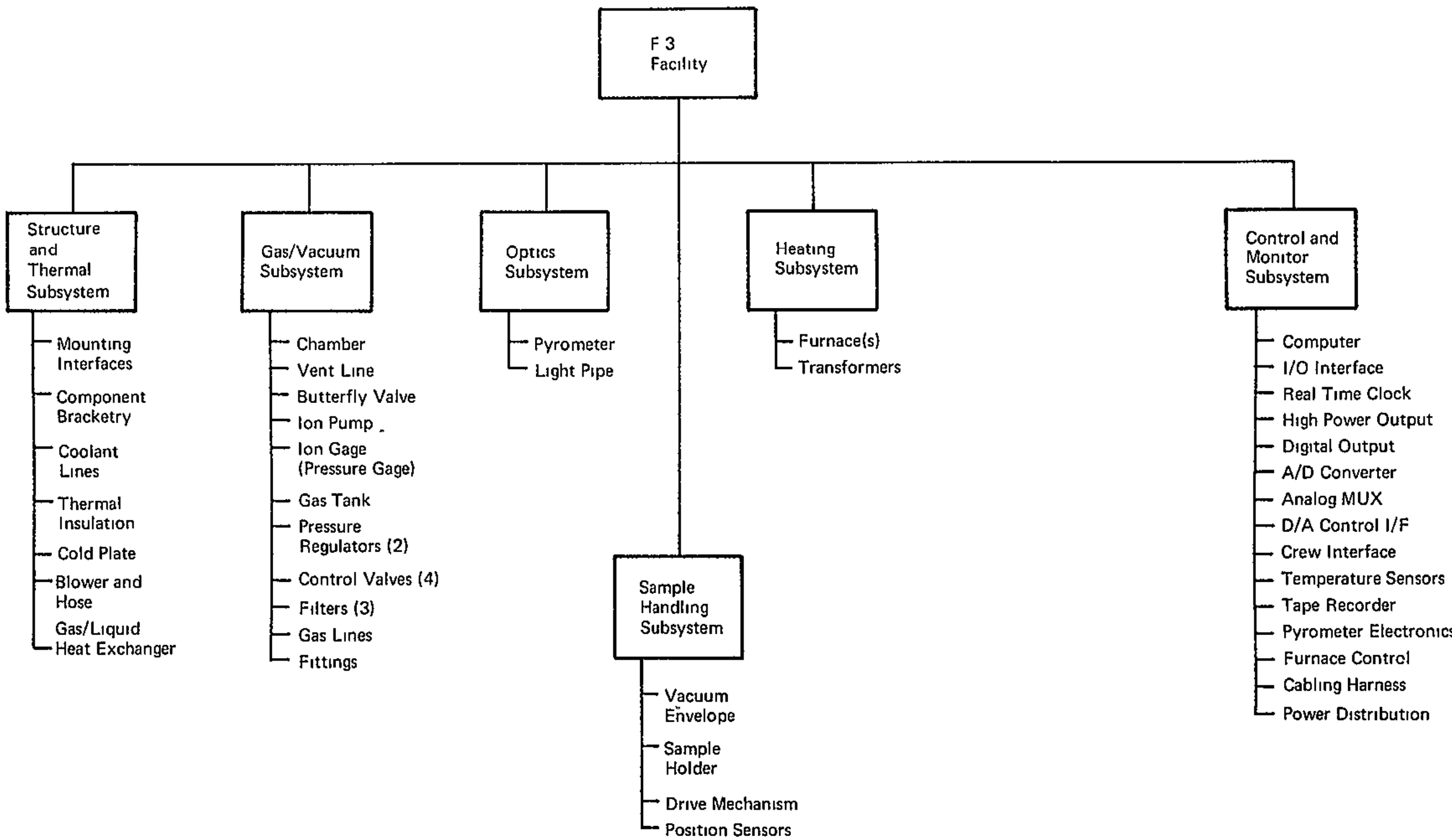

Figure 4-7 F-3 Hardware Tree

4.3.3 Electrophoresis Experiment

The electrophoresis experiment (E-1) requirements are summarized as follows:

- Process up to three samples.
- Collect and store up to 56 separated fractions per sample.
- Cell electric field constant voltage 5 to 50 V/cm.
- Buffer temperature maintained at 15 to 25°C.
- Sample storage 0 to 5°C.
- Collected fractions storage 0 to 5°C.
- Purge system between samples.
- Data collection (cell electrode voltage, flow rates, and separated fraction detection).
- Automatic operation.
- Caution and warning displays.

The major elements of the experiment design requiring precise control or automation are:

- Buffer flow system.
- Sample injection system.
- Electrode system.
- Electrode buffer flow.
- Electrode buffer phase separation.
- Sample collection system.
- Sample preservation and storage.

A hardware tree for the experiment is shown in Figure 4-8.

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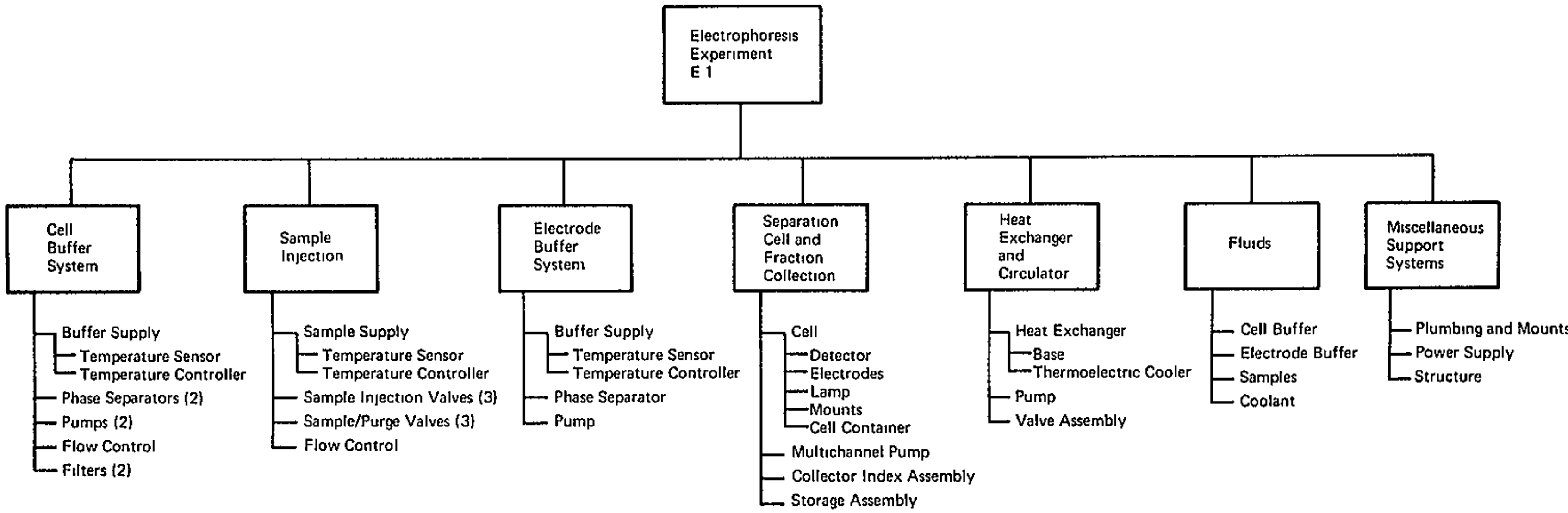

Figure 4-8 E-1 Electrophoresis Hardware Tree

SECTION 5

SPACE PROCESSING PAYLOADS CONCEPTUAL AND PRELIMINARY DESIGN

5.1 INTRODUCTION

Four levitation, three furnace, and one electrophoresis facility, corresponding to the experiment groupings, were reviewed for design and equipment requirements. The specific equipment required to implement the facilities was identified and layouts of the concepts were prepared to determine facility interfaces, volume requirements, and weight requirements.

Representative facilities (L-1, L-4, F-2, F-3, and E-1) and variations of them were conceptually designed and documented. In addition, the modifications required to adapt these facilities for the requirements of L-2, L-3, and F-1 were defined. Typical operational sequences were defined to permit identification of required instrumentation and control equipment. Characteristics of the 12 conceptual designs of the facilities are summarized in Table 5-1.

Five of the most representative of these concepts were selected for further more-detailed design and analyses. The concepts selected were:

- Electromagnetic Levitation (L-1).
- Acoustic Levitation (L-4A).
- Furnace Facilities (F-1 and F-2).
- Zone Refining Facility (F-3).
- Electrophoresis Facility (E-1).

Each facility was subjected to further analysis and preliminary design. Special consideration was devoted to mechanical, thermal, and electrical interfaces with the spacecraft. The functions of the core equipment, with a view toward standardization, were also investigated. Developmental requirements were identified, and qualification and acceptance testing needs were noted.

Table 5-1

Concept Summary

Concept	Description	Facility/Experiment Capability
L-1	Electromagnetic Levitation (35 kHz). Vacuum (10^{-5} to 10^{-7} Torr). Electron-Beam Heating. Multiple Samples (6).	Spherical samples, 1 to 4 cm diameter. Low resistivity, high secondary emission. Melting, purification, and homogeneous solidification of metals, their alloys and compounds, and chalcogenide glasses.
L-2	Electromagnetic Levitation (100 kHz). Vacuum or Atmosphere (10^{-7} Torr to several atmospheres). Induction Heating. Multiple Samples (6).	Spherical samples, about 2 cm diameter. Low resistivity, low secondary emission, e.g., beryllia dispersion in beryllium.
L-3	Electromagnetic Levitation (15 MHz). Vacuum or Atmosphere (10^{-7} Torr to several atmospheres). Induction Heating. Pre-Heating (imaging or resistance). Multiple Samples (6).	Spherical samples, 1 cm diameter. High resistivity materials requiring pre-heating to improve electromagnetic efficiency, e.g., high melting point oxide glasses. Controlled cooling.
L-4	Acoustic Levitation. Inert or Active Gas (5 Torr to several Atmospheres).	Spherical samples, 1 to 4 cm diameter. Ultra-high resistivity, glasses and crystals, controlled cooling.
L-4A	(a) Resistance Heater.	(a) Low absorptivity materials.
L-4B	(b) Arc Imaging Heater. Multiple Samples (6).	(b) High absorptivity materials.
F-1	High-Temperature Resistance Heater. Tube Furnace.	Self-contained cartridge samples. Equivalent diameter 4 to 10 cm.
F-1A	(a) Multiple Furnace Units (6).	Glasses and crystals to 2,200°C.
F-1B	(b) Sample Handling (6).	Controlled cooling.
F-2	Low-Temperature Resistance Heater. Tube Furnace.	Self-contained cartridge samples. Equivalent diameter 1 to 2 cm.
F-2A	(a) Multiple Furnace Units (6).	Immiscibles, composites, and
F-2B	(b) Sample Handling (6).	low-temperature (less than 1,200°C) crystals.
F-3A	(a) Moving-Zone Image Heater.	Zone refining and directional solidification. Rod-shaped samples. (a) 1 cm diameter by 58 cm long, to 1,100°C.
F-3B	(b) Fixed-Zone, moving sample, multiple samples or large rod.	(b) 2 cm diameter by 58 cm long, to 1,900°C.
E-1	Continuous Flow. Electrophoresis Unit.	Three biological specimens. Collect up to 50 separated fractions.

5.2 ELECTROMAGNETIC LEVITATION FACILITY (L-1)

The electromagnetic levitation (L-1) facility features the capability for containerless processing of various materials by suspension of the sample specimen in a shaped electromagnetic field.

5.2.1 Design Description

An artist's concept of the L-1 facility, showing the major components, is illustrated in Figure 5-1. Figure 5-2 is a layout drawing of the facility. The heart of the facility is a spherical vacuum chamber in which the specimen is processed. Near the center of the chamber is the coil that generates the levitation field. The coil is driven by an rf generator mounted externally, but adjacent to the chamber, to permit short electrical connections.

A gate valve on one side of the chamber permits introduction of sample specimens by a manipulator. The gate valve is electrically-controlled and pneumatically-actuated, using gas stored in an ellipsoidal tank.

On the lateral diameter of the chamber, an electron-beam gun is mounted, its output focussed on the center of the levitation coil. The gun serves as the primary heat-source for the facility.

Sample temperatures are monitored by an optical pyrometer, and a visual record of the process is maintained by a TV camera. These two devices share a beam-splitting mirror, which protects their optical apertures from direct deposition of material from the hot sample.

The chamber is vented to space through an electrically-controlled butterfly valve, and its pressure is continuously monitored by an ion gage. A second gate valve permits the connection of an ion pump for further reducing the chamber pressure and accommodating outgassing of the specimen and the chamber. A mass spectrometer permits analysis of residual gases.

Control of the facility is accomplished by a mini-computer. Interface electronics permit inputting data to the computer and outputting control commands to valves, the heat source, the manipulator, and other devices. Tape recorders record data from the computer and picture data from the TV camera.

5.2.2 System Interfaces

The principal interfaces of the L-1 facility with the spacecraft are mechanical, thermal, and electrical.

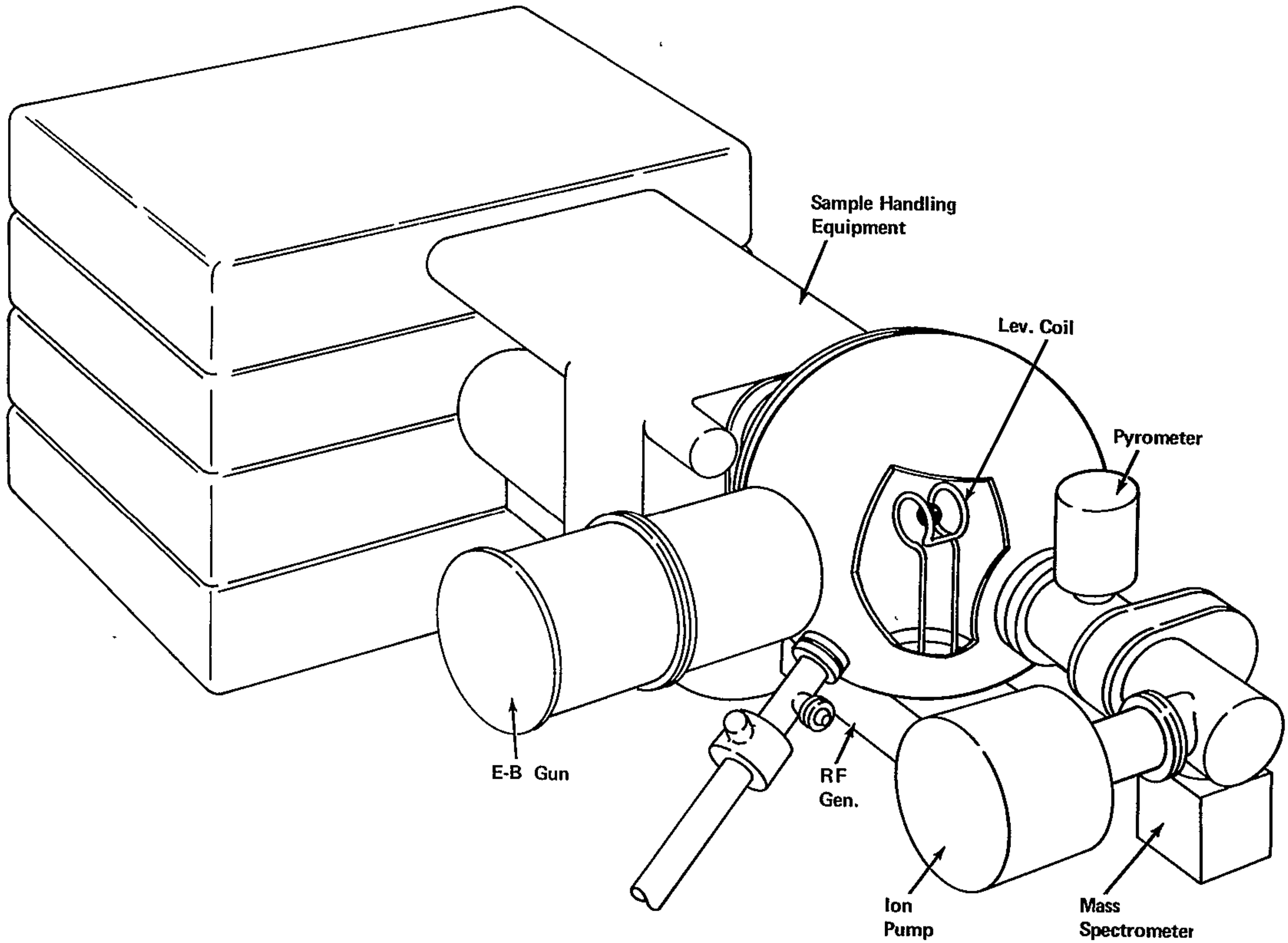

Figure 5-1 Electromagnetic Levitation Facility (L-1)

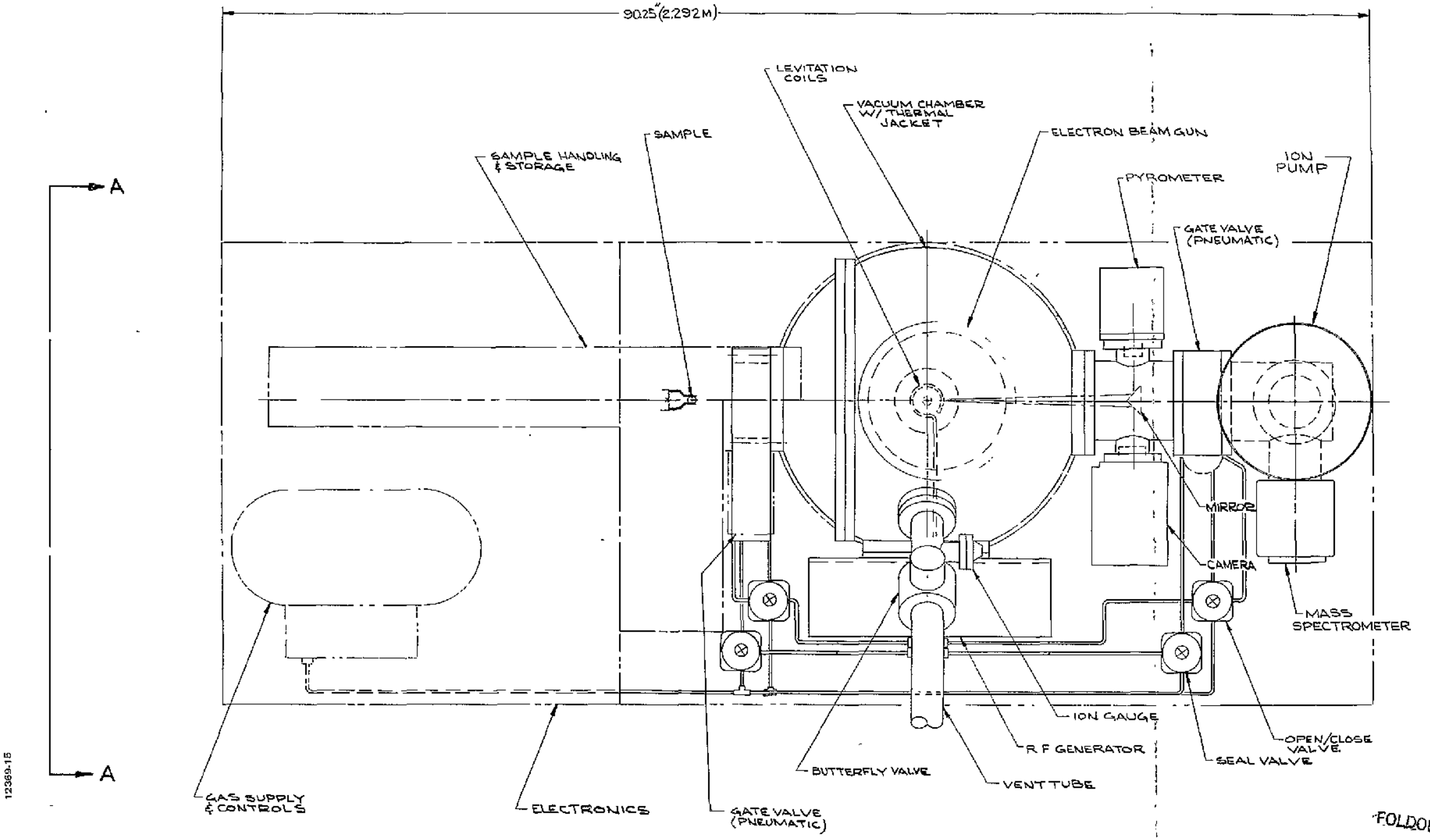

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Figure 5-2 Electromagnetic Levitation (L-1)

Figure 5-3 shows the structure of the L-1 facility and typical hard-points for mounting the facility to the Shuttle. The hard-points will be designed to carry the structural load in 1-g environments and the acceleration and shock expected during launch, boost, and landing.

The hard-points will also minimize thermal transfer between the L-1 facility and the spacecraft. The major cooling requirement of the facility relates to the levitation coil, which must be kept cool to keep its electrical resistance low. The coolant pumped through the coil can be passed through the jacket of the chamber, the electron-beam gun power supply, and the cold plate for the electronics. A flow of 0.13 ℓ per sec (2 gal per min) of Monsanto Coolanol-20 or equivalent at an inlet temperature of 38°C (311°K) and pressure differential of 69,000 N/m^2 (10 psi) will be adequate. Interface connections remain to be specified.

A 5.1-cm (2-in.) diameter vent line interface to outer space is specified. Flange definition remains to be accomplished.

The L-1 facility receives all of its electrical power from the spacecraft. Specific requirements are listed in Table 5-2. Conversion losses for ac are not included. Connector details are to be determined.

Table 5-2

L-1 Facility Electrical Power Interface

Electrical Service		Peak Power (kW)	Average Run Power (kW)
DC	26 to 32 V	2.0	0.5
AC	400 Hz 230V and 115V	3.3	1.1

In addition to the power interface, a control and display interface must also be implemented. As a minimum, this interface includes a START button for the crewman to initiate and a STOP button for the crewman to terminate the processing sequence. The START button is expected to be the normal ON switch for the facility; the STOP button would be used only under emergency conditions to interrupt the normal cycle.

A small display panel, tracking the status of the processes and indicating alarm conditions, is also desirable. Panel space of approximately 23 by 10 cm (9 by 4 in.) will be required for all interface switches and indicator lamps.

5.2.3 Weight Estimate

An estimate of the weight of the L-1 facility is shown in Table 5-3.

Table 5-3

L-1 Facility Weight Estimate

Component	Weight (kg)	Weight (lb)
Interface structure and braces	82	178
Chamber and associated structure	65	143
Sample handling system	66	145
Gate valves	43	94
Vent valves	5	10
Gas supply and plumbing	9	20
Ion pump and controller	113	250
Ion gage and control unit	9	20
Programmable controller and electronics	29	63
Electron-beam gun and power supply	30	65
Optical pyrometer	11	25
Mass spectrometer	5	12
Camera and lamp	6	13
Levitation generator and coil	3	7
Tape recorders	15	34
Cables, terminations, and ties	5	11
Cold plates, plumbing, and coolant	40	89
TOTAL	536	1,179

5.2.4 Performance Features

The L-1 facility is designed to process, in vacuum, spherical metallic and chalcogenide glass sample specimens of up to 4.1 cm (1.6 in.) in diameter, masses up to 0.2 kg (0.5 lb) and at temperatures up to 3,410 °C (3,683 °K) subject to the limitation $d^2T^4 \leq 193.5$, where d is the sample diameter in centimeters and T is the highest process temperature in kilokelvins.

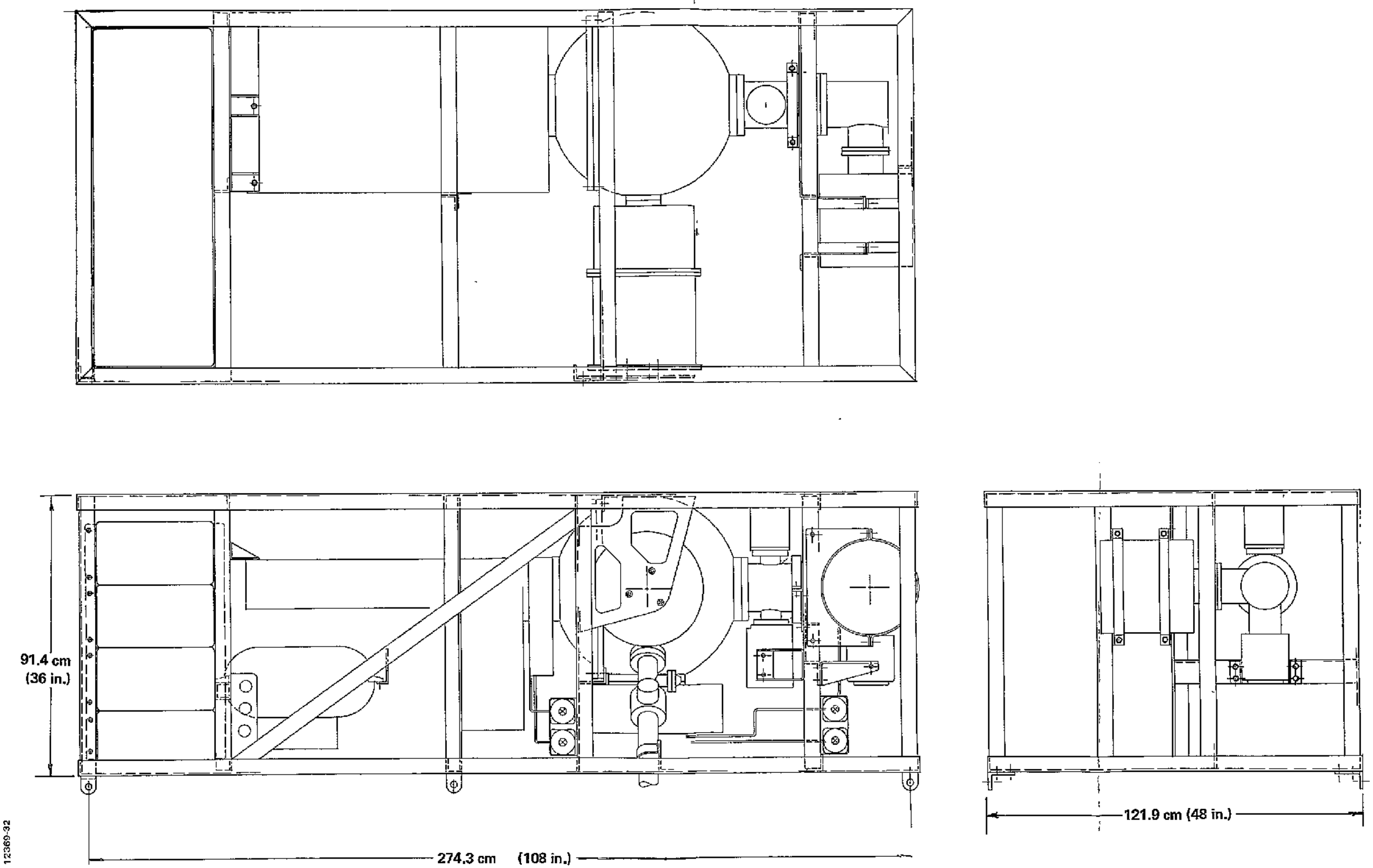

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Figure 5-3 L-1 Interface Configuration

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The process time is not limited by the facility design but only by the available maneuver-free period in the mission time-line and by the available energy allocated to space processing. Typical process times of less than 1 hour should be compatible with most mission plans.

5.2.4.1 Power Analysis

Power estimates for each of the major system components are detailed in the following paragraphs.

Electron-Beam Gun. - Taking a 1-cm-diameter sample of tungsten as the worst-case material because of its high melting-temperature and assuming a two-turn levitation coil, as described in Reference 5*, the following is an analysis of the facility power requirement.

With the coil temperature kept low by liquid cooling, the proximity of the coil will not appreciably affect the radiation of heat from the sample specimen. Then, to just compensate for radiation from the sample at the melting point, the power delivered by the electron-beam gun must be

$$P = \sigma A \epsilon T^4,$$

where:

- P is the power in watts.
- σ is the Stefan-Boltzmann constant.
- A is the sample surface area in cm^2.
- ϵ is the emissivity of tungsten.
- T is the sample temperature in °K.

Substituting the appropriate numbers,

$$P = 5.67 \times 10^{-12} \times \pi (1)^2 \times 0.4 \, (3,683)^4 = 1,311 \text{W}.$$

Adding an allowance of 35W for heat of fusion (10.1 g at 184 Joules) to melt in 54 seconds from a dwell temperature of 2,400°C (2,673 °K) results in a total of 1,346 W.

Using the efficiency factors of Reference 1, and assuming that the electron-beam gun operates directly from the 28 Vdc supply, the facility power used by the electron-beam gun during this peak is

$$P = 1.4 \times 1,346 = 1,884 \text{ W}.$$

*References can be found in Paragraph 5.7 of this section.

For the lower dwell temperature of 2,400°C, the required facility power is

$$P = 1.4\,[5.67 \times 10^{-12} \times \pi(1)^2 \times 0.4(2,673)^4] = 509 \text{ W}.$$

Electromagnetic Levitation. - Reference 1 shows a peak levitation power of 50 W required for a tungsten sample. However, other typical material samples which the L-1 facility might be called on to process might have sample diameters up to 4 cm (1.6 in.) and require more power. For example, calculations for levitating a 4-cm specimen of PdSi, compensating for larger sample size, larger coil size, lower density, and higher resistivity; result in a requirement for a delivered rf power (35 kHz) of 76 W. This requires a total of 141 W of facility power at 28 Vdc.

This is the peak power value. As noted in Reference 5, the running power can be dropped to 1% of the value required during sample insertion and retrieval, or 0.76 W. Assuming an efficiency of only 10% at this low power-level, the dc power required would be 7.6 W.

Core Equipment. - The power requirements of the core equipment identified for the L-1 facility are described below.

Ion Pump. - This device, described in Book 2 Appendix B of this report, is the principal power user among the core equipment. It operates from a 230 Vac circuit and draws a starting current of 12 A. Allowing for conversion losses, peak power is

$$\frac{4}{3}\,(12 \times 230) = 3,680 \text{ W}.$$

After initial starting, the power consumption is related to chamber pressure. Since the vent to space will be opened if the pressure rises above 0.01 N/m^2 (10^{-4} Torr), a conservative estimate of average chamber pressure is 0.001 N/m^2 (10^{-5} Torr). At this level, in accordance with Figure B-6 of Appendix B, pump current runs about 90 mA at a potential of 5,200 V. Assuming an internal efficiency of 90% and allowing for conversion losses at 25%, the average running power is

$$\frac{4}{3}\;\frac{0.09 \times 5,200}{0.9} = 693 \text{ W}.$$

Ion Gage. - The ion gage is also described in Appendix B. It draws a continuous current of 1.6 A at 230 Vac for a running power of 360 W. Allowing for conversion losses, average power is

$$\frac{4}{3}\,(360) = 480 \text{ W}$$

Programmable Controller. - Typical of the process controllers which might be used is the Rolm Ruggednova controller. It has a typical power dissipation of 175 W at 115 Vac. Accessories providing the required electronic interfaces and their power dissipations are shown in Table 5-4.

Allowing for conversion losses, average power of the controller and electronics is $\frac{4}{3}(175 + 55) = 307$ W.

Sample Handling System. - The sample handling system includes motors for driving the probe of the sample manipulator and the storage wheel. The peak power requirement is 125 W, with a standby requirement of, perhaps, 10% of that figure. Average power, assuming operation directly from the 28 Vdc power supply, is:

$$\frac{(2 \times 125) + (24 \times 12.5)}{26} = 21 \text{ W.}$$

Table 5-4

Electronic Accessory Power Dissipation

Accessories	Power Dissipation (W)
Real-time clock	2.0
Parallel Input/Output buffer	5.0
Analog Multiplexer	3.7
Analog-to-digital converter	6.4
Digital-to-analog converter	4.6
Data channel controller	6.0
Relays and switches	1.5
Caution and warning display	25.0
Hall probe	0.5
Temperature sensors	0.3
TOTAL	55.0

Miscellaneous Accessories. -

Tape Recorders

Small tape recorders interface with the programmable controller to record critical parameters correlated with time and with the TV camera. Estimated average power dissipation is 17 W. This power is taken from the 28 Vdc line.

TV Camera

A small TV camera is included in order to provide a permanent record of process steps which take place within the chamber. Estimated power dissipation is 20 W. This power is taken from the 28 Vdc line. A small lamp used to provide illumination for photography when the sample is cool uses 10 W.

Optical Pyrometer

The optical pyrometer continuously measures sample temperature during the process. The power requirement is 15 W from the 115 Vac line. The pyrometer is energized only during the heating program. Allowing for conversion losses, the power required is

$$\frac{4}{3}(15) = 20 \text{ W.}$$

Mass Spectrometer

Certain processes will require monitoring of outgassing products. This can be done by means of a small mass spectrometer with peak power of 17 W and running power of 10 W obtained from the dc source.

Valves

The vent valves and gate valves require 5 W and 3 W, respectively, for operation. However, since they consume power only in transition, their average power and energy consumptions are negligible.

Peak Power and Total Energy Summary. - The L-1 requirements for peak power, average power, and the total energy per sequence are summarized in Table 5-5 by component. Peak power for the facility is determined by the starting power of the ion pump and the running power of the components in operation when the pump is started.

Table 5-5

L-1 Power and Energy Summary

Component	Power (Peak W)	Energy per Tungsten Sequence (Whr)	(kilojoules)
Electron-beam gun	1,884	179	644
Electromagnetic levitation	141	8	29
Ion pump	3,680	300	1,080
Ion gage	480	208	749
Programmable controller and electronics	307	133	479
Sample handling	125	9	32
Tape recorders	34	15	53
Camera and lamp	30	11	40
Optical pyrometer	20	3	11
Mass spectrometer	17	4	14
Valves	5		
TOTAL	4,467	870	3,131

Average power per sequence = $\frac{870}{26/60}$ = 2,008 W, including conversion losses for ac power.

Average power is based on the tungsten sequence and is typical for the class of materials to be processed by this facility.

Assuming a total of six samples processed during a mission, the total energy requirement is only 5.2 kWhr plus liquid cooling requirements.

5.2.4.2 Time Estimate

The typical (tungsten) experiment requires approximately 36 minutes for the first run, allowing about 10 minutes for venting the chamber and about 26 minutes for each succeeding run. For a total of six samples, the mission elapsed time will be approximately 2.8 hours.

Other L-1 experiments may require longer times. Processing six tungsten carbide samples, for example, would require about 4.3 hours.

5.2.4.3 Temperature Profile

A temperature profile of a typical material (tungsten) processed in the L-1 facility is shown as Figure 5-4. The total temperature sequence time consists of 24 minutes divided into three phases; (1) low-power heating (364 W to sample), (2) high-power heating (1,346 W to melt and 1,311 W to hold), and (3) passive cooling (heating power off).

The example uses a 1-cm diameter sample of tungsten with an effective radiative heat-sink temperature of 422°K (300°F).

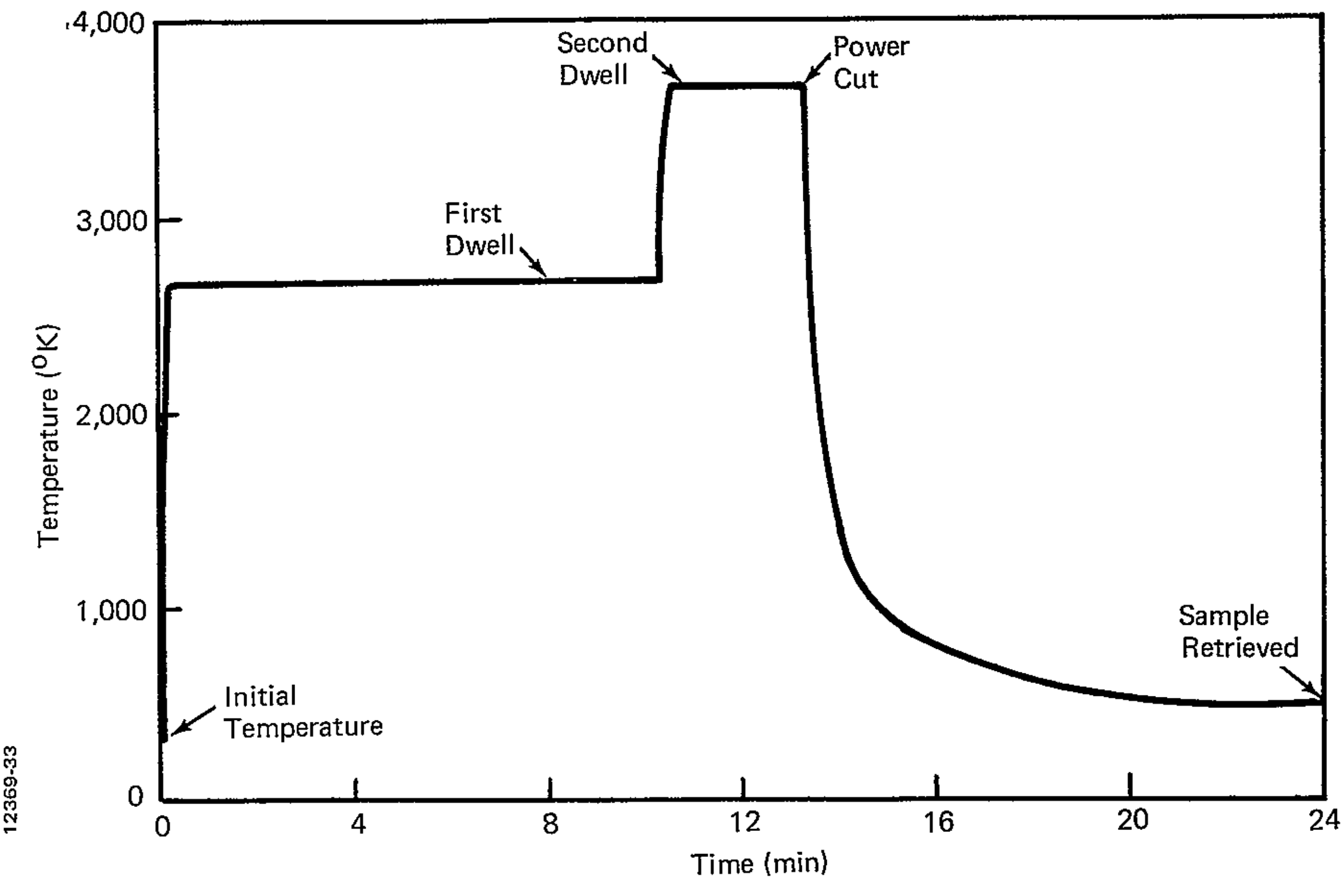

Figure 5-4 Temperature Profile of Tungsten Sample

Figure 5-5 details the two upward temperature transitions. In Figure 5-5a, the heating to the first dwell temperature of 2,400°C (2,673°K) is shown. This phase requires about 24 seconds to complete and is followed by a "dwell" at this temperature for about ten minutes.

Figure 5-5b shows the heating to the second dwell (and melt) temperature of 3,410°C (3,683°K). It requires only about 3 seconds to bring the sample up to temperature; however, as melting takes place, the heat of fusion absorbs the incoming heat with no further rise in temperature. After about 54 seconds, the sample is completely molten. At this point, the heat input to the sample can be reduced to 1,311 W or the sample can be allowed to stabilize at the slightly higher temperature of 3,434°C (3,707°K). A dwell period of about 2 minutes in the molten state is then programmed.

At this point in the process, the electron-beam gun power is cut off. The sample temperature becomes somewhat indeterminate for a period of several seconds, as shown in Figure 5-6, as the heat of fusion is given up by the solidifying metal. Three of the possible temperature excursions are represented by curves A, B, and C.

Curve A describes the result of a cooling process in which solidification begins immediately after the heating power is turned off. Heat of fusion given off in the process of solidification is matched by radiation of heat from the sample's surface, with little net change of temperature.

The process described by curve B represents the situation in which undercooling of about 800°C is experienced by the sample before solidification starts. Nucleation is then completed in about 1 second, with an attendant temperature rise as the heat of fusion is given up at a higher rate than can be dissipated by surface radiation. Although a linear temperature rise is shown, some non-linear transition function is more probable. When the solidification is complete, the temperature again drops rapidly.

Curve C also represents an undercooling of about 800°C, with a more gradual nucleation maintaining a relatively constant temperature until fusion is complete.

A fourth possibility is a temperature curve which oscillates as the recovery of heat of fusion alternates with radiation as the dominating influence on sample temperature.

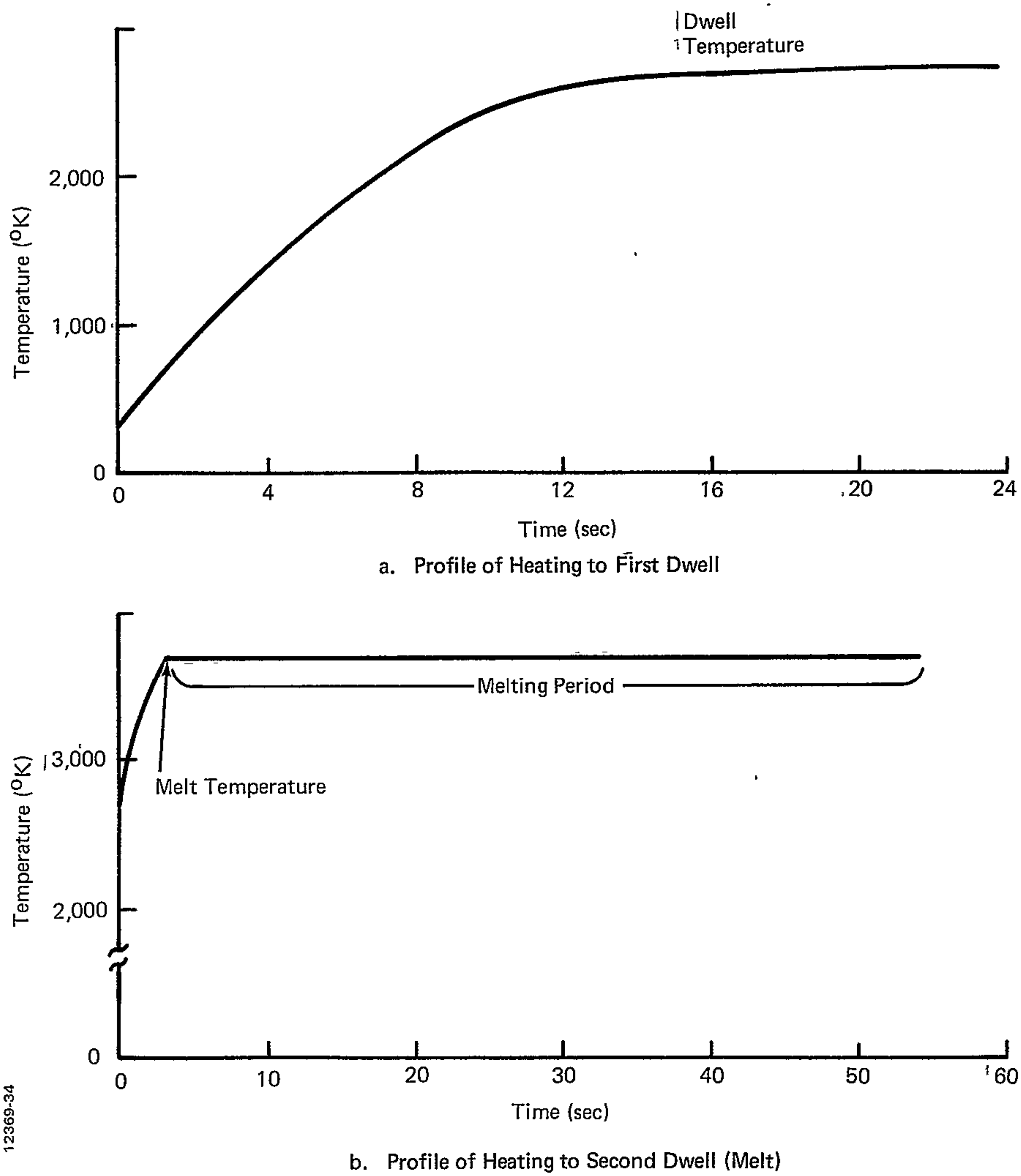

Figure 5-5 Tungsten Dwell Profiles

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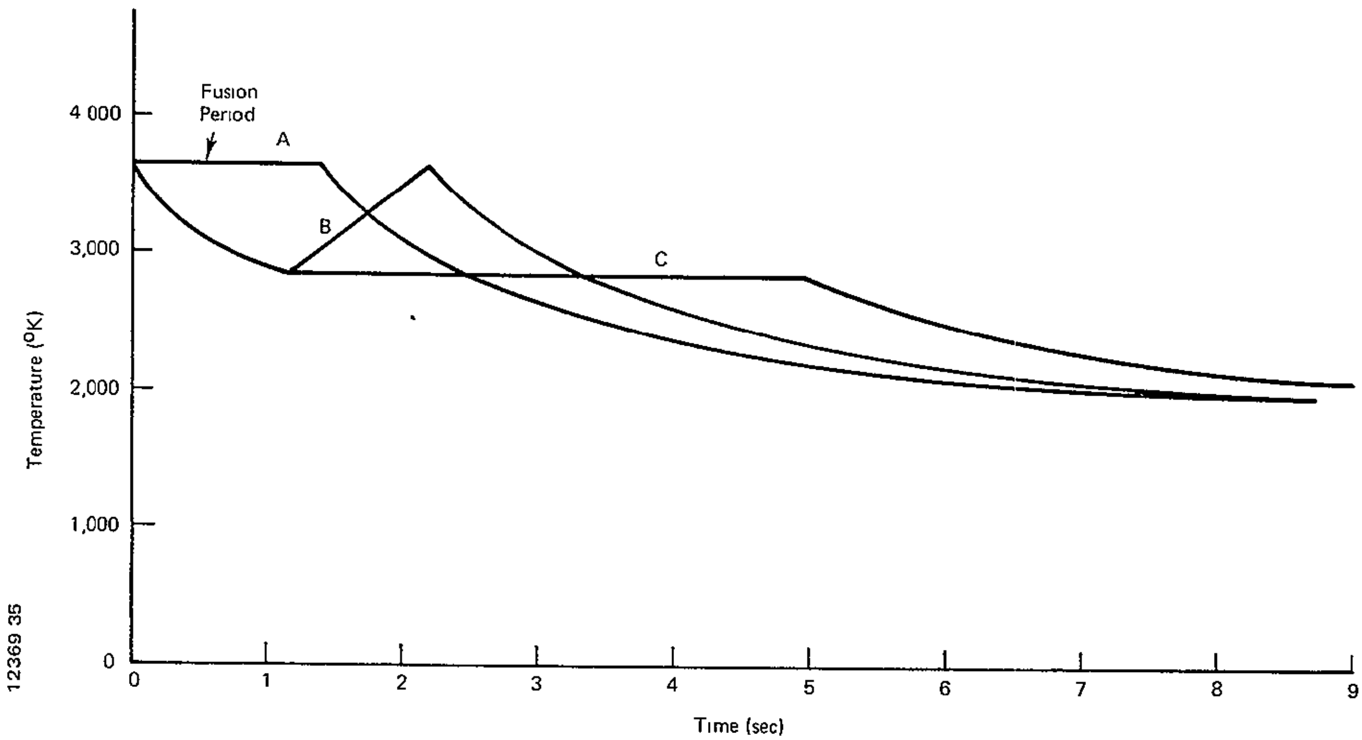

Figure 5-6 Profile of Early Cooling Period

5.2.4.4 Power Profile

A typical power profile is shown in Figure 5-7. Peak power consumption of 3,350 W is shown to occur during start-up of the ion pump. Power levels shown do not include conversion losses. Average power for the sequence is 1,636 W.

