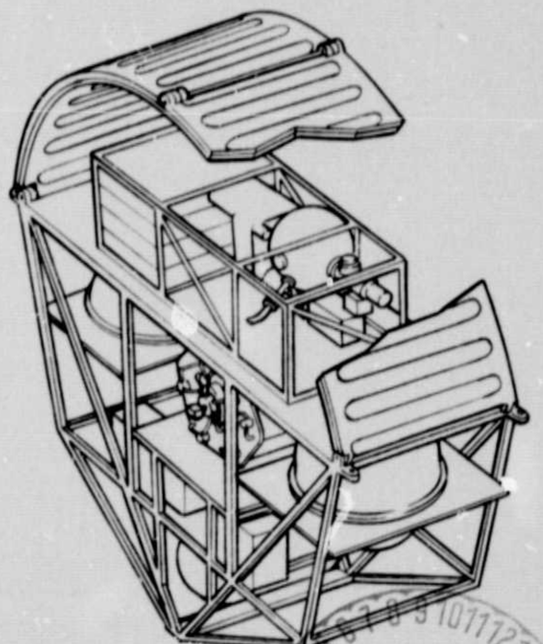
Automated Space Processing Payloads Study

(Contract NAS 8-30741)

Volume III
Equipment Development Resource Requirements

Final Report
BSR 4171

January 1975



Bendix **Aerospace Systems Division**

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Equipment Development Resource Requirements

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SECTION 1

INTRODUCTION

As part of the overall study effort, Bendix has identified the required resources (schedule, costs, and supporting research and technology effort) to develop the major equipment items or facilities forming automated space processing payloads. In particular, this volume addresses those facilities on which detailed preliminary design was undertaken and which may be used on early Space Shuttle missions in the 1979 to 1982 time-frame.

Section 2 describes the facilities and identifies the major hardware components making up each facility. Section 3 contains development schedules for the major hardware items and the payload buildup in accordance with the NASA Space Processing Applications Strawman Program for Early Space Shuttle Flights. Section 4 presents the cost data for the facilities and the assumptions and ground rules supporting these data. Section 5 presents a recommended listing of supporting research and technology needed to ensure high confidence in the ability to achieve successful development of the equipment and the technology necessary for the program.

SECTION 2

HARDWARE DESCRIPTION

Preliminary designs of six space processing facilities and variations of them were performed in the study and the development resource requirements were defined for each of the following processing hardware and associated equipment:

- L-1 Electromagnetic Levitation Facility
- L-4 Acoustic Levitation Facility
- F-1A Multiple High-Temperature Furnace Facility
- F-2A Multiple Low-Temperature Furnace Facility
- F-3A Zone Refining Facility
- E-1 Continuous Flow Electrophoresis Facility
- Core Control Facility

The following paragraphs summarize the hardware associated with each facility. A more detailed description of these facilities is contained in Volume II of this report.

2.1 ELECTROMAGNETIC LEVITATION FACILITY (L-1)

This facility features the capability for containerless processing of various materials by suspension of the sample specimen in a shaped electromagnetic field. A hardware tree for the facility is shown in Figure 2-1.

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 which 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.

On one 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.