5.2.5 Control System

5.2.5.1 Objectives

The objective of the L-1 experiment control system is to provide pre-programmed and real-time control of all the functions which must be performed during the execution of the experiment. The intent is that there shall be no crew participation except that necessary to initiate the experiment and, in an emergency, to terminate it.

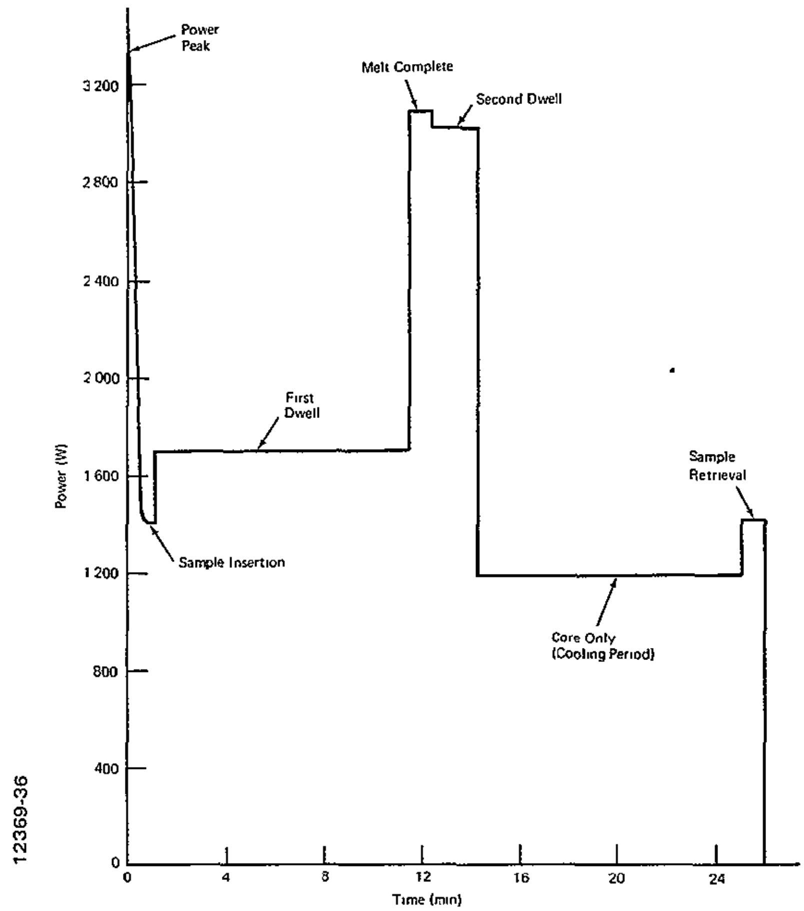

Figure 5-7 Tungsten Sequence Power Profile

5.2.5.2 General System Description

The control system consists of a central computer/controller which interfaces with and directs the operation of all equipment required for the performance of the experiment. The computer, working to a pre-programmed time-line, turns on the equipment as required; inserts and retrieves samples from the work area; initiates and maintains heating and cooling cycles; and measures, records, and maintains the working environments of temperature, pressure, and partial pressures of gases produced during the process. In addition, the computer continuously monitors for hazardous conditions and takes precautionary actions which are pre-programmed or identifies the condition to the crew for its action.

Peripheral equipment consists of the levitation rf generator, the electron-beam gun, the sample manipulator, and all of the measurement and recording devices. The computer either controls these devices directly or initiates control via the device's own control electronics.

5.2.5.3 Computer

The computer, when initiated by the crew, will control all functions by following a pre-programmed sequence. While following the sequence, the key parameters, such as pressure, will be continuously checked and programmed. Corrective action will be taken if a deviation is observed. A real-time clock will provide timing information for correlation of the recorded events. All peripheral systems will interface with the computer, as shown in Figure 5-8. There are some functions which require real-time control, such as sample manipulation and chamber pump-down if excessive outgassing is observed. These functions will be fully controlled by the computer through feedback of status signals or indications of parameters being within predetermined limits. Thus, control will not be on a purely sequential basis.

The computer will control the retrieval and storage of data required for post-mission analysis of the experiments.

A control panel will be provided in the Spacelab to provide the crew with the facility to start and stop the experiments. Status lights will be provided to give warning of impending problems and to give an indication of where the experiment is in the sequence. The latter indications are provided for the benefit of the crew if a change in mission profile is required during an experiment sequence.

A qualified computer which would furnish all the facilities need for this experiment is the Rolm Corporation 1602 Ruggednova. The characteristics of this machine are identified in Table 5-6.

Computer Interfaces. - The computer interfaces with the system components are identified in Figure 5-9. The interface components will be standard items supplied by the computer manufacturer. The high-power output interfaces will, typically, be contact closure types driving latching relays for such items as power on/off, 35 kHz generator control, and control of the electron-beam gun circuits. The low-level signals for commands and lamp drivers will, typically, be of the contact-closure type.

Those signals of the measurement devices which are digital will be inputted directly to the computer via parallel data input lines and those signals which are analog will be multiplexed and converted by an analog-to-digital converter before being inputted to the computer. Status signals will be processed as discrete digital inputs.

The characteristics of typical interface circuits are given in Tables 5-7 through 5-10.

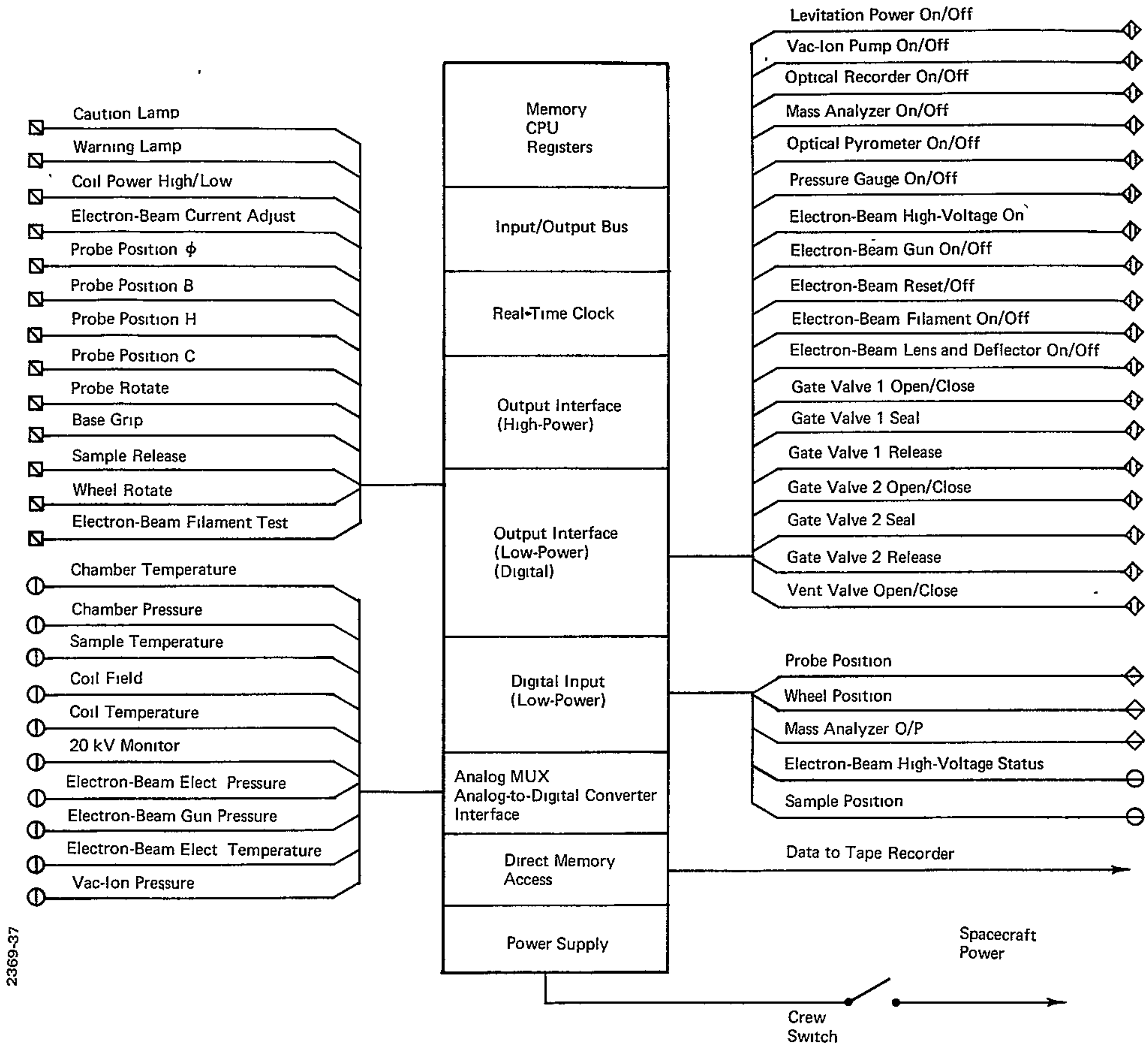

Figure 5-8 Computer Interfaces

Table 5-6

Minicomputer Characteristics

MODEL

1602 Ruggednova (AN/UYK-19V)

PERFORMANCE SPECIFICATIONS

Word length - 16 bits.

Maximum memory - 8 K words in CPU chassis.
- 256 K words maximum in four external chassis.

Memory access time - 0.4 μsec.

Add time - 1.0 μsec.

Microprogrammable.

Registers - four accumulators.
three index.
25 microprogram.

Interrupts - automatic vectored and nested.

Hardware multiply/divide.

Instructions - 249.

CPU I/O channels - 61.

CPU - independent DMA operating at up to 1 MHz.

Remote-control panel - plug-in.

ENVIRONMENTAL SPECIFICATIONS

Case temperature: -55 to +95°C (218 to 368°K).

Vibration: 10 g, 5 to 2,000 Hz with vibration isolators; 2 g hard-mounted.

Shock: 15 g, 11 msec.

Humidity: 95% relative.

RFI: MIL-STD-461.

POWER

175 W, 28 Vdc (typical CPU +8K core).

WEIGHT

34 lb (15 kg).

VOLUME

Approximately 1 cu ft (0.03 m^3).

PACKAGING/MOUNTING

One conductively-cooled 12.56-in. (32 cm) ATR chassis.

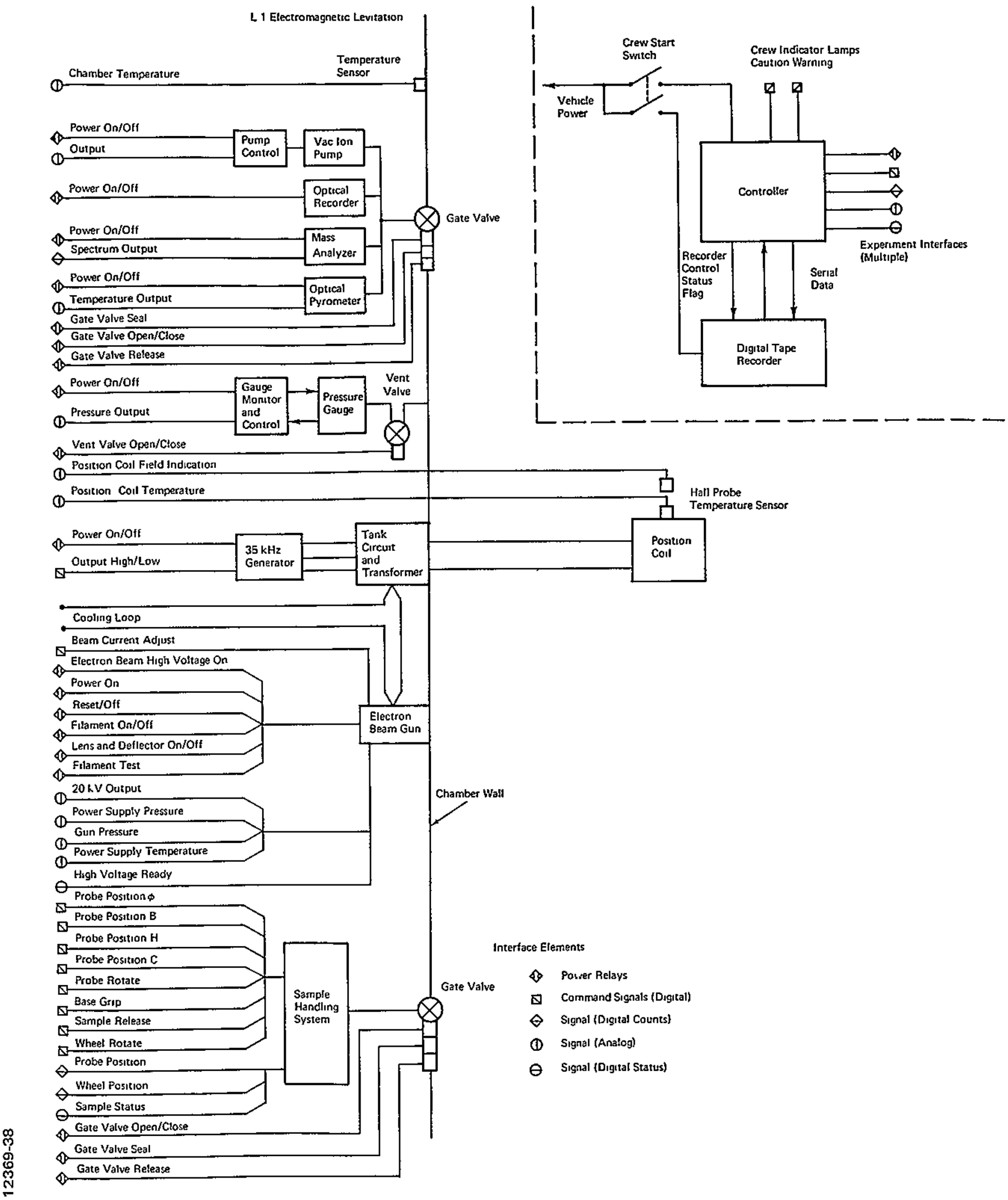

Figure 5-9 System Interfaces

Table 5-7

Contact Closure Module Characteristics

Number of outputs	Nine.
Output range - Volts	Up to 28 Vdc (external supply).
- Current	250 mA maximum (eight outputs).
	500 mA maximum (one output).
Saturation voltage	0.5 V at 250 mA.

Table 5-8

Parallel Digital Data Input and Discrete Input Characteristics

Number of inputs	18.
Input range - Logic 0	-1.0 to +0.8 Vdc.
- Logic 1	Up to 48 Vdc.

Table 5-9

Analog Multiplexer Characteristics

Number of channels	16.
Input signal range	± 10 V.
Input impedance	10^9 ohms.
Crosstalk	80 dB rejection.
Offset voltage	Less than 1 mV.
Net weight	1 lb (0.5 kg).
Power	5 V, 0.5 A
	± 24 V, 25 mA.

Table 5-10

Analog-to-Digital Converter Characteristics

Resolution	8, 10, or 12 bits.
Accuracy	±0.2% full scale.
Temperature coefficient	±15 ppm per °C for zero and range.
Conversion time	2 μsec per bit.
Input impedance	10^9 ohms.
Input voltage range	±5 or ±10 V.
Net weight	1 lb (0.5 kg).
Power	+5 V, 1 A.
	±24 V, 30 mA.

Timing. - A real-time clock will be used for timing process events and for providing timing of the recorded data for analysis purposes. Table 5-11 provides data on a typical clock.

5.2.5.4 Program Sequence

The sequence of events to be performed during this experiment is indicated in Figure 5-10. The sequence will be programmed into the computer and controlled in conjunction with the real-time clock.

The computer programs will consist of subroutines controlled by an executive supervisor program. The executive supervisor will control the main sequence of events, handle interrupts on a priority basis, and institute periodic scans of data outputs in conjunction with the real-time clock.

The subroutines will handle the repetitive functions of control loop monitoring and algorithm processing, data handling and recording, sample handling and status, and alarm communication with the remote control panel.

5.2.5.5 Chamber Environmental Control

Chamber environmental control information is contained in Appendix B of this volume.

Table 5-11

Real-Time Clock Characteristics

Oscillator	
Initial accuracy at 25°C (298°K).	±0.002%.
Temperature stability, -55 to +95°C case (218 to 368K).	±0.005%.
Warm-up time to achieve ±0.005% accuracy.	None.
Interrupt Rates	10, 60, 100, and 1,000 Hz.
External Generator Input	Two TTL loads plus resistive termination, 330 ohms to +5V and 390 ohms to ground.
Auxiliary Output	SN 5400 series TTL.
Auxiliary Frequencies	500 and 1,500 Hz; 3, 6, 12, 24, 48, 96, 192, 384, 768, and 1,536 kHz.
Net Weight	1.1 lb (0.5 kg).
Power Requirements (supplied by computer power supply)	+5 V, 300 mA. +12 V, 10 mA. -12 V, 30 mA.
Thermal Dissipation	2 W (conductively-cooled to ATR box side-plates).

5.2.5.6 Levitation Control

A low-power induction system will be used to levitate the experiment samples. The system, shown diagramatically in Figure 5-11, contains a low-frequency chopping mode pre-regulator to establish a dc bus voltage, which will be varied to control the output power. The output inverter will be operated at a frequency dictated by the coil design and the sample properties. A matching transformer will be used external to the supply, and the load will be parallel-tuned at the drive coil.

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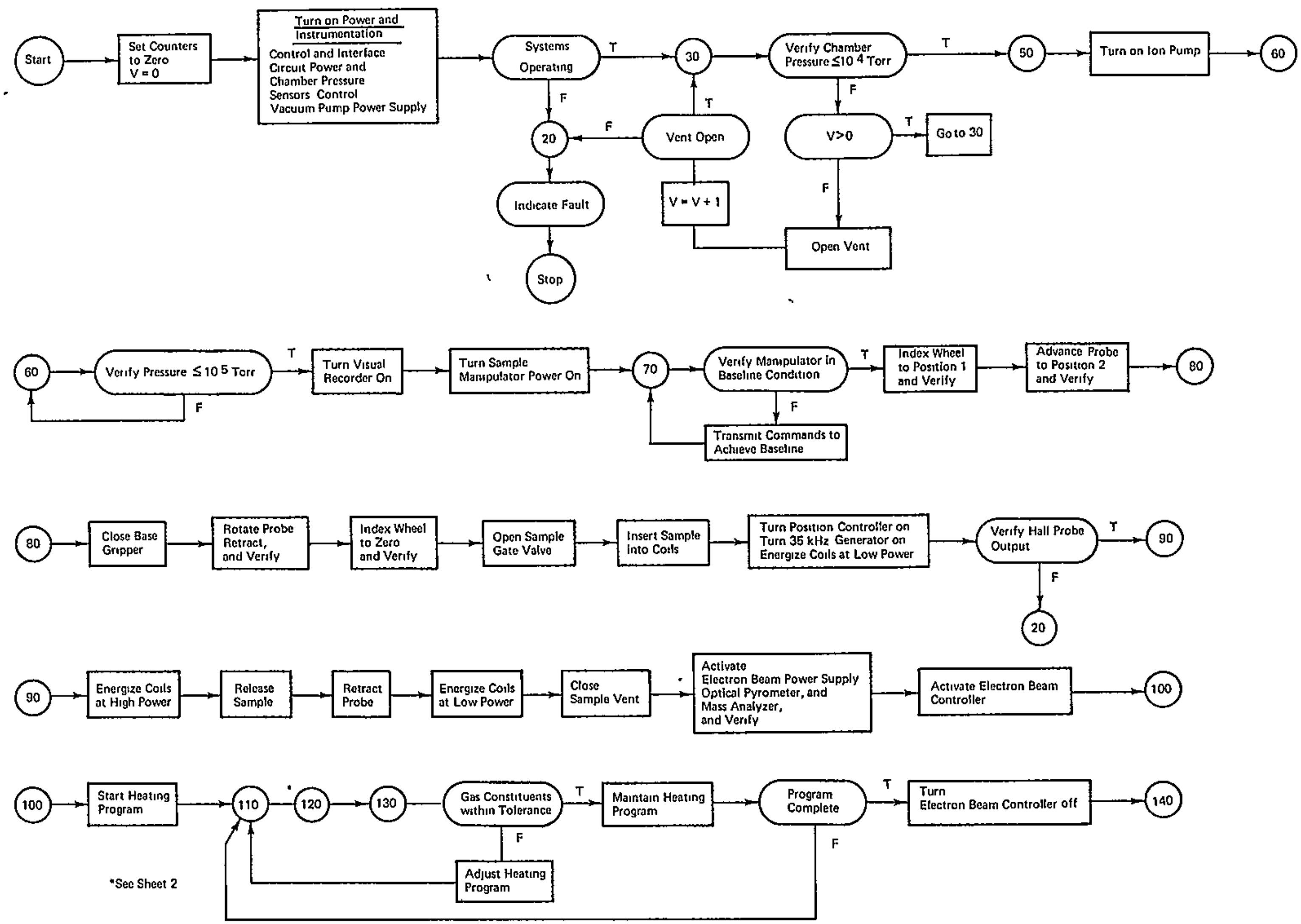

Figure 5-10 Electromagnetic Levitation Program Sequence (Sheet 1 of 2)

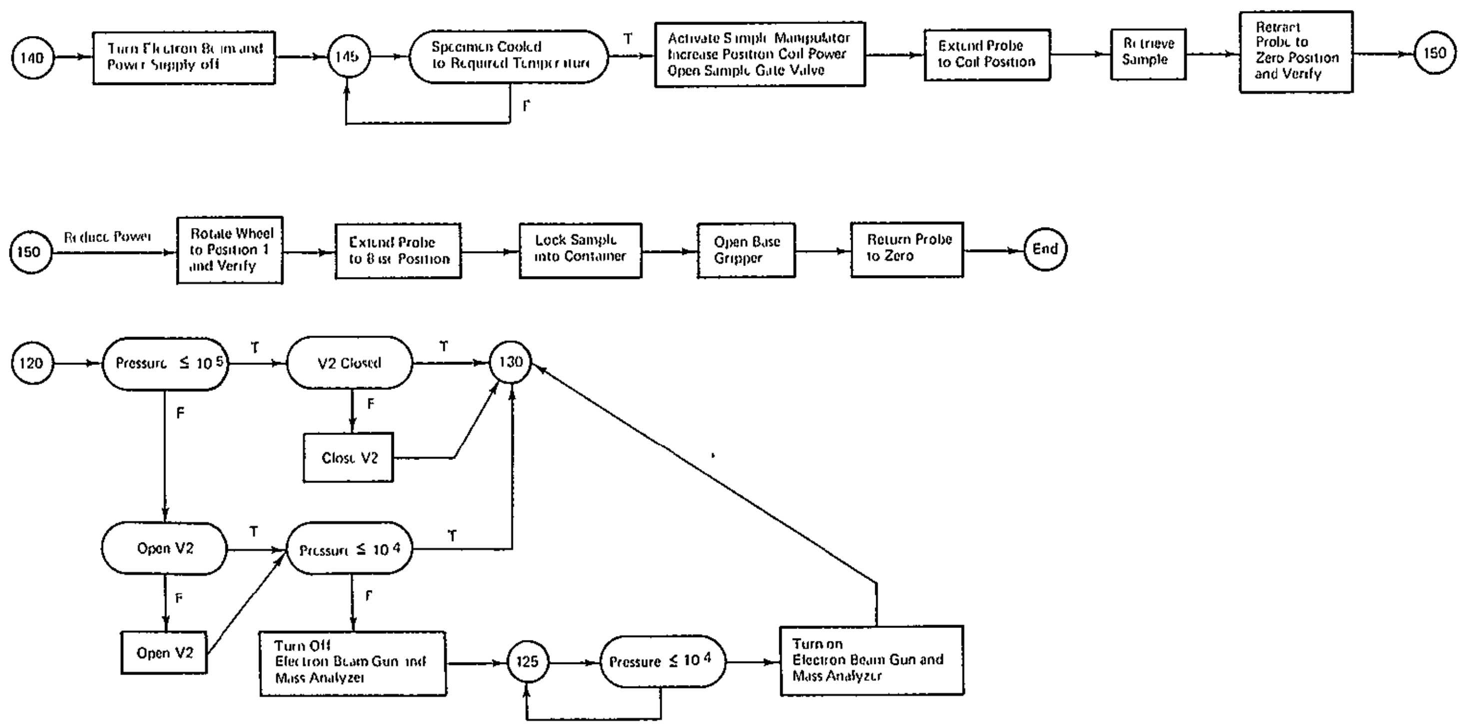

Figure 5-10 Electromagnetic Levitation Program Sequence (Sheet 2 of 2)

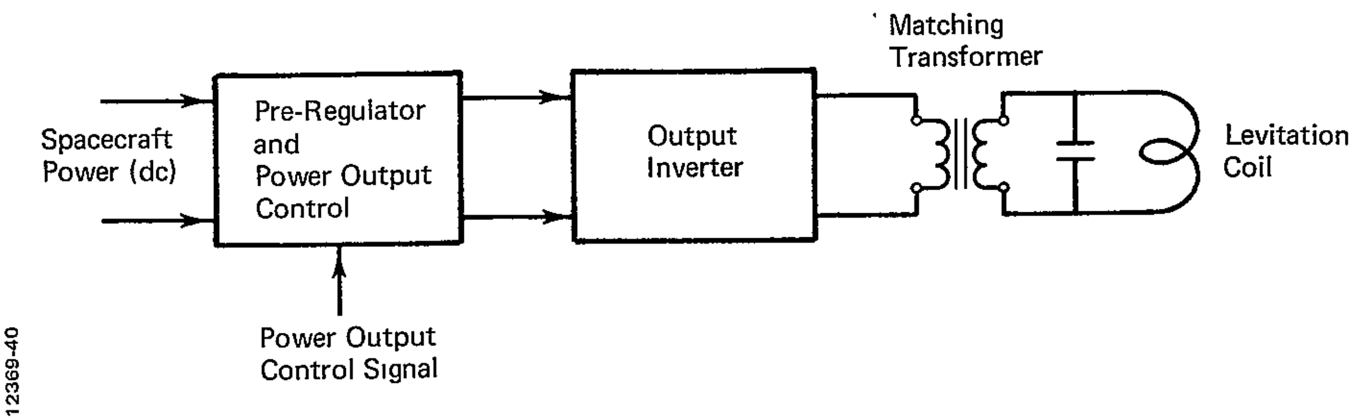

Figure 5-11 Levitation Generator Block Diagram

The output power will be controlled at three discrete levels (by the computer under program control). The levels are off, normal running, and high-power for sample insertion and retrieval.

5.2.5.7 Sample Temperature Control

The sample temperature will be measured by an optical pyrometer, the output of which will be monitored at regular intervals by the computer. The signal from the pyrometer will be processed and compared with set limits. When the sample temperature is outside these limits, a subroutine that will calculate the required corrective action will be implemented. The calculation will result in a signal being communicated to the electron-beam gun to change its current in the required direction.

Control of the electron-beam gun will be maintained in a similar fashion in response to data from the pressure measurement system or from gun safety monitors.

Sample temperature will be recorded at regular intervals throughout the experiment cycle.

The pertinent characteristics of a representative optical pyrometer are shown in Table 5-12.

5.2.5.8 Data Collection and Recording

The data collection takes the forms:

1. Analog data signals.
2. Digital data signals.
3. Digital status signals.
4. Television picture signals.

Data from Items 1, 2, and 3 are used for both control and permanent record purposes.

The analog data will be multiplexed, converted in the analog-to-digital converter, and stored under computer program control. The digital data will be transferred in parallel form to the computer. The status signals will be transferred as discrete elements of a 16-bit word. Control loop subroutines will use the stored data to maintain the required status, such as temperature and pressure, of the various systems.

A visual record of each experiment will be made using a television system and a magnetic tape recorder. A typical imaging system which could be used for experiment recording is the General Electric Charge Injection Device. This is a solid state image sensing device which uses no sweep circuits, focus regulators, or complex yoke and coil assemblies. The present state of the art uses a 100 by 100 element array, giving 10,000 sensing elements.

The major characteristics of the image sensor are:

<u>Operating Conditions</u>

100 by 100 Imager.
60-cycle field-rate (30-cycle frame-rate, 2 to 1 interlace).

<u>Power Requirements</u>

-30 V at 25 mA.
+ 5 V at 200 mA.
- 5 V at 10 mA.

Table 5-12

Optical Pyrometer Specifications

Supplier: Ircon.

Model: Modline 2000 Series.

Performance Specifications:

- Temperature ranges; 40 to 3,000 °C (313 to 3,273 °K), dependent on head and indicator.
- Spectral response; 0.70 to 0.97 μm.
- Calibration accuracy; ± 1% full-scale temperature or ± 10 °F (± 5 °K), whichever is greater.
- Repeatability; ± 0.3% full-scale temperature.
- Response time at output; 95% full-scale input within 10 msec.
- Indicator/controller ambient temperature range; 50 to 150 °F (283 to 339 °K).
- Sensing head ambient temperature range; 0 to 200 °F (256 to 367 °K).

Data Output:

0 to 100 mVdc (100 Vdc source) standard. Up to 10 V at 5 mA as optional extra.

Power:

15 W maximum (115/230 V ± 10%, 50 to 60 Hz).

Weight:

Head 15 lb (7 kg).

Volume:

Head 435 in.^{3} (6,750 cm^3).

Indicator/controller; 870 in.^{3} (13,500 cm^3).

Output Signals

Preamplifier Video	0.5 V peak-to-peak (1,000-ohm load).
Horizontal Drive	3.5 ± 0.5 V peak-to-peak (75-ohm load).
Vertical Drive	3.5 ± 0.5 V peak-to-peak encoded signal (75-ohm load).

A typical video tape recorder which could be used for recording the experiment processes is the Odetics Inc. Model DDS-3100. Odetics recorders are also proposed for the Spacelab. A photograph and specifications of an Odetic recorder are shown in Figure 5-12 and Table 5-13, respectively.

5.2.5.9 Emergency Warning and Display

A display panel will be provided in the Spacelab to give an indication of the experiment status and to give warning of any dangerous conditions. This facility will provide the crew with information which will aid them in making decisions about possible mission time-line changes or similar events which might be desirable during the time that an automatic experiment is in progress. For example, the fact that a molten tungsten ball is levitated in the facility is a useful data point.

Table 5-13

Tape Recorder Specifications

Record time	50 min.
Tape length	1,800 ft (549 m).
Longitudinal tape speed	36 ips (0.91 m/sec).
Reel size	6 in. (15 cm) NAB hub.
Tape width	0.25 in. (6.4 mm).
Video writing speed	72 ips (1.8 m/sec).
Type of recording	NRZ-L plus clock.
Size	6 by 9 by 12 in. (15 by 23 by 30 cm).
Weight	17 lb (7.7 kg).
Power	30 W reproduce. 17 W record.
Operating voltage	24 to 32 Vdc.

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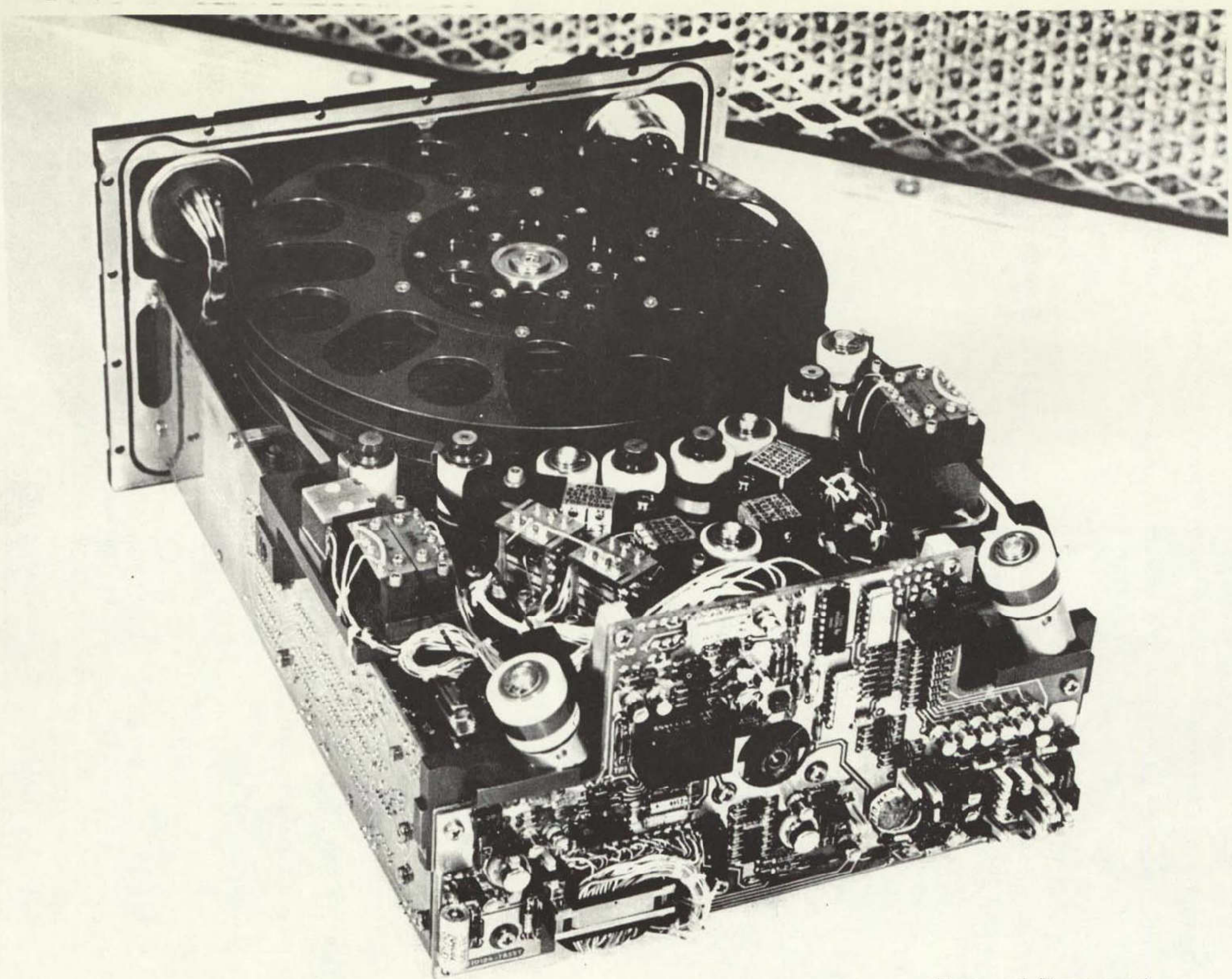

Exposed Transport
DDS-3000
LMSC/STP 71-2

Figure 5-12 Dual-Channel Tape Recorder Option 1

A series of status lamps will be provided which will indicate the major points in the experiment sequence and when it is reasonable to perform a maneuver or terminate an experiment prematurely. All normal contingencies will be controlled by the computer to provide a fail-safe mode of operation or controlled shutdown while maintaining the integrity of the system.

5.2.6 Extension of Range

A description of how the L-1 facility could be modified to extend its capabilities follows.

5.2.6.1 Larger Samples

The accommodation of larger samples requires a redesign of the levitation, sample handling, heating, and cooling equipment, with attendant impact on weight, volume, and power.

The levitation coil must be made larger to provide appropriate clearance between the coil and the sample. Levitation power will require an increase to provide additional force to position the greater mass.

The sample handling manipulator must be scaled-up to accommodate the larger sample diameter. Similarly, the sample storage containers must be enlarged.

The power output of the electron-beam gun must be increased to supply the additional heat required by the larger sample. This will require redesigning the gun cathode-structure and increasing the current capacity of the high-voltage supply.

Table 5-14 shows the power requirements for various sizes of tungsten samples. It should be noted that processing of tungsten samples greater than 3 cm (1.2 in.) in diameter will require significant levels of power and heat rejection capability (up to 22 kW average and 50 kW peak).

The principal weight and volume impacts of larger samples are reflected in the electron-beam gun or levitation and sample handling system parameters. Weight impact estimates are shown in Table 5-15 and volume estimates are listed in Table 5-16. It should be noted that estimates for the largest sample sizes include batteries for peak loads. Batteries are sized on the assumption that they can be recharged between sequences.

Table 5-14

Power Impact of Increasing Sample Size

Tungsten Sample Diameter (in.)	(cm)	Peak Power (W) Electron-Beam Gun	Levitation	Facility Average Running Power (kW)
0.4	1.0 Design Value	1,884	16	2.0
0.6	1.5	4,245	34	3.4
0.8	2.0	7,615	56	4.8
1.0	2.5	12,007	93	6.7
1.2	3.0	17,445	122	9.0
1.4	3.6	23,955	175	11.7
1.6	4.1	31,563	215	14.9
1.8	4.6	40,295	282	18.5
2.0	5.1	50,178	347	22.5

Additional coolant-flow through the levitation coil and through the power supply of the electron-beam gun will be required to accommodate the higher heat dissipation in these components.

5.2.6.2 Material Options

The list of materials which can be processed by the L-1 facility can be extended to include some higher-resistivity materials by one of the following techniques:

- Pre-heating. Pre-heating can be done easily through a minor programming change. The sample is held in the levitation coil by the manipulator and heated by the electron-beam gun to the temperature at which electrical conduction becomes adequate to permit electromagnetic levitation. The sample is then released, and the manipulator is withdrawn.

Table 5-15

Weight Impact of Increasing Sample Size

Tungsten Sample Diameter		Weight								Increase of Basic Facility Weight (%)
		Electron-Beam Gun		Batteries		Levitation		Sample Handling		
(in.)	(cm)	(lb)	(kg)	(lb)	(kg)	(lb)	(kg)	(lb)	(kg)	
0.4	1.0 (basic)	65	29	—		7	3	145	66	—
0.8	2.0	174	79	—		7	3	147	67	12
1.2	3.0	379	172	—		9	4	149	68	36
1.6	4.1	670	304	40	18	16	7	153	69	75
2.0	5.1	1,049	476	100	45	26	12	161	73	125

Table 5-16

Volume Impact of Increasing Sample Size

Tungsten Sample Diameter		Volume						Increase of Basic Facility Volume (%)
		Electron-Beam Gun		Batteries		Levitation		
(in.)	(cm)	(ft^3)	(m^3)	(ft^3)	(m^3)	(ft^3)	(m^3)	
0.4	1.0 (basic)	2.2	0.06	—		0.1	0.003	-
0.8	2.0	3.4	0.10	—		0.1	0.003	1
1.2	3.0	5.1	0.14	—		0.1	0.003	3
1.6	4.1	8.1	0.23	0.2	0.006	0.2	0.006	7
2.0	5.1	13.0	0.37	0.5	0.014	0.4	0.011	12

- Increasing the frequency of the levitation rf generator. Materials with higher resistivities can be levitated by higher frequency fields. The lower "skin depth" at the higher frequency improves the efficiency of levitation.

- Increasing levitation power. Increasing the power level will permit levitation of marginal materials at the expense of inefficient coupling to the sample.

5.2.7 Potential Integration Problems

The L-1 facility should be kept evacuated from the time of factory bake-out until launch in order to minimize the space pump-down time, avoid sample contamination, and conserve energy. This can be accomplished by a vacuum pump on the spacecraft's vent line, with provision for closing off the L-1 facility vent-valve just prior to launch.

The balance of the integration should be straightforward, using standard build-up practices.

5.2.8 Alternate Manual Mode

As the sample handling equipment of the L-1 facility is fairly bulky, an alternate configuration, featuring manual sample insertion and retrieval may be considered for dedicated and shared missions. Required modifications of the L-1 facility are:

- Provide sample storage within the processing chamber, e.g., restrained by spring-clips.
- Add a built-in manipulator, controlled by the crewman, to pick up a specific sample and insert it in the levitation field and, subsequently, to retrieve and restore the specimen.
- Provide an optical port in the chamber (or, alternatively, closed-circuit television) for viewing the sample manipulation.
- Sequence control by a crewman is desirable. Portions of the sequence could still be automated, with provision for interrupts.
- Add visual indicators of sample temperature, time, and other process parameters.
- Remove the existing sample-handling system.

It is estimated that by these changes the volume of the L-1 facility can be reduced by about 0.6 m^3 (20 cu ft) and the total weight can be reduced by about 91 kg (200 lb), facilitating mounting of the equipment in the pressurized cabin.

With the addition of closed-circuit television, visual indicators of process parameters, and a remote-controlled sample manipulator, crew operation of pallet mounted facilities is also practical.

5.2.9 Data Management

The L-1 facility provides a visual record of critical process steps and a data record of critical parameters. The value of such records lies in the contribution to post-mission analyses to identify deviations from planned sequences and to quantify precisely the parameters in sequences with planned variations.

The TV camera provides a visual record, on a frame-by-frame basis, of the sample's progress through the sequence, from its initial insertion into the levitation coil until its retrieval by the manipulator. Individual-frame exposures are triggered by the programmable controller at critical points in the sequence and at regular intervals during less critical phases. Video data are recorded on tape.

A tape recorder also provides a digital record of important process parameters, formatted by the programmable controller. Among the data recorded are:

- The temperatures of the sample, chamber wall, electronics cold plate, levitation coil, and electron-beam power supply.
- The pressures of the chamber and electron-beam gun power supply.
- The computer time-words.
- The power levels of the electron-beam gun and levitation.
- The positions of the manipulator probe and the sample wheel.
- The status words identifying operational conditions of the valves and other components.
- The supply voltages.

After the spacecraft has landed, NASA will remove the tapes for processing. The TV frames will be identified by sequence number, and photographic copies will be made for delivery to the principal investigator (PI) associated with the processing experiment.

Similarly, copies of the digital tape will be made, and printouts of the data will be delivered to the PIs.

NASA will retain record copies of all data for the use of other interested scientists.

5.2.10 Development Requirements

There are only a few developmental problems associated with the L-1 facility. They include:

- Developing the sample manipulator with the required precision for inserting and retrieving samples.
- Developing the storage system to preserve sample identification and to prevent contamination.
- Optimizing the electron-beam gun configuration for continuous duty at the required power levels.
- Developing input/output circuitry for the programmable controller to scale sensor outputs and to interface with controlled circuits.
- Defining interfaces to the precision required for successful integration.
- Optimizing the levitation coil and circuitry matching the coil to the rf generator.
- Optimizing the liquid cooling system in order to eliminate hot spots and minimize the required flow-rate.
- Developing calibration techniques for the sample temperature monitoring circuitry and sensor.

5.2.11 Test Requirements

Before delivery for the first flight, the L-1 facility must be completely space-qualified and checked out operationally. Figure 5-13 shows a typical test flow diagram.

5.2.11.1 Qualification Tests

A single L-1 facility will be tested at qualification levels for the following:

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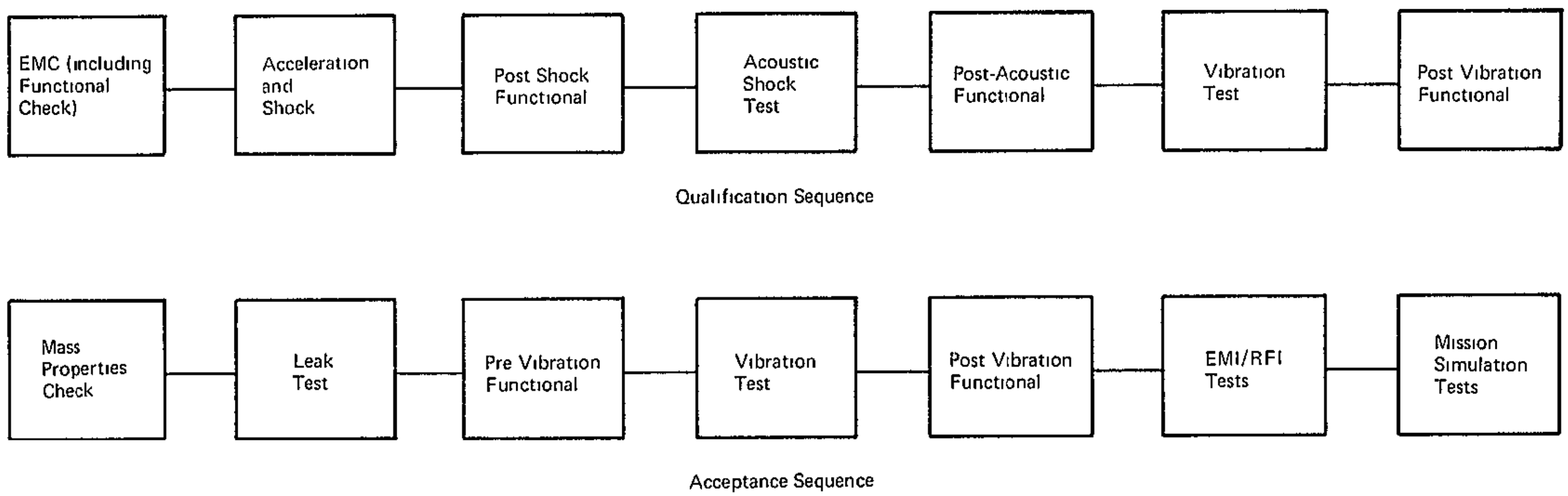


Figure 5-13 L-1 Facility Qualification and Acceptance Test Flows

- Acceleration and shock, to ensure survival of launch, boost, landing, and braking loads, as defined by NASA. This is a non-operating test.
- Vibration, in accordance with specifications to be developed by NASA. This is also a non-operating test; however, it is preceded and followed by short operational test sequences.
- Acoustic shock, to ensure survival in the launch noise environment, as defined by NASA. This is also a non-operating test.
- Electromagnetic compatibility (EMC), to ensure that the L-1 facility will not interfere with critical spacecraft communications and other priority experiments and to ensure that the L-1 facility will not be adversely affected by signals generated by other mission operations, through conductive or radiative coupling. This is an operational test.

Subsequent units will be qualified by analysis or by limited additional testing.

5.2.11.2 Acceptance Tests

The following tests will comprise the L-1 acceptance sequence to be performed on all delivered models.

- Mass Properties Check. Weight, center of gravity, and outline and critical dimensions, including location of attachment points and electrical and liquid-coolant interface connections, will be checked against specifications.
- Leak Test. Vacuum and gas equipment will be checked for leaks in their integrated configuration.
- EMI/RFI Tests. These tests are similar to ECM qualification tests but are tailored to a specific equipment complement and are less intensive in implementation.
- Functional Tests. This test will be performed in three phases. The first is an operational test to verify that all units are functioning properly. The test will employ a special test program. This test will be followed by vibration tests. After post-vibration verification and EMI/RFI testing, a third functional sequence will be performed under conditions as close to mission environment as can be simulated.
- Vibration Test. This is a low-level vibration test, using expected mission frequencies and levels. It is intended to verify that all components and integration hardware are mechanically intact.

5.3 ACOUSTIC LEVITATION FACILITY (L-4)

The acoustic levitation facility features the capability for containerless processing of various materials by suspending the sample specimen in an acoustic force field.

5.3.1 Design Description

The configuration of the L-4 facility, shown in Figure 5-14, is based on the same spherical chamber used in the L-1 facility; however, in the L-4 facility, the chamber is not evacuated, except for purging in special cases, but will contain gases compatible with the materials being processed at pressures in the range of 0.03 to 0.3 MN/m^2 (5 to 50 psi).

Across the sphere and connecting two of its ports is the cylinder-shaped acoustical chamber, a portion of which is the high-temperature furnace. External to the sphere and connected to the acoustical chamber is an acoustic elbow. The elbow permits mounting the acoustic transducer out of the line-of-sight from the molten sample.

An optical window in the elbow permits viewing the sample specimen with a TV camera and with an optical pyrometer through the use of a dichroic mirror.

On the opposite side of the chamber is an acoustical reflector. By means of the reflector, an acoustical standing-wave is established. A microphone, located in the reflector, provides feedback for maintaining the frequency of the acoustical generator at chamber resonance. A door in the reflector permits access for sample insertion and retrieval by the sample manipulator. The door is identical to that used in the L-1 facility.

The electronics is similar to that employed in the L-1 facility and includes a furnace controller.

5.3.2 System Interfaces

The system interfaces of the L-4A facility are comparable to those of the L-1 facility. Specific details are included in the following paragraphs.

5.3.2.1 Mechanical Interface

Mounting arrangements and venting provisions are similar to those shown in Figure 5-3 for the L-1 facility.

5.3.2.2 Electrical Interface

The L-4 facility gets all of its electrical power from the spacecraft. Specific requirements (excluding conversion losses for ac) are:

Service	Power (kW)	
	Peak	Average
DC, 26 to 32 V	0.2	0.1
AC, single-phase, 400 Hz, 115 V	4.5	2.5

5.3.2.3 Liquid Coolant

As the L-4A facility is to be thermally isolated from the spacecraft, it must be cooled by pumping liquid coolant through cooling coils and cold plates which serve as heat-sinks for power-dissipating units. A flow-rate of 0.2 ℓ per second (3 gallons per minute) at an inlet temperature of about 38°C (311°K) will be required. A pressure drop of about 0.03 MN/m^2 (5 psi) is anticipated. The coolant is assumed to be Monsanto Coolanol 20 or equivalent.

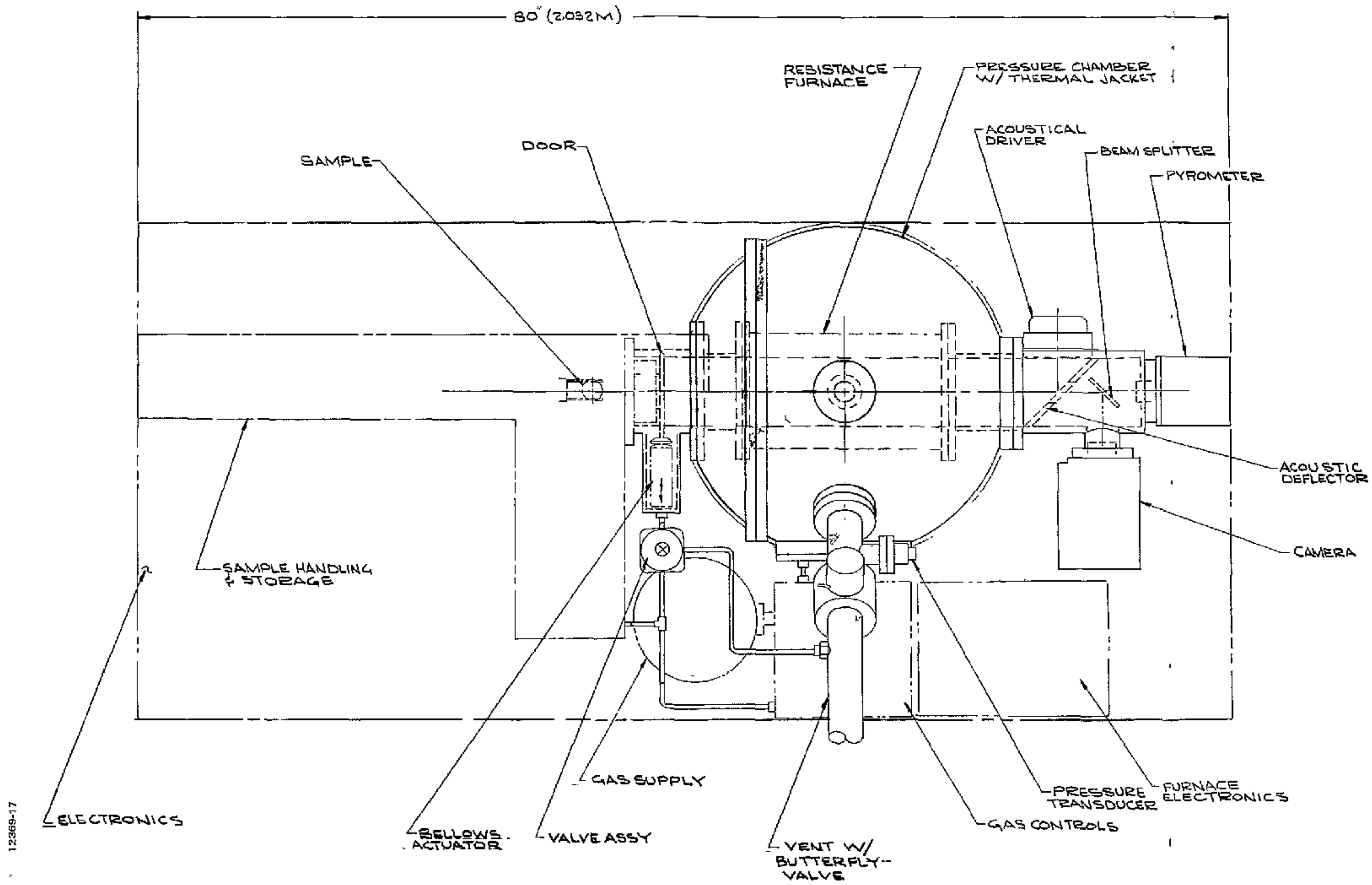
5.3.3 Weight Estimate

An estimate of the weight of the L-4A facility is detailed in Table 5-17. The estimate is based on the 0.6-m- (2-ft-) diameter spherical chamber described for the L-1 facility, but with the vacuum components deleted.

The electronic equipment is comparable to that described for the L-1 facility.

5.3.4 Performance

The L-4A facility is designed to process, in a gas typically at 0.1 MN/m^2 (one atmosphere) of pressure, spherical samples of up to 4 cm (1.5 in.) in diameter and up to 71 g in mass at temperatures up to about 2,200°C (2,473°K). Process time is not limited by the facility itself but only by the available maneuver-free period in the mission time-line and by the available energy allocated to space processing. Typical process times of 2 to 6 hours should be compatible with most mission plans.



FOLDOUT FRAME 1

FOLDOUT FRAME 2

Figure 5-14 L-4 Facility Configuration

Table 5-17

L-4A Facility Weight Estimate

Component	Weight (lb)	Weight (kg)
Interface structure and braces	160	72
Chamber and associated structure	140	64
Sample handling system	145	66
Furnace	46	21
Furnace controller	34	15
Programmable controller and electronics	63	29
Optical pyrometer	25	11
Camera and lamp	13	6
Tape recorders	34	15
Acoustic levitation	26	12
Gas system	45	20
Cold plates, plumbing, and coolant	89	40
Cables, terminations, and ties	8	4
Total	828	375

5.3.4.1 Power Analyses

Furnace. - The power requirements of high-temperature furnaces are somewhat independent of sample characteristics. A furnace pre-heating time of about 60 minutes is required prior to sample processing. Typical of furnaces that might be employed is the Artcor zirconia heater furnace. It requires a peak power of about 4, 100 W for the L-4A facility application (2, 050 °C for alumina) plus about 90 W for the controller. Allowing for conversion losses, its peak power is 5.5 kW.

Acoustic Levitation. - The L-4A facility depends on an acoustical standing-wave to levitate the sample. To size the equipment required, we must satisfy the relationship

$$F = ma,$$

where m is the sample mass, typically 69.5 g for 4-cm- (1.5-in.-) diameter samples of silicon or high-silicate glass, and a is expected acceleration, 10^{-4} g or 0.09807 cm per sec^2. Therefore,

$$F = 69.5 \times 0.09807 = 6.8 \text{ dynes.}$$

Total force in the 12.7-cm- (5-in.-) diameter acoustic chamber is

$$(5)^2/(1.5)^2 \times 6.8 = 76 \text{ dynes.}$$

Per Reference 2, typical transducers generate 10^{-3} to 10^{-2} Newtons per watt. Assuming the lower figure, this is equivalent to 100 dynes, and we find that 1 W of electrical power is needed. With a conservative safety factor, 10 W of electrical power will be adequate.

Core Equipment. - The L-4A core equipment is similar to that of the L-1 facility with the exception that the vacuum equipment has been deleted. Power consumption was described previously in the L-1 facility description.

Power and Energy Summary. - The power requirements and energy consumption of the L-4A facility are summarized in Table 5-18. Both parameters include conversion losses. The peak power calculation is based on a 1 cm alumina sample at 2,050 °C. Energy and average power are calculated for silicon (4 cm diameter and 1,410 °C).

5.3.4.2 Time Estimate

The L-4A facility is intended to process relatively high-temperature crystal and glass materials. Because of the requirement for pre-heating the furnace and the long cooling phase prescribed for the crystal and glass materials to ensure stress relief, L-4A facility processes, typically, require longer time-periods that those of the L-1 facility.

The longest cycle identified is for a silicon process requiring continuous heating, including furnace warm-up for 291 minutes, followed by a programmed cooling sequence of 120 minutes, for a total time of almost 7 hours. For processing a total of six samples, the time required would be over 41 hours or almost 2 days.

One of the glass experiments requires a sequence time of only 136 minutes; 116 minutes for melting the sample (including furnace warm-up) and holding it in the molten state and 20 minutes for programmed cooling. Processing six samples would require only 14 hours.

Table 5-18

L-4A Facility Power and Energy Summary

Component	Peak Power (W)	Total Energy per Silicon Sequence (Whr)
Programmable controller	307	2, 103
Sample handling	(125) 12	86
Tape recorder	(47) 34	233
Camera and lamp	30	174
Optical pyrometer	19	130
Valves	(5)	---
Furnace	5, 505	15, 760
Furnace controller	120	342
Acoustic levitation	10	68
Total	6, 037	18, 896
Silicon sequence average run power = $\frac{18,896}{411/60}$ or 2, 759 W, including conversion losses.		

5.3.4.3 Temperature Profile

A temperature profile of one of the L-4 facility experiments, using silicon for the process material, is shown in Figure 5-15. The total process requires 411 minutes. Of this total, 60 minutes are used to pre-heat the furnace to 1, 000°C (1, 273°K) and 41 minutes are used to bring the sample up to melting temperature, 1, 410°C (1, 683°K). The sample is maintained at this temperature for another 190 minutes and is then cooled along a programmed profile (in this case, linear with time) by gradually reducing furnace power for 120 minutes.

Other typical L-4 facility processes require only 2 to 4 hours to complete, with similar profiles.

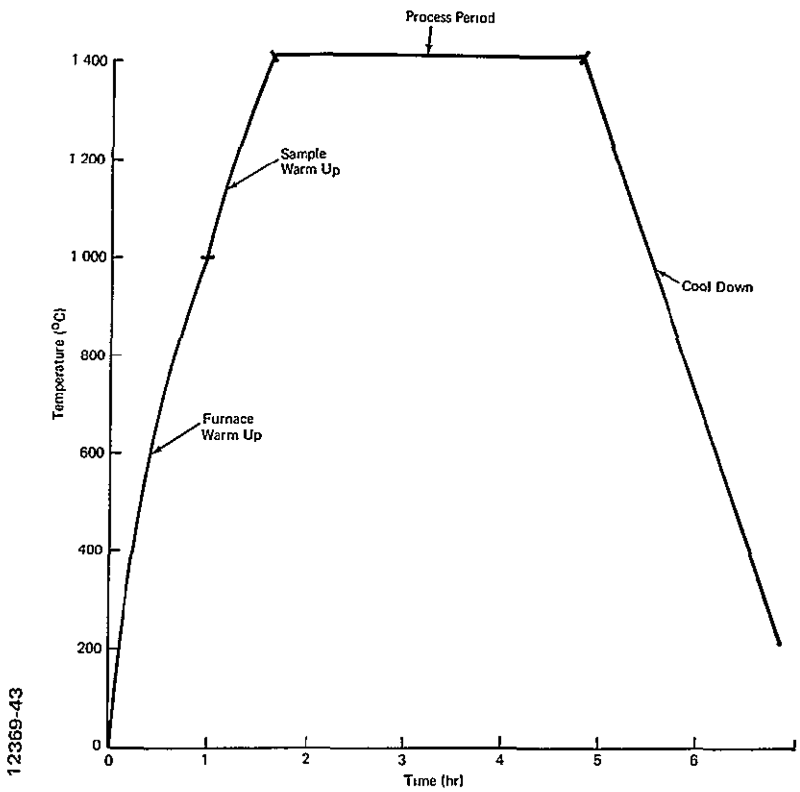


Figure 5-15 Silicon Process Temperature Profile

5.3.4.4 Power Profile

The power profile which corresponds with the temperature profile of Figure 5-15 is shown in Figure 5-16. Power values do not include conversion losses. Peak power is seen to be about 2.5 kW, and average power is about 2.1 kW.

5.3.5 Control System

The control system for the L-4 facility is similar to that described for the L-1 facility with the following exceptions:

- The system controls a resistance furnace instead of an electron-beam gun. The furnace has more thermal inertia, and control is more sluggish.
- The system controls gas at moderate pressure, rather than vacuum.

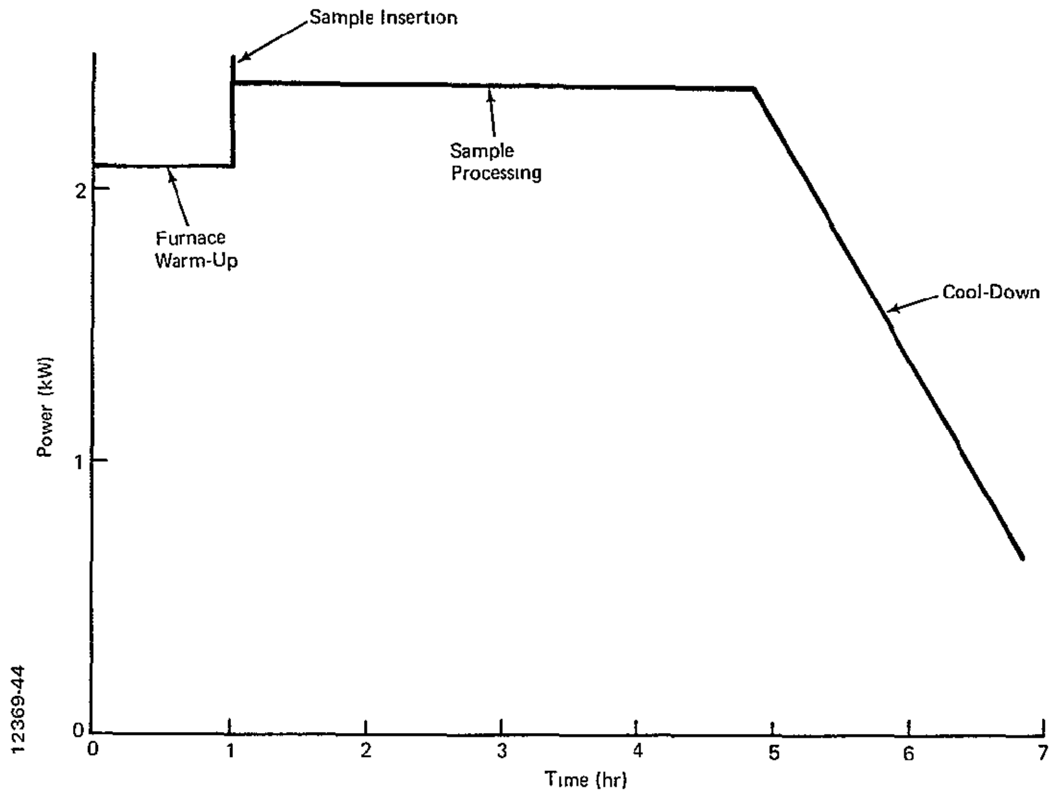


Figure 5-16 L-4 Facility Silicon Power Profile

- The system controls the acoustic generator, in place of the electromagnetic (rf) generator.

Control interfaces in all cases are similar to those of the L-1 facility.

5.3.5.1 Chamber Environmental Control and Monitoring

For proper operation of the acoustic levitation facility, facility L-4, the gas pressure should be maintained between 34 and 172 kN/m^2 (5 and 25 psi). Argon or another monatomic inert gas will be used. The chamber may be purged between sample processing. During sample insertion and withdrawal, it is important that a positive gas flow be established between the sample handling and storage section and the processing chamber in order to avoid contamination of the samples. The chamber volume is approximately 120 ℓ (4.2 ft^3). The sample handling and storage area is also approximately 120 ℓ (4.2 ft^3) for a total volume of 240 ℓ (8.4 ft^3). The total gas required for processing six samples, including purging the chamber between samples, is approximately 3 x 10^6 Torr ℓ of gas. Ten times the requirement will be provided in order to allow for leakage and contingencies. Therefore, 30 x 10^6 Torr ℓ of gas must be supplied.

Figure 5-17 shows a schematic diagram of the gas system. Using the gas supplied for chamber pressurization and purging, the door between the chamber and the sample handling section is pneumatically-actuated via valves V_2 and V_3. Gas for pressurization and purging is admitted to the chamber through the sample handling volume and through valve V_1. When the door between the two volumes is opened, valve V_1 is opened and butterfly valve V_4 is throttled to allow a continuous flow of gas through the chamber, thereby preventing contamination of the sample handling and storage area.

Gas is stored at 1.5 MN/m^2 (220 psi), and a pressure regulator controls the pressure to 0.1 MN/m^2 (15 psi). Approximately 250 ℓ (8.7 cu ft) of gas are required; thus, the storage bottle is about 80 cm (13 in.) in diameter for a spherical shape. Several cylindrical bottles may be supplied and manifolded together, depending on the space and weight available.

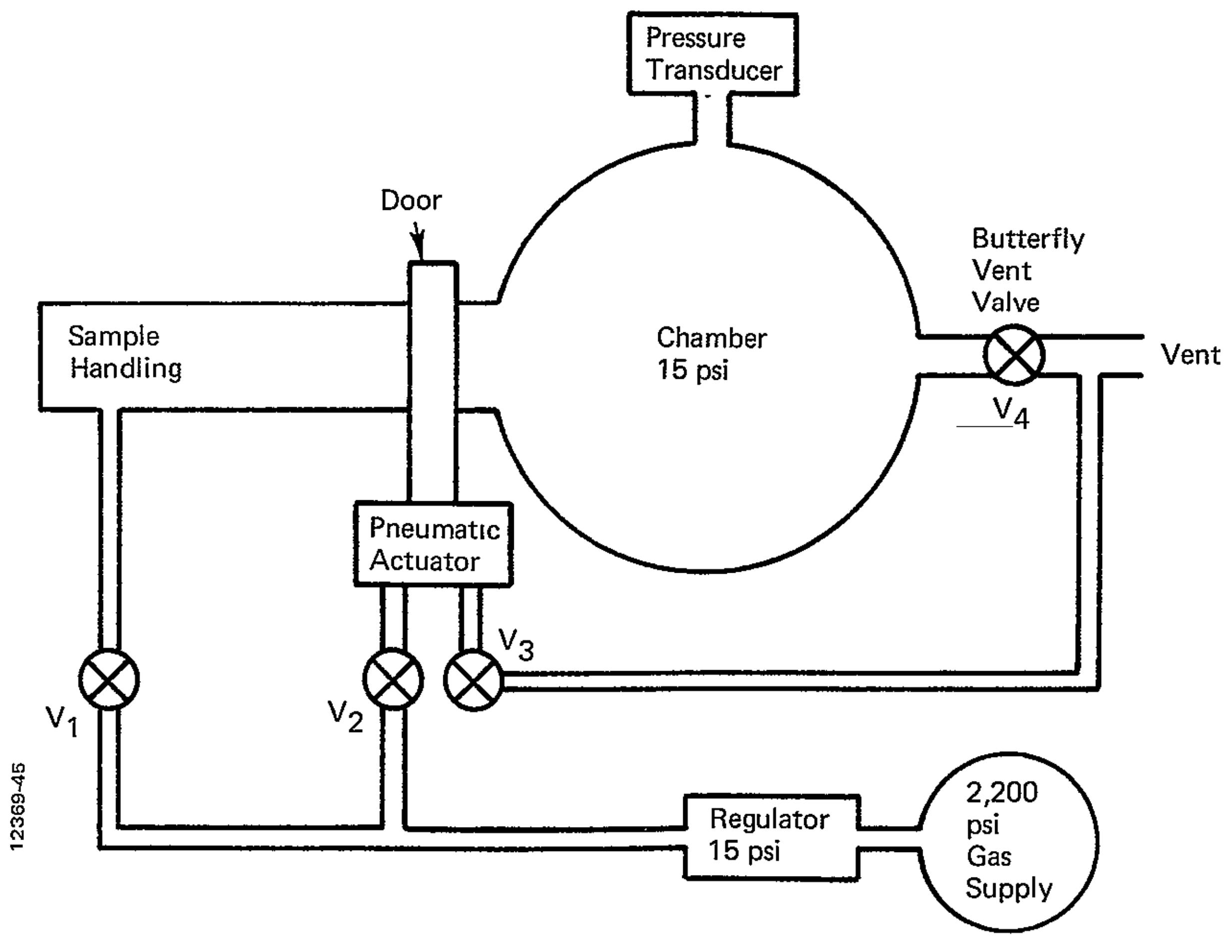


Figure 5-17 L-4 Facility Gas Supply System

Chamber pressure is sensed and controlled by a pressure transducer mounted in the chamber. A low-impedance quartz pressure transducer with built-in amplifier may be used. Characteristics of such a unit are given in Table 5-19. When the chamber pressure exceeds an upper limit of about 172 kN/m^2 (25 psi), it will be necessary to take corrective action. This can consist of holding the process and venting the excess gas overboard in a delicately-controlled manner in order to avoid disturbing the levitated sample. The function must also include verifying the closure of the inlet gas valve system.

Table 5-19

Pressure Transducer Characteristics

Dynamic range	0.01 to 100 psi (69 N/m^2 to 0.7 MN/m^2).
Sensitivity	50 mV/psi (7 μV/N/m^2).
Resolution	0.004 psi (28 N/m^2).
Linearity	1%.
Output impedance	100 ohms.
Vibration	2,000 g's.
Shock	20,000 g's.
Temperature range	-100 to +275°F (200 to 408°K).
Temperature sensitivity	0.03%/°F (0.05%/°K).

5.3.5.2 Levitation Control

The samples will be levitated using a single acoustical driver inside a cylindrical column, which is formed by an extended tube furnace.

The acoustic driver is protected from direct heat radiation by being positioned in an extension at a right angle to the main furnace cavity. The acoustic energy is coupled to the cavity by a reflector containing an optically-transparent window, which permits using an optical pyrometer and TV camera to view the sample. A beam splitter is used to allow both optical instruments to view the sample.

A second furnace extension houses the sample storage and manipulator facility. The door to this facility acts as the acoustical reflector at the end of the standing-wave column.

The position of the sample is maintained by a frequency controller of the type described in Paragraph 5.7 Reference 1. A block diagram of the system is shown in Figure 5-18. The basis of the control system is a phase-lock loop, which maintains the driving signal at 90° phase-lead with respect to the acoustical signal within the chamber. The difference in phase is detected, and the resulting signal is used to vary the frequency output of a voltage-controlled oscillator, the output of which is amplified and sent to the acoustic driver. The automatic frequency control maintains resonance within the chamber despite changes in gas temperature. The power output is controlled so that, during sample manipulation, the output is high so as to restrain the sample but, during normal processing, the power output can be low. The recommendation is made that an accelerometer be provided so that if spacecraft accelerations which might disturb the sample occur, the accelerations can be detected and used to cause an increase in acoustic power, thereby putting increased restraint on the sample. In addition, insulated metallic strips will be placed inside the furnace cavity, around the walls, to form short cylinders which will be separated at the extremities so that their diameter cross-sections form two plates of a capacitor. Several of these will be used to form a capacitive positional pick-off, which will give a qualitative indication of the sample position and which could be used for gross positional control by causing an acoustical power increase if large positional deviations were detected. The capacitive pick-off is detailed in Figure 5-19.

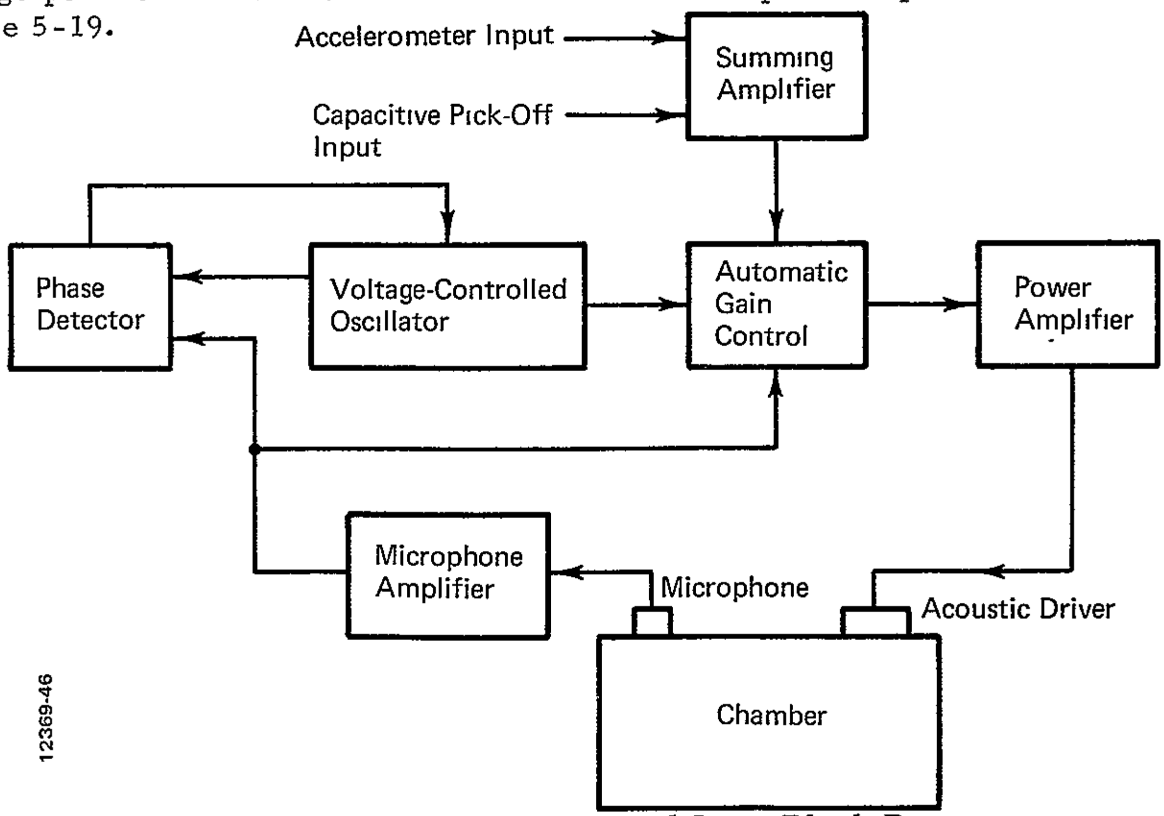


Figure 5-18 Frequency Control Loop Block Diagram

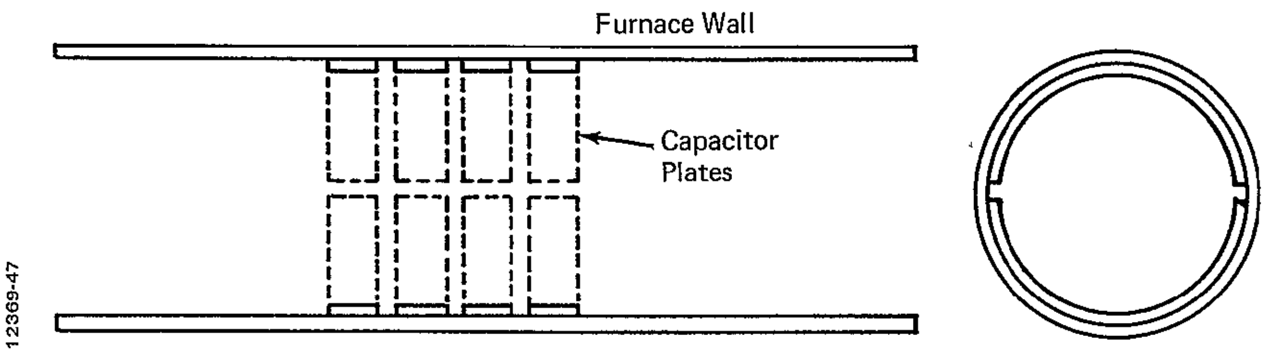


Figure 5-19 Details of a Capacitive Position Pick-Off

5.3.5.3 Sample Temperature Control

The heating profile will be initiated by the computer.

The heating cycle is initiated by applying power to the furnace pre-heater, which heats the elements of the main heater to the temperature at which the resistance is sufficiently low for the elements to conduct adequately. When this state is reached and the main elements are fully powered, the pre-heater is turned off.

The temperature of the sample is controlled by varying the power to the furnace. The sample temperature is monitored via an optical pyrometer and is compared with set limits in the computer. The computer processes the temperature data using a proportional control algorithm in a subroutine. The temperature data is recorded at regular intervals throughout the experiment cycle.

The optical pyrometer has been described previously in the description of the L-1 facility.

5.3.6 Extension of Range

The L-4 facility could be modified to extend its capability by using larger samples and/or denser specimens.

5.3.6.1 Larger Samples

Increasing the maximum specimen diameter will necessitate replacing the furnace with one having a larger diameter, as the furnace tube serves as a portion of the acoustic resonance chamber, which must be dimensionally large with respect to sample size. Increasing the furnace diameter increases its weight and power consumption. The components of the acoustic levitation system must also be enlarged to match the furnace dimensions. The frequency of the acoustic generator should be adjusted downward to optimize the force-to-power ratio. The acoustic power must be increased to account for the increased mass of the larger samples.

Table 5-20 shows the impact of increasing sample size, assuming silicon as a typical material.

Table 5-20

Impact of Increasing Sample Size

Sample Diameter		Furnace Facility					Peak Power		Energy per Sequence	
		ID		Weight		Percent Increase		Percent Increase		
(in.)	(cm)	(in.)	(cm)	(lb)	(kg)		(kW)		(kWhr)	(MJ)
1.5	3.8	5	13	811	368	Base	3.3	Base	19	68
2.5	6.4	6	15	843	382	4	4.4	33	25	90
3.5	8.9	7	18	890	404	10	5.3	61	30	108
4.5	11.4	8	20	953	432	18	5.8	76	33	119

5.3.6.2 Denser Specimens

The L-4 facility is designed to levitate relatively light materials having densities under about 4 g per cm^3. As the required levitation force is proportional to the sample mass, doubling the density doubles the power consumption of the acoustic generator, with attendant proportional weight penalities.

Table 5-21 shows the impact of using materials having higher density.

5.3.7 Potential Integration Problems

No particular problems are foreseen in integrating the L-4 facility. The facility should probably be sealed with a small positive pressure of inert gas in order to prevent contamination of the chamber. This pressure should be checked in the last phase of the build-up.

Table 5-21

Impact of Increasing Sample Density

Specific Gravity	Percent Facility Weight Increase	Percent Running Power Increase
4	Base	Base
8	2	0.3
12	3	0.7
16	5	1.0
20	7	1.4

5.3.8 Manual Mode

As with the L-1 facility, the L-4 facility can be adapted to eliminate the automatic sample manipulator and other automatic process functions, such as temperature control. The volume of the facility could, thus, be reduced by about 0.6 m^3 (20 cu ft) and the weight could be reduced by about 91 kg (200 lb), making it feasible to mount the facility inside the pressurized cabin.

The semi-manual mode might be especially advantageous in processes requiring precise control of the sample position.

5.3.9 Data Management

The data management philosophy for the L-4 facility is identical to that described for the L-1 facility in Paragraph 5.2.9.

5.3.10 Development Requirements

Development requirements for the L-4A facility are similar to those for the L-1 facility with the following additional specifics.

5.3.10.1 Furnace

The L-4 facility uses a high-temperature tube furnace as a portion of the acoustic chamber and as the primary heat source. It will be necessary to verify by developmental testing the following:

- Ability of the furnace to survive launch acceleration, acoustic shock, and mission vibration in a non-operating mode.
- Compatibility of the furnace with the acoustic environment required for levitation in its operational mode.

5.3.10.2 Levitation

Although the principles of acoustical levitation have been rather thoroughly investigated; as described in Paragraph 5.7 References 1, 2, and 3; an optimized facility for space processing must be developed. Some aspects to be studied are:

- Optimum ratio of transducer diameter to chamber length.
- Optimum frequency for a given specimen and chamber size.
- Sensors for monitoring sample position and controls for adjusting sample position to correct for drift induced by changes in temperature or pressure of the gaseous medium.
- Operational procedures and software relating to sample introduction and retrieval, sample position monitoring, and sample control, and maintenance of resonance by control of the frequency and the chamber dimensions.

5.3.11 Test Requirements

Test requirements for the L-4 facility are similar to those described for the L-1 facility in Paragraph 5.2.11.

5.4 FURNACE FACILITIES

Three types of furnace facility designs have been generated. The types correspond to the furnace experiment groups F-1, a high-temperature tube furnace, performing processes requiring temperatures higher than 1,200°C for their operation; F-2, a low-temperature tube furnace for processes operating at temperatures lower than 1,200°C; and F-3, equipment providing a precisely-controlled temperature gradient and means for transporting the sample through the gradient.

5.4.1 Furnace Facilities F-1 and F-2

The facility F-1 and F-2 furnaces are both tube furnaces with temperature range differences as noted above. Typical furnaces used for design definition are, for the F-1 facility, the Artcor zirconia furnace described in Paragraph 5.7 Reference 4 and, for the F-2 facility, the Varian Marshall Model 1332.

5.4.1.1 Design Description

Two automated furnace facility configurations were developed for the F-1 and F-2 facility furnaces. A multiple furnace concept, designated A, and a single furnace concept with multiple samples, designated B. Facilities F-1A and F-2A are multiple furnace configurations in which banks of six furnaces are mounted in a cluster, as shown in the artist's concept of Figure 5-20 and the layout drawing of Figure 5-21. Encapsulated samples are stored in the furnace prior to launch and are recovered after completion of the mission. Control electronics is similar to that used for levitation systems but simpler, as fewer functions require control and no visual record is planned. Depending on power availability, the furnaces may be individually energized in sequence, or two or more may be operated concurrently.

Facilities F-1B and F-2B are single-furnace concepts with provisions for multiple-sample handling. Figure 5-22 depicts the layout of the single-furnace configuration and Figure 5-23 is an artist's concept. Provision is made for storage of up to six encapsulated specimens on an indexing wheel. The furnace is mounted on a traversing carriage. Under control of the onboard computer, the furnace is moved to enclose the capsule which has been indexed into position for processing. Each capsule is equipped with an integral furnace cap. The furnace picks up the sample and backs off for the duration of the process sequence. It then restores the sample to its original position on the wheel. The furnace again backs off and the storage wheel indexes the next capsule into position for processing.

The sample cartridges are instrumented for temperature measurement and maintain their own gas or vacuum environments.

5.4.1.2 System Interfaces

Major interfaces of the furnace systems with the spacecraft are the mechanical, thermal, and electrical interfaces.

Mechanical Interface. - Figure 5-24 shows the major bracketry of the single-furnace configuration (F-1B and F-2B) and the location of potential hard-points. Hard-point mounting will be designed for minimum thermal transfer between the furnace facility and the spacecraft. The multiple furnace facility (F-1A and F-2A) mechanical interface is similar.

Thermal Interface. - The furnace facility is designed to be liquid-cooled. The furnaces are cooled to maintain electrical integrity and to provide a fast thermal response at the expense of efficiency. The balance of the facility equipment is also cooled to prevent thermal contamination of the spacecraft.

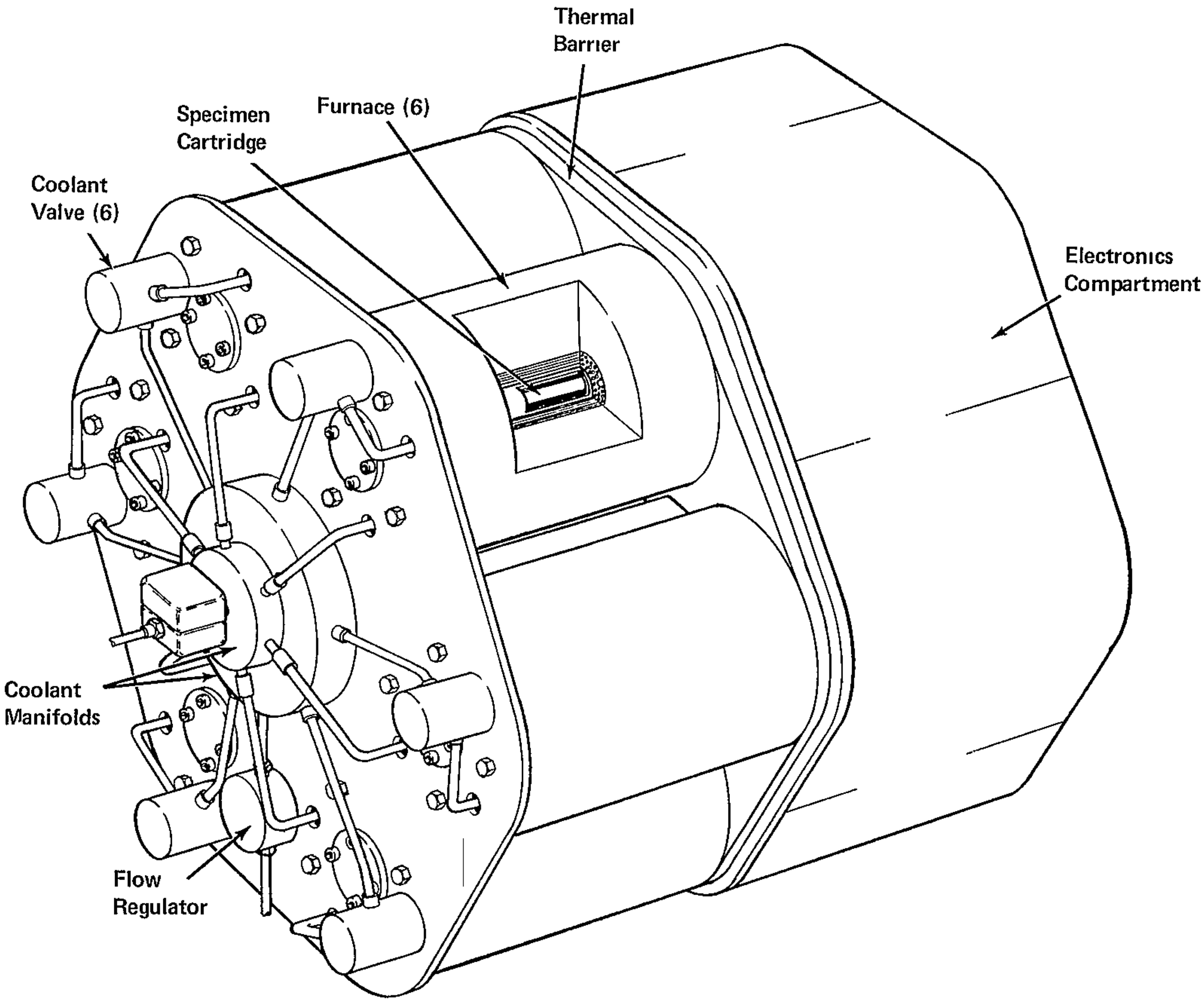
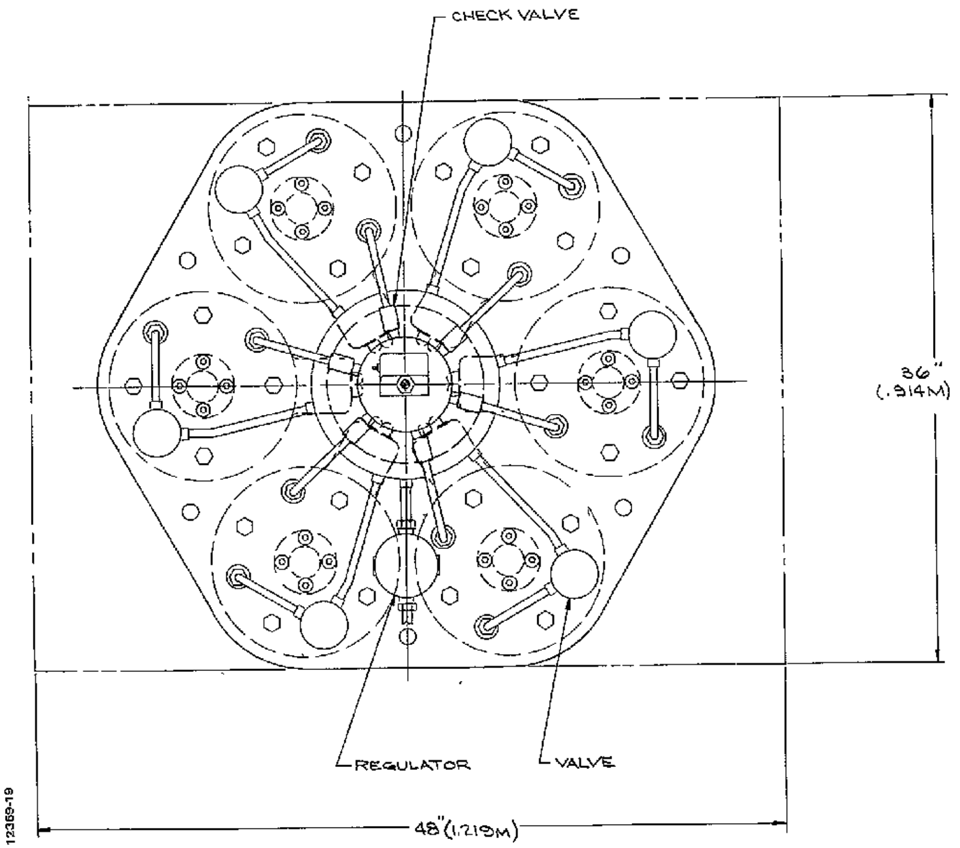
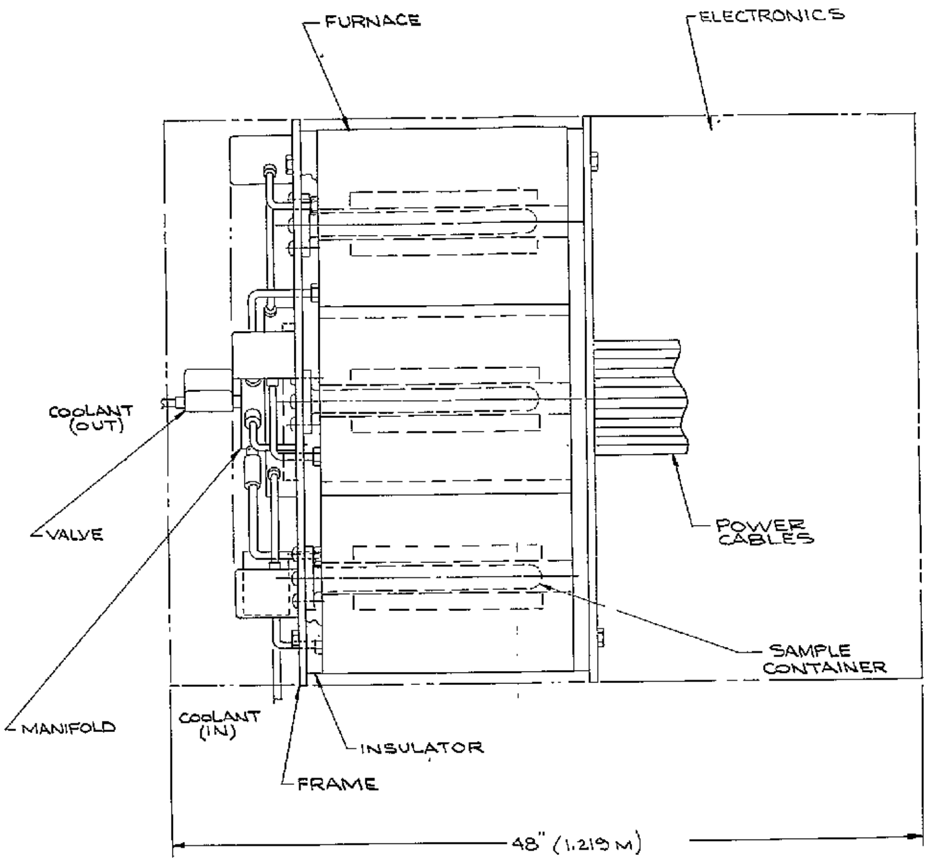


Figure 5-20 Multiple Furnace Facility F-1A and F-2A





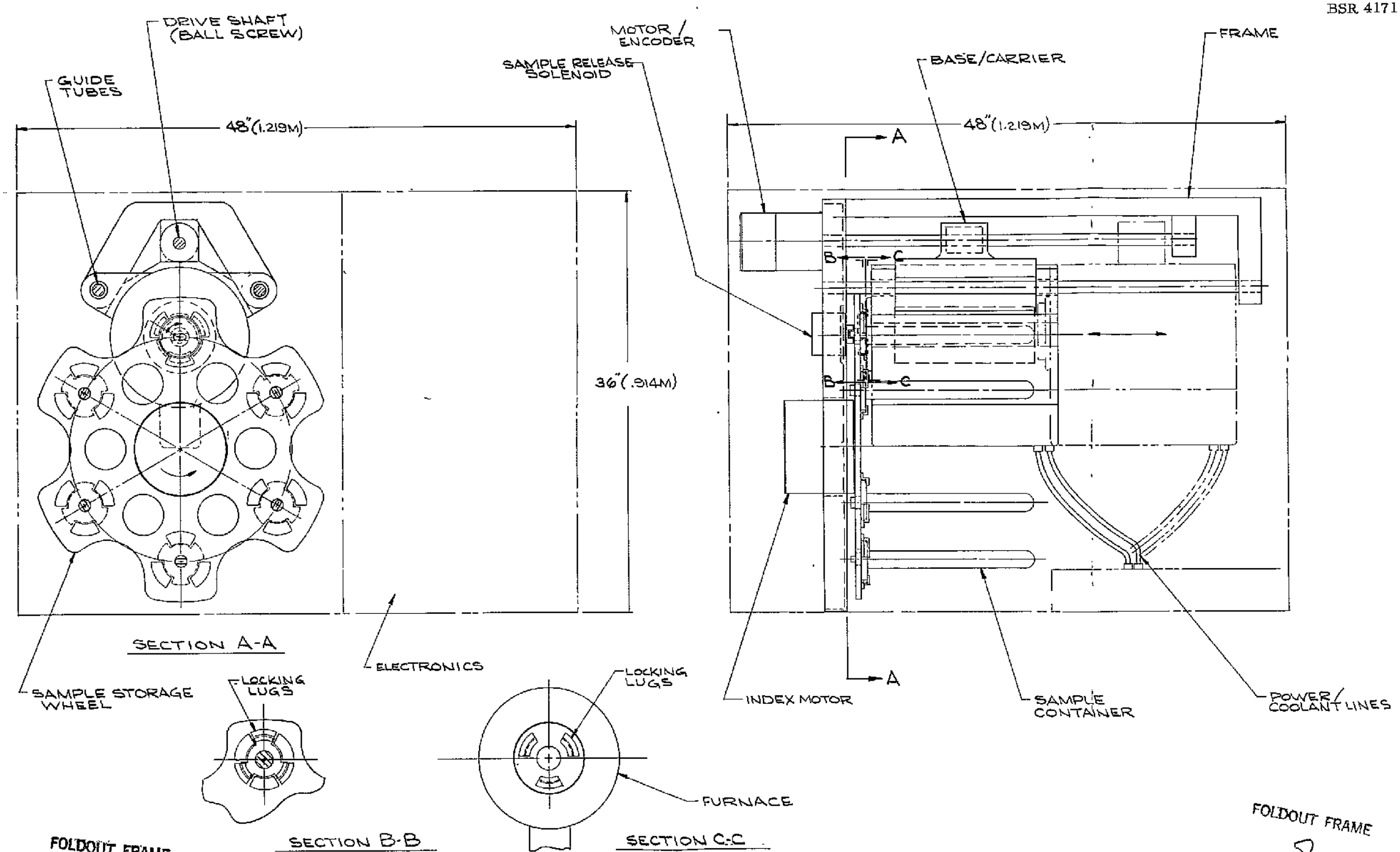
FOLDOUT FRAME

1

FOLDOUT FRAME

2

Figure 5-21 Multiple Furnace Facility F-1A and F-2A Layout



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FOLDOUT FRAME 2

Figure 5-22 Single-Furnace Facility F-1B and F-2B Configuration

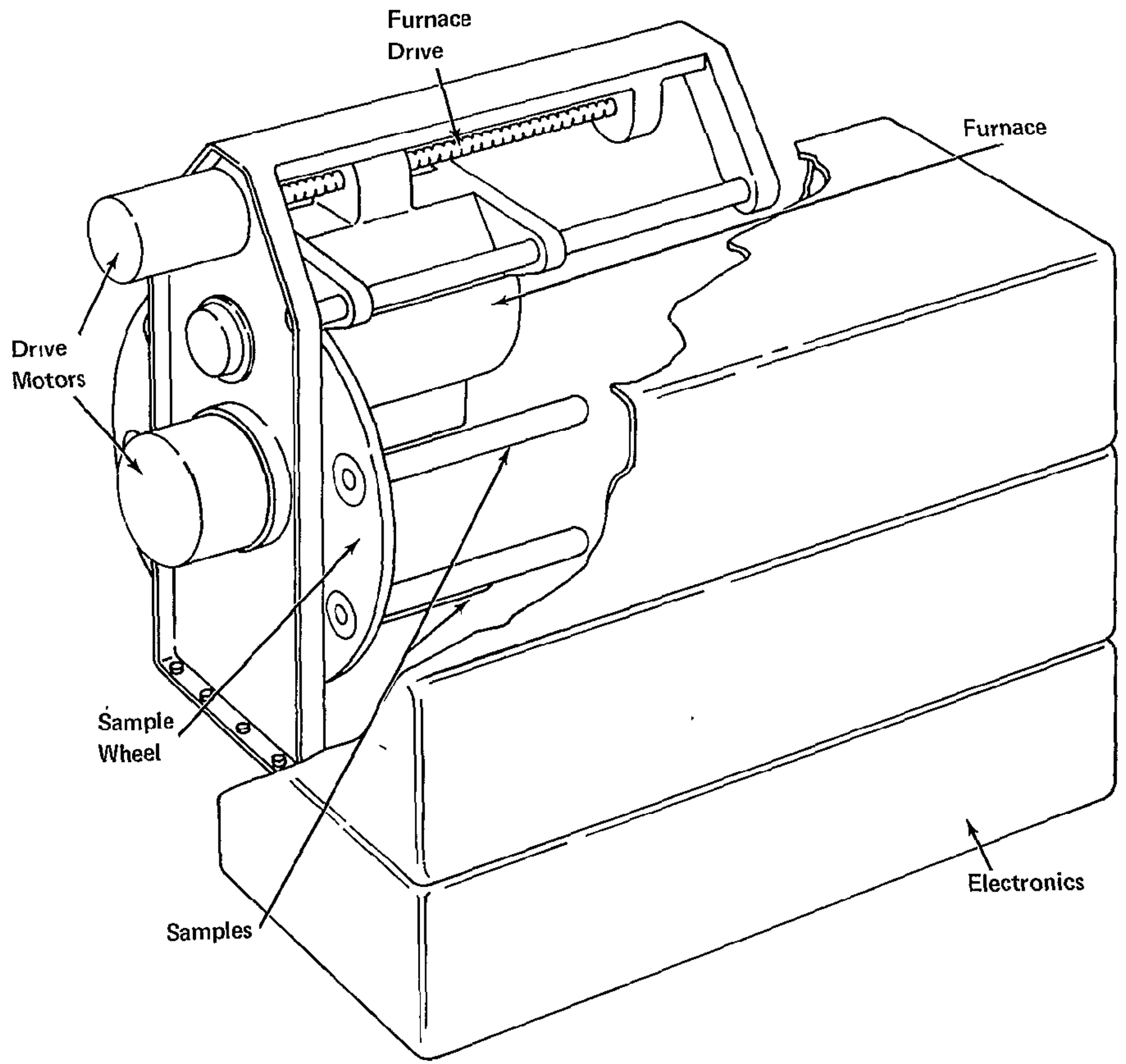


Figure 5-23 Multiple-Sample Furnace Facilities F-1B and F-2B

For high-temperature facilities, F-1A and F-1B, the coolant should be Coolanol-20 or equivalent at a flow-rate of 0.23 ℓ per second (3 gallons per minute), having an inlet temperature of about 38°C (311°K) and a design pressure drop of 27.6 kN/m^2 (4 psi). For the moderate-temperature facilities, F-2A and F-2B, the flow-rate should be 0.08 ℓ per second (1 gallon per minute) for 6.9 kN/m^2 (one psi).

Electrical. - The furnace facility receives all its electrical power from the spacecraft. Specific power requirements (excluding conversion losses for ac) are based on a temperature of 1,850°C for facilities F-1A and F-1B and a temperature of 1,100°C for facilities F-2A and F-2B. The requirements are:

Service	F-1A and F-1B		F-2A and F-2B
DC: 26 to 32 V	Peak	0.4 kW	0.4 kW
	Average run	0.1 kW	0.1 kW
AC: 115 V, 400 Hz	Peak	3.6 kW	2.4 kW
	Average run	2.5 kW	2.1 kW

Connector details are yet to be determined.

The control and display interface is similar to that described for the L-1 facility.

5.4.1.3 Weight Estimate

An estimate of the weight of the single-furnace facility is shown in Table 5-22. It is estimated that the multiple-furnace configuration F-1A and F-1B will weigh approximately 68 kg (150 lb) more than the single-furnace facility, reflecting the weight of additional furnaces and the deletion of the furnace traverse and sample storage mechanisms.

5.4.1.4 Performance

The F-1A and F-1B facilities are designed to process cartridge-enclosed materials at temperatures up to about 2,200°C (2,473°K). Capsules up to 10.7 cm (4.2 in.) in diameter and 20.3 cm (8 in.) long can be accommodated. Special adapters for crystal seed or cold finger insertion are integral parts of the capsule design.

The F-2A and F-2B facilities are designed to process materials enclosed in capsules up to 2 cm (0.8 in.) in diameter and up to 25 cm (10 in.) long at temperatures up to 1,200°C (1,473°K).

FOLDOUT FRAME 2

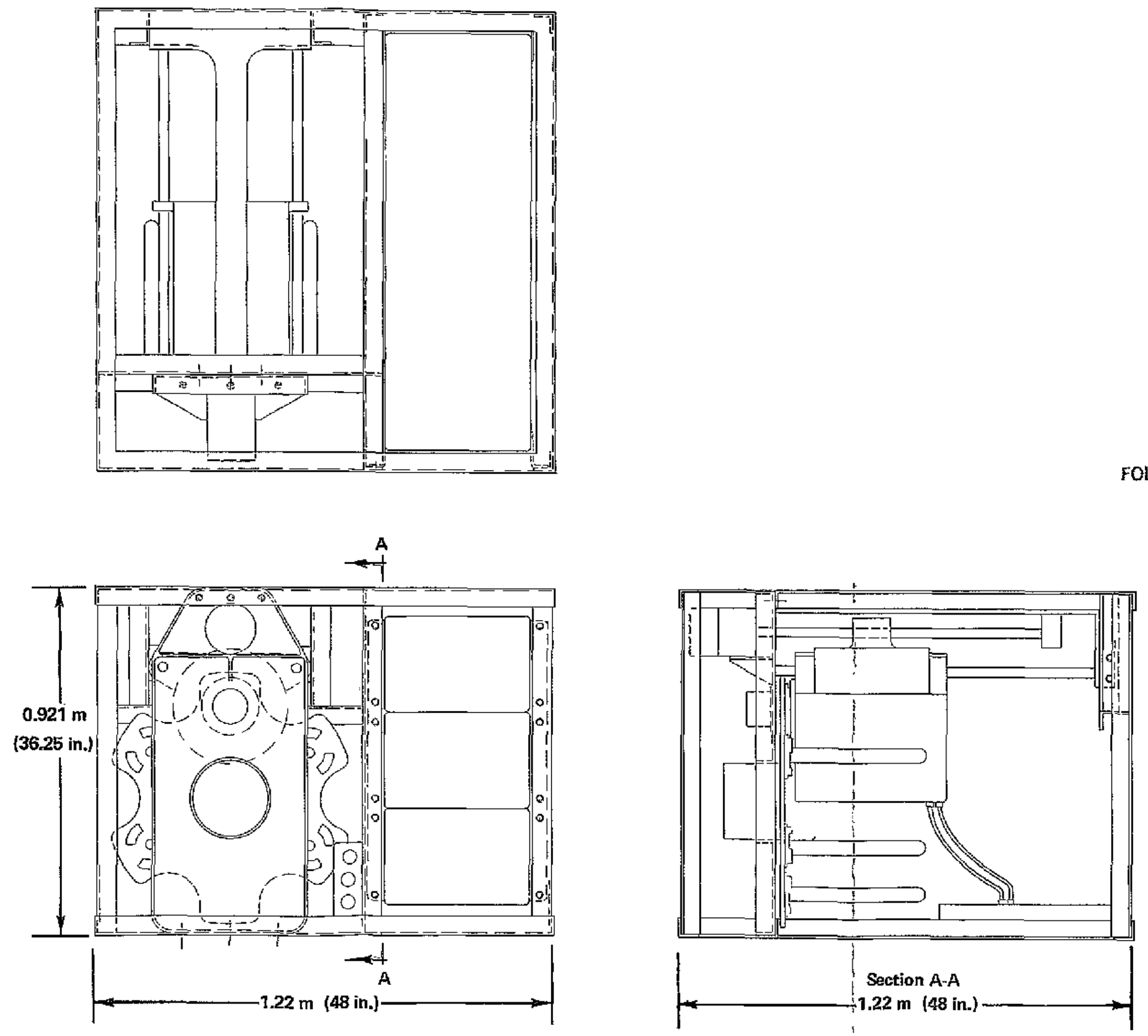


Figure 5-24 Furnace Facility Interfaces

FOLDOUT FRAME 1

Table 5-22

Furnace Facility Weight Estimate

Component	F-1B Weight		F-2B Weight	
	(lb)	(kg)	(lb)	(kg)
Structure	84	38	84	38
Furnace	46	21	41	19
Transformer			40	18
Sample handling and traverse	172	77	172	77
Tape recorder	17	8	17	8
Process controller and electronics	63	29	63	29
Cold plate, plumbing, and coolant	82	37	82	37
Furnace controller	34	15	30	14
Cabling	10	5	4	2
Total	508	230	533	242

Power Analysis. - The power required by the core equipment for the furnace facilities is somewhat less than that required for the levitation facilities because no vacuum, gas, levitation, and optical instruments are included in the complement of equipment. The electronics and recording equipment are comparable to those used in the L-1 facility.

Furnace Power. - The furnace is the chief power consumer in both the F-1 and F-2 facilities. Because these facilities are designed around different furnaces and operate in different temperature ranges, they will be analyzed separately here.

The furnaces employed in the F-1A and F-1B facilities are high-temperature tube furnaces. Although several furnace designs are applicable, we have selected, as typical, the Artcor furnace described in Paragraph 5.7 Reference 4.

For processing a typical material, titanium dioxide, at 1, 850°C (2, 123°K), the Artcor furnace will require about 3, 300 W. Allowing for conversion losses, facility power of about 4.4 kW is required. The furnace requires pre-heating at 1, 800 W for 1 hour.

An additional 70 W is required to power the furnace controller.

The furnaces employed in the F-2A and F-2B facilities are resistance tube furnaces, such as the Varian Marshall Model 1332 or equivalent. A transformer is required with this furnace.

For an 1, 100 °C (1, 373 °K) experiment, an electrical input of about 2, 200 W is required to bring the sample to temperature in 45 minutes. Allowing for conversion losses, this amounts to a facility power requirement during melting of 2.9 kW. The power consumption can then be reduced to 1 kW for the balance of the processing time.

An additional 50 W of dissipation in the furnace controller requires 67 W of facility power. Transformer dissipation is, typically, 10% of the furnace dissipation.

Power and Energy Summary. - The power and energy requirements of the furnace facilities are tabulated in Table 5-23. Peak power is computed on the basis of the highest typical temperature requirements, 1, 850 °C for F-1 and 1, 100 °C for F-2. Energy consumption and average power are calculated for the longest typical sequence, 33 hours for the SiO_2 and 11 hours for CdSe. Figures include conversion losses for ac power. The figures are based on a 7.4 cm (2.9 in.) equivalent SiO_2 sample diameter and a 1.3 cm (0.5 in.) CdSe sample diameter.

Time Estimates. - The materials for which the F-1A and F-1B processing facilities are designed are, typically, glasses and crystals, requiring, typically, about a day to process. However, at least one of the crystal experiments, the YIG, will require a much longer period, varying with the amount of material to 5 days or more. Much of this time is cool-down time and reasonable spacecraft maneuvers could probably be tolerated for at least the latter portion of the period.

Metallurgical experiments conducted with the F-2A and F-2B facilities typically require about an hour. However, some crystal experiments, such as growth from vapor transport, will require more than 10 hours to complete, and this requirement must be kept in mind for mission planning.

Temperature Profile. - The temperature profiles of the F-1 experiments are similar to one another in featuring a relatively rapid heating time, a processing period of closely-controlled level temperature, and a long cool-down period with a well-defined temperature curve.

Table 5-23

Furnace Facility Power and Energy Summary

Component	F-1A and F-1B Peak Power (W)	F-1A and F-1B Energy per SiO_2 Sequence (kWhr)	F-1A and F-1B Energy per SiO_2 Sequence (MJ)	F-2A and F-2B Peak Power (W)	F-2A and F-2B Energy per CdSe Sequence (kWhr)	F-2A and F-2B Energy per CdSe Sequence (MJ)
Furnace	4,399	65.0	234	2,890	14.3	51.6
Transformer	----	----	----	289	1.4	5.0
Process controller and electronics	307	10.2	37	307	3.2	11.5
Furnace controller	93	1.4	5	67	0.4	1.4
Sample handling	320	----	----	320	----	----
Tape recorder	17	0.5	2	17	0.2	0.7
Total	5,136	77.1	278	3,890	19.5	70.2

Average power:

F-1: $\frac{77.1 \text{ kWhr}}{33.3 \text{ hr}} = 2.3 \text{ kW}.$

F-2: $\frac{19.5 \text{ kWhr}}{10.6 \text{ hr}} = 1.8 \text{ kW}.$

Figure 5-25 shows a typical profile, that of a TiO_2 experiment. For other experiments, the processing temperature and the duration and slope of each transition period will be tailored to the requirements of the specific material.

In general, two types of experiments will be conducted with the F-2 facility, metallurgical processes and crystal growth. The crystal process temperature profile is similar to that shown in Figure 5-25. A typical temperature profile for the metallurgical types of processes is shown in Figure 5-26.

In the process depicted in Figure 5-26, the furnace with its enclosed capsule is heated in a 45-minute period to the process design temperature. The temperature is then held at this value for an additional period, typically 15 minutes, after which, a fairly rapid cool-down occurs.

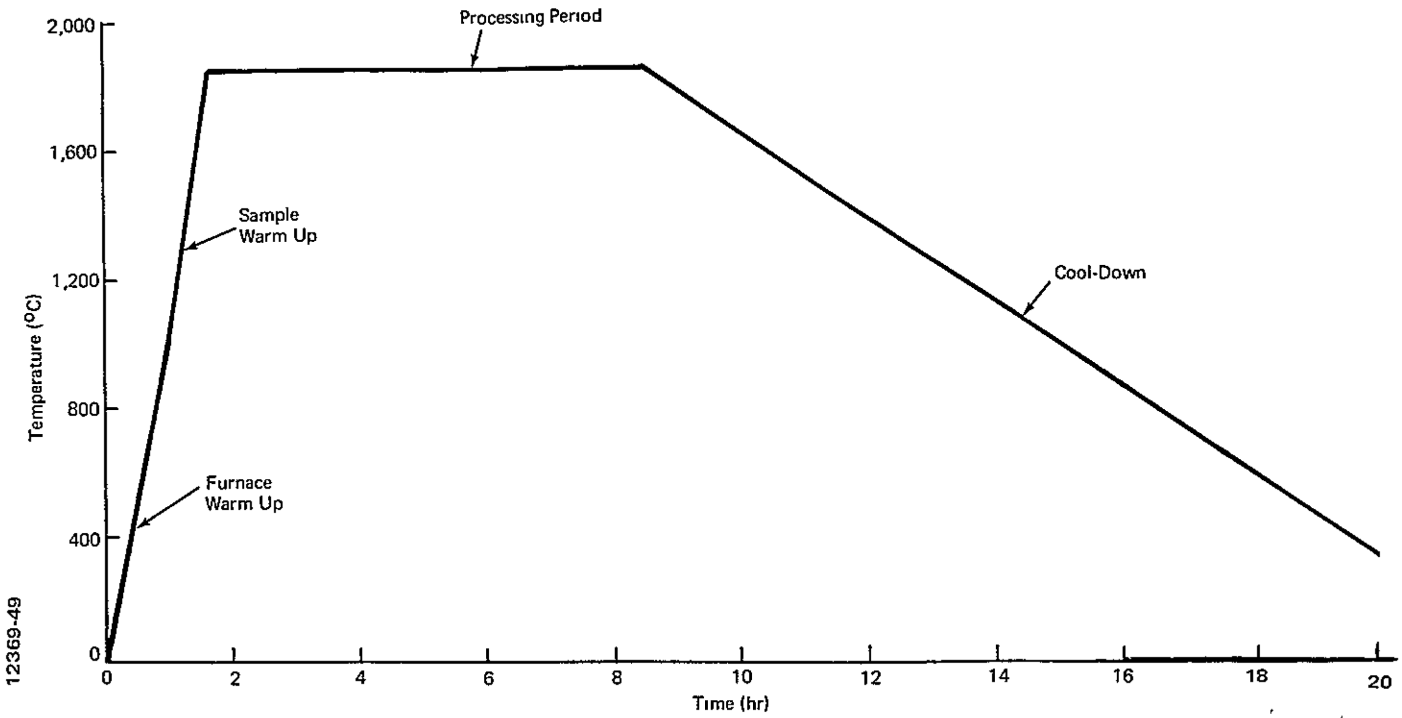


Figure 5-25 Typical F-1 Temperature Profile

Power Profile. - The power profiles for the typical furnace experiments described in the preceding section are shown in Figure 5-27 and 5-28, respectively. Power levels do not include conversion losses for ac power.

5.4.1.5 Furnace Facility Control Systems

The purpose of the furnace facility control systems is to provide a fully automatic process control which gives close temperature tolerance and a uniform hot-zone over the temperature range of operation, using an efficient heat source.

General Description. - The general-purpose facilities will use catalog item furnaces with minor modifications for use in a space environment. The control system for the furnace will consist of a computer, sample manipulator, and environmental sensing devices and controls.

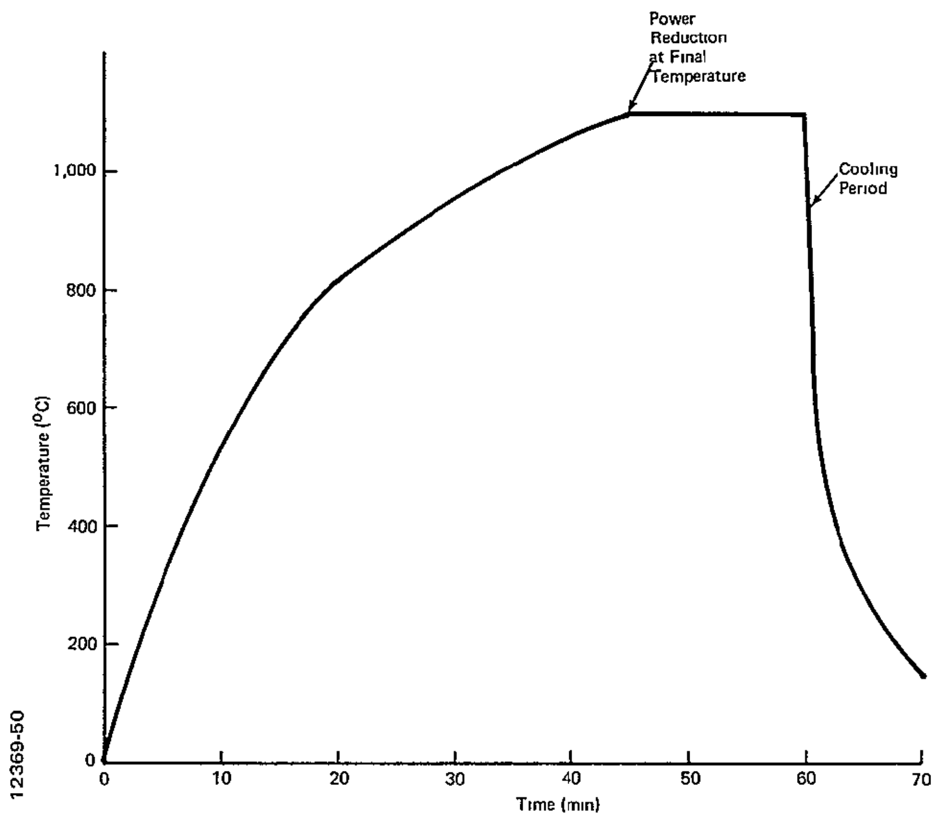


Figure 5-26 Typical Metallurgical Experiment Temperature Profile

The systems will be completely automatic, crew participation being required only to initiate the sequence at the control panel. The system will be fail-safe, pre-programmed correction sequences being provided for normal contingencies. A series of indicator lamps will be provided on the control panel to allow assessing experiment progress.

Computer. - The computer, when initiated by the crew, will control all functions by following a pre-programmed sequence. While following the sequence, the key parameters, such as temperature, will be continuously checked, and programmed corrective action will be taken if a deviation is observed. A real-time clock will provide timing information for correlation of the recorded events. All peripheral systems will interface with the computer, as shown in Figure 5-29. There are some functions which require real-time control, such as sample manipulation. These functions will be fully controlled by the computer by its waiting for the feedback of status signals or indications of parameters being within pre-determined limits. Thus, control will not be on a purely sequential basis.

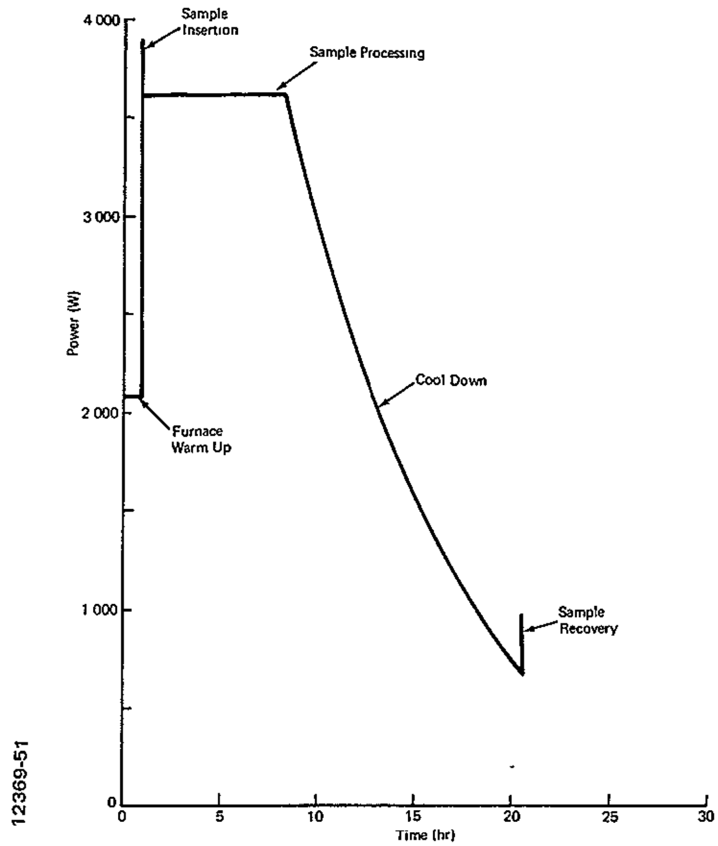


Figure 5-27 F-1 TiO_2 Power Profile

The computer will control the retrieval and storage of the data required for post-mission analyses of the experiments.

A control panel will be provided in the Spacelab to allow the crew to start and stop the experiments. Status lights will be provided to give warnings of impending problems and to give an indication of what stage in its sequence the experiment is. The latter indications are provided for the benefit of the crew in the event that a change in the mission profile is required during an experiment sequence.

A qualified computer which would furnish all the facilities needed for this experiment is the Rolm Corporation 1602 Ruggednova. The characteristics of this machine are identified in Table 5-6.

Computer Interface. - Computer interfaces with the system components are identified in Figure 5-30.

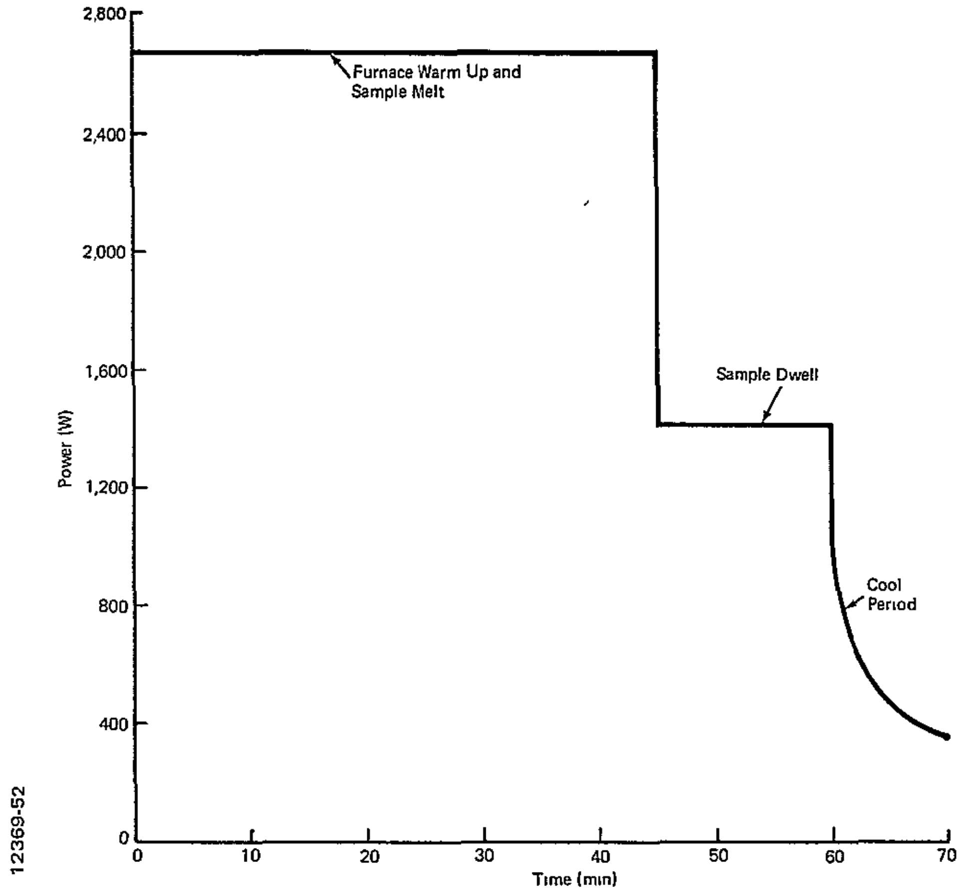


Figure 5-28 Metallurgical Experiment Typical Power Profile

The interface components will be standard items supplied by the computer manufacturer. The high-power output interfaces will, typically, be contact-closure types that drive latching relays for such items as power on/off. An alternative method of controlling these circuits could be through the use of latching solid state driver interface modules. The low-level signals for commands and lamp drivers will, typically, be of the contact-closure type.

The measurement devices which provide digital signals will be inputted to the computer via parallel data input lines. The analog signals will be multiplexed and converted by an analog-to-digital converter. Status signals will be processed as discrete digital inputs.

The characteristics of typical interface circuits are given in Tables 5-7 through 5-11.

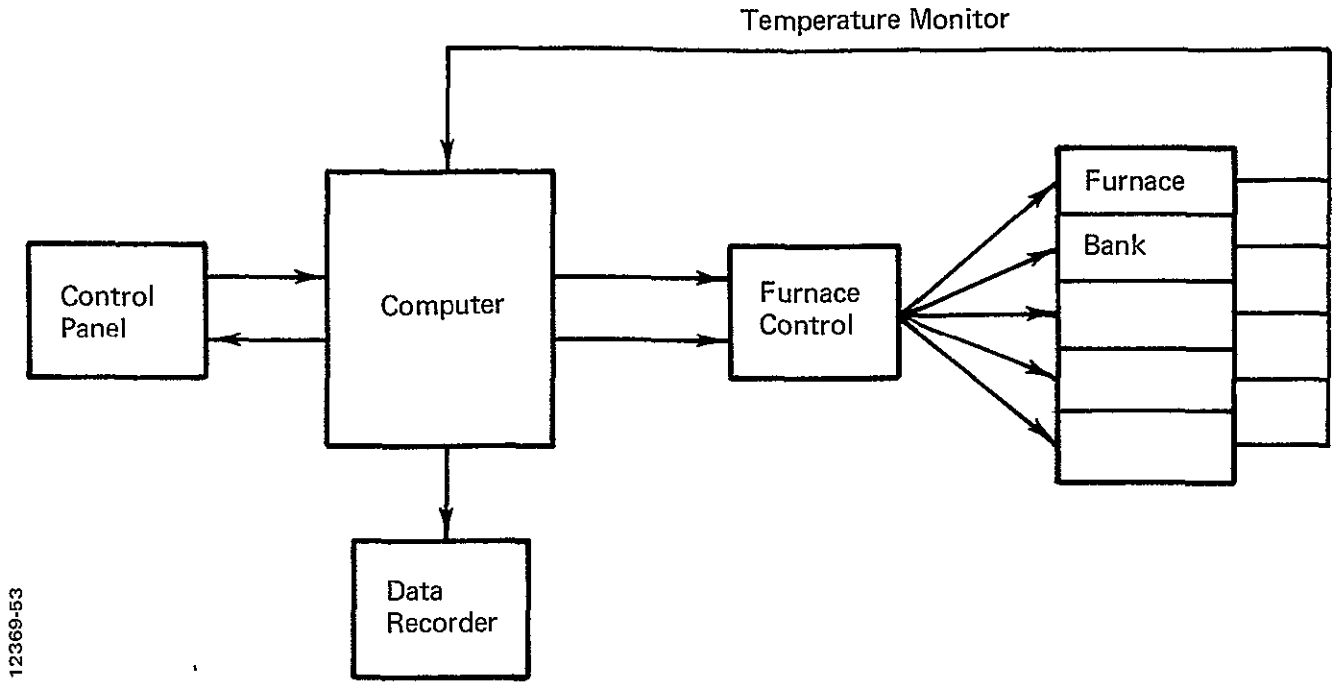


Figure 5-29 F-1 and F-2 Facility Block Diagram

Timing. - A real-time clock will be used for timing process events and for timing a recorded data for analysis purposes. Table 5-11 provides data on a typical clock.

Program Sequence. - The sequences of events to be performed during these experiments are discussed in the relevant sections. The sequences will be programmed into the computer and controlled in conjunction with the real-time clock.

The computer programs will consist of subroutines controlled by an executive supervisor program. The executive supervisor will control the main sequence of events, handle interrupts on a priority basis, and institute periodic scans of data outputs in conjunction with the real-time clock.

The subroutines will handle the repetitive functions of control loop monitoring, algorithm processing, data handling, data recording, sample handling, and status and alarm communication with the control panel.

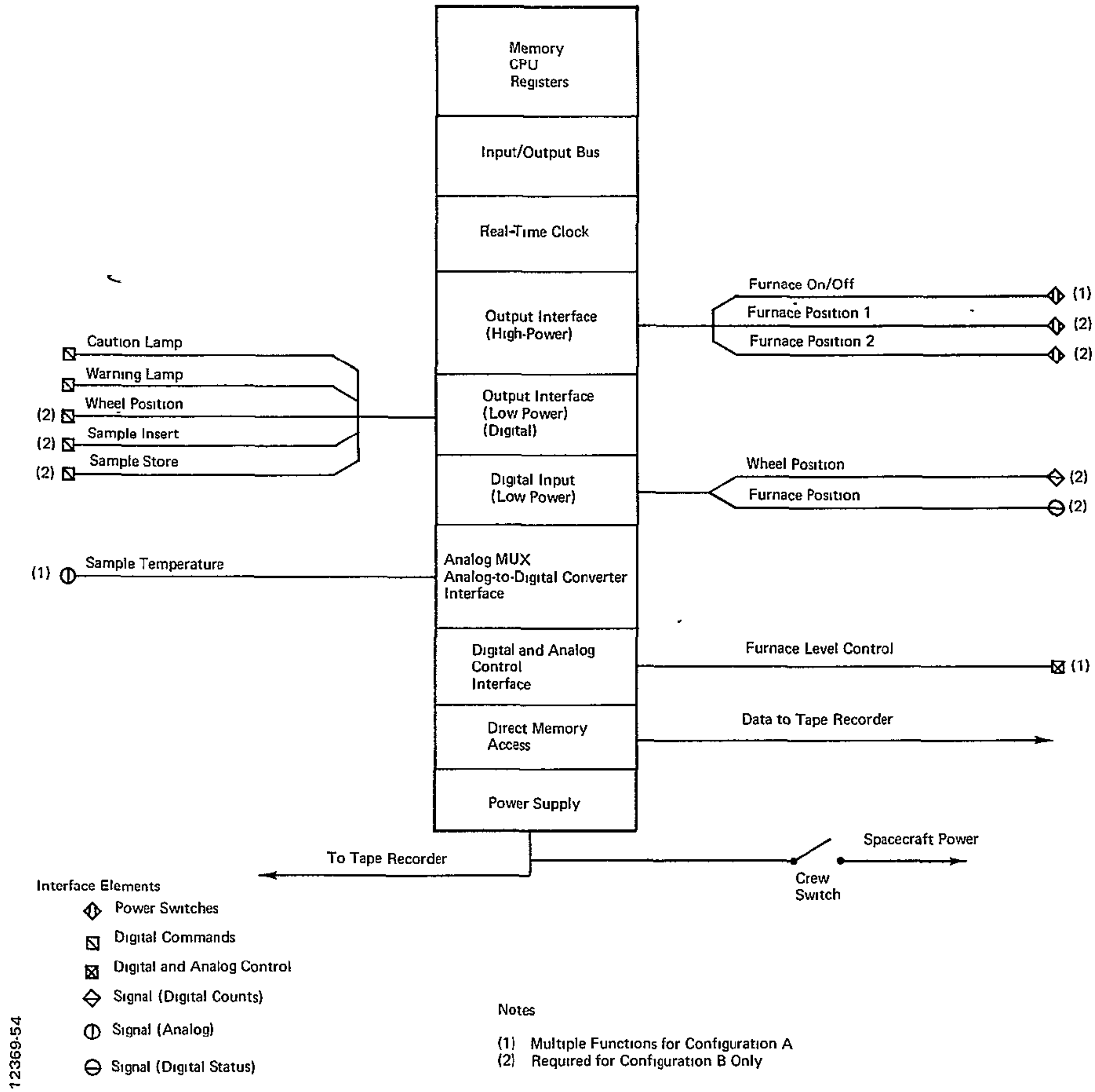


Figure 5-30 F-1 and F-2 Facility Computer Interface

Data Collection and Recording. - Data collection takes the forms of analog data signals, digital data signals, and digital status signals.

Data from all items are used for both control and permanent-record purposes.

The analog data will be multiplexed, converted in the analog-to-digital converter, and stored under computer program control. The digital data will be transferred in parallel form. The status signals will be transferred as discrete elements of a 16-bit word.

The control-loop subroutines will use the stored data to maintain the required status of the various systems, such as temperature and pressure status.

The data to be permanently recorded will be transferred to magnetic tape, using the direct-memory access port of the computer.

A typical recorder specification sheet is shown in Table 5-13.

Emergency Warning and Display. - A display panel will be provided in the Spacelab to give an indication of the experiment status and to give warning of any dangerous conditions. The panel will provide the crew with information which will aid them when making decisions about possible mission time-line changes or similar events which might be desirable during the time that an automatic experiment is in progress. When an experiment is in progress, it is desirable not to have appreciable acceleration until the molten material has been allowed to cool.

A series of lamps will be provided which will indicate the major points in the experiment sequence and will indicate when it is reasonable to perform a maneuver or terminate an experiment prematurely.

All normal contingencies will be controlled by the computer, to provide a fail-safe mode of operation or controlled shut-down while maintaining the integrity of the system.

Sample Handling Control. - The F-1A and F-2A configurations use two or more furnaces. The samples are inserted with their capsules and remain in position until retrieved after the mission. No manipulation of the samples is performed during the mission. The furnaces are controlled, either concurrently or in sequence, to perform the required process on each sample.

The approaches used in the F-1B and F-2B facility configuration concepts are those of using a single furnace with multiple samples which are inserted into the furnace and processed in sequence. The samples, in their capsules, are mounted to a wheel which can rotate about an axis through its center. The furnace is caused to move along its longitudinal axis by a motor-driven screw-shaft and guide tubes. The furnace is retained in its processing position (the position farthest from the samples) with the heating elements off. The sample wheel is indexed to a position where the axis of the sample required for processing is co-linear with the axis of the furnace. The furnace is then driven to a position where the sample is fully inserted, with the sample locking lugs located on the furnace, co-planar with the lugs on the sample storage wheel. The sample release solenoid is then activated to rotate the sample, thereby moving the sample locking lugs from the wheel locking position to the furnace locking position. The sample is now locked into the furnace, which is driven back to the processing position for the duration of the experiment.

When the process is complete, the sample is returned to the storage wheel and locked in position.

The sample retrieval procedure is then repeated for the remaining samples. A block diagram of the control system is given in Figure 5-31.

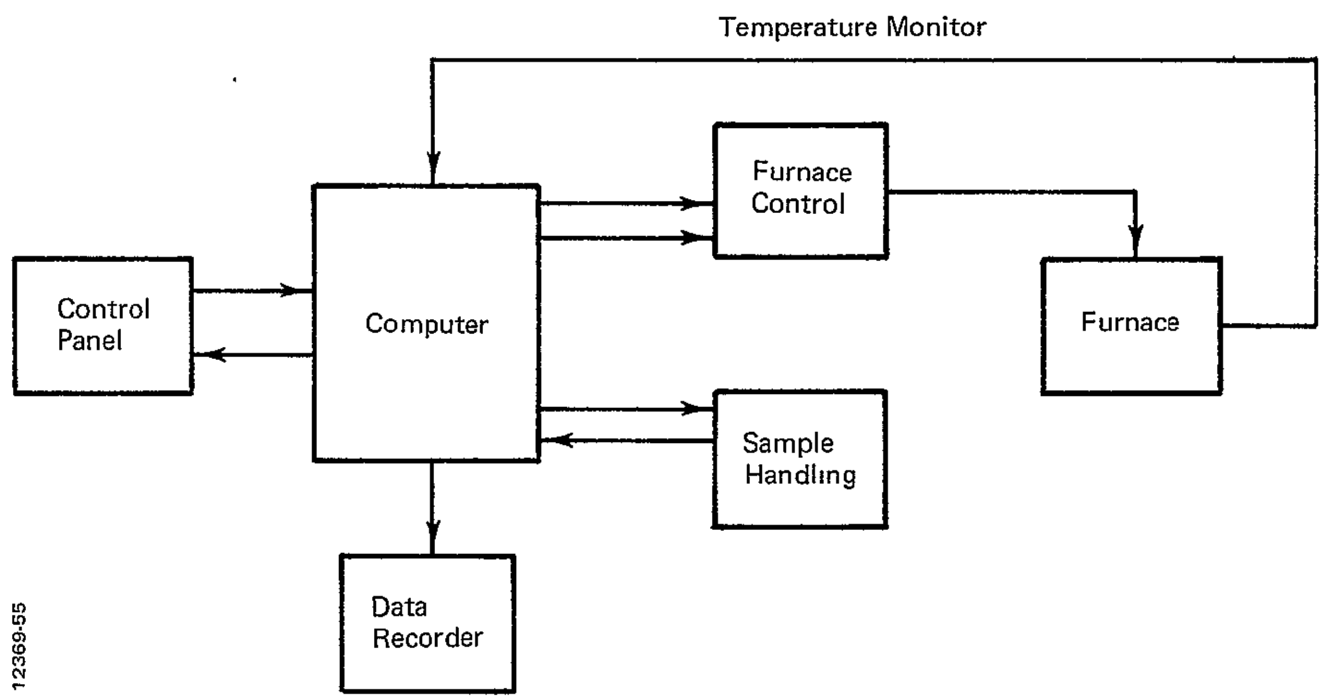


Figure 5-31 F-1 and F-2 Facility Configuration B Block Diagram

Sample Temperature Control. - In either facility concept, the sample capsules will be instrumented so that the experiment process can be accurately controlled.

The temperature data from the capsules will be periodically sampled, recorded on magnetic tape, and passed to a subroutine within the computer. The subroutine will solve an algorithm for the transfer function, which will result in a signal to the furnace controller directing it to modify the output of the furnace to maintain the correct sample temperature.

5.4.1.6 Design Approach to Extending Range

Two parameters may be considered in extending the range of the F-1 or F-2 facilities; processing temperature and sample size.

Processing Temperature Extension. - The temperature capability of the F-1 and F-2 facilities can be extended by replacing the Varian or Artcor furnace with any of a number of high-temperature furnaces which can be adapted for this application. Furnaces equipped with tungsten mesh or graphite heating elements can be expected to reach operating temperatures of up to 3,000°C (3,273°K) with impacts of greater size and weight for the furnace, insulation and liquid-coolant provisions, and greater power consumption required to reach the higher temperatures.

Design Approach to Extending Cartridge-Size Range. - If samples larger in diameter or length than the design limits of the facility must be processed, they can be accommodated by scaling the furnace to the larger capsule, with attendant weight and power penalties. The F-1 facility accommodates cartridges up to 10.7 cm (4.2 in.) in diameter and 20.3 cm (8 in.) long, which is expected to meet all anticipated requirements of the early missions. Table 5-24 shows the relative weight increases of the F-2B facility for typical increases in cartridge size.

Some volume impact is also incurred as the length and outside diameter of the furnace is expanded to accommodate larger cartridges.

Table 5-25 shows the relative power consumption impact of increasing sample size.

As the sample size is increased, the power absorbed by the specimen in processing becomes significant. For example, to melt equal parts by volume of lead and copper in the largest crucible described above requires about 12.5 megajoules. To melt the same material in one hour, 3.5 kW of furnace power (42% of the total facility power) would be absorbed by the sample during the melting period.

Table 5-24

F-2B Facility Weight Increases Required by Increasing Sample Size

Cartridge Dimension				Weight				Percent Increase in Facility Weight above Base
Diameter		Length		Six Cartridges		Furnace		
(in.)	(cm)	(in.)	(cm)	(lb)	(kg)	(lb)	(kg)	
0.8	2.0	10	25	11	5	41	19	Base
1.3	3.3	10	25	29	13	44	20	6
1.8	4.6	10	25	56	25	46	21	13
2.8	7.1	10	25	135	61	63	29	37
0.8	2.0	14	36	15	7	51	23	4
1.3	3.3	14	36	41	19	55	25	11
1.8	4.6	14	36	78	35	58	26	21
2.8	7.1	14	36	189	86	79	36	55
3.8	9.7	14	36	347	157	84	38	96
0.8	2.0	18	46	20	9	62	28	8
1.3	3.3	18	46	52	24	66	30	17
1.8	4.6	18	46	101	46	69	31	30
2.8	7.1	18	46	243	110	95	43	72
3.8	9.7	18	46	444	201	101	46	125

Table 5-25

F-2B Facility Power Increases Required by Increasing Sample Size

Cartridge Dimension				Peak Facility Power (kW)	Percent Increase above Baseline
Diameter		Length			
(in.)	(cm)	(in.)	(cm)		
0.8	2.0	10	25	2.7	Base
1.3	3.3	10	25	3.3	22
1.8	4.6	10	25	3.9	44
2.8	7.1	10	25	5.8	115
0.8	2.0	14	36	3.2	19
1.3	3.3	14	36	4.0	48
1.8	4.6	14	36	5.0	85
2.8	7.1	14	36	6.9	156
3.8	9.7	14	36	7.9	193
0.8	2.0	18	46	4.2	56
1.3	3.3	18	46	5.1	89
1.8	4.6	18	46	6.1	126
2.8	7.1	18	46	7.9	193
3.8	9.7	18	46	8.3	207

5.4.1.7 Integration Problems

The furnace facilities are relatively simple, and no specific integration problems are foreseen.

5.4.1.8 Manual Mode

The small size of the furnace facilities makes them uniquely adaptable to mounting within the pressurized cabin where control functions could be performed by the crew. Some specific applications include experiments requiring adaptive adjustment of temperature, precise control of vapor pressure, and exact positioning of the sample or accessories (e.g., insertion of seed crystal). Special attention must be given to thermal control in order to preclude burn hazards for the crew.

5.4.1.9 Data Management

Data management for the F-1 and F-2 facilities is similar to that described previously for the L-1 facility in Paragraph 5.2.9 with the exception that no visual recording is done, since visual recording is effectively precluded by the opaque walls of the capsule cartridge.

5.4.1.10 Development Requirements

Core equipment development has been described in Paragraph 5.2.10 and furnace development has been described in Paragraph 5.3.10. Development of a unique sample handling system is also required for the F-1 and F-2 facilities, as described below.

Three techniques may be employed for sample handling, depending on payload configuration:

- Single furnace - single sample.
- Multiple furnace - single sample.
- Single furnace - sequential processing.

For the first two techniques, each furnace is equipped with its own sealed capsule prior to launch. The capsule remains in the furnace throughout the entire process and is recovered from the furnace after the spacecraft has landed. Development of the capsule is the responsibility of the principal investigator associated with the specific experiment.

For the third technique, a sample handling system for sequential processing of several specimens is required. One possible configuration, shown in Figure 5-23, features an indexing storage wheel on which the specimen cartridges are stored, each attached to an identical furnace end-cap. In operation, the furnace is traversed to enclose the sample and the furnace captures the end-cap and moves away for processing. After the process is completed, the furnace returns the end-cap, with the cartridge attached, to the storage wheel. The wheel indexes to the next detent, and the sequence is repeated.

As above, development of the cartridge is the responsibility of the principal investigator. However, the sample storage wheel and the mechanisms for indexing the wheel, traversing the furnace, and latching the end-cap also require development and testing. Control procedures, associated position and status monitors, and software must also be developed.

5.4.1.11 Test Requirements

Qualification and acceptance test requirements for the F-1 and F-2 facilities are comparable to those described for the L-1 facility in Paragraph 5.2.11 with the exception that there are no optical, vacuum, or gas components in the furnace facility.

5.4.2 F-3 Furnace Facilities; Zone Refining Facilities

5.4.2.1 Design Description

The F-3 facility is designed to accommodate experiments requiring transit of a molten zone through a rod of sample material, e.g., zone refining or directional solidification. Two configurations, designated F-3A and F-3B, have been investigated. They are briefly described in the following paragraphs.

F-3A Facility. - In the F-3A facility, the sample rod is held in a fixed position, and the furnace is traversed along the rod to provide a moving molten zone. Motion is derived from an electrically-driven ball-screw mechanism. The advantage of this arrangement is the absence of mechanism-induced vibration in the molten sample.

Bellows seals isolate the mechanism shafts from the processing environments, which may be, for various experiments, vacuum, inert gas, or other gases. The entire facility is enclosed in a cylindrical chamber equipped, as required, with a vent tube, an ion pump, and a vacuum gage or with a gas supply, a pressure gage, and controls. Provisions are also included for cooling fluids for furnace temperature control.

The electronic control system is similar to that described previously for the F-1 and F-2 facilities in Paragraph 5.4.5. Figure 5-32 shows the general layout of the F-3A facility and Figure 5-33 shows an artist's concept of the F-3A facility

F-3B Facility. - In the F-3B facility, the furnace remains stationary and the sample rod, supported by a tripod holder, is traversed through the furnace by a mechanism similar to that used in the F-3A facility. The furnace assembly consists of two resistance-tube furnaces, between which is mounted a ring heater. The ring heater is equipped with reflector barriers to concentrate the energy in a narrow molten zone.

Bellows seals isolate the traverse mechanism from the processing environment. The entire facility is enclosed in a cylindrical chamber; equipped with a vent valve and an ion pump and vacuum gage or with a gas supply, pressure gage, and controls; as required for specific experiments.

Electronic equipment is comparable to that required for the F-3A facility. Figure 5-34 shows the general layout of the F-3B facility.

5.4.2.2 System Interfaces

The F-3 facilities have mechanical, thermal, and electrical interfaces with the spacecraft.

Mechanical Interfaces. - The mechanical interface must support the weight of the facility in the 1-g environment and must sustain the loads of launch and landing. The design of the mechanical interface must also limit heat transfer between the F-3 facility and the spacecraft. Figure 5-35 shows a typical F-3B facility structural design, including the potential location of "hard-points".

Thermal Interfaces. - Both F-3 facilities will require liquid cooling. Facility F-3A requires liquid cooling to maintain mirror integrity and proper focus of the radiant energy. Both facilities use liquid cooling to dissipate thermal energy without distorting spacecraft structure. Requirements for the F-3 facilities are 0.1 ℓ per sec (2 gal per min) at an inlet temperature of 38°C (311°K) and with an anticipated pressure drop of 6,895 N/m^2 (1 psi).

Electrical Interfaces. - The F-3 facilities derive all of their electrical power from external sources. Either of the two configurations can be operated on the following allocations (excluding conversion losses for ac):

DC; 28 V: 0.4 kW.
AC; 115 V, single-phase, 400 Hz, 3 kW.

Connector specifications remain to be developed.

5.4.2.3 Weight Estimates

The weight estimates of the two F-3 facilities are tabulated, for comparison, in Table 5-26.

Table 5-26

Estimated Weight of F-3 Facilities

Component	Weight			
	F-3A		F-3B	
	(lb)	(kg)	(lb)	(kg)
Structure	68	30.8	220	99.8
Furnace(s)	5	2.3	100	45.4
Traverse mechanism	30	13.6	130	59.0
Transformers	--		80	36.3
Furnace controller	47	21.3	47	21.3
Vacuum/gas system	115	52.2	115	52.2
Process controller and electronics	63	28.6	63	28.6
Pyrometer	25	11.3	25	11.3
Tape recorder	17	7.7	17	7.7
Cabling	9	4.1	13	5.9
Cold plates, plumbing, and coolant	87	39.5	84	38.1
Total	466	211.4	894	405.6

5.4.2.4 Performance

The two F-3 facilities are designed to process two widely different ranges of experiments.

The F-3A facility is designed to process rod-shaped specimens, in vacuum or gas environment, requiring temperatures up to about 1,000°C. The facility can handle rods up to 1 cm (0.4 in.) in diameter that require up to 3 kW for processing. Because an imaging furnace is used as the heat source, the thermal absorptivity of the material should be high relative to its thermal conductivity.

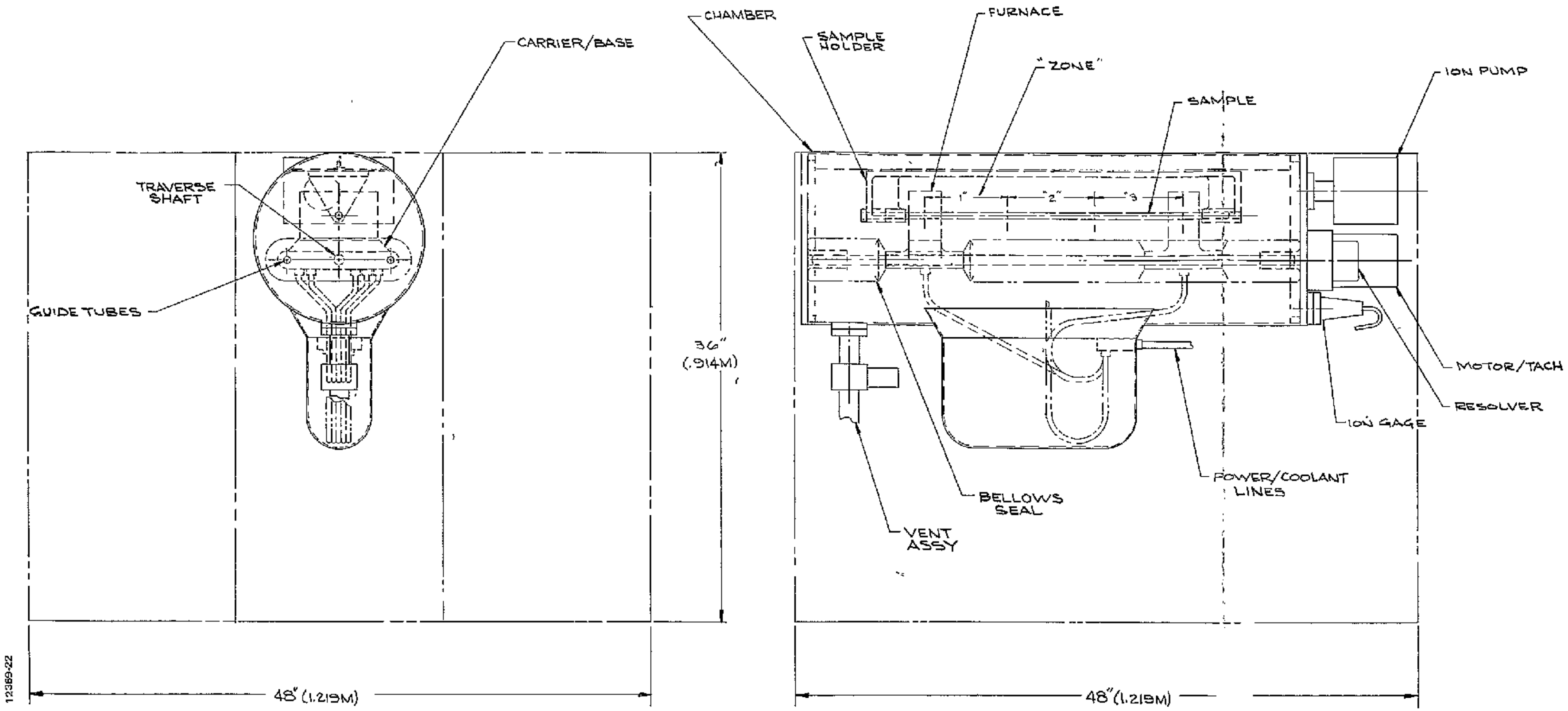


Figure 5-32 F-3A Facility Zone Refining

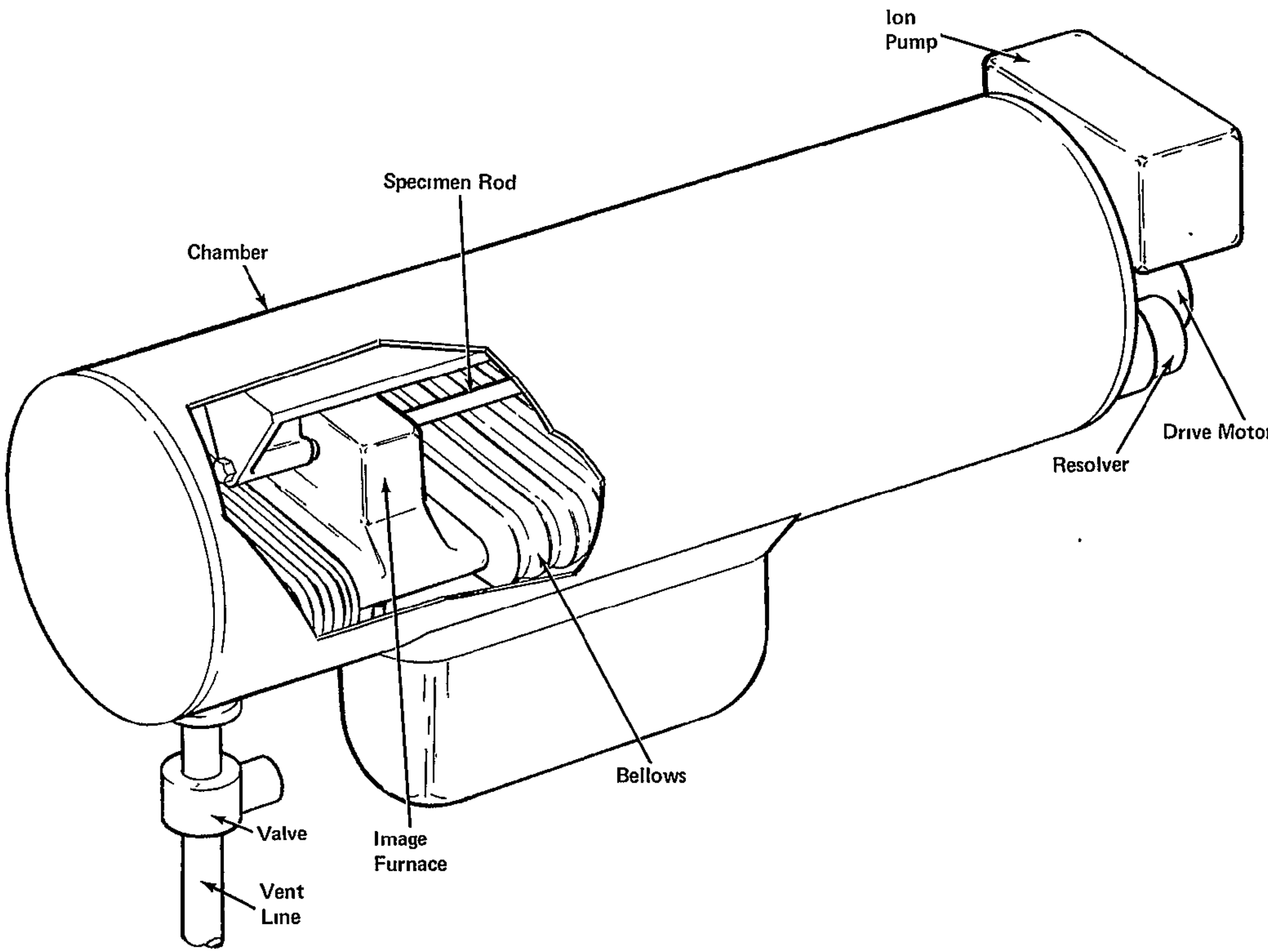


Figure 5-33 F-3A Facility Zone Refining

The F-3B facility is designed to process rod-shaped specimens in a vacuum or gás environment at temperatures up to 1,800°C. The facility can handle rods up to 2 cm (0.8 in.) in diameter that require power levels up to 3 kW.

Power Analysis. - The furnaces employed in the two versions of the F-3 facility are vastly different. To accomplish zone refining and directional solidification, the F-3A facility uses a lamp furnace which is traversed along the rod-shaped specimen. The F-3B facility uses resistance heaters to control zone temperatures as the rod is traversed through the heaters.

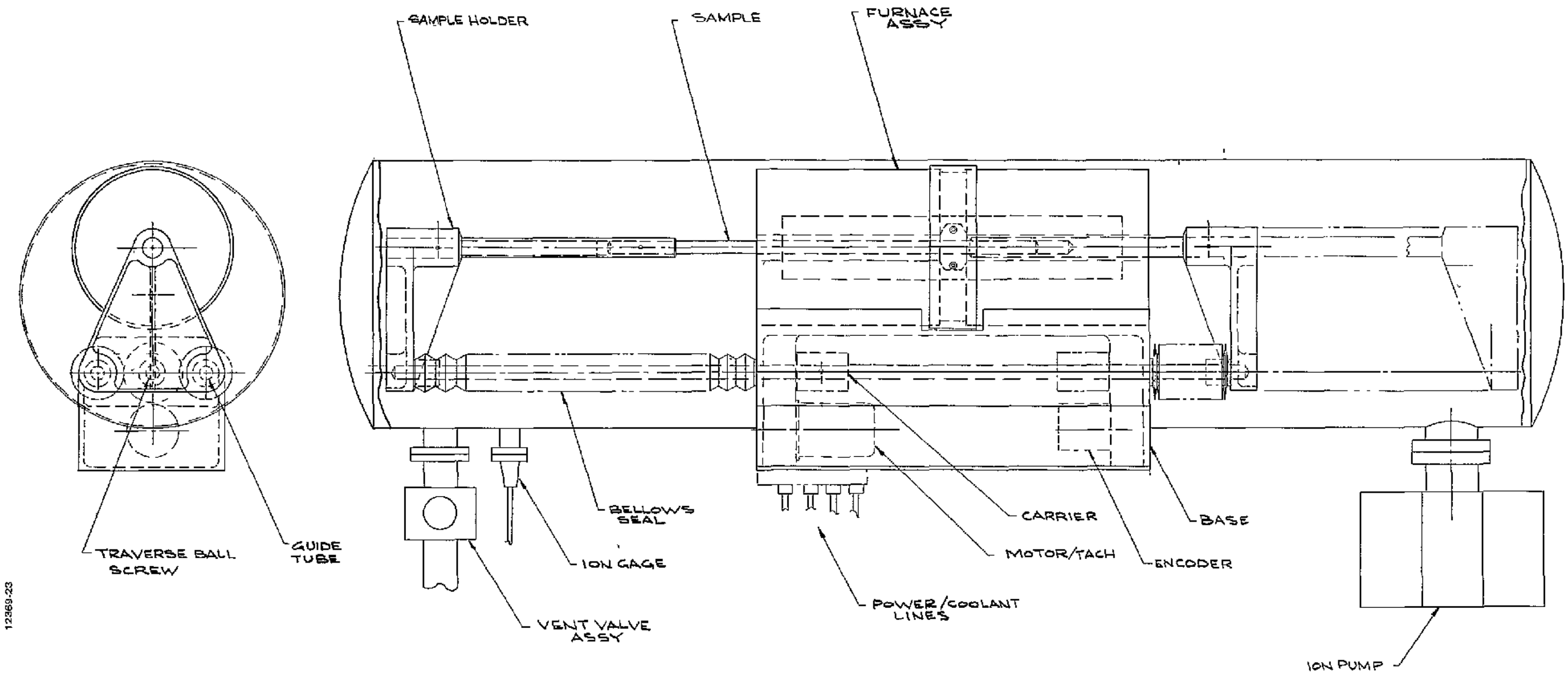
Imaging Furnace (F-3A). - The F-3A facility features a three-zone furnace (Research Inc. Model ZH3A or equivalent), heated by tungsten lamps. For a typical material (a copper-aluminum eutectic rod 1-cm in diameter with a melting point of 540°C), the furnace requires a power input of about 1.7 kW. An additional 300 W is required for the blower and 40 W for the furnace controller. Allowing for conversion losses, total power required for the furnace is about 2.8 kW. After melt is achieved, the power is reduced to maintain the temperature. This power averages 2.4 kW.

Resistance Furnace (F-3B). - The F-3B facility makes use of two resistance furnaces (e.g., modified Varian Model Marshall 1521 or equivalent) to bring the specimen rod up to temperature. A special ring heater, located axially between the two furnaces, accommodates the molten zone of the sample.

For a typical material (a silicon rod with a diameter of 2 cm and a melting point of 1,410°C), the heaters require a total peak power of about 2.3 kW and a run power of about 1.4 kW. Transformers for the furnaces dissipate about 90 W, and separate controllers for the three zone heaters also require about 50 W. Allowing for conversion losses, the peak power totals about 3 kW.

Core Equipment. - The core equipment for the F-3 facility is comparable to that employed in the levitation facilities described previously. It includes the sample (or furnace) transport system, the gas or vacuum system, the pyrometer, and the process controller and its interface electronics. The core equipment run power requirement is estimated at about 0.86 kW. Allowing for conversion losses, about 1 kW is required for the core equipment.

Power and Energy Summary. - The power and energy requirement for the typical materials specified previously are tabulated in Table 5-27 for the two F-3 configurations. The power calculations are based on a 1-cm CuAl rod for the F-3A facility and a 2-cm Si rod for the F-3B facility. Power levels include conversion losses.



FOLDOUT FRAME 1

FOLDOUT FRAME 2

Figure 5-34 F-3B Facility Zone Refining

FOLDOUT FRAME 1

FOLDOUT FRAME 2

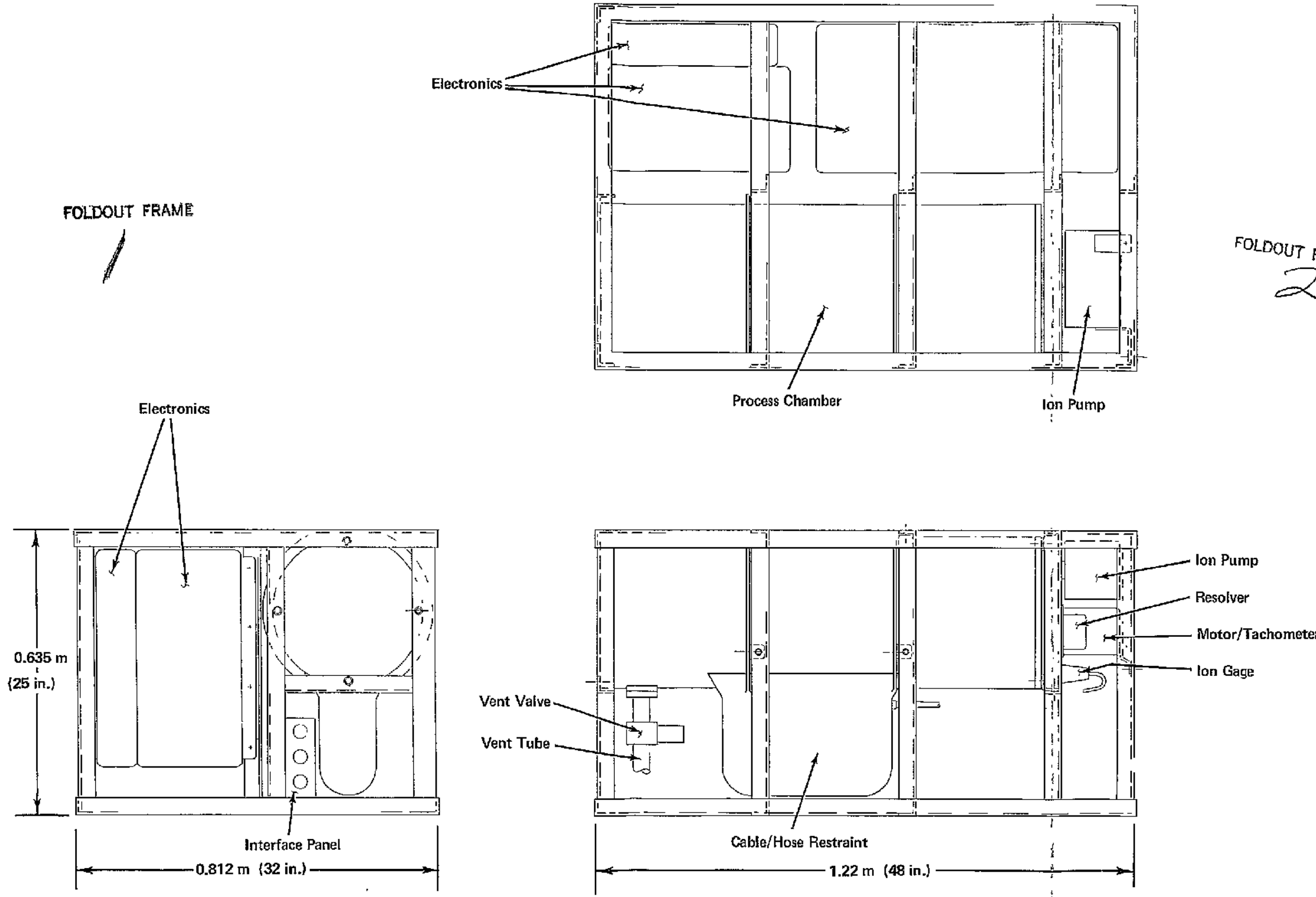


Figure 5-35 Typical F-3B Facility Structural Design

Table 5-27

F-3 Facility Power and Energy Summary

Component	Peak Power (W)		Energy per Sequence (Whr)	
	F-3A	F-3B	F-3A	F-3B
Furnace	2, 297	3, 042	15, 937	43, 748
Blower	400		3, 380	
Transformers		91		2, 560
Furnace controllers	53	67	448	972
Sample (furnace) transport	320	320	2, 714	7, 616
Gas/vacuum system	264	264	2, 240	6, 415
Process controller and electronics	307	307	2, 604	7, 452
Tape recorder	17	17	144	413
Pyrometer	19	19	215	485
Total	3, 677	4, 127	27, 682	69, 661
Average power: F-3A = 3, 263 W. F-3B = 2, 867 W.				

Time Estimate. - Except for the furnace warm-up period, the sequence times of the two F-3 facilities are comparable. Most of the time is taken up in the process of directional solidification or zone refining, and the total time depends on how many passes over the specimen length are required to achieve the desired results. For purposes of this study, we have assumed a single pass for directional solidification and three passes for the zone refining experiment.

The time estimate for the directional solidification experiment is about 8.5 hr and, for the three-pass zone refining, about 24 hr, assuming a traverse rate of 5 cm per hr (2 in. per hour) for both experiments. A 52-cm (20-in.) long specimen is assumed for both experiments.

Temperature Profile. - Typical temperature profiles for the F-3A and F-3B facilities are shown in Figures 5-36 and 5-37, respectively. Passive cooling of samples at the end of each process is not shown.

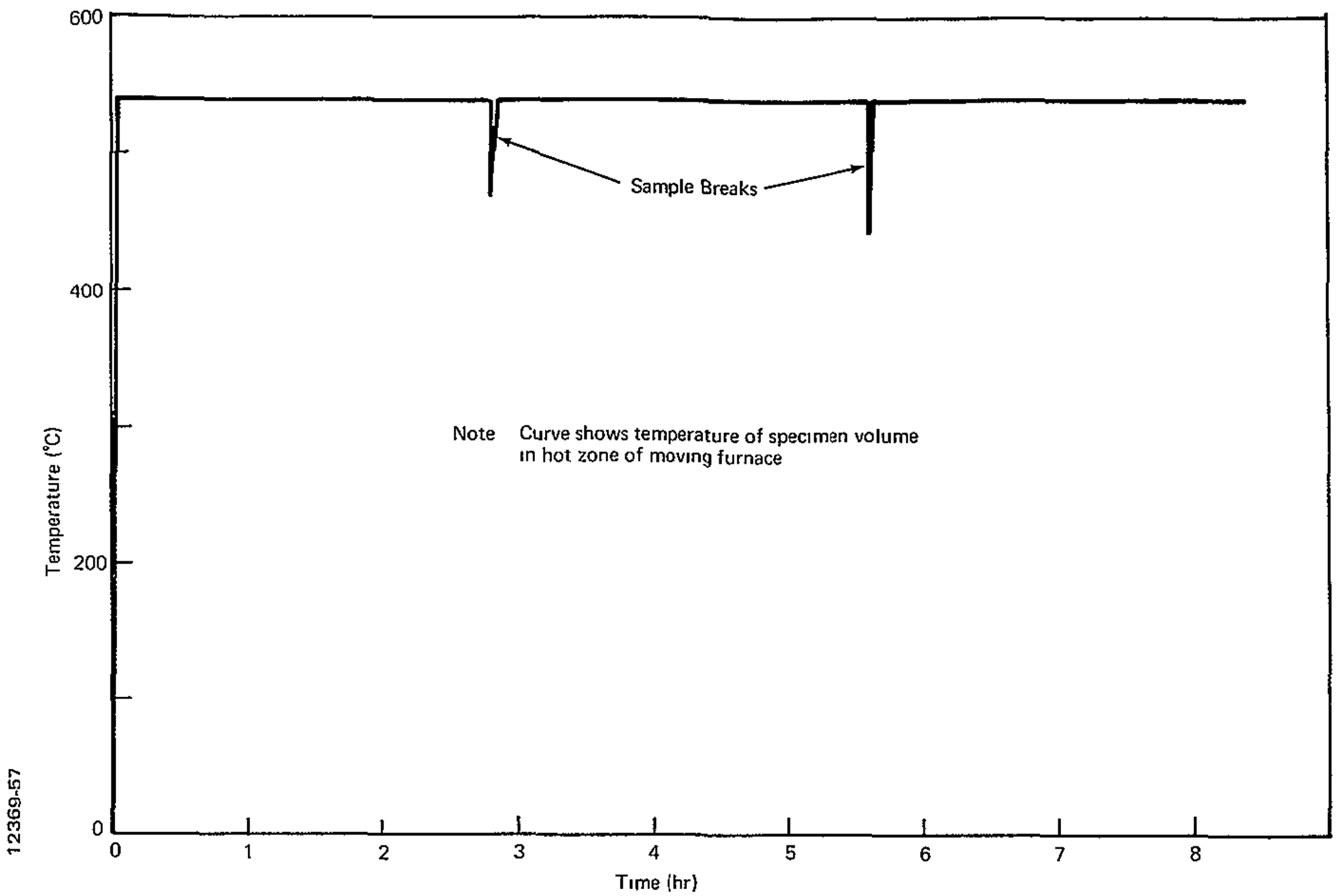


Figure 5-36 Typical F-3A Facility Temperature Profile

In Figure 5-36, an assumption is made that the rod-shaped specimen is divided into three processing zones. The furnace is cut off when it reaches the end of the first zone. At that time, the traverse mechanism is speeded up from its normal rate of 5 cm per hour to 2 cm per minute. At the end of 1 minute, the normal speed is resumed and the furnace is turned on. In the meantime, the original molten zone has solidified and the furnace begins a new melt from a fairly-high base-temperature resulting from the gradient in the rod.

In Figure 5-37, the assumption is again made that the rod-shaped specimen is divided into three zones, each sequentially-refined, with a 1-cm buffer between zones. The rod is traversed through the furnace at a rate of 5 cm per hour. When the end of the first zone is reached, the hot-zone heater is cut off, allowing the molten rod to solidify. The traverse mechanism is then speeded up to 4 cm per minute. At the end of 1 minute, the mechanism is slowed, the hot-zone heater is re-energized, and melting begins at the start of the new zone. At the end of the third zone, after solidification, the mechanism is reversed, and the first

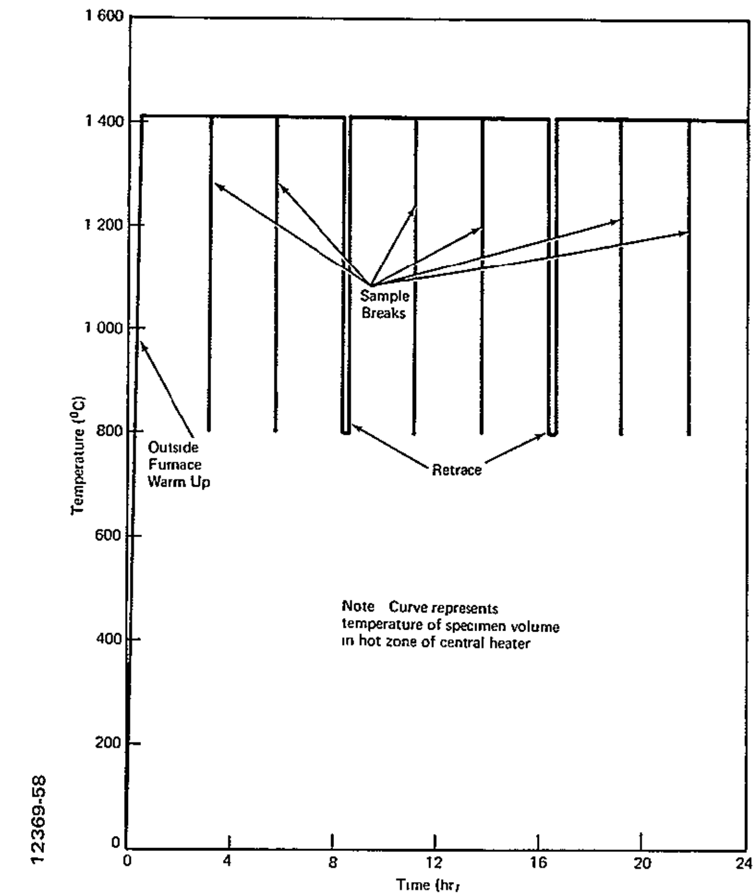


Figure 5-37 Typical F-3B Facility Temperature Profile

zone is again positioned for refining. After three passes of all three zones through the furnace, the facility is shut down. Because of the fairly-high thermal conductivity of the specimen rod, the temperature of the zone of interest drops rapidly to that of the outside furnaces (typically about 800 °C) when the central heater is de-energized.

Power Profile. - Actual power consumption for the experiments described above is plotted in Figures 5-38 and 5-39 for the F-3A and F-3B configurations, respectively. The power does not include conversion losses for alternating current.

Figure 5-38 illustrates how conduction losses diminish as the furnace moves away from the end of the rod and increase as the furnace approaches the far end. While the furnace is traversing the buffer zone between samples, the heater power is cut off, leaving only the power drain of the core equipment.

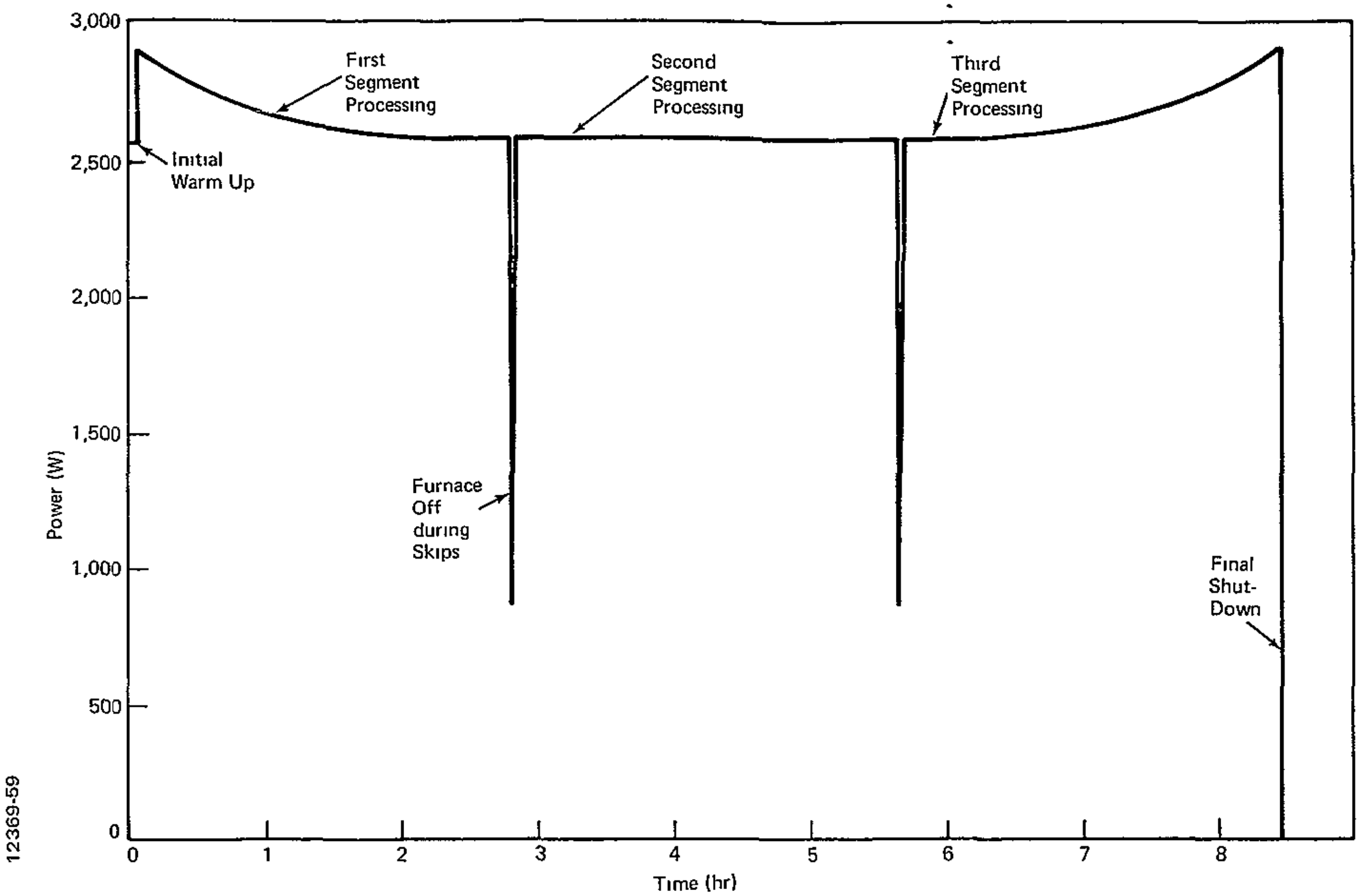


Figure 5-38 Typical F-3A Facility Power Profile

Figure 5-39 illustrates a typical zone refining experiment (silicon), featuring three processing passes of a rod, divided into three specimen segments, through the refining furnace. The profile shows the power requirement dropping off as the molten zone progresses away from the end of the sample and increasing again as it approaches the other end.

The central heater is cut off for 2 minutes after processing the first and second segments and is cut off again for 6 minutes after processing the third to allow solidification and repositioning of the rod for the next phase.

5.4.2.5 Control System

Sample Handling Control. - The requirements of the zone refining facility are to provide a high temperature-gradient, a narrow molten-zone, and a vibrationless movement of the hot-zone along the sample.

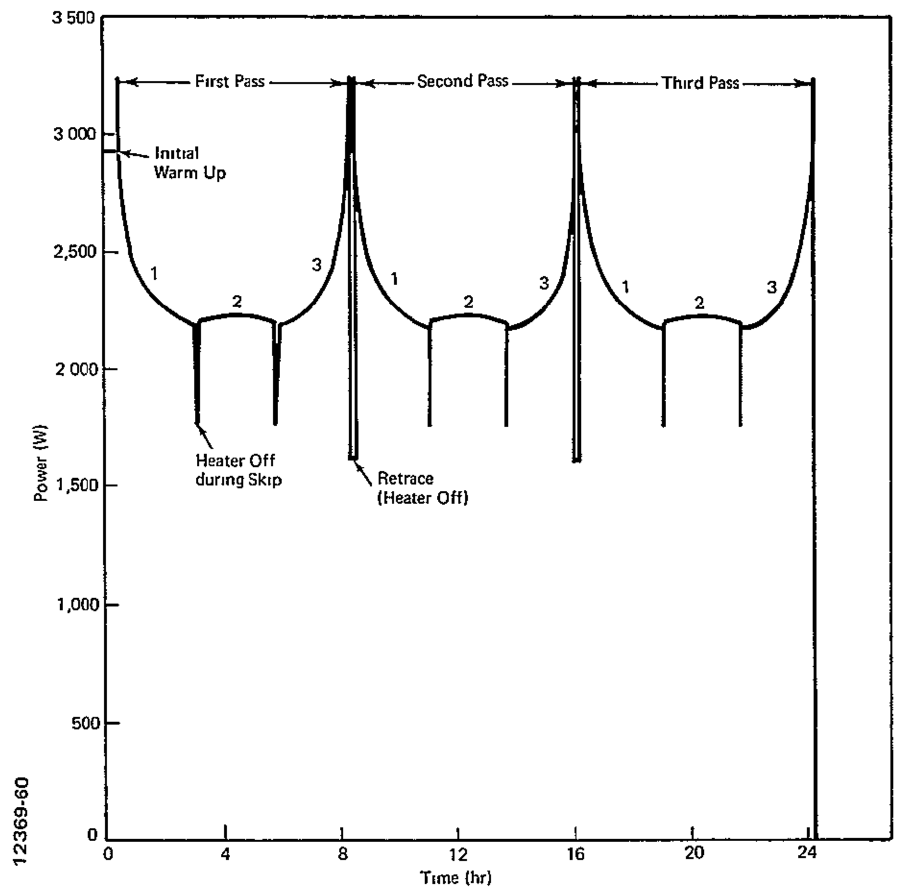


Figure 5-39 Typical F-3B Facility Power Profile

One facility which meets the requirements very efficiently is not acceptable for highly-transparent or very-reflective materials because its method of operation depends on absorption of the output from a lamp furnace. In these instances an alternative method, using resistance furnaces and a ring heater, is proposed.

<u>Configuration F-3A</u>. - In this configuration, the sample is held by end-supports which provide for thermal expansion and contraction. A small light-weight three-zone lamp furnace surrounds a portion of the sample. A motorized ball-screw drive positions the furnace anywhere along the sample and, since there is no contact with the sample, no mechanical vibration is transmitted to it. The complete system is enclosed in a sealed vessel so that either vacuum or gaseous conditions can be maintained. Figure 5-33 shows the configuration.

In operation, the rod is brought up to melting temperature at the center zone of the lamp furnace, and the sample rod is traversed by the zone in accordance with the preprogrammed sequence. Continuously throughout the process, the computer monitors the zone temperature, furnace position, and speed. The traversing program followed by the furnace will vary, depending on the objectives of the experiment. Three main programs are possible; namely:

- One full-length pass, repeated several times.
- Several short consecutive passes, separated by "isolation" zones over the length of the rod, which are repeated several times.
- Several short passes over the same area, followed by similar processing of other areas which are separated by isolation zones along the total rod length.

Configuration F-3B. - This configuration uses fixed furnaces and moves the rod sample through them in accordance with the planned program. The concept is depicted in the block diagram of Figure 5-40.

The molten zone is formed at the center of the furnace assembly by the ring heater. The zone is positioned along the length of the sample by a motor-driven ball-screw drive, which moves the sample through the furnace assembly. All other features are similar to the configuration for facility F-3A. A typical event sequence, applicable to either configuration is given in Table 5-28.

Sample Temperature Control. - The method for controlling the temperature of the sample at the molten zone will be similar for both configurations. An optical pyrometer, described in Paragraph 5.2.5, will view the sample via a light-pipe. The output of the pyrometer will be applied to the computer, which will record the data and also process them to provide the necessary feedback to the furnace controller so as to maintain the desired temperature profile. The computer will also control the gas or vacuum environment throughout the process period.

Computer Interfaces. - The interfaces of the F-3 facility control system computer with other facility elements are similar to those described previously for other facilities. Figure 5-41 illustrates these interfaces.

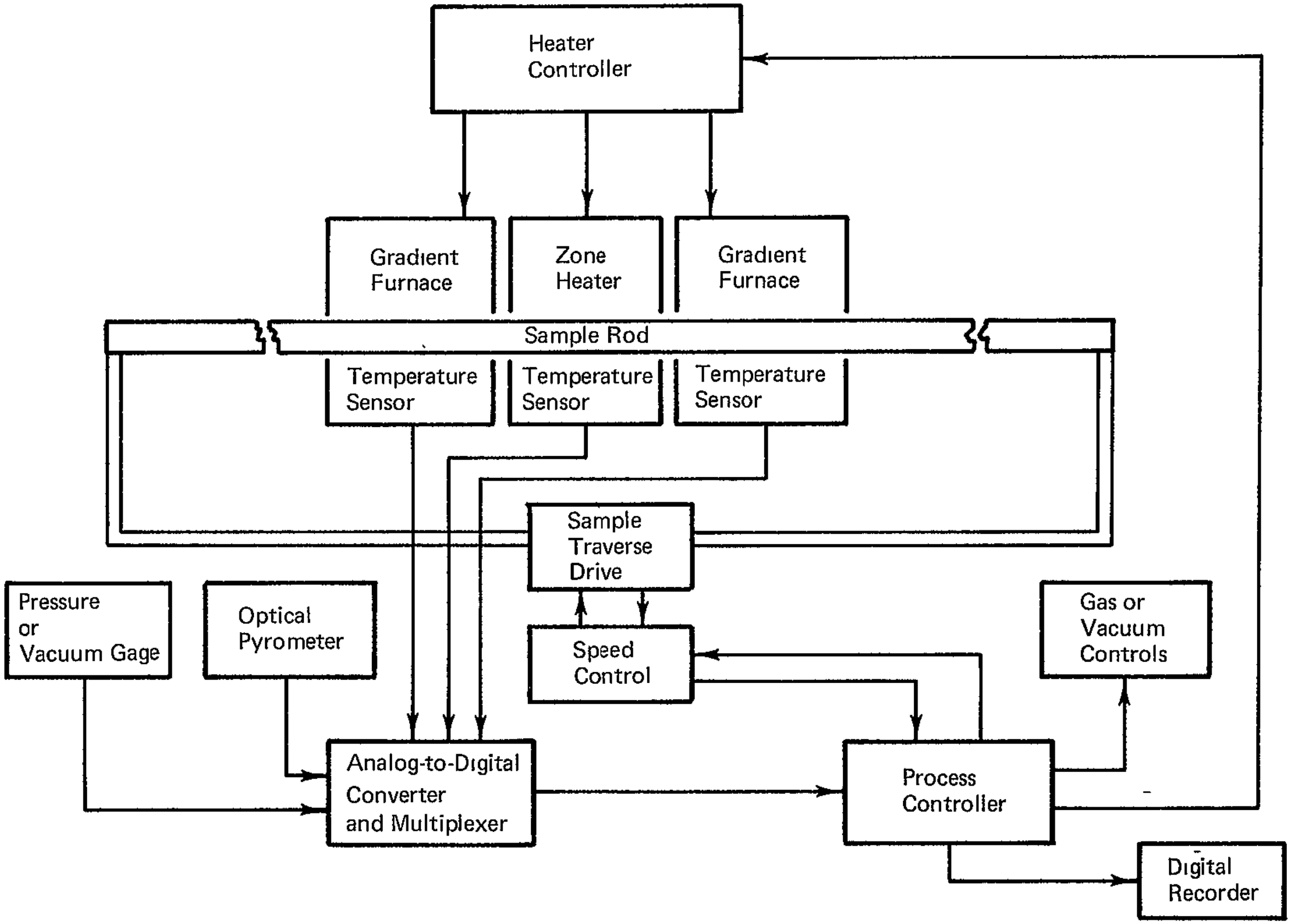


Figure 5-40 F-3B Zone Refining Facility Block Diagram

Table 5-28

F-3 Facility Typical Event Sequence

1. Turn system power on.
2. Check functioning system status automatically.
3. Initiate chamber evacuation or pressurization as required for process.
4. Verify that required environment is attained.
5. Verify status of sample position relative to furnace.
6. Initiate heating program.
7. Verify correct operation of pyrometer and furnace controls.
8. Maintain controls of environmental conditions.
9. Verify correct status of molten zone.
10. Initiate sample traverse program.
11. Maintain:
    - Sample temperature gradients and temperature levels at melt zone.
    - Chamber environments.
    - Traverse position and speed.
    - Data recording.
    - Control panel status indicator.
12. Initiate cooling period and re-position sample (or furnace).
13. Verify end of cooling period(s) and resume heating program.
14. Initiate shut-down of data and environmental systems.
15. Indicate termination of process at control panel.

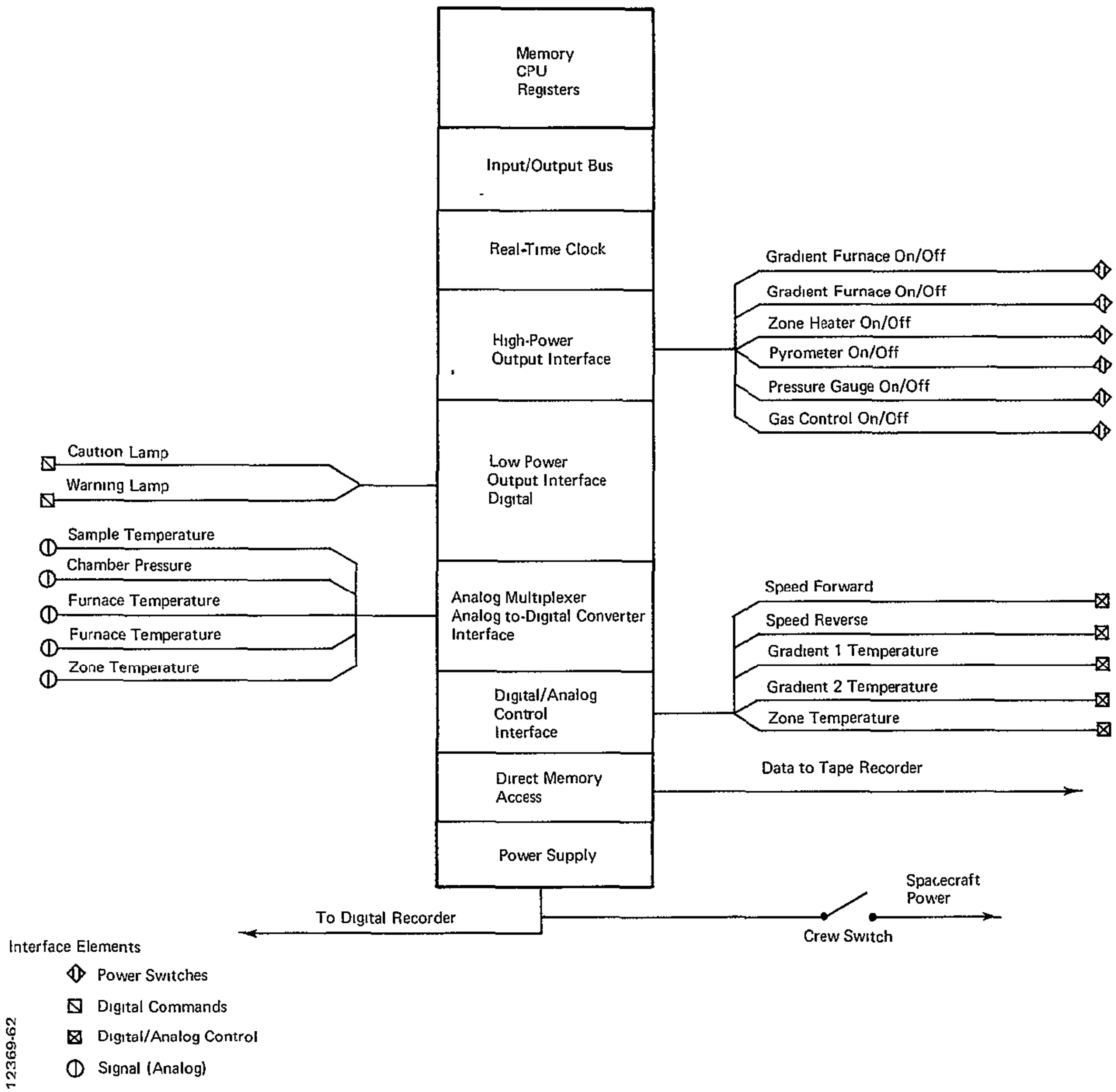


Figure 5-41 F-3 Facility Computer Interfaces

5.4.2.6 Design Approach to Extending Range

F-3A Facility. - Three constraints of the present facility that can be somewhat relaxed by design changes are:

- Temperature limit.
- Specimen-size limit.
- Material absorptivity/conductivity ratio limit.

Temperature Extension. - The temperature limit can be extended by custom-designing the lamp furnace to produce the desired temperature. The range can be extended to about 2,400 °C by using larger lamps with special focussing reflectors to concentrate the radiant energy on the sample. Depending on the specific requirements, this design change could add up to 9.1 kg (20 lb) to the furnace weight, necessitating an upgrading of the transport mechanism and supporting structure, for a total weight increase of about 13.6 kg (30 lb). Additional power will also be required.

Size Extension. - The present design can be adapted to accommodate larger specimens up to about 2 cm (0.8 in.) in diameter. Above this size, a major design modification, with impacts as noted above, will be required.

Since the thermal conduction losses increase with the square of the diameter, the larger samples will require a greater power and energy allocation.

Material Characteristics. - Effective zone-refining depends on a high temperature-gradient in the region near the zone interface. This implies a large flow of thermal energy through the sample. This flow must be balanced by input of energy absorbed by the zone.

Materials with low coefficients of absorptivity can be processed in the F-3A facility by brute-forcing the specimen, i.e., by increasing the radiated power-level by design change, if necessary, until the required input power is attained.

F-3B Facility. - The F-3B facility is presently constrained by temperature limit and sample size.

Temperature Extension. - By a design change of the two "outside" furnaces and the central heater, the F-3B facility can be adapted to handle samples requiring temperatures higher than 1,800 °C (2,073 °K) for processing. Changing the heater configuration of these furnaces to tungsten mesh, graphite, or zirconia (per the Artcor design) can extend the temperature range to higher levels (up to 3,000 °C).

While these design changes add little to the weight or volume of the facility, increasing the temperature results in significantly higher power-consumption.

Sample Size Extension. - Extending the sample size can be accomplished by expanding the inside diameter of the furnaces and central heater. This, of course, impacts the furnace outside-diameter and the weight and power consumption of the facility.

5.4.2.7 Integration Problems

The F-3 facility is fairly simple in design, and no specific integration problems are foreseen.

5.4.2.8 Manual Mode

The small size, weight, and power-demand of the F-3 facility makes it a desirable candidate for installation inside the pressurized cabin. This is particularly true for planned research on materials for which simple in-flight tests can be devised and test results are put to immediate use by revising processing programs.

The degree of crew participation in process control can be quite flexible. It is recommended that the traverse rate and zone temperature remain under computer control in any circumstances, but provision can be easily made for crew adjustment of a number of parameters (sample length, distance between skips, number of passes, vacuum level or gas pressure, gas content, and other process parameters).

5.4.2.9 Data Management

Data management requirements for the F-3 facility will be essentially the same as those for the other furnace facilities; namely, recording and processing of data on magnetic tape. No visual recording is planned.

5.4.2.10 Development Requirements

The F-3 facilities are based on well-established concepts. However, the following items will require some development effort:

- Sample (furnace) transport system.
- Control programs (software) for sample transport, temperature, and pressure control.
- Interface electronics.

5.4.2.11 Test Requirements

The entire F-3 facility must be flight-qualified and must undergo extensive acceptance testing before integration with the spacecraft. Requirements are comparable to those of the L-1 facility described in Paragraph 5.2.11.

5.5 ELECTROPHORESIS EXPERIMENT (E-1)

5.5.1 Requirements

The electrophoresis experiment preliminary design described here is based on the prototype development work on a continuous-flow electrophoresis apparatus conducted for the Skylab Program. The system is designed to accept three separate samples and collect and maintain the fractions produced by the electrophoresis operation. The cell electric field-strength is maintained at a constant voltage (5 to 50 V per cm). The buffer temperature in the cell is to be controlled within the range of 15 to 25°C (288 to 298°K). There is to be one sample inlet port located to one side of the separation cell so as to allow maximum deflection for the separated fractions. The buffer inlet will be made up of multiple ports in order to allow a uniform inlet and flow through the cell. Forty-six product fraction collection ports shall span the width of the cell. The ports are to be spaced to provide separate collection of adjacent product fractions greater than 1 mm apart. The product fraction collection containers are to be indexed so that the fractions from one sample separation are not mixed with those from the next. A purge of the system with the buffer solution must be provided between processing of the individual samples.

The collected fractions are to be stored between 0 and 5°C (273 and 278°K) for return to the earthbound laboratory. Data to be collected include cell electrode voltage, flow-rates, and the detection of separated fractions. Operation is to be automatic except for initial switching. Caution and warning displays are to be included to indicate, in the event of hazardous operations, that shut-down is required.

5.5.2 Preliminary Design Description

The preliminary design of the experiment, based on the above requirements, is shown in the functional diagram of Figure 5-42.

The cell buffer solution circulates through a phase separator in order to remove air bubbles from the solution and travels through a pump and filter into the separation cell. From there, the solution goes through the multichannel collection pump and into the collection storage, from where it is collected with the sample fractions or returns to the collection portion of the cell buffer storage assembly. The collection and storage portions of this unit are separated by a bladder arrangement, so the cell buffer is only used once and is not re-circulated through the system.

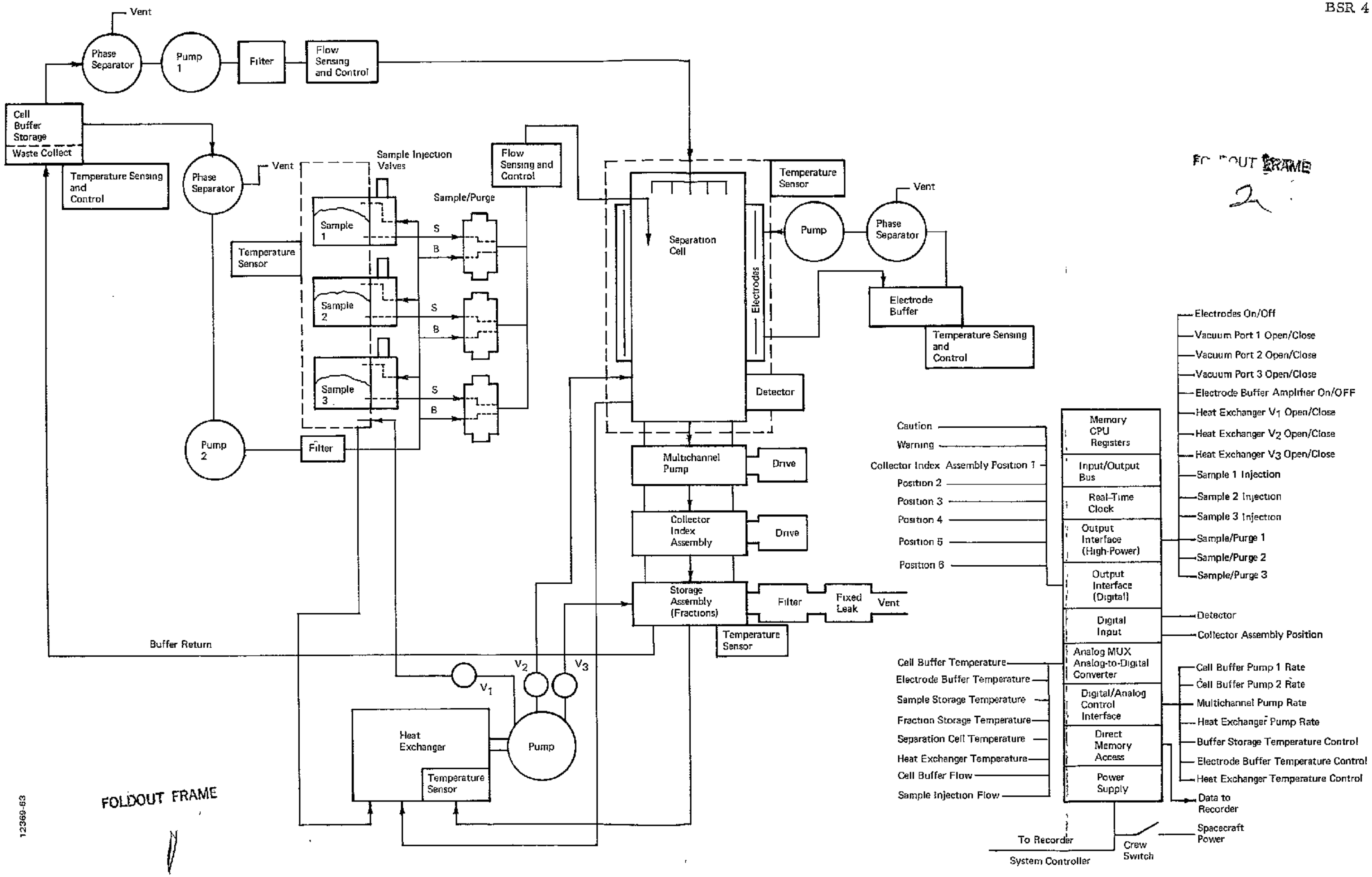


Figure 5-42 Electrophoresis Experiment E-1 Functional Diagram

Part of the cell buffer solution is routed to the sample injection system, where it is used to either force injection or purge the system. The sample injection valves in the closed position route fluid to force the sample from the bladder surrounding it. The sample/purge valve allows selection of the mode of operation and routes cell buffer solution through the system to purge it. The sample injection port is at one side of the separation cell, as shown in Figure 5-43, which also shows the details of the sample separation and collection scheme. The separated fractions are detected by an optical arrangement consisting of a light source and a self-scanning diode array. The fractions are pumped via a 46-channel peristaltic pump to the collection indexer assembly, which provides six positions, allowing for system purge and collection of three sample fractions with system purges between. The fraction collectors consist of an array of collection bladders with a vacuum suction backing. The inlet tube arrangement interfaces with the bladder via a flexible (check valve) arrangement, as shown in the figure, to prevent the fractions from back-flowing into the system. A valve and flow restriction arrangement connects each sample fraction collection system to space vacuum via a vent line.

The electrode buffer flow assembly provides for circulation of the buffer fluid by the electrodes and removal of the gas bubbles formed at the electrode via a phase separator.

Thermal control of the sample storage and injection system, the separation cell, and the fraction storage assembly is achieved via a heat exchanger and recirculating fluid. The sample storage and fraction storage assemblies are maintained at 0 to 5°C (273 to 278°K) while the separation column is 15 to 25°C (288 to 298°K). It is important that the temperature variation (±0.5%) be closely maintained during an individual separation. The heat exchanger temperature, approximately 0°C (273°K) is maintained by a thermo-electric cooler coupled to a heat-transfer path of the spacecraft.

Control of the experiment is accomplished using a central computer/controller which interfaces with and directs the operation of all the equipment required. The computer follows a preprogrammed sequence. While following the sequence, the key parameters, such as fluid temperatures and flow-rates, are continuously checked and, if a deviation is observed, programmed correction action is taken. A real-time clock provides timing information for the correlation of recorded events. All peripheral systems interface with the computer, as shown in Figure 5-42. There are some functions requiring real-time control, such as correlation of the flow-rates of the various fluid loops (sample and buffer). These functions are fully controlled by the computer, using feedback signals to determine the correlation of the rates. Status lights will provide the crew with warnings of impending problems and the sequence status of the experiment.

Figure 5-44 shows a packaging arrangement for the various components. Figure 5-45 is an artist's concept. The equipment is contained within a package 61 by 33 by 74 cm (24 by 12.88 by 29.25 in.). A weight summary for the experiment is given in Table 5-29. No attempts have been made to optimize the packaging arrangement or minimize the weight. The numbers given represent a conservative estimate of the resources required to implement a fully-automated electrophoresis experiment. Equipment estimates were derived from generally available equipment.

Table 5-30 presents the power requirements for the experiment. Both peak and operating power levels are given. It is assumed that dc power at 24 to 32 V will be supplied. The peak power requirements are generally short-duration spikes for such operations as valve solenoids and cell start-up. Conservative estimates have been used for pump power and power supply efficiency estimates. Through careful design and selection of components specifically tailored to this application, large savings in power could be realized, reducing the operating power to about 0.5 kW or less.

Table 5-29

Electrophoresis Experiment E-1 Weight Summary

Item	Weight (lb)	Weight (kg)
Cell Buffer System		
Buffer supply, including temperature sensing and control	5.0	2.3
Phase separator (2)	3.0	1.4
Pumps (2)	12.0	5.3
Flow control	2.0	0.9
Filters (2)	3.0	1.4
	25.0	11.3
Sample Injection		
Sample supply assembly, including temperature sensing and control	1.0	0.5
Sample injection valves (3)	6.0	2.7
Sample/purge control valves (3)	6.0	2.7
Flow control	2.0	0.9
	15.0	6.8

Table 5-29 (Cont.)

Item	Weight (lb)	Weight (kg)
Electrode Buffer System		
Buffer supply, including temperature sensing and control	5.0	2.3
Phase separator	1.5	0.7
Pump	8.0	3.6
	14.5	6.6
Separation Cell and Fraction Collection		
Separation cell, including detector, electrodes, and mounts	5.0	2.3
Multichannel pump	7.5	3.4
Collector index assembly	9.0	4.1
Storage assembly	10.0	4.5
	31.5	14.3
Heat Exchanger and Circulation		
Heat exchanger	10.0	4.5
Pump	8.0	3.7
Valve assembly	6.0	2.7
	24.0	10.9
Plumbing and Mounts	5.0	2.3
System Controller	58.0	26.2
Power Supply	15.0	6.8
Fluids		
Cell buffer (8 ℓ)	18.0	8.2
Electrode buffer (1 ℓ)	2.5	1.1
Samples (0.075 ℓ)	0.2	0.1
Coolant (8 ℓ)	18.0	8.2
	38.7	17.6
Structure	23.3	10.6
Total	250.0	113.4

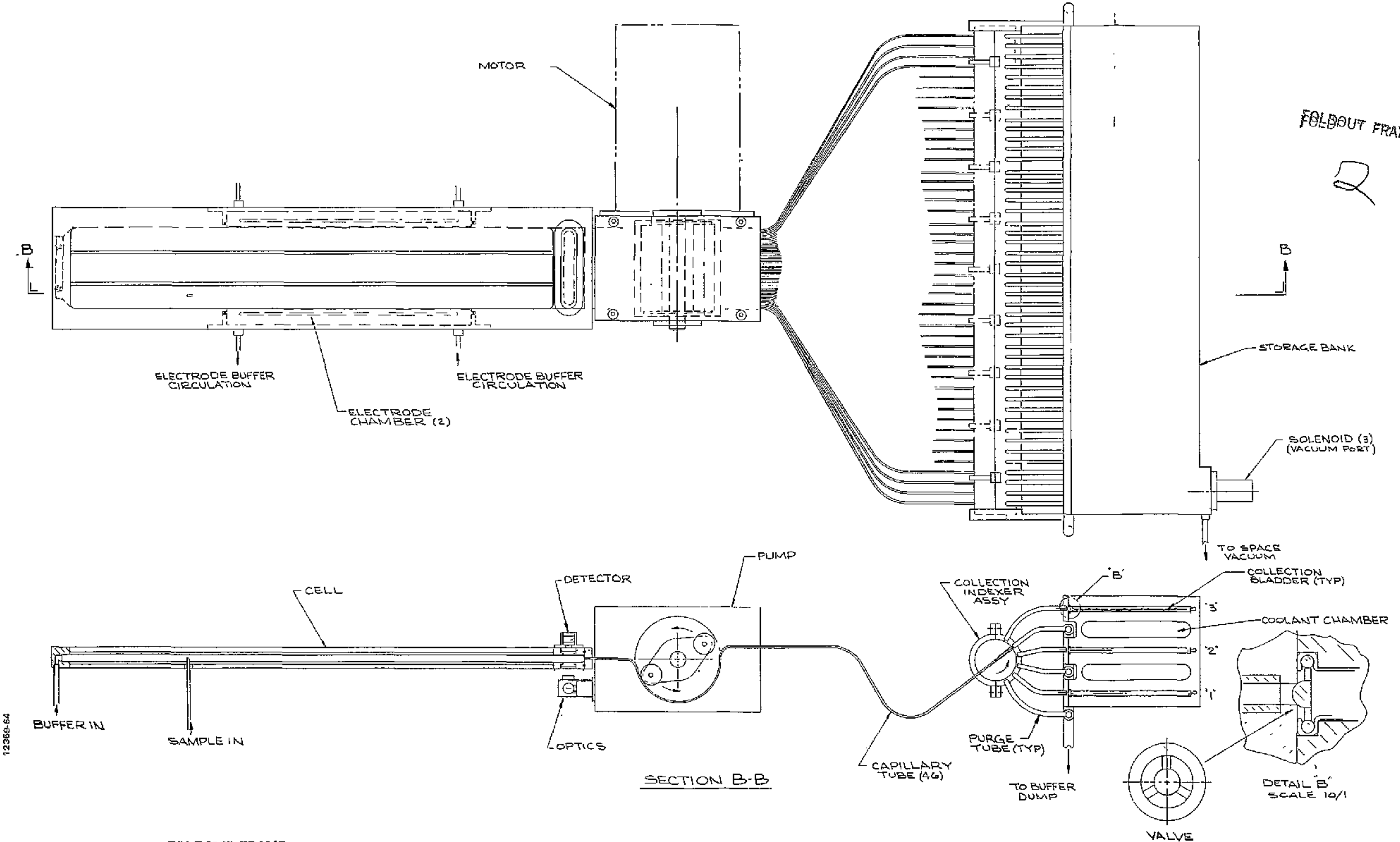
Table 5-30

Electrophoresis Experiment Power Requirements

	Power (W)	
	Operating	Peak
Buffer pumps (2)	200	200
Flow sensing and control	10	10
Sample injection valves		5
Sample/purge control valves		5
Electrode buffer pump	100	100
Separation cell detector	10	10
Multichannel pump	50	50
Collector index assembly		10
Heat exchanger assembly	50	250
Pump	100	100
Valve		5
System controller	175	225
Separation cell	20	200
	715	1, 170
Power supply	150	250
Total	865	1, 420

5.6 CORE FACILITIES

The core facilities have been included in each of the hardware descriptions for the separate facilities. However, in establishing various combinations of facilities for different payloads, a common core unit may be used. Therefore, in the costing and development resource determination, we have identified the core unit as a separate facility, deleted the core equipment from each separate facility, and included it under this item.



FOLDOUT FRAME

FOLDOUT FRAME

Figure 5-43 Electrophoresis Cell and Storage Layout

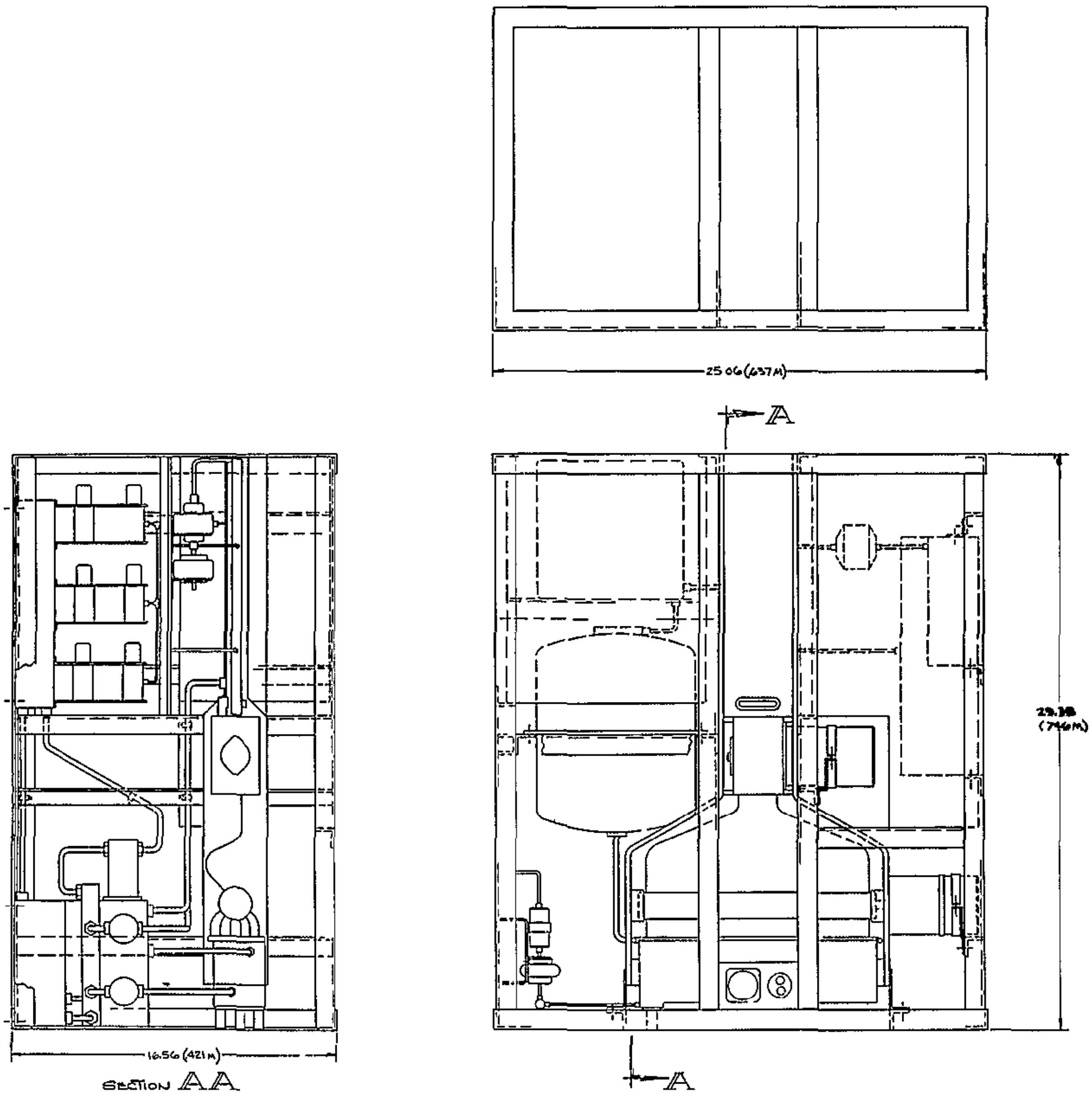


Figure 5-44 Electrophoresis Experiment Package

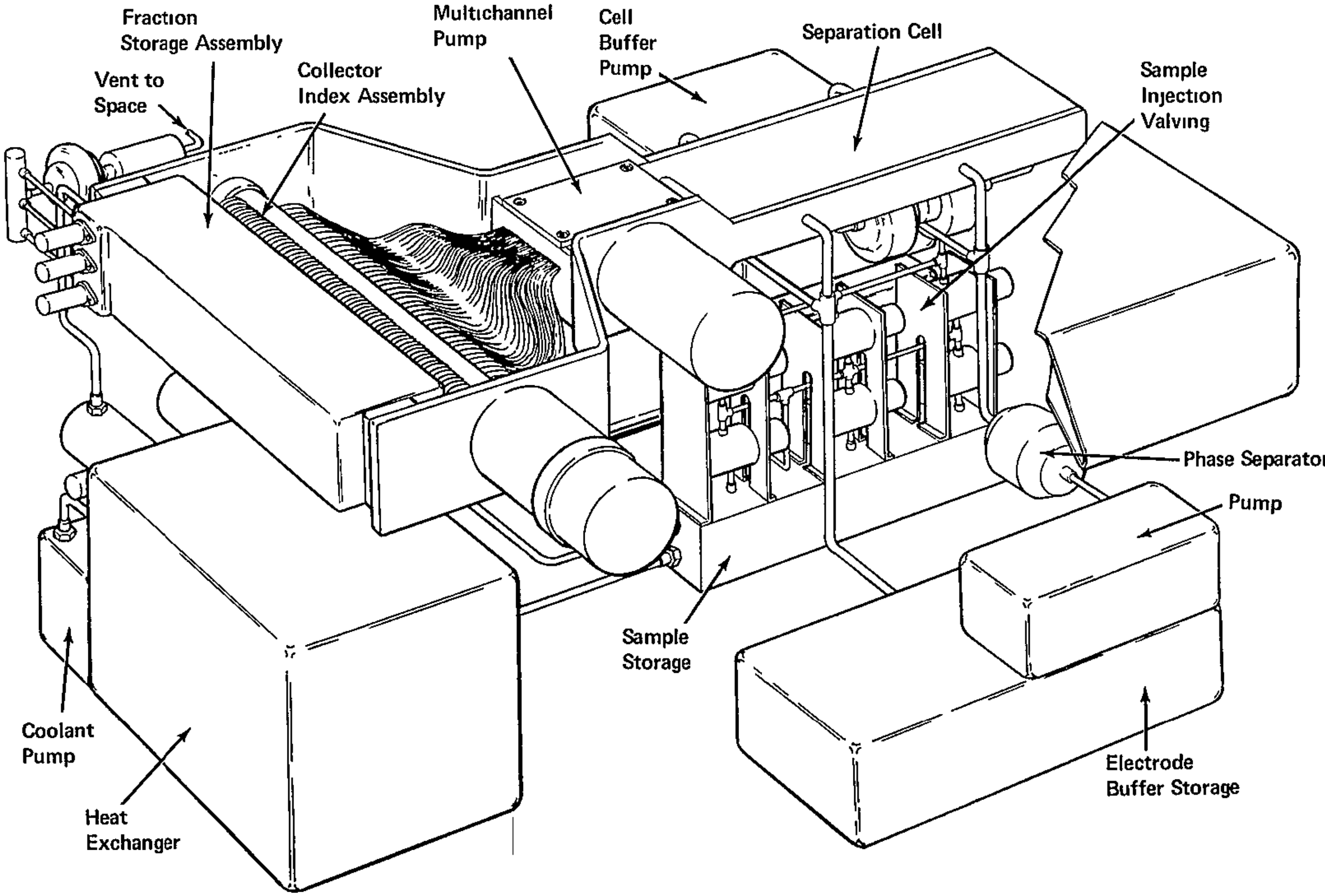


Figure 5-45 Electrophoresis Experiment (E-1)

The core unit consists of a central computer/controller which interfaces witl and directs the operation of all equipment required for the performance of the expe ment. The computer, working to a pre-programmed time-line, turns on the equip ment as required; inserts and retrieves samples from the work area; initiates and maintains heating and cooling cycles; and measures, records, and maintains the working environments of temperature, pressure, and partial pressures of gases produced during the process. In addition, the computer continuously monitors for hazardous conditions and takes precautionary actions, which are pre-programmed, or identifies the condition to the crew for its action.

Peripheral equipment includes the input-output bus, real-time clock, high-power and low-power output interface drivers, digital and analog input controller direct memory access, and the mass memory tape recorder.

5.7 REFERENCES

1. Acoustical Positioning Chamber for Space Processing; T. G. Wang et al; Proceedings: Third Space Processing Symposium; Marshall Space Fligh Center; 30 April 1974.

2. Ultrasonic Methods for Positioning and Stirring Molten Materials in Zero-Gravity Environments; Report; Contract 73/131 PAMIS 234; E. G. Lierke; Jan 1974.

3. Acoustic Field Positioning for Containerless Processing; R. R. Whymarl Proceedings: Third Space Processing Symposium; Marshall Space Fligh Center; 30 April 1974.

4. 2,200 °C Oxidizing Atmosphere Furnace for Space Manufacturing; AIAA 12th Aerospace Science Meeting; Washington, D. C.; R. J. Page et al; 1 Feb 1974.

5. Design Analysis of Levitation Facility for Space Processing Applications Final Report; Contract NAS 8-29680 Mod. 3; General Electric; 15 Nov 1974.

SECTION 6

AUTOMATED SPACE PROCESSING PAYLOADS FOR EARLY SHUTTLE MISSIONS

6.1 INTRODUCTION

The objective of this effort was to define automated payloads consisting of one or more facilities for conducting equipment and technique verification tests and space processing experiments on Shuttle flights in the 1979 to 1982 time-period.

The approach taken was to:

- Identify the mission constraints on automated payloads. Review the Spacelab and Shuttle cargo bay payload constraints. Derive Auxiliary Payload Power System (APPS) constraints on automated payload equipment.
- Review the NASA early mission Space Processing Payloads Strawman Program and select typical payloads.
- Formulate payload concepts and configurations and perform operational and mission analysis of the payloads.

Table 6-1 is a summary of the characteristics of the payloads studied in this task. Three Shuttle cargo bay payloads (Payloads 1, 2, and 3) and three APPS unit payloads (Payloads 4, 5, and 6) were configured, and their characteristics were determined. The three payloads most closely matching the NASA Strawman Program are Payloads 4, 5, and 6. Perspective views of Payloads 3, 5, and 6 are shown in Figures 6-1 through 6-3. The APPS concepts are artist's representations of the subsystems only. The study has determined that it is entirely feasible to provide automated payloads meeting the constraints and resources available on the early Shuttle mission opportunities existing in the 1979 to 1982 time-period.

6.2 PAYLOAD CONSTRAINTS

Several potential mission modes exist for the automated space processing payloads, as shown in Figure 6-4. The goal of the study is to define payload concepts capable of taking advantage of every possible mission opportunity. Therefore, an analysis was conducted to determine the constraints imposed by the potential payloads or mission modes in order to provide guidelines as to the payload equipment groupings for early space processing missions.

Table 6-1

Automated Space Processing Payloads for Early Missions

Payload	Equipment	Weight (lb)	Weight (kg)	Peak Power (kW)	Average Power (kW)	Total Energy (kWhr)
1	Low-Temperature Multiple Furnaces. Electrophoresis. Core.	1,329	604 [a]	3.3	1.9	138
2	Low-Temperature Multiple Furnaces. Electromagnetic Levitation. Core.	2,219	1,008 [a]	4.1	2.3	116
3	Low-Temperature Multiple Furnaces. Electromagnetic Levitation. Electrophoresis. Core.	2,508	1,140 [a]	4.3	2.0	143
4	Low-Temperature Multiple Furnaces. Electromagnetic Levitation. Electrophoresis. Core.	2,048	931 [b]	4.3	2.0	143
5	High-Temperature Multiple Furnaces. Electromagnetic Levitation. Core.	1,749	795 [b]	5.9	3.3	410
6	Acoustic Levitation. Low-Temperature Multiple Furnaces. Zone Refiner. Molten Zone Crystal Growth. Core.	2,392	1,086 [b]	15.2	12.5	1,500

Notes: (a) Includes truss structure and battery.
(b) Payload only; APPS not included.

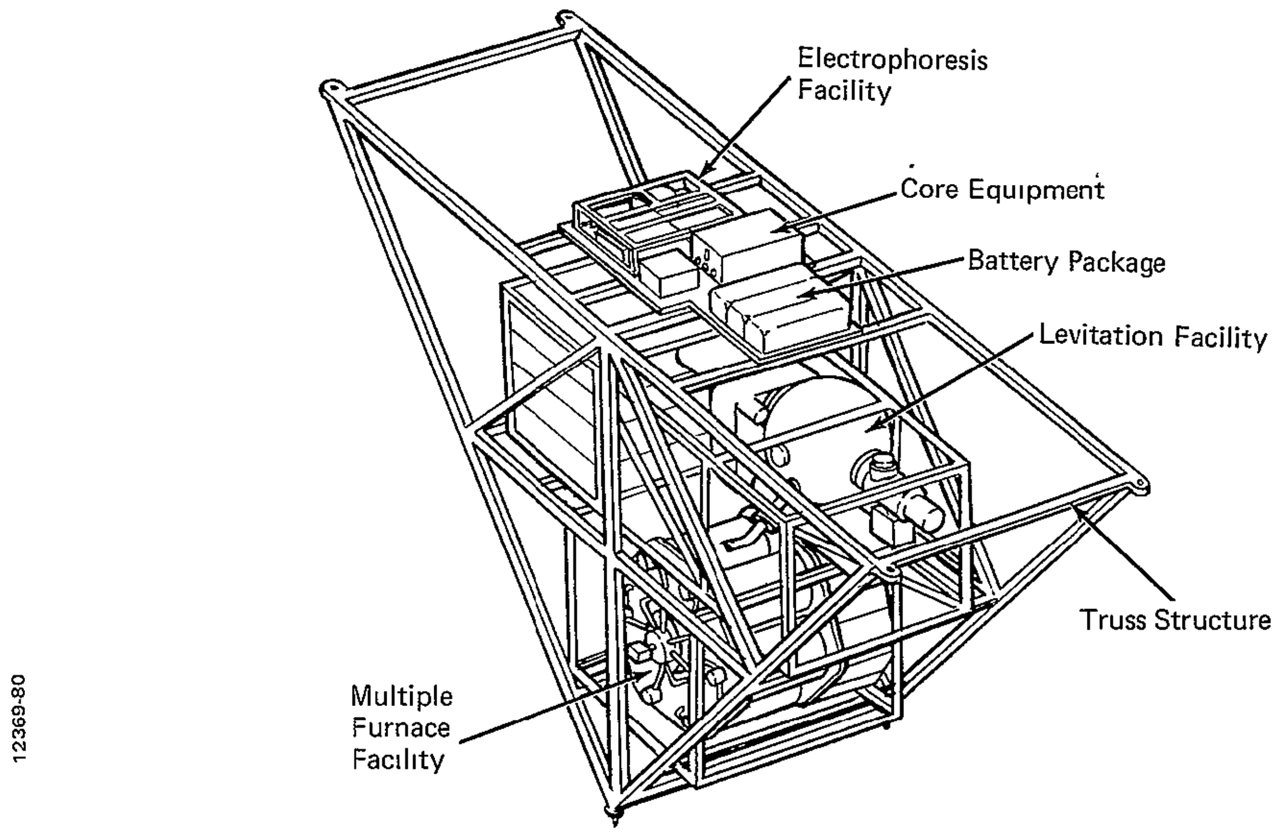


Figure 6-1 Payload 3; Electromagnetic Levitation Facility, Multiple Low-Temperature Furnace Facility, and Electrophoresis Facility Mounted in a Truss Structure

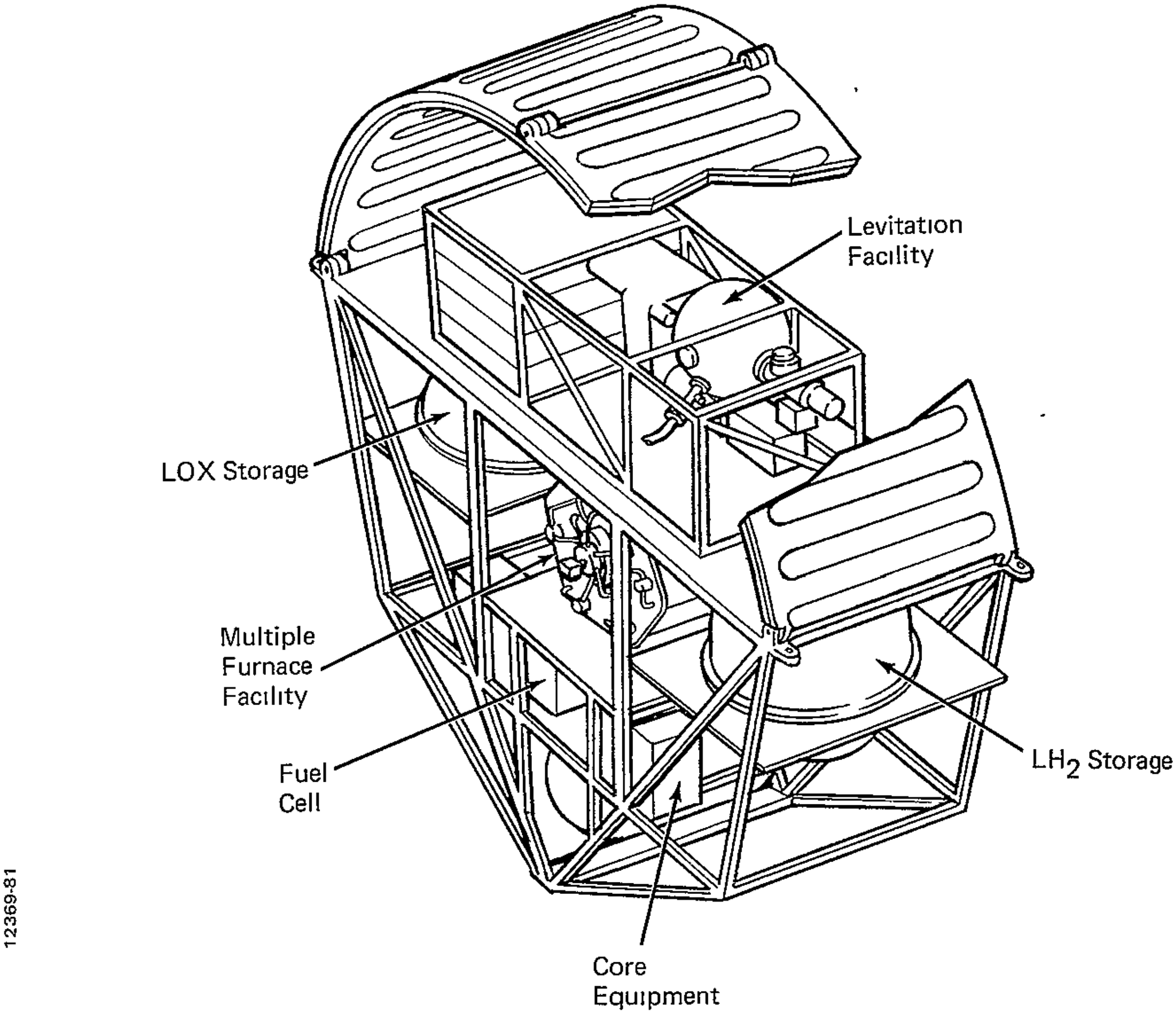


Figure 6-2 Payload 5; Electromagnetic Levitation Facility and Multiple High-Temperature Furnace Facility Mounted in a Representative 7.5-kW APPS Unit

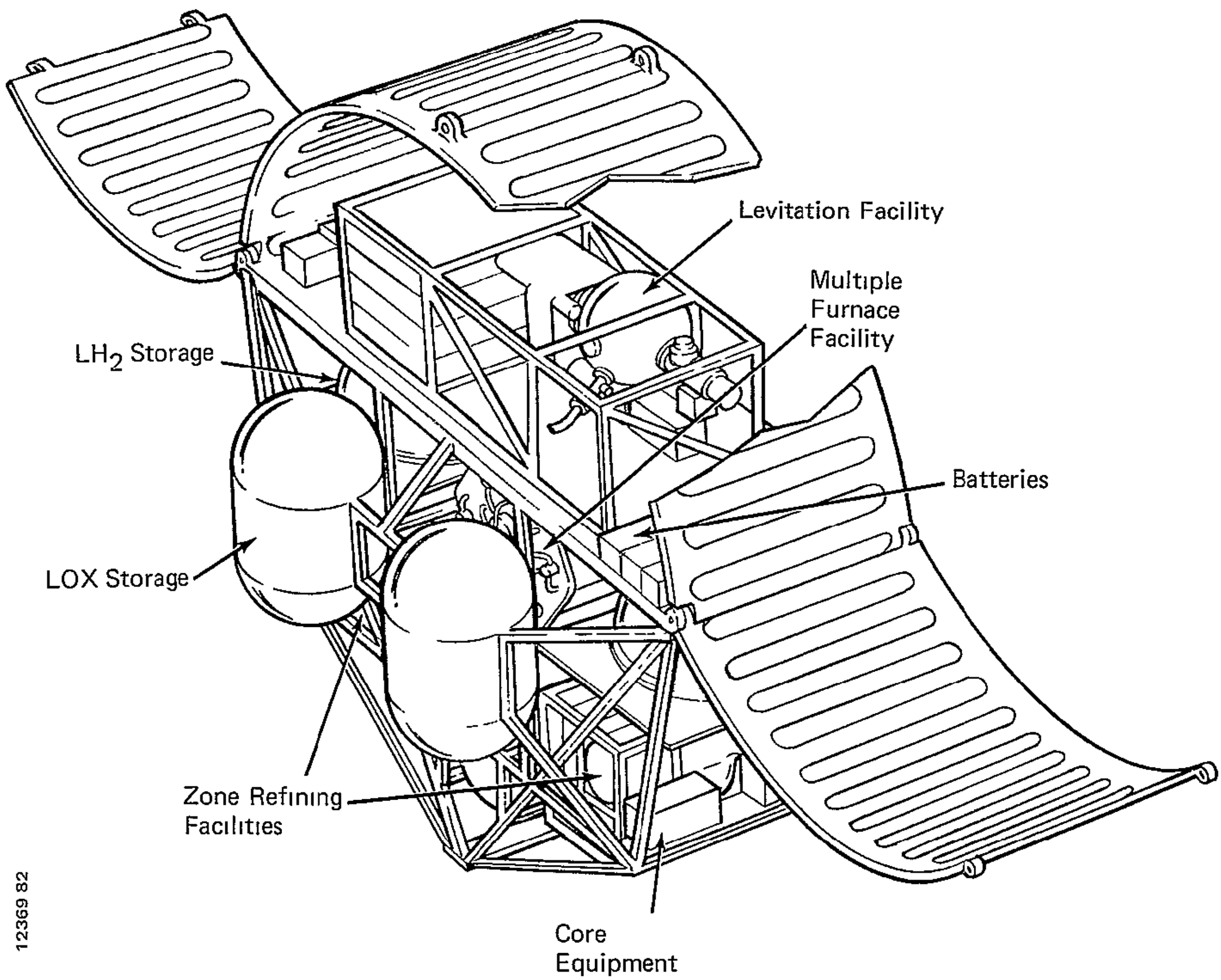


Figure 6-3 Payload 6; Acoustic Levitation Facility, Multiple Furnace Facility, and Two Zone Refiners Mounted in a Representative 15-kW APPS Unit

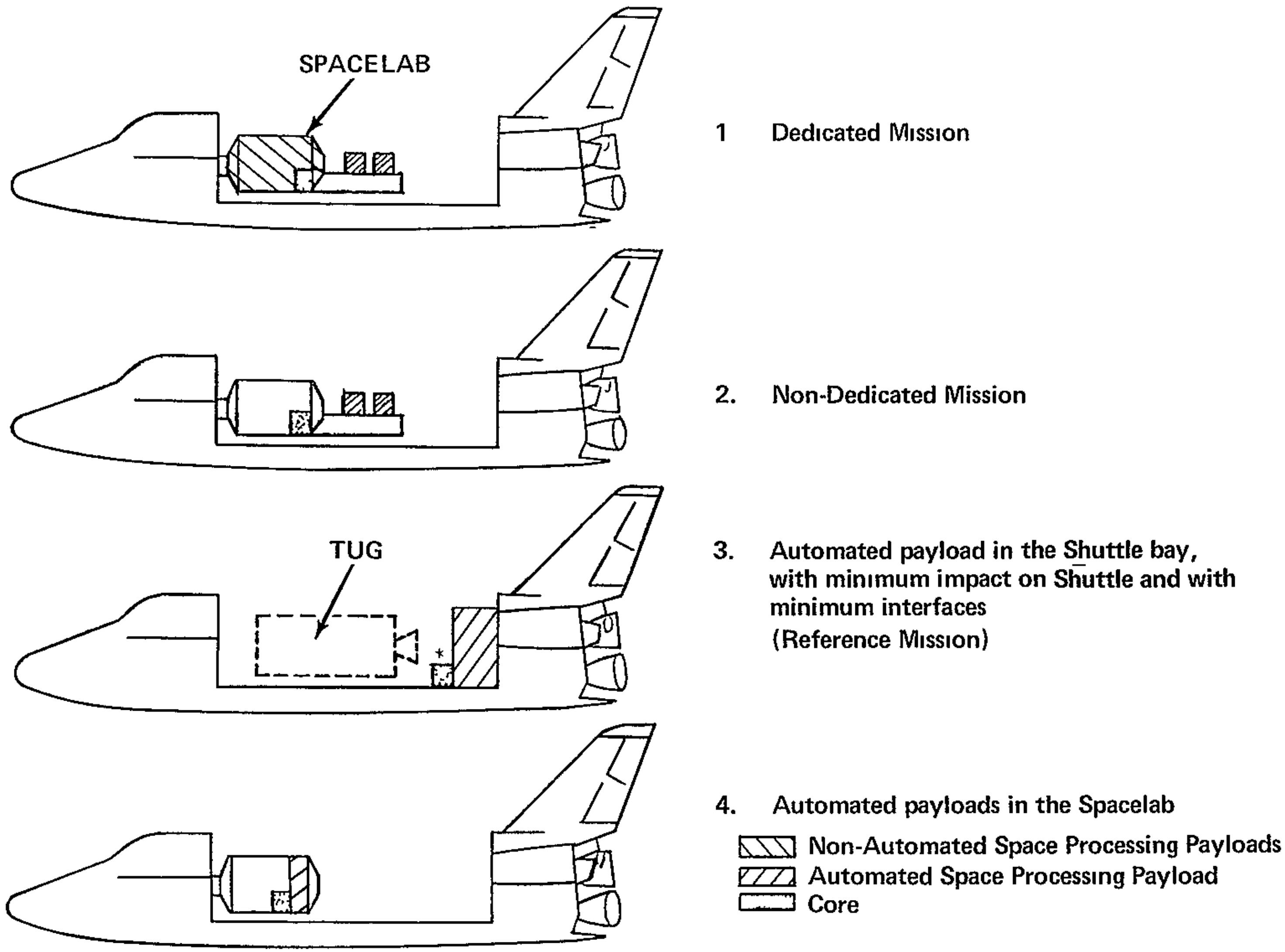


Figure 6-4 Potential Mission Modes for Automated Space Processing Payloads

6.2.1 Spacelab and Pallet

The space processing payload equipment may be mounted within the Spacelab or on the pallet. The resources available from this configuration are summarized in Table 6-2. If power, energy, or power conditioning beyond that outlined is required, it must be supplied from the experiment payload. Figures 6-5, 6-6, and 6-7 show the available payload mounting volume and arrangements for the Spacelab and pallet equipment.

6.2.2 Auxiliary Payload Power System

An Auxiliary Payload Power System (APPS) unit consists of a fuel-cell, cryogen storage, heat exchangers, coolant loops, a radiator, and a thermal capacitor as required to augment the basic Spacelab electrical power/thermal rejection capability during the performance of high-power space processing experiments or to contain and support space processing application experiments on missions of opportunity. The baseline APPS unit is to supply 15 kW of power and heat rejection capability.

Baseline concepts for the APPS unit have been developed by NASA and NASA contracts. Figure 6-8 shows a concept developed by TRW for NASA in the Space Processing Applications Payload Equipment Study. Figure 6-9 shows a concept produced in-house at NASA MSFC. In the present study, the MSFC concept was used as a guideline for the payload configuration, and for the artist's concepts shown in Figures 6-1 through 6-3.

6.2.3 Cargo Bay-Mounted Payloads

To take advantage of some early missions prior to the availability of the APPS unit, it may be advantageous to supply a payload mounted on a truss structure to be located in the Orbiter cargo bay. Power and thermal control would be supplied from the Orbiter and will depend on what is available over and above that used for the primary mission. It has been assumed that approximately 2 kW average power will be available for the payload.

6.3 STRAWMAN PROGRAM FOR EARLY MISSIONS

Table 6-3 shows a preliminary definition of a space processing program for the early Shuttle missions. The definition was provided by NASA as an input to the study. Three missions of varying sophistications and payload accommodations have been defined for automated payloads; Missions 3, 6, and 10. These early missions will provide the opportunity to check out equipment for future missions and to provide some material processing.

Table 6-2

Resources Available to the User of the Spacelab Pressurized Module and Pallet

Resource	Capability/Characteristic
ELECTRICAL	
Total energy (per 7-day mission)	400 to 500 kWhr.
Average electrical power	4 kW.
Peak electrical power	9 kW for 15 min each 3 hr.
Type	Unregulated dc, 24 to 32 V. Mission dependent: Regulated dc, 28 ± 2% V. 400 Hz, 115/200 Vac ± 5%, three-phase. 50 Hz, 220 Vac ± 5%, one-phase. 60 Hz, 115 Vac ± 5%, one-phase.
THERMAL CONTROL	Air cooling or cold plates.
Air cooling	18 to 27°C (1 kW), cabin. 22 to 24°C (3.13 kW), avionics.
Cold plates	24 to 40°C (4.85 kW).
COMPUTER	
Word length	16 bits.
Memory size	39 K, 16-bit words, expandable to 64 K words.
Speed (add 16-bit word)	1.8 μsec.
COMMUNICATIONS	
50 Mbps (via TDRSS)	
50 MHz (via TDRSS)	
2 by 1 Mbps (via TDRSS narrowband and STDN)	
20 kbps telemetry	
Voice	

Table 6-2 (Cont.)

Resource	Capability/Characteristic
TAPE STORAGE	
Data rate	30 Mbps.
Record time	20 min.
Tape length	2, 804 m (9, 200 ft).
Record/reproduce speed	234 cm per sec (92 ips).
FILM STORAGE	
550 kg (1, 212 lb)	
EXPERIMENTAL PAYLOAD WEIGHT	
5, 500 kg (12, 100 lb)	

In Mission 3, the mission duration for payload operations may extend to 3 days. The payload is accommodated within the cargo bay, must supply its own structural support arrangement, and is dependent on the Shuttle Orbiter resources for power and heat rejection. It is possible to check the orbital operation of the electromagnetic facility and to perform some low-temperature furnace experiment programs. Mission 6 is the first flight of the Auxiliary Payload Power System (APPS). Primary objective of the mission is to test interfaces of the APPS with the Shuttle Orbiter. The program calls for a reduced APPS assembly to be flown. This unit will contain a single fuel-cell and reduced cryogens. Because of the extended time and potentially higher resources available, it will be possible to extend the Skylab and ASTP results into a higher temperature regime and to obtain processed samples from the levitation facility.

Mission 10 is the first flight of a full-up (15 kW) APPS unit. In this mission, the resources are greatly increased. Therefore, a more extensive experimental program can be undertaken than in any previous mission. New processes, including crystal growth and zone refining, can be undertaken, and the results of the experiments performed on the previous missions can be extended.

6.4 CARGO BAY-MOUNTED PAYLOADS (PAYLOADS 1, 2, AND 3)

Three payloads were investigated relative to cargo bay operation. A common truss structure has been defined, and the payload characteristics have been determined. All payloads are dependent on the Shuttle Orbiter for power and heat rejection. It has been assumed that 2 kW will be available.

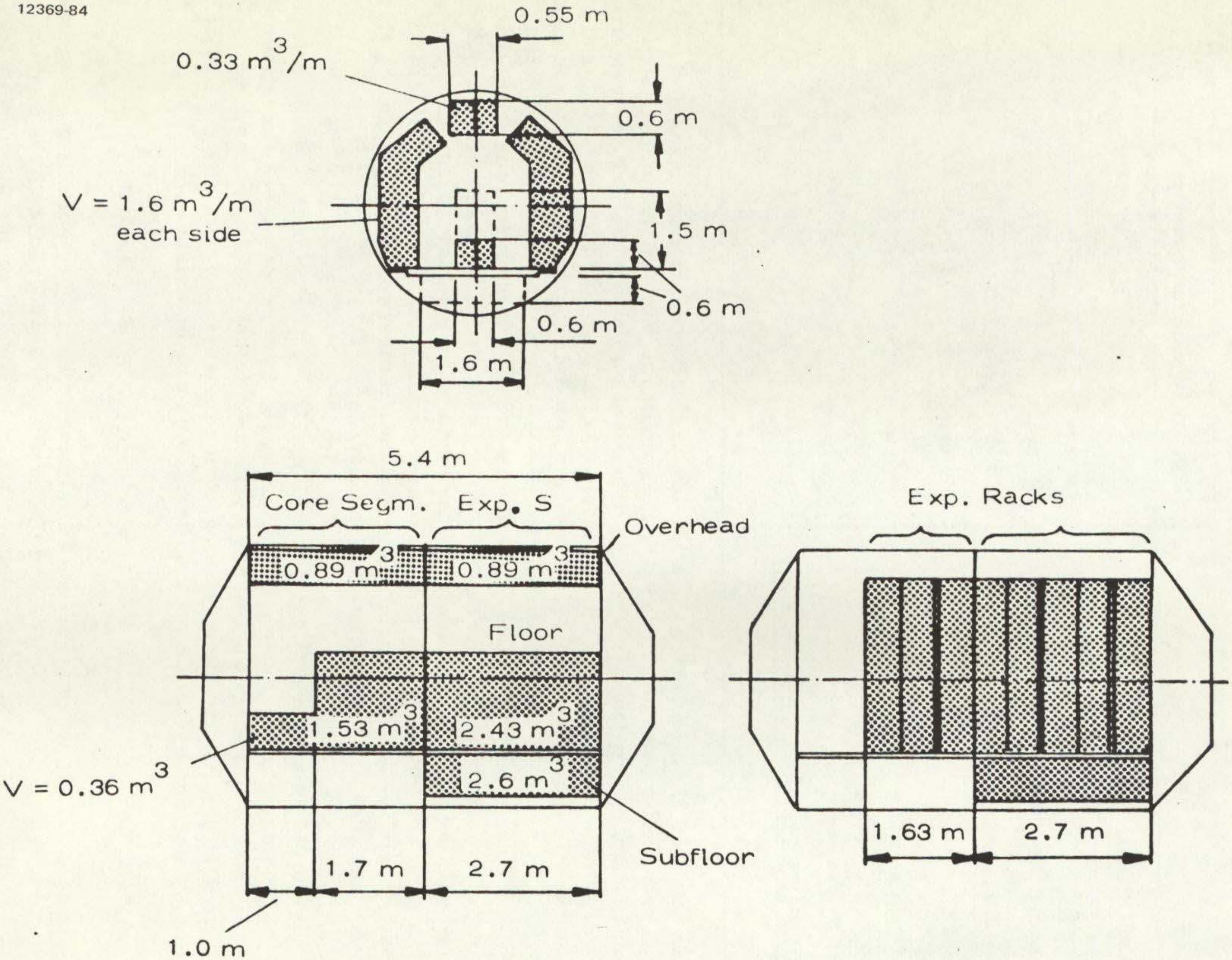


Figure 6-5 Spacelab Module Payload Volume

3

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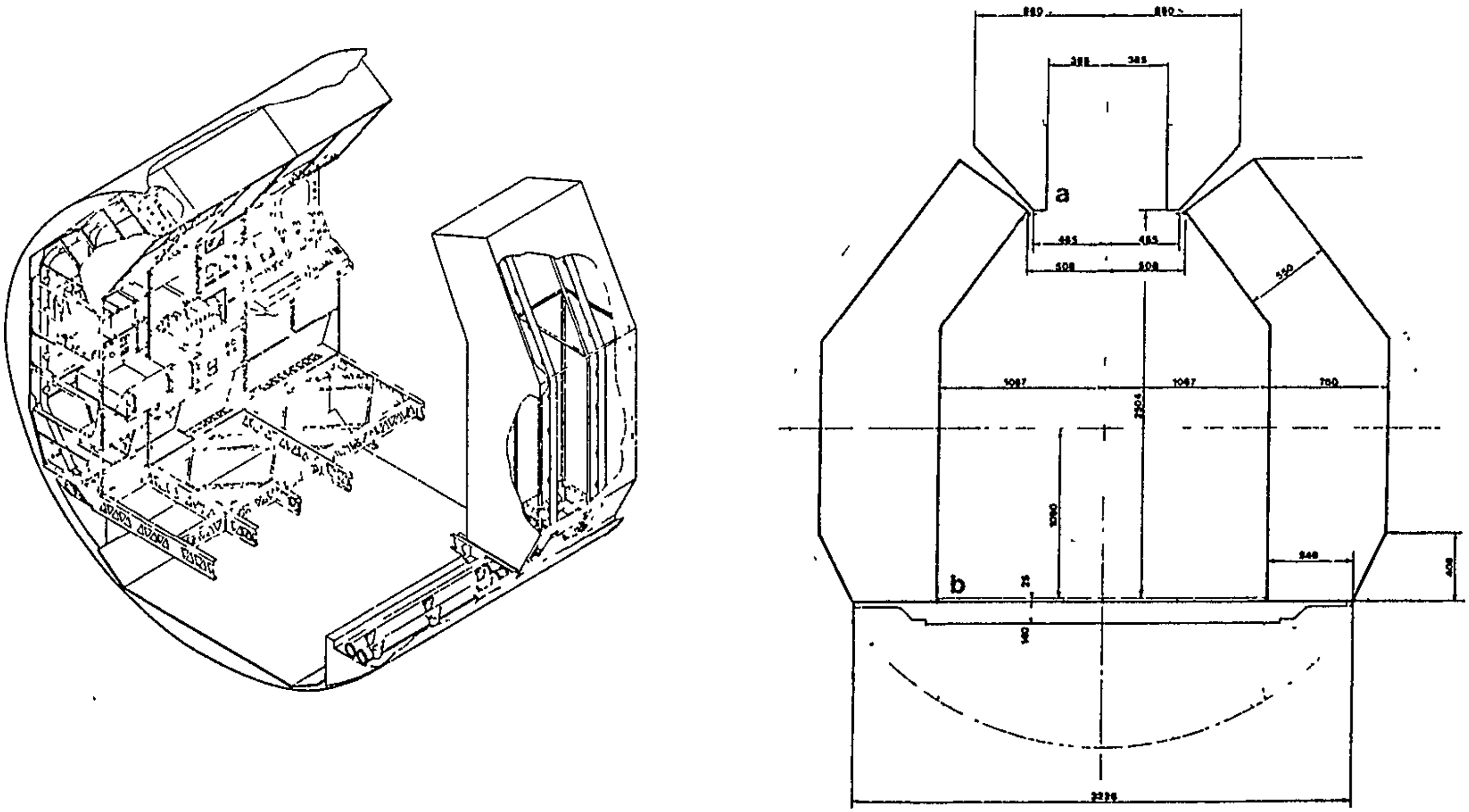

EXPERIMENT RACK VOLUME 0.8 m^3 PER 19″ RACK

Figure 6-6 Experiment Racks

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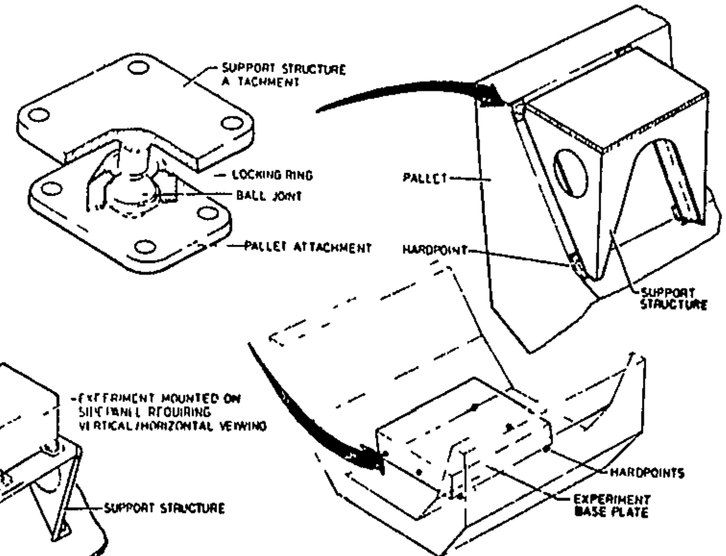
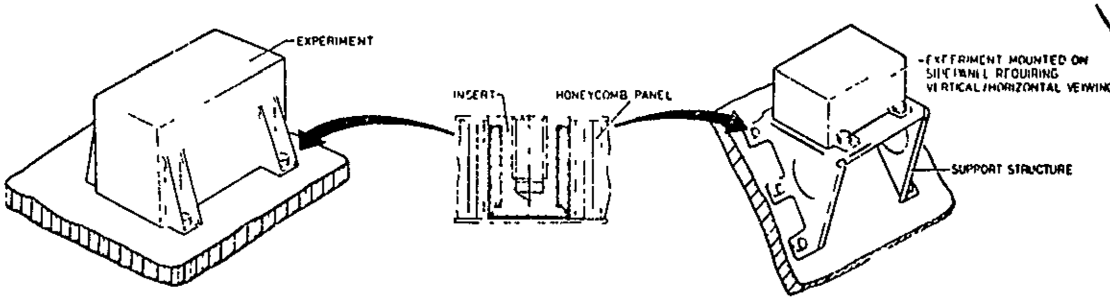
VOLUME AVAILABLE TO PAYLOADS ON THE PALLET

	PER METER	15m PALLET
USABLE VOLUME	12 m^3	180 m^3
FLAT MOUNTING AREA	6.8 m^2	110 m^2

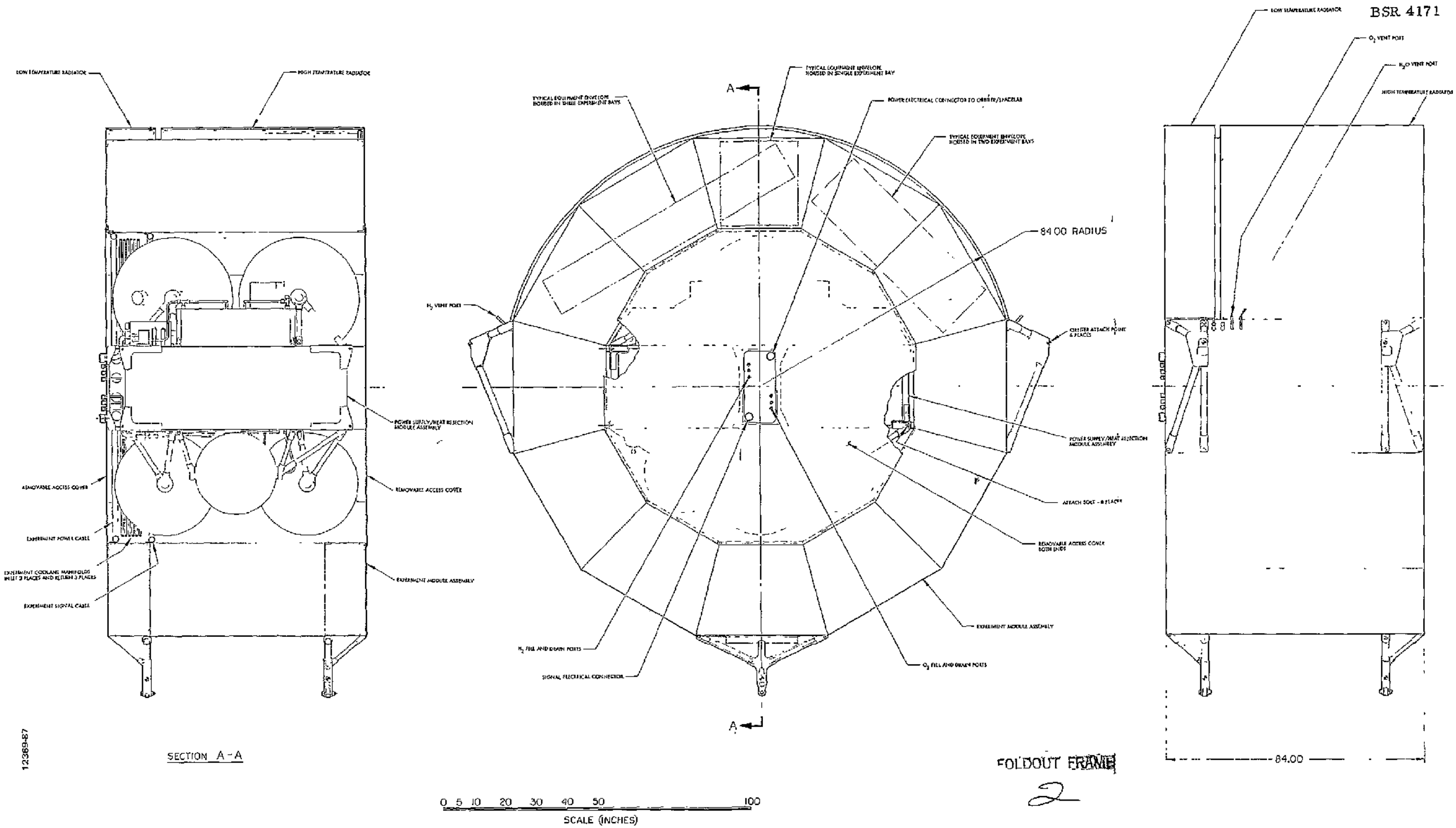


Typical Heavy Experiment
Equipment Installation



Lightweight Experiment Equipment Installation

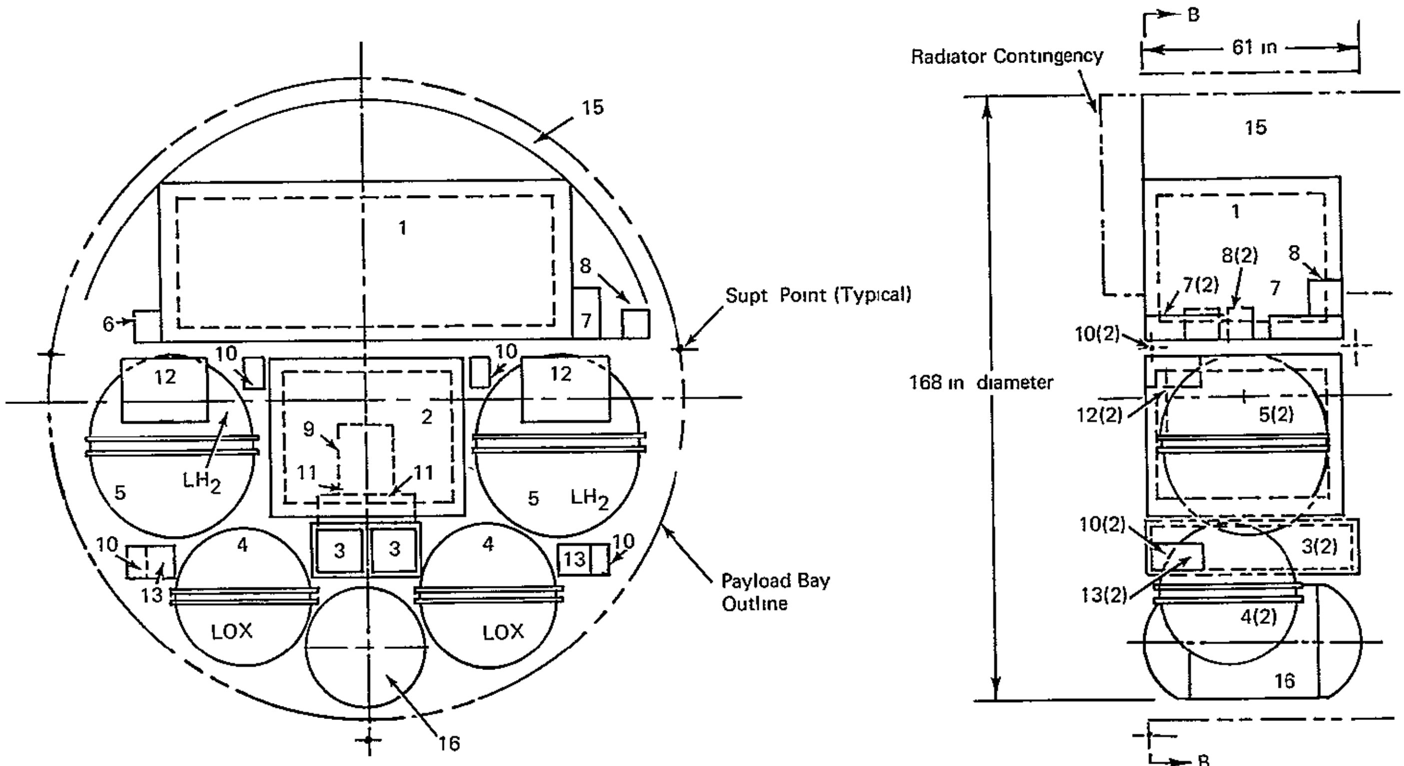
Figure 6-7 Equipment Installation



FOLDOUT FRAME 2

FOLDOUT FRAME 1

Figure 6-8 APPS Unit, TRW Configuration



Section B-B

Legend Automated Space Processing Pallet Payload Components

Number[a]	Name	Number Required	Dimensions (in)
1	Levitation[a]	1	36 by 48 by 108
2	Furnace	1	36 by 48 by 48
3	Fuel cells	2	13 by 13 by 57
4	O_2 Tanks	2	39 diameter by 39
5	H_2 Tanks	2	46 diameter by 50
6	Pump	1	6 by 6 by 12
7	Batteries	3	21 by 7 by 7
8	Controller	3	10 by 9 by 8
9	Distributor	1	16 by 19 by 5
10	Pressure Assembly	4	5 31 by 16 by 8 5
11	Control Assembly	2	5 31 by 8 by 8 5
12	Core Assembly	2	24 by 18 by 6
13	Inverter	2	14 by 10 by 8
14	Converter	1	12 by 9 by 7
15	Radiator	1	14 ft diameter by 5 ft thick by 150°
16	Water Collection Tank	1	33 5 diameter by 61 (45° bulkheads)

(a) Payload components are identified by number on figure

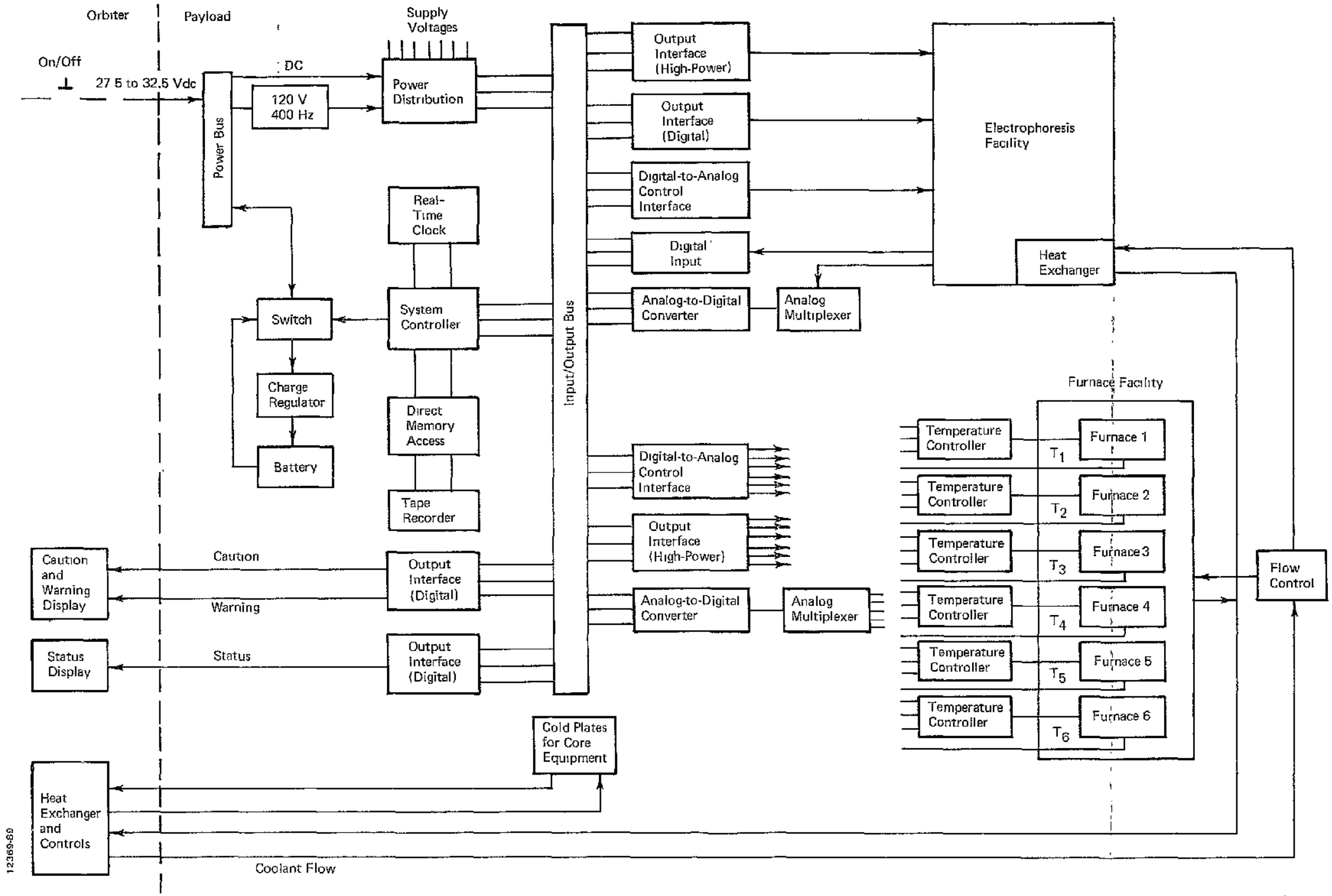
12369-88

Figure 6-9 APPS Unit; MSFC Configuration

Table 6-3

Space Processing Payloads;
Strawman Program for Early Missions

Shuttle Orbiter Flight and Duration	Objective	Payload	Accommodation
Flight 2 (1 to 3 days)	1 Longer duration to extend rocket experiment results.	1 Rocket Spinoff Payload.	Cargo bay
Flight 3 (1 to 3 days)	1 Verify and extend results from Skylab and ASTP 2 Performance test critical equipment technology for Spacelab flight. 3. Investigate metallurgical phenomena. 4 Investigate crystal growth phenomena 5. Test major APPS systems. 6. Verify payload/Shuttle interface 7. Verify Shuttle payload support systems	1 Multiple Furnace Facility. 2. Utility Contactless Processing 3 Electrophoresis Technology (Test). 4 Core Unit.	APPS (unpowered)
Flight 6 (7 days)	1 Crystal growth and metallurgical processing that exceeds Skylab/ASTP capability 2. Test of new apparatus, e.g., contactless processing facility with electron-beam heating. 3 Purification of high melting-point materials in contactless processing facility. 4 Comparison of contact versus contactless high-temperature processing. 5 Checkout of APPS power and the thermal subsystems. 6 APPS/STS thermal control interface test 7. Payload/STS interface verification test.	1 Contactless Processing Facility with electron-beam gun. 2. Multiple Furnace Facility. 3 Core.	APPS (7.5 kW)
Flight 8 (Joint NASA/ESRO Spacelab Mission) (7 days)	1 Electrophoresis of live samples 2. Extend crystal growth results from previous missions. 3. Extend metallurgical results. 4 Investigate fluid phenomena	1. Low-Temperature Furnaces. 2. Electrophoresis (Continuous-Flow and Static Separation). 3 General Purpose Sub-element	Spacelab
Flight 10 (7 days)	1 Contactless processing of unique glasses 2 Purification of high-temperature materials by zone refining 3 Metallurgical processing by zone refining 4 Crystal growth by contactless processing 5 Extension of previous crystal growth and metallurgical processes. 6 Checkout of all up APPS power and thermal subsystems 7 APPS/STS thermal control interference test	1. Contactless Processing Facility (Acoustic). 2 High-Temperature Multiple Furnaces. 3. Float Zone Refiner (2). 4. Core	APPS (15 kW)



FOLDOUT FRAME 1

FOLDOUT FRAME 2

Figure 6-10 Payload 1 Functional Diagram

6.4.1 Payload 1

Payload 1 consists of an automated continuous-flow electrophoresis facility and a bank of six low-temperature furnaces. Figure 6-10 shows a system functional block diagram, indicating the functional interface between the Orbiter and the payload. Primary interfaces include dc power and a coolant loop for active thermal control. Figure 6-11 shows the structure arrangement of the payload. The truss structure interfaces with the cargo bay at the hard-points defined on the Shuttle interface drawings. The payload is spaced between the 152.4 cm (60-in.) attach points in the cargo bay. Table 6-4 is a weight and power summary of the components comprising the payload. The peak power required is 3.3 kW. Average power is 1.9 kW and total energy is 138 kWhr. Figure 6-12 shows a typical power profile for the payload. The figure represents a 72-hr mission, which consists of one electrophoretic separation and collection and six low-temperature crystal-growth experiments. The processing need not be continuous over a 72-hr period, but may be interrupted at convenient intervals. The 400 Hz inverter power supply powers the core equipment and the furnace heater. An efficiency of 90% has been assumed for this unit. A 9-kWhr AgZn peaking-battery is supplied to accommodate the peak power demands.

6.4.2 Payload 2

Figure 6-13 shows the functional diagram for the payload, including the interfaces with the Shuttle Orbiter. This payload consists of a bank of low-temperature furnaces and an electromagnetic levitation facility. The levitation facility may include active vacuum system components or may use space vacuum, depending on the resources available from the Shuttle Orbiter for this flight. Figure 6-14 shows the payload configured within the truss structure. Table 6-5 is a weight and power summary of the payload components. A typical power profile for six low-temperature crystal growth processes and the containerless processing of six samples is shown in Figure 6-15. The mission profile may be broken into low-g segments as available. A continuous period of 51 hours at 10^{-4} g or less is not required. Note the scale change on the figure. The peak power required (4.1 kW) is of a short duration (about ten minutes) during initial start-up and pump-down of the levitation facility chamber. If space vacuum is used, this peak will not exist, and the levitation facility requirements will be reduced to about 3 kW peak. The total mission duration for the experiment program is about 51 hours. A 90%-efficient 400-Hz inverter has been assumed for powering the furnace and core equipment.

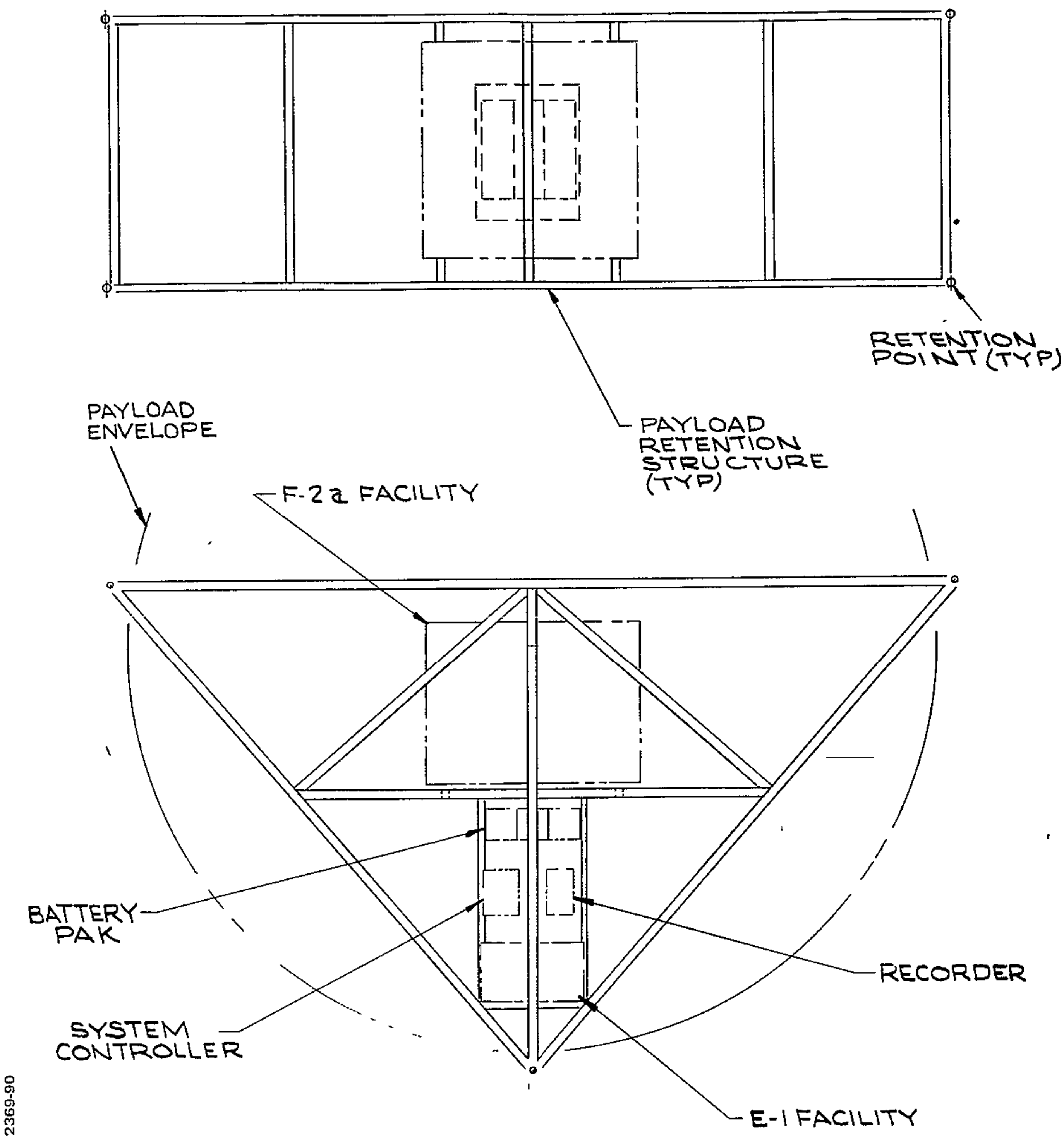


Figure 6-11 Payload 1 Configuration

Table 6-4

Payload 1 Weight and Power Summary

Item	Weight (lb)	Weight (kg)	Peak Power (W)
MULTIPLE FURNACE FACILITY			F-2
Enclosure and structure support	145	66	---
Furnaces (6)	240	109	2,250
Transformer	40	18	250
Power controller	30	14	50
Interface electronics	12	5	10
Interface cabling	12	5	---
Cold Plate, plumbing, and coolant	82	38	---
	561	255	2,560
ELECTROPHORESIS FACILITY			
Cell buffer system	25	11	210
Sample buffer system	15	7	10
Electrode buffer system	15	7	100
Separation cell and fraction collector	32	15	270
Heat exchanger and circulation	24	11	355
Plumbing and mounts	5	2	---
Power supply	15	7	250
Fluids	39	18	---
Structure	23	10	---
	193	88	1,195
CORE UNIT			
Controller and input/output interfaces	63	28	307
Recorder	17	8	17
Power supply (400 Hz)	50	23	120 (250)
Power distribution	15	7	20
Batteries (9 kWhr) and charger	210	95	---
	355	161	464
SUPPORT STRUCTURE	220	100	
TOTAL	1,329	604	3,274

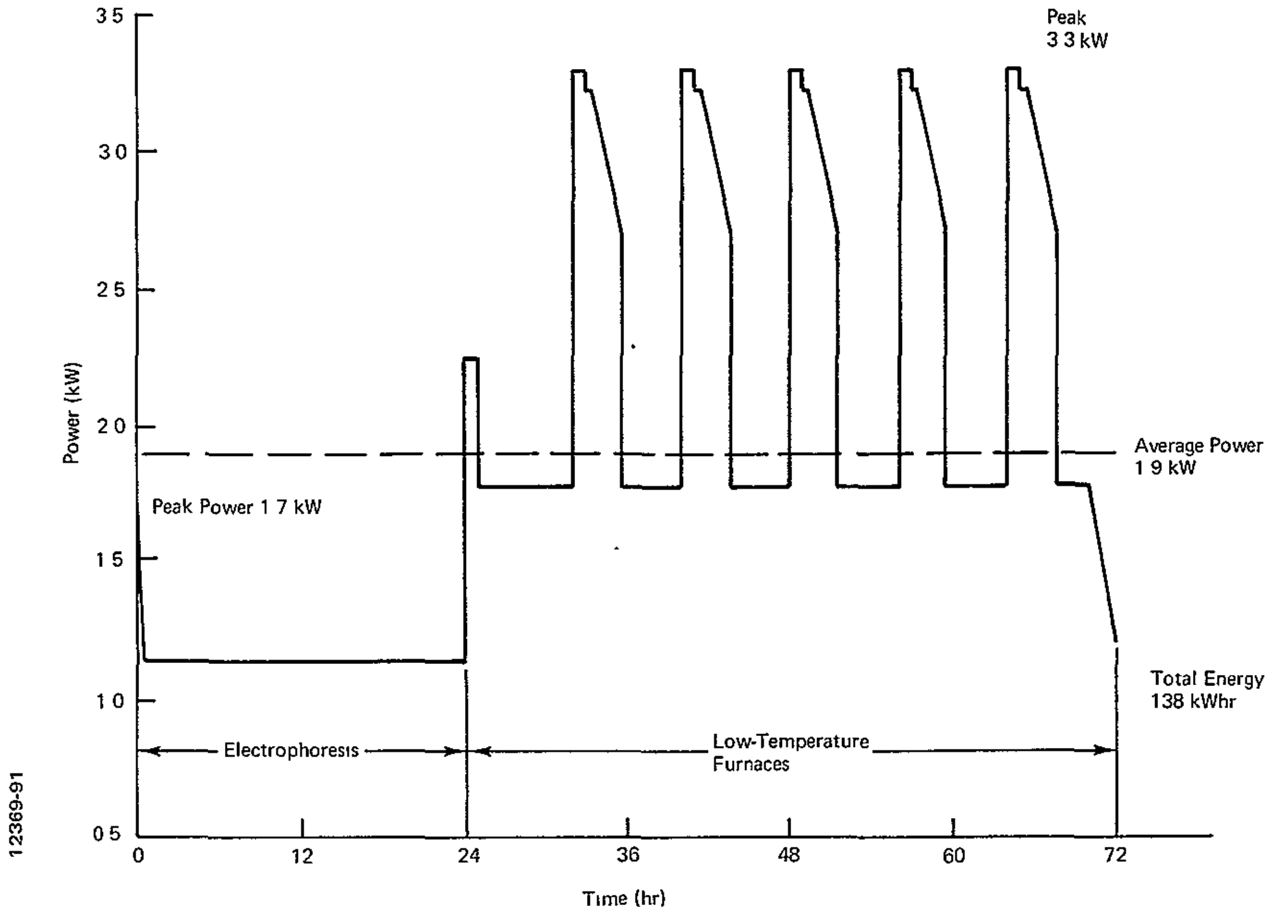


Figure 6-12 Payload 1 Typical Power Profile

6.4.3 Payload 3

Payload 3 contains three processing facilities; an electrophoresis facility, an electromagnetic levitation facility, and a multiple low-temperature furnace facility. Figure 6-16 is a functional diagram of the payload, and Table 6-6 is a weight and power summary for the components making up the system. This payload, packaged into the truss structure, is shown in Figure 6-17. A typical power profile for the payload for a 3-day mission is shown in Figure 6-18. The mission consists of one electrophoresis separation, followed by six low-temperature crystal growth processes and processing of six samples in an electromagnetic levitation facility using an electron-beam gun heating source. (Note the scale differences on the power profile.) A continuous segment of greater than 72 hours at 10^{-4} g or less is not required for the mission. Processing functions may be undertaken during any convenient interval. A 90%-efficient 400-Hz inverter supplies the furnace and core equipment power. This payload also operates in conjunction with the Shuttle Orbiter power and heat rejection scheme and uses the same 1.524 m (5-ft)-long truss structure as the other cargo bay-mounted payloads.

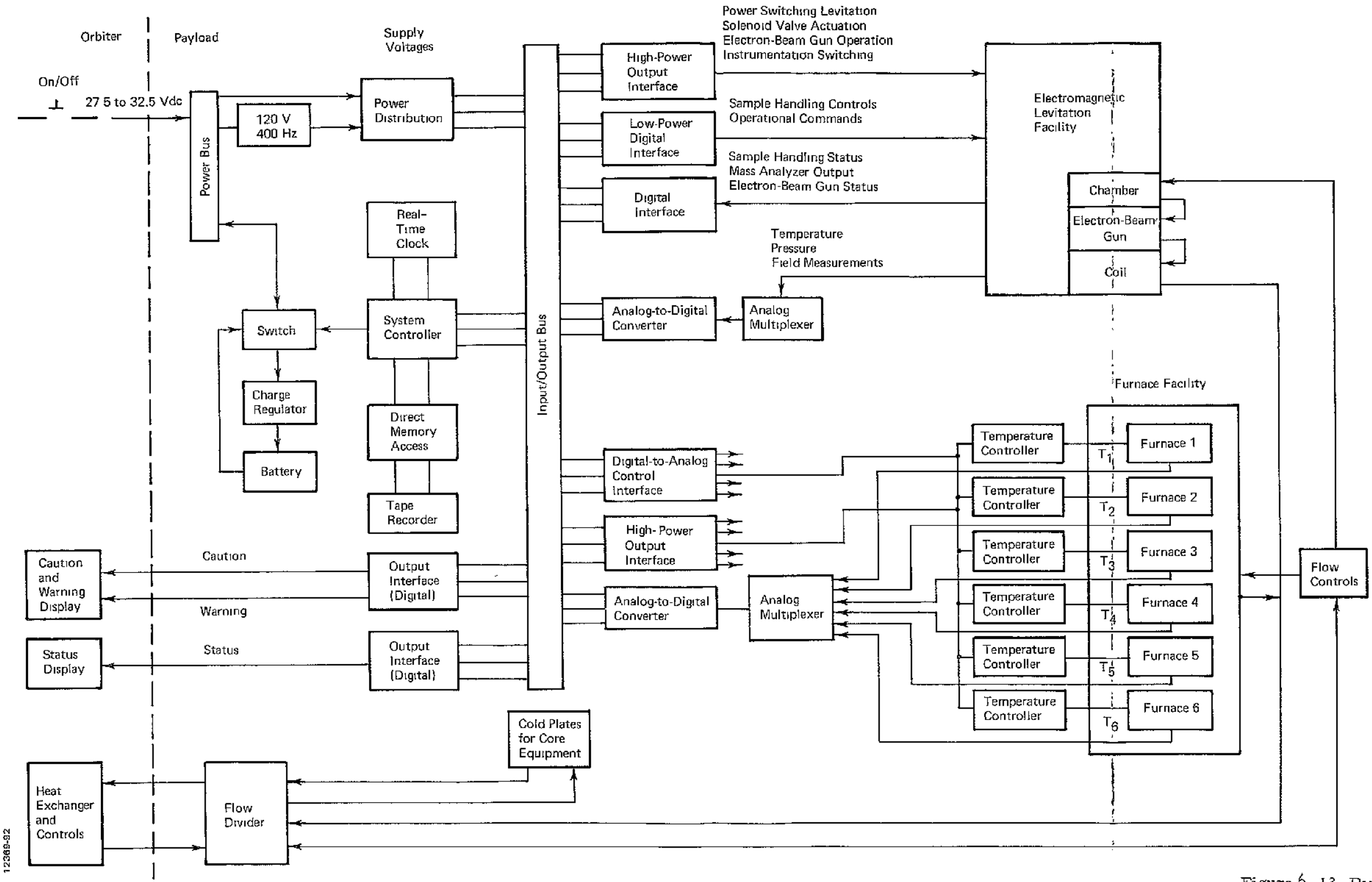


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Figure 6-13 Payload 2 Functional Diagram

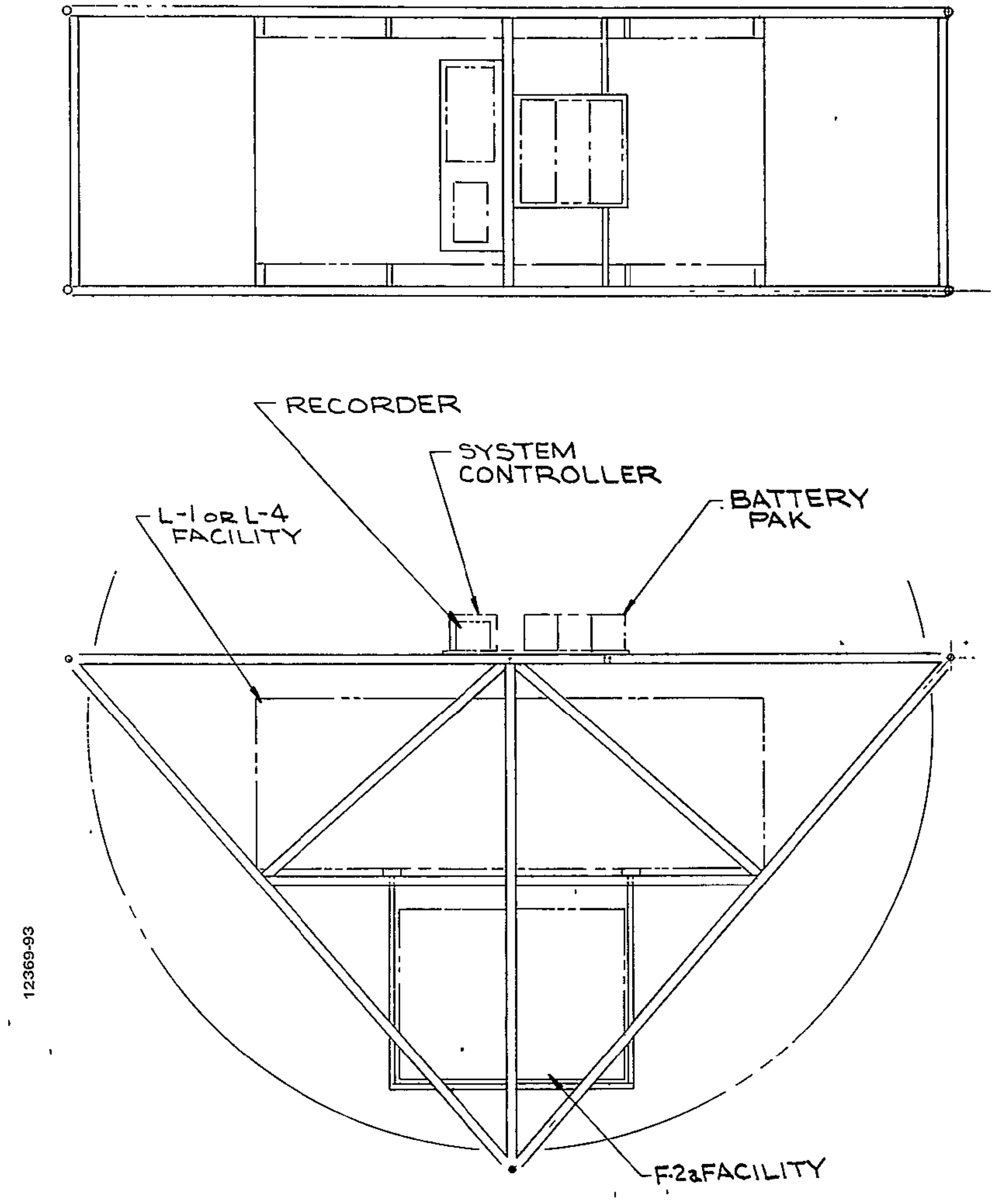


Figure 6-14 Payload 2 Configuration

Table 6-5

Payload 2 Weight and Power Summary

Item	Weight (lb)	Weight (kg)	Power (W)	
MULTIPLE FURNACE FACILITY				F-2
Enclosure and support structure	145	66		---
Furnaces (6)	240	109		2, 250
Transformer	40	18		250
Power controller (6)	30	14		50
Interface electronics	12	5		10
Interface cabling	12	5		---
Cold Plate, plumbing, and coolant	82	38		---
	561	255		2, 560
ELECTROMAGNETIC LEVITATION FACILITY				
Structure	178	81	---	
Chamber and structure	143	65	---	
Sample handling	145	66	(125)	
Plumbing, valves, and gas supply	125	56	(5)	
Ion pump and controller	250	114	3, 680	(325)
Instrumentation	70	32	(550)	
Electron-beam gun and power supply	65	30	(1, 884)	
Levitation generator and coil	7	3	(141)	
Interface cabling	11	5	---	
Cold Plates, plumbing, and coolant	89	40	---	
	1, 083	492	3, 680	(2, 900)
CORE UNIT				
Controller and input/output interfaces	63	28	307	
Recorder	17	8	17	
Power supply (400 Hz)	50	23	120	(250)
Power distribution	15	7	20	
Batteries (9 kWhr) and charge regulator	210	95	---	
	355	161	464	
SUPPORT STRUCTURE	220	100	---	
TOTAL	2, 219	1, 008	4, 144	(3, 274)

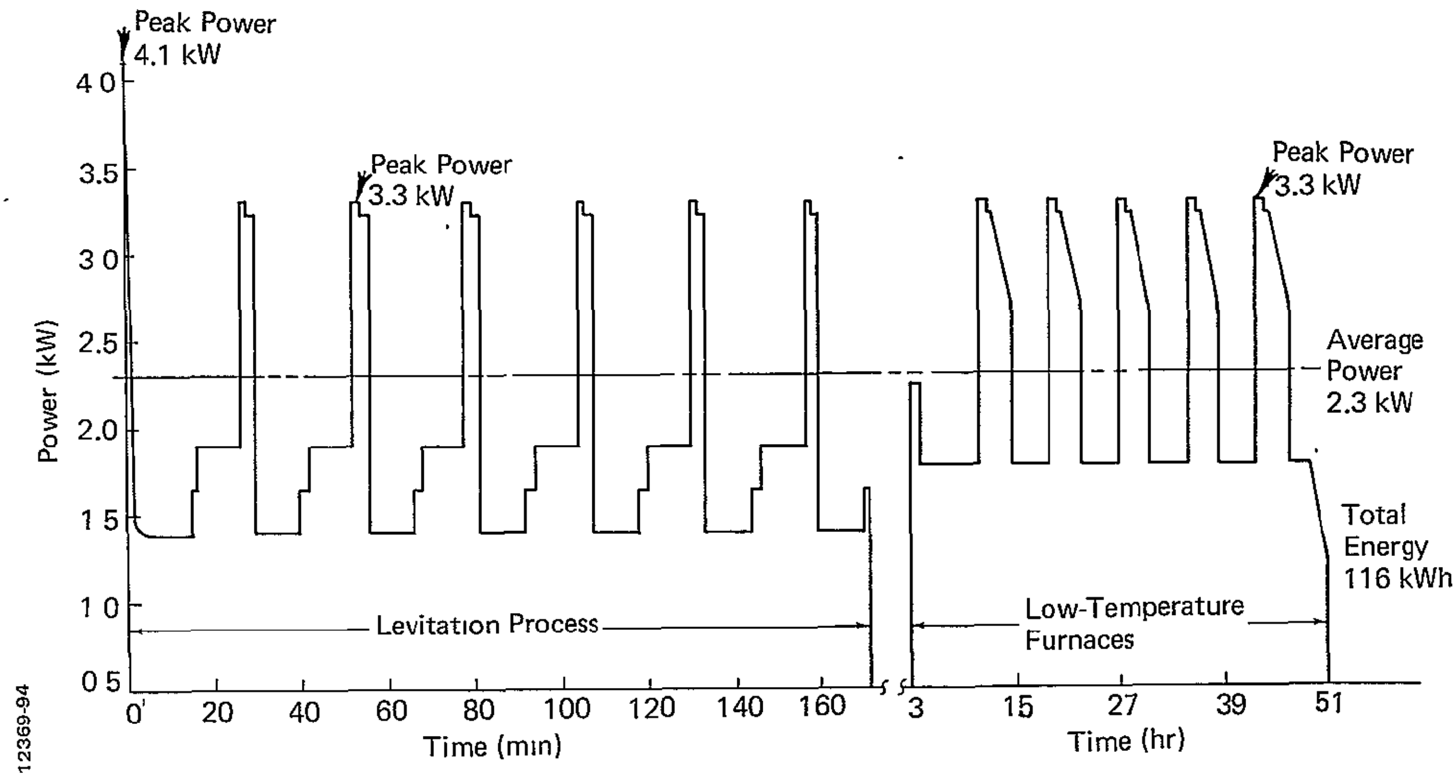


Figure 6-15 Payload 2 Typical Power Profile

6.5 AUXILIARY PAYLOAD POWER SYSTEM PAYLOADS

Three payloads have been configured using the Auxiliary Payload Power System (APPS) unit. One payload consists of the experimental equipment mounted on the APPS for test purposes, but the system obtains power and thermal control support external to the payload. A second payload consists of the experimental equipment and a 7.5-kW APPS unit. The third payload is a full-up (15-kW) APPS unit and experiment payload.

6.5.1 APPS (Unpowered) Payload; Payload 4

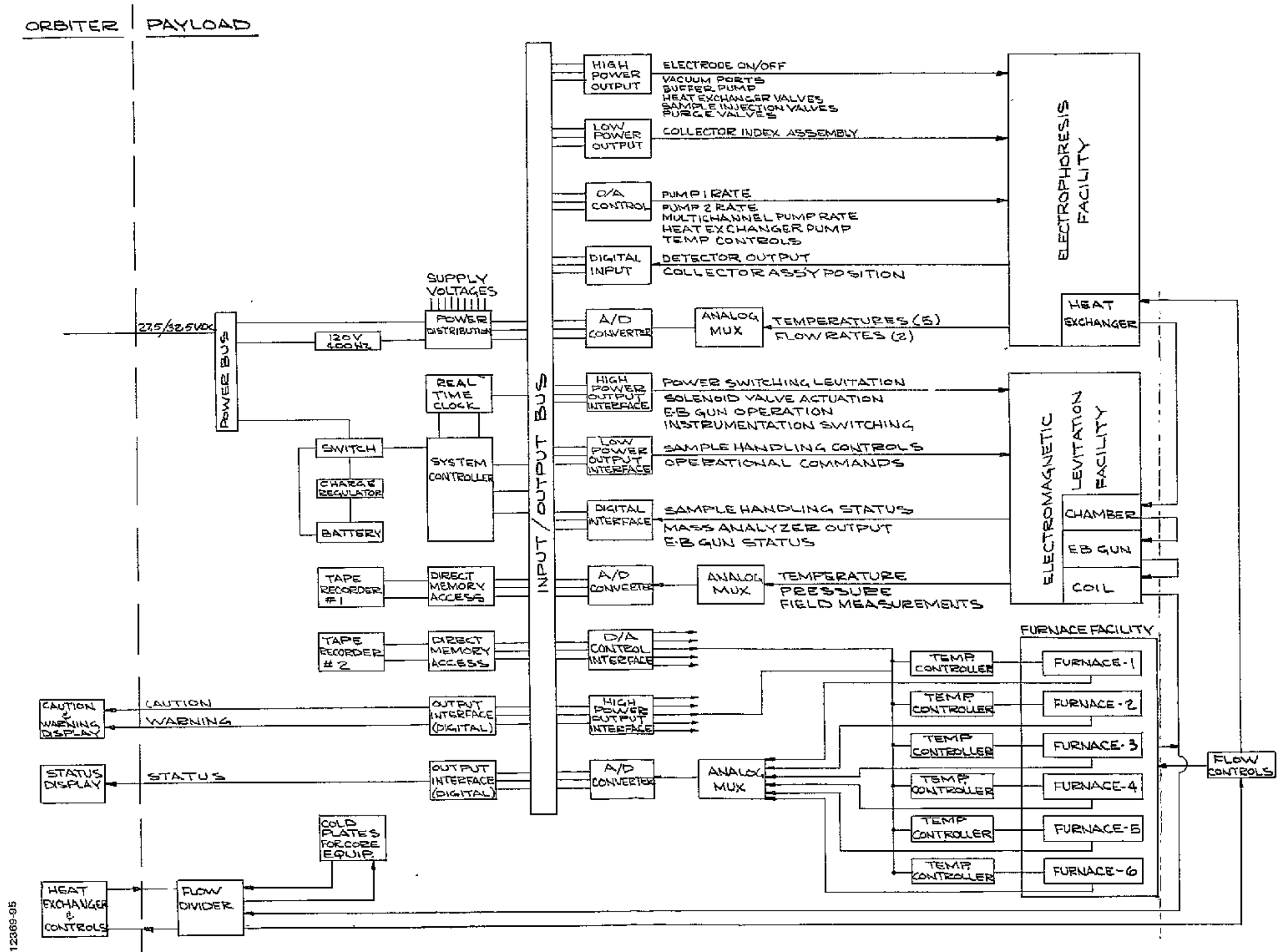
The purpose of this payload is to check out interfaces between the APPS Unit and the Shuttle Orbiter with a reactive payload and live interfaces. The payload consists of the same experiment facilities as those listed for Payload 3. The APPS would contain the basic tankage and hardware, including radiator, to be used on future missions. However, the radiator would not be deployed and the equipment would operate in a mode similar to that of Payload 3, i.e., it would draw power and thermal control from the Shuttle Orbiter. Table 6-7 contains a weight and power summary of the equipment to be incorporated, not including the basic APPS unit. The power and energy requirements and the mission are similar to those of Payload 3. Figure 6-19 is a layout drawing of Payload 4.

6.5.2 APPS (7.5-kW) Payload, Payload 5

The purpose of this payload is to check out interfaces between the APPS unit and the Shuttle Orbiter and to perform a limited experimental program. The NASA Materials Science Unit Feasibility Study has been used as the basis of the configuration. The payload is shown in Figure 6-20. A weight and power summary for the experiment equipment portion of the payload is given in Table 6-8. The payload is similar to Payload 2 from a functional standpoint except that high-temperature furnaces have been substituted for the low-temperature crystal growth furnaces of Payload 2. Because of the extended orbital duration (up to 5 days), a more extensive experiment program can be performed. A typical power profile for a mission, consisting of six high-temperature glass processes followed by six containerless processing operations using an electromagnetic levitation facility and electron-beam gun, is shown in Figure 6-21. A continuous period of 120 hours at 10^{-4} g or less is not required. The mission profile may be broken in any convenient segment. The furnace heating power is supplied by a 90%-efficient 400-Hz inverter, which may be supplied as a part of the experiment payload or as part of the APPS unit.

6.5.3 APPS (15-kW) Payload, Payload 6

This payload utilizes the full capability of the APPS unit and is a self-contained unit. All power and heat rejection requirements are supplied by the APPS unit. The only functional interface with the Shuttle Orbiter or Spacelab is a caution and warning signal and some start-up power to the fuel-cell system. Figure 6-22 shows a functional diagram of the system. The diagram shows one definition of the APPS/Payload interface. In this concept, the APPS supplies dc power from the fuel-cells and from a peaking battery to the payload. The payload provides its own 400 Hz inversion, as required, to operate the experimental equipment, in particular, the furnaces and zone-refining facilities. Three coolant loops with associated pumps, coolant, and radiators are included. A central sequencer aboard the APPS unit is used to activate the primary sequence of events and to control the fuel-cell and thermal-control operation. The core equipment in the payload includes two processors, input/output equipment, two tape recorders, the 400-Hz inverter, and the power distribution system. Table 6-9 is a summary of the weight and power requirements of the equipment. A typical power profile for a 5-day mission is given in Figure 6-23.



FOLDOUT FRAME 1

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Figure 6-16 Payload 3 Functional Diagram

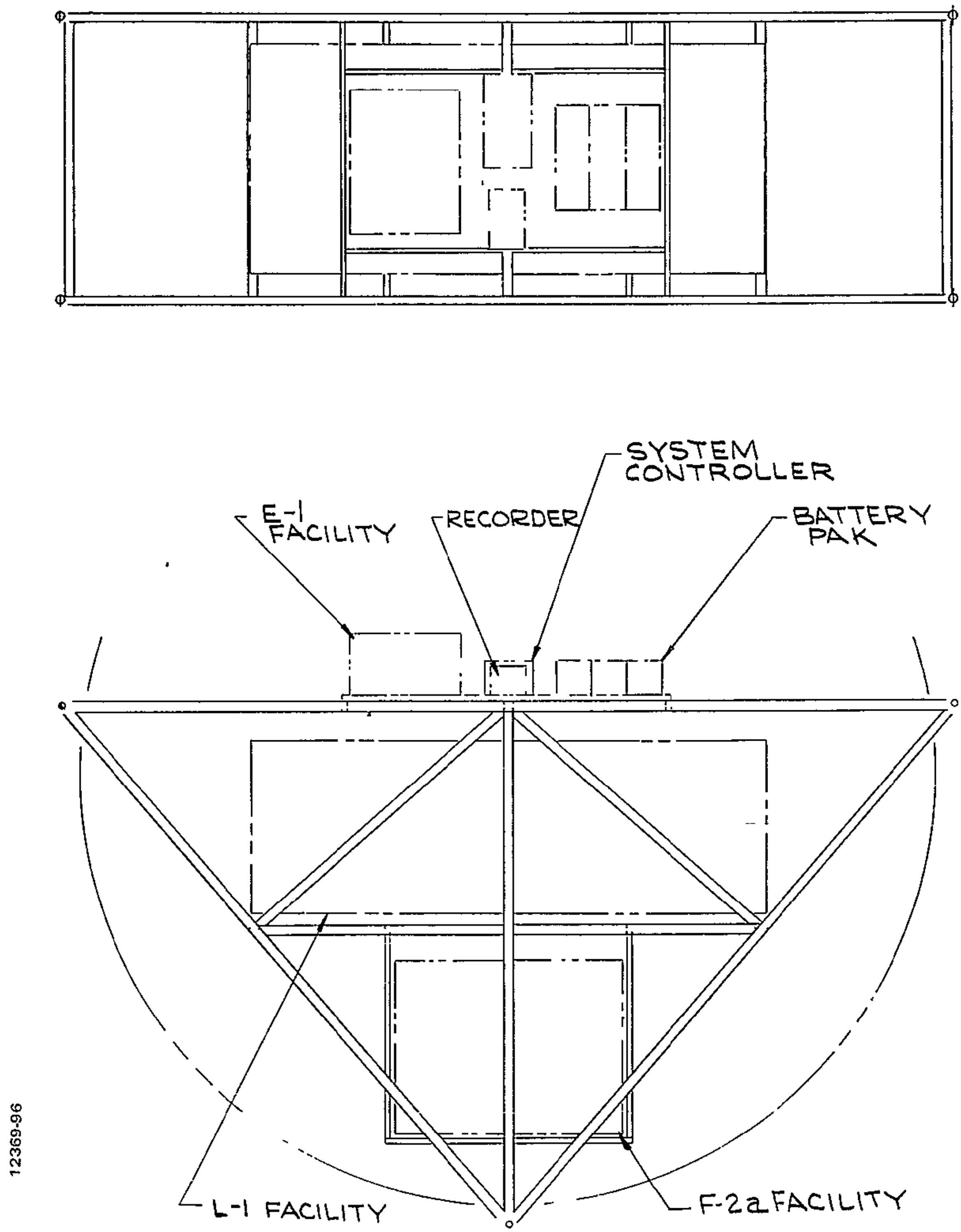

Figure 6-17 Payload 3 Configuration

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Table 6-6

Payload 3 Weight and Power Summary

Item	Weight (lb)	Weight (kg)	Peak Power (W)	
MULTIPLE FURNACE FACILITY			F-2	
Enclosure and structural support	145	66		----
Furnaces (6)	240	109		2, 250
Transformer	40	18		250
Power controller (6)	30	14		50
Interface electronics	12	5		10
Interface cabling	12	5		----
Cold Plate, plumbing, and coolant	82	38		----
	561	255		2, 560
ELECTROMAGNETIC LEVITATION				
Structure	178	81	----	
Chamber and structure	143	65	----	
Sample handling	145	66	(125)	
Plumbing, valves, and gas supply	125	56	(5)	
Ion pump and controller	250	114	3, 680	(325)
Instrumentation	70	32	(550)	
Electron-beam gun and power supply	65	30	(1, 884)	
Levitation generator and coils	7	3	(141)	
Interface cabling	11	5	----	
Cold Plates, plumbing, and coolant	89	40	----	
	1, 083	492	3, 680	(2, 900)
ELECTROPHORESIS FACILITY				
Cell buffer system	25	11	210	
Sample injection	15	7	10	
Electrode buffer system	15	7	100	
Separation cell and fraction collector	32	15	270	
Heat exchanger and circulation	24	11	355	
Plumbing and mounts	5	2	----	
Power supply	15	7	250	
Fluids	39	18	----	
Structure	23	10	----	
	193	88	1, 195	

Table 6-6

Payload 3 Weight and Power Summary (Cont.)

Item	Weight (lb)	Weight (kg)	Peak Power (W)	
CORE UNIT				
Controller and input/output interfaces	102	46	420	
Recorders (2)	34	15	34	
Power supply (400 Hz)	50	23	150	(250)
Power distribution	25	11	25	
Batteries (9 kWhr) and charger	210	96	----	
	421	191	629	
STRUCTURE	250	114	----	
TOTAL	2, 508	1, 140	4, 309	

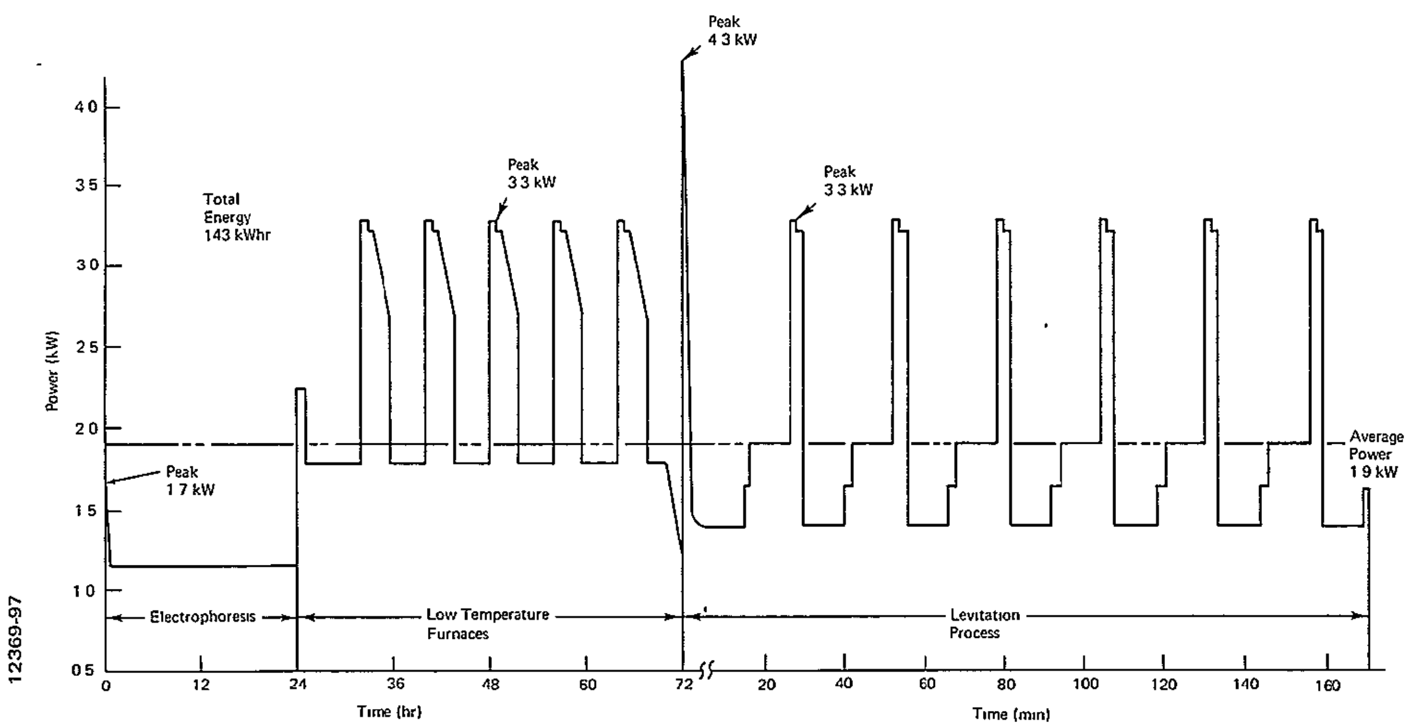

Figure 6-18 Payload 3 Typical Power Profile

Table 6-7

Payload 4 Weight and Power Summary

Item	Weight (lb)	Weight (kg)	Peak Power (W)	
MULTIPLE FURNACE FACILITY			F-2	
Enclosure and structural support	145	66	----	
Furnaces (6)	240	109	2, 250	
Transformer	40	18	250	
Power controller (6)	30	14	50	
Interface electronics	12	5	10	
Interface cabling	12	5	-----	
Cold plate, plumbing, and coolant	82	38	-----	
	561	255	2, 560	
ELECTROMAGNETIC LEVITATION FACILITY				
Structure	178	81	-----	
Chamber and structure	143	65	-----	
Sample handling	145	66	125	
Plumbing, valves, and gas supply	125	56	5	
Ion pump and controller	250	114	3, 680	(325)
Instrumentation	70	32	550	
Electron-beam gun and power supply	65	30	1, 884	
Levitation generator and coils	7	3	141	
Interface cabling	11	5	-----	
Cold plates, plumbing, and coolant	89	40	-----	
	1, 083	492	3, 680	(2, 900)
ELECTROPHORESIS FACILITY				
Cell buffer system	25	11	210	
Sample injection	15	7	10	
Electrode buffer system	15	7	100	
Separation cell and fraction collector	32	15	270	
Heat exchanger and circulation	24	11	355	
Plumbing and mounts	5	2	---	
Power supply	15	7	250	
Fluids	39	18	---	
Structure	23	10	---	
	193	88	1, 195	
CORE UNIT				
Controller and input/output interfaces	102	46	420	
Recorders (2)	34	15	34	
Power supply (400 Hz)	50	23	150	(250)
Power distribution	25	11	25	
	211	95	629	

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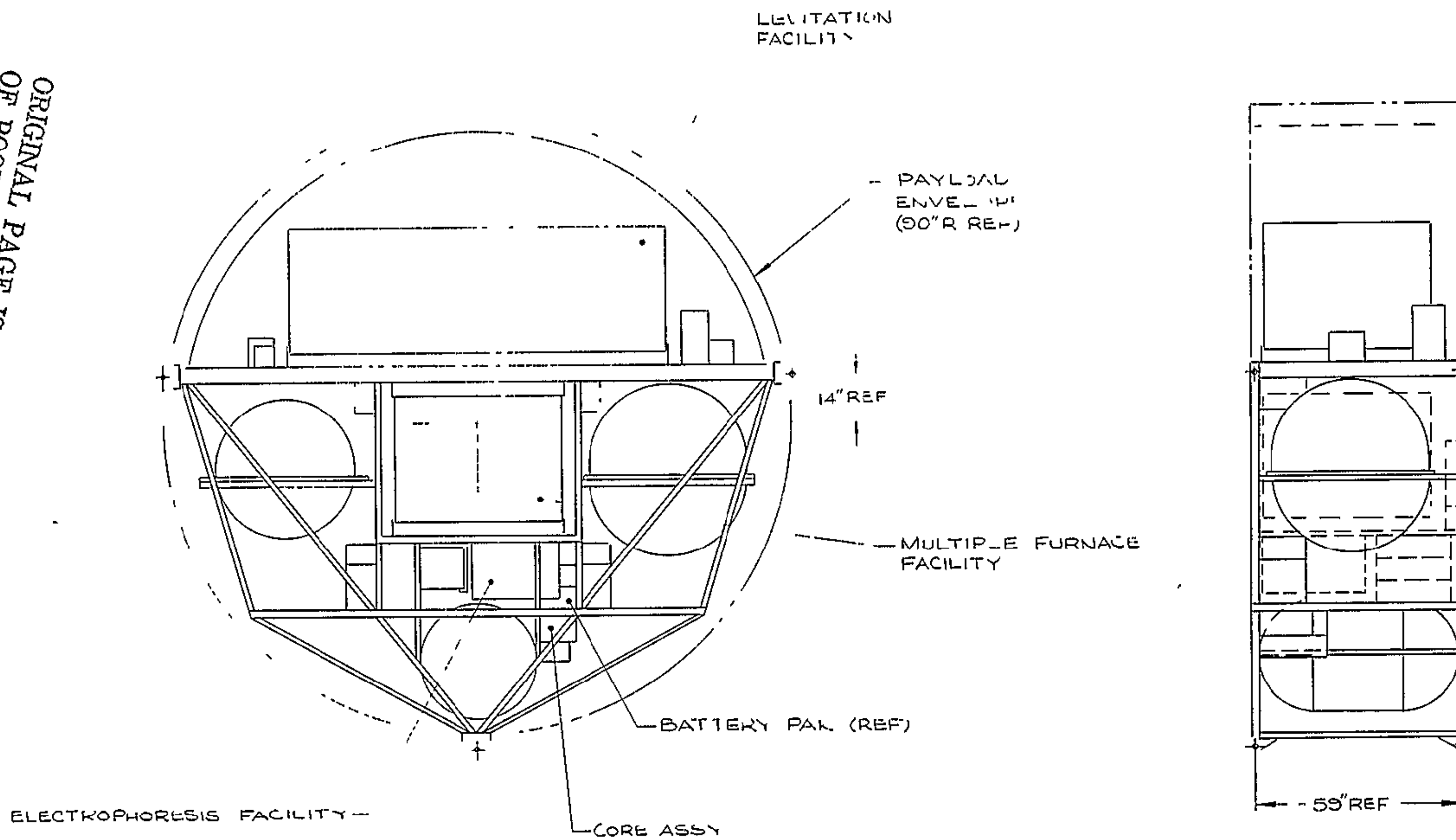

Figure 6-19 Payload 4 Configuration

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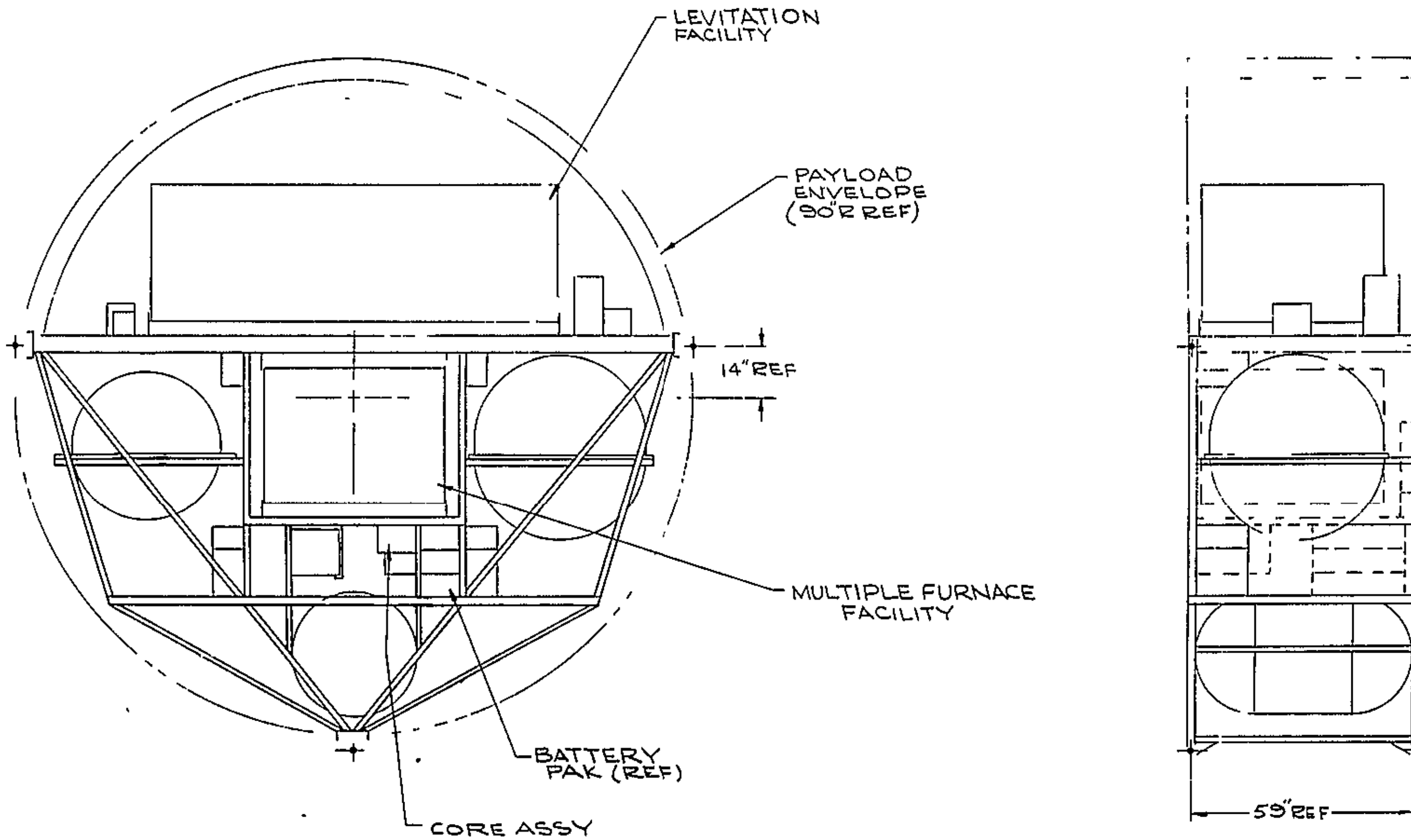

Figure 6-20 Payload 5 Configuration

Table 6-8

Payload 5 Weight and Power Summary

Item	Weight (lb)	Weight (kg)	Peak Power (W)	
MULTIPLE FURNACE FACILITY				
Enclosure and structural support	145	66		
Furnaces (6)	240	109	4, 399	
Power controller (6)	30	14	90	
Interface electronics	12	5	10	
Interface cabling	12	5		
Cold Plate, plumbing, and coolant	82	38		
	521	237	4, 499	
ELECTROMAGNETIC LEVITATION FACILITY				
Structure	178	81		
Chamber and structure	143	65		
Sample handling	145	66	(125)	
Plumbing, valves, and gas supply	125	56	(5)	
Ion pump and controller	250	114	3, 680	(325)
Instrumentation	70	32	550	
Electron-beam gun and power supply	65	30	1, 884	
Levitation generator and coils	7	3	141	
Interface cabling	11	5	----	
Cold Plate, plumbing, and coolant	89	40	----	
	1, 083	492	4, 230	
CORE UNIT				
Controller and input/output interfaces	63	28	307	
Recorder	17	8	17	
Power supply	50	23	120	(575)
Power distribution	15	7	20	
	145	66	464	
TOTAL	1, 749	795	5, 863	

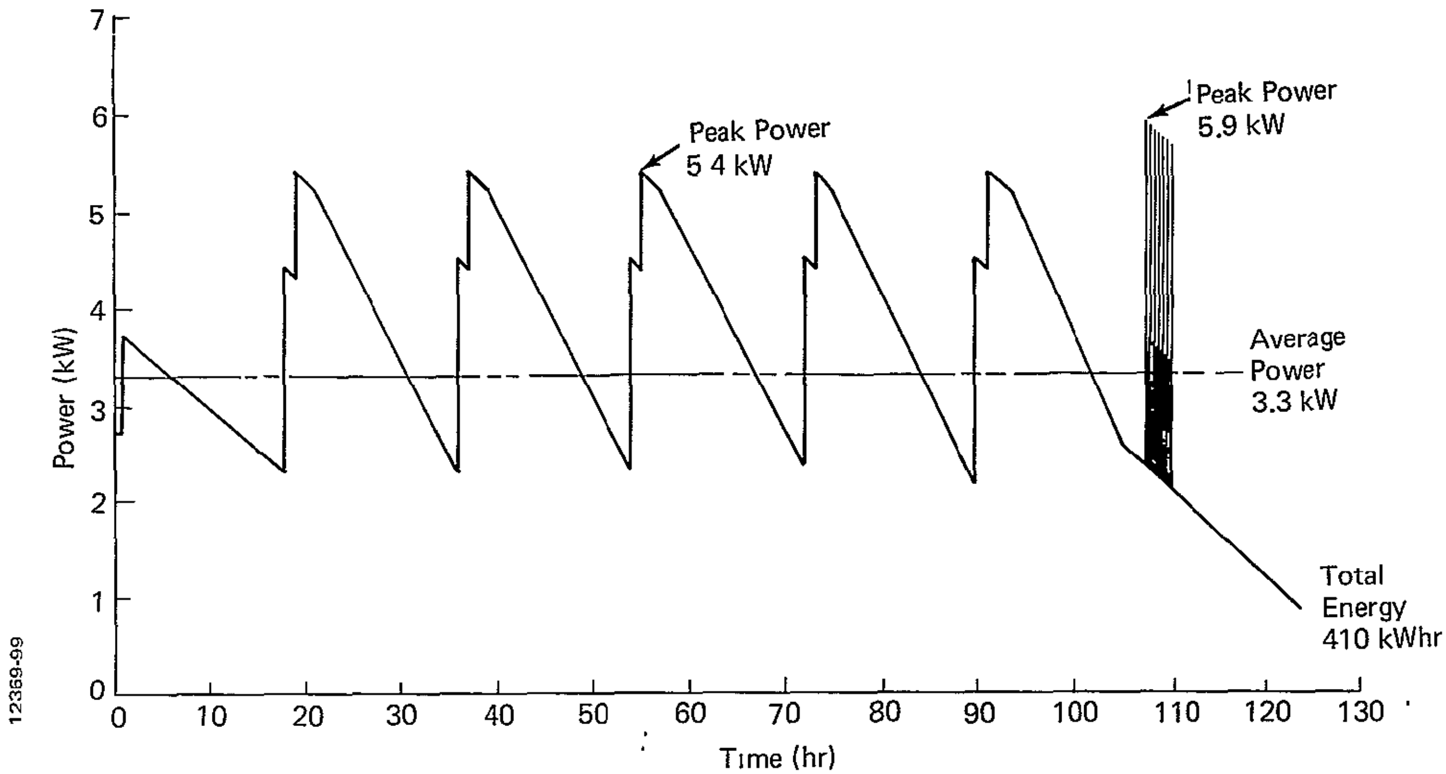

Figure 6-21 Payload 5 Typical Power Profile

The power profile is based on the following equipment and mission parameters:

- Molten Zone Crystal Growth Experiment - 120 hours.
- Material Purification - 120 hours (three passes over a 40-cm rod at a rate of 1 cm per hr).
- Low-Temperature Furnaces - Six crystal growth processes.
- Acoustic Levitation - Containerless processing of six samples.

Processing operations may be undertaken in any convenient segments. A period of 120 hours continuously at 10^{-4} g or less is not required. Energy of 1,500 kWhr is required for this mission. The payload configured in a 15-kW APPS unit is shown in Figure 6-24. The payload can be accommodated in about 2.44 m (8 ft) of cargo bay length. The structure is similar to that used for the 7.5-kW unit except for the additional tankage supports required to accommodate the cryogenics necessary to supply the system.

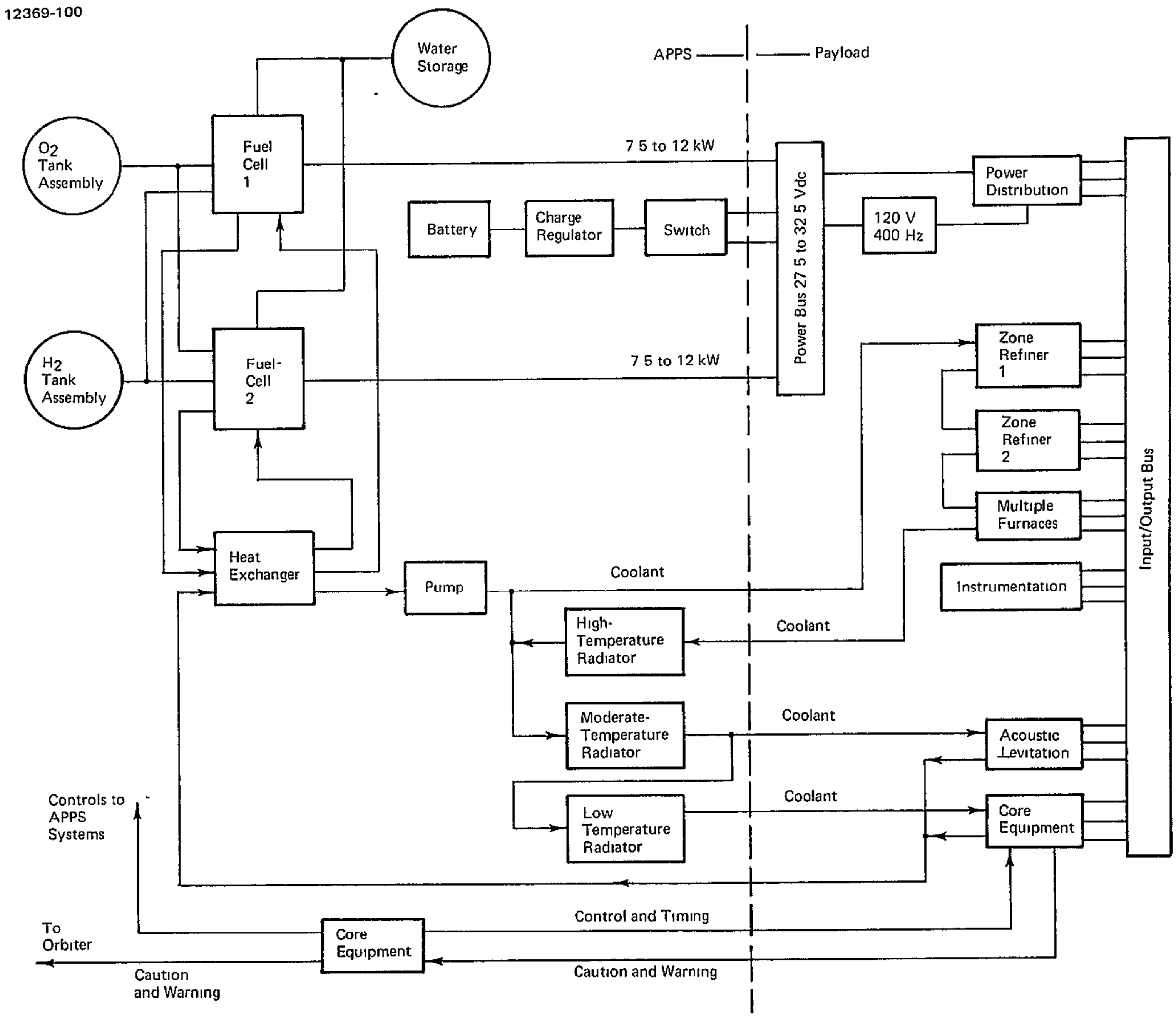

Figure 6-22 Payload 6 Functional Diagram

Table 6-9

Payload 6 Weight and Power Summary

Item	Weight (lb)	Weight (kg)	Power (W)	
ACOUSTIC LEVITATION FACILITY				
Structure	160	73	----	
Chamber and support structure	140	64	----	
Sample handling system	145	66	125	
Furnaces	46	21	1,770	
Furnace controller	34	15	120	
Instrumentation	38	17	49	
Gas system	45	20	5	
Acoustic levitation	26	12	10	
Interface cabling	8	4	----	
Cold plates, plumbing, and coolant	89	40	----	
	731	332	2,077	
MULTIPLE FURNACE FACILITY				
Enclosure and support structure	145	66	----	
Furnaces (6)	240	109	2,250	
Transformer	40	18	250	
Power controller	30	14	50	
Interface electronics	12	5	10	
Interface cabling	12	5		
Cold plate, plumbing, and coolant	82	38		
	561	255	2,560	
			Crystal Growth	Purification
ZONE REFINING FACILITIES (2)				
Structure	136	62		
Furnaces	10	5	4,500	1,800
Traverse mechanism	60	27	320	320
Furnace controllers	94	43	53	53
Vacuum and gas system	230	105	264	264
Instrumentation	50	23	19	19
Interface cabling	18	8	----	----
Cold plates, plumbing, and coolant	168	76	----	----
	766	348	5,756	2,456

Table 6-9

Payload 6 Weight and Power Summary (Cont.)

Item	Weight (lb)	Weight (kg)	Power (W) Crystal Growth	Power (W) Purification
CORE UNIT				
Controllers and input/output units	160	73		455
Recorders (2)	34	15		34
Power supply	100	45	150	(2, 750)
Power distributions	40	18		50
	334	151		689
TOTALS	2, 392	1, 086		15, 200

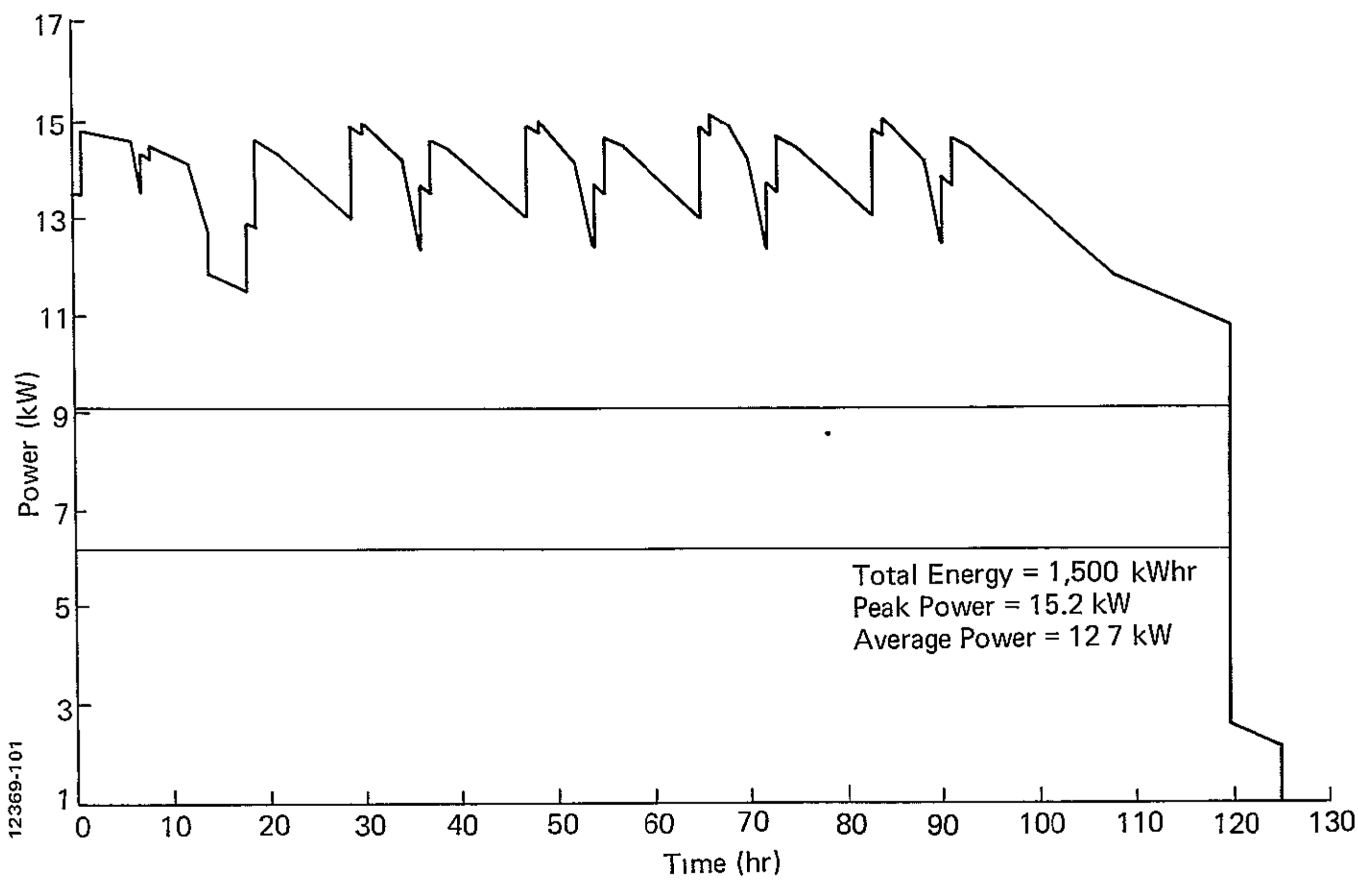

Figure 6-23 Payload 6 Typical Power Profile

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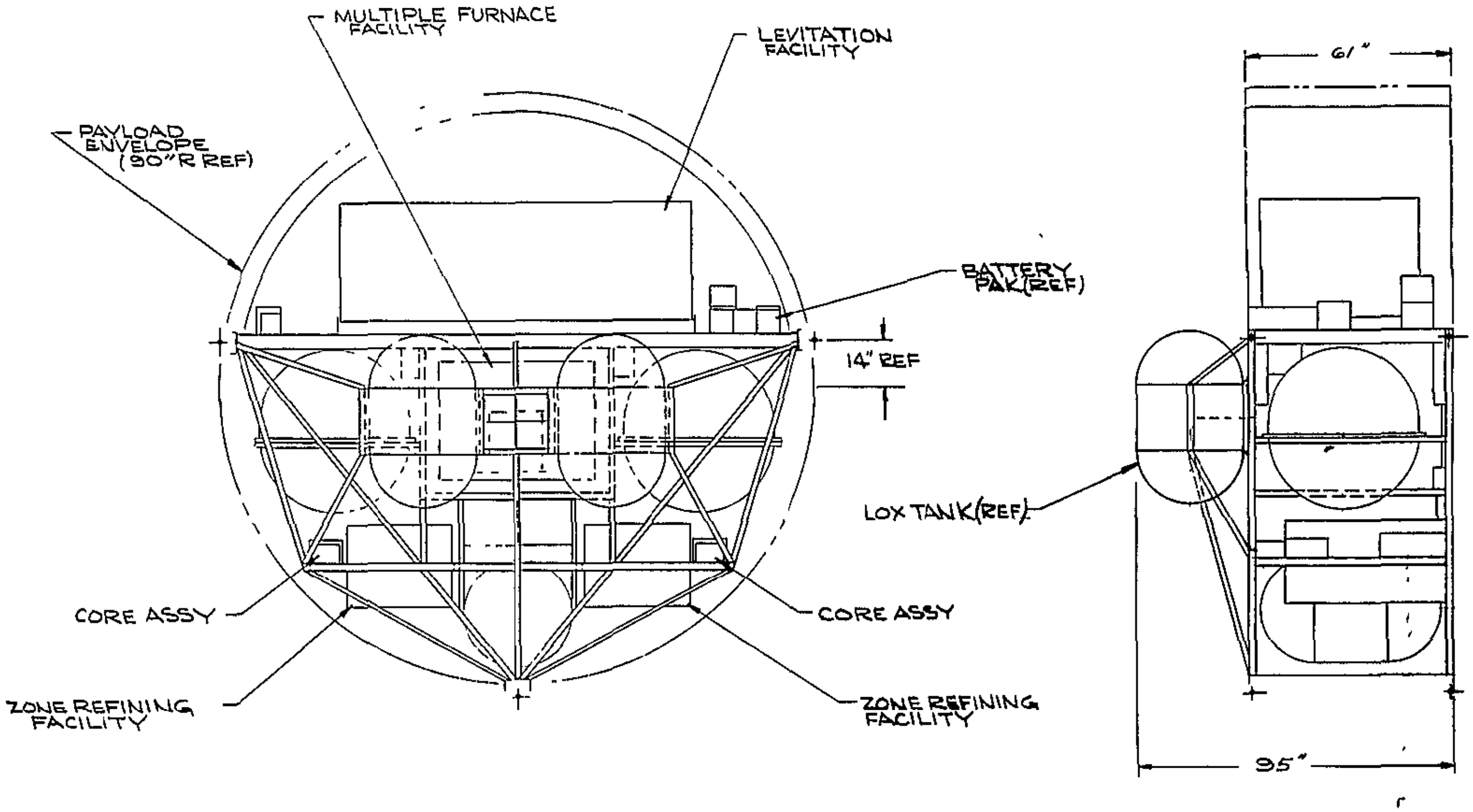

Figure 6-24 Payload 6 Configuration

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