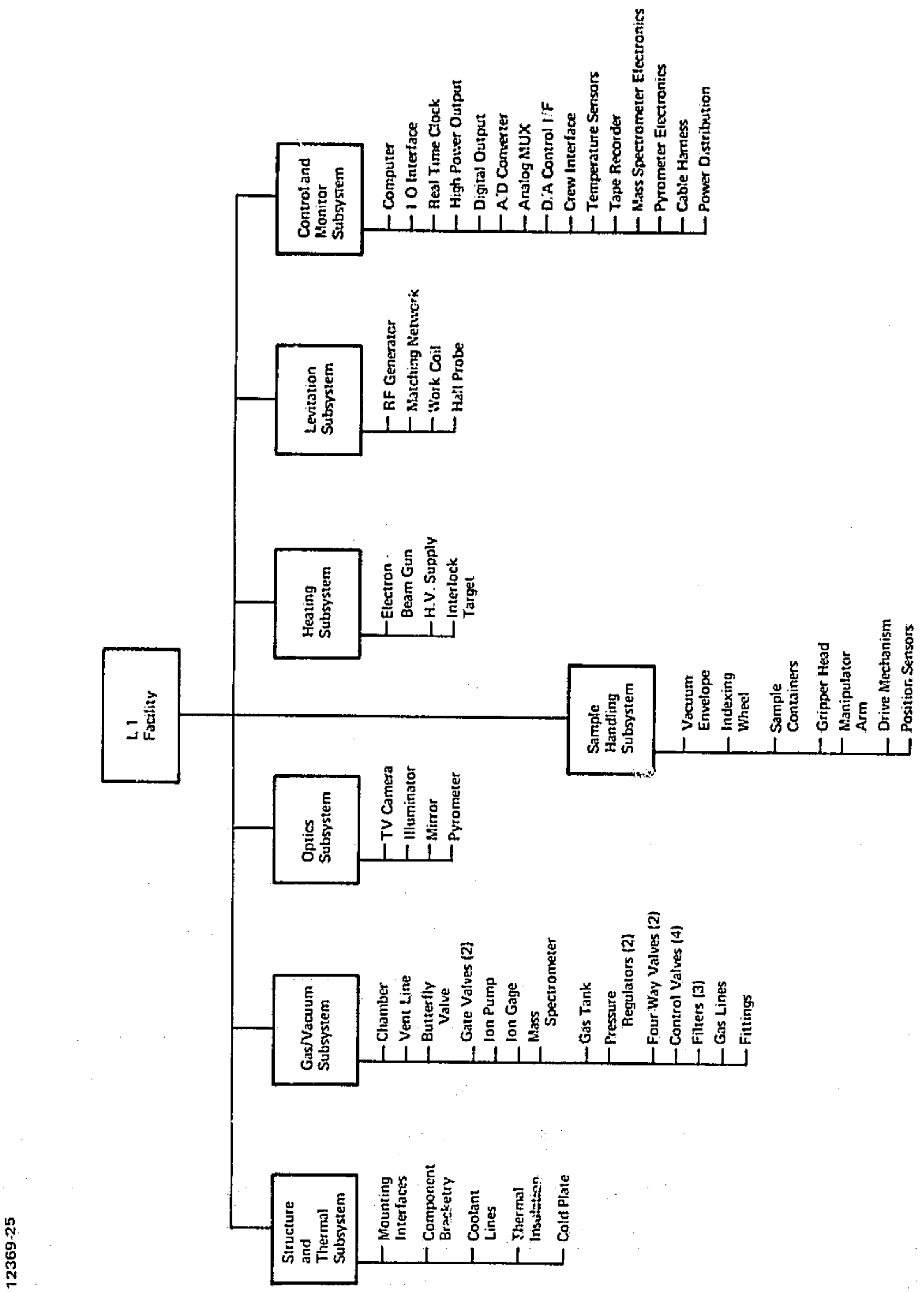

Figure 2-1 L-1 Facility Hardware Tree

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. Chamber 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 minicomputer, which is supplied as core equipment. Interface electronics permit inputting data to the computer and outputting control commands to valves, the heat source, the manipulator, and other devices. A tape recorder records data from the computer and picture data from the TV camera.

2.2 ACOUSTIC LEVITATION FACILITY (L-4)

This facility features the capability for containerless processing of various materials by suspension of the sample specimen in an acoustic force field. A hardware tree for the facility is shown in Figure 2-2.

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

Across the sphere and connecting two of its ports is the cylindrical 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 a line-of-sight from the molten sample.

An optical window in the elbow and dichroic mirror permit viewing the sample specimen with a TV camera and an optical pyrometer.

On the opposite end of the chamber, external to the sphere, is an acoustical reflector which establishes the acoustical standing wave. A microphone, located in the reflector, provides feedback for tuning the acoustical generator in order to maintain chamber resonance. A door in the reflector permits sample insertion and retrieval by the sample manipulator. The manipulator is identical to that used in L-1.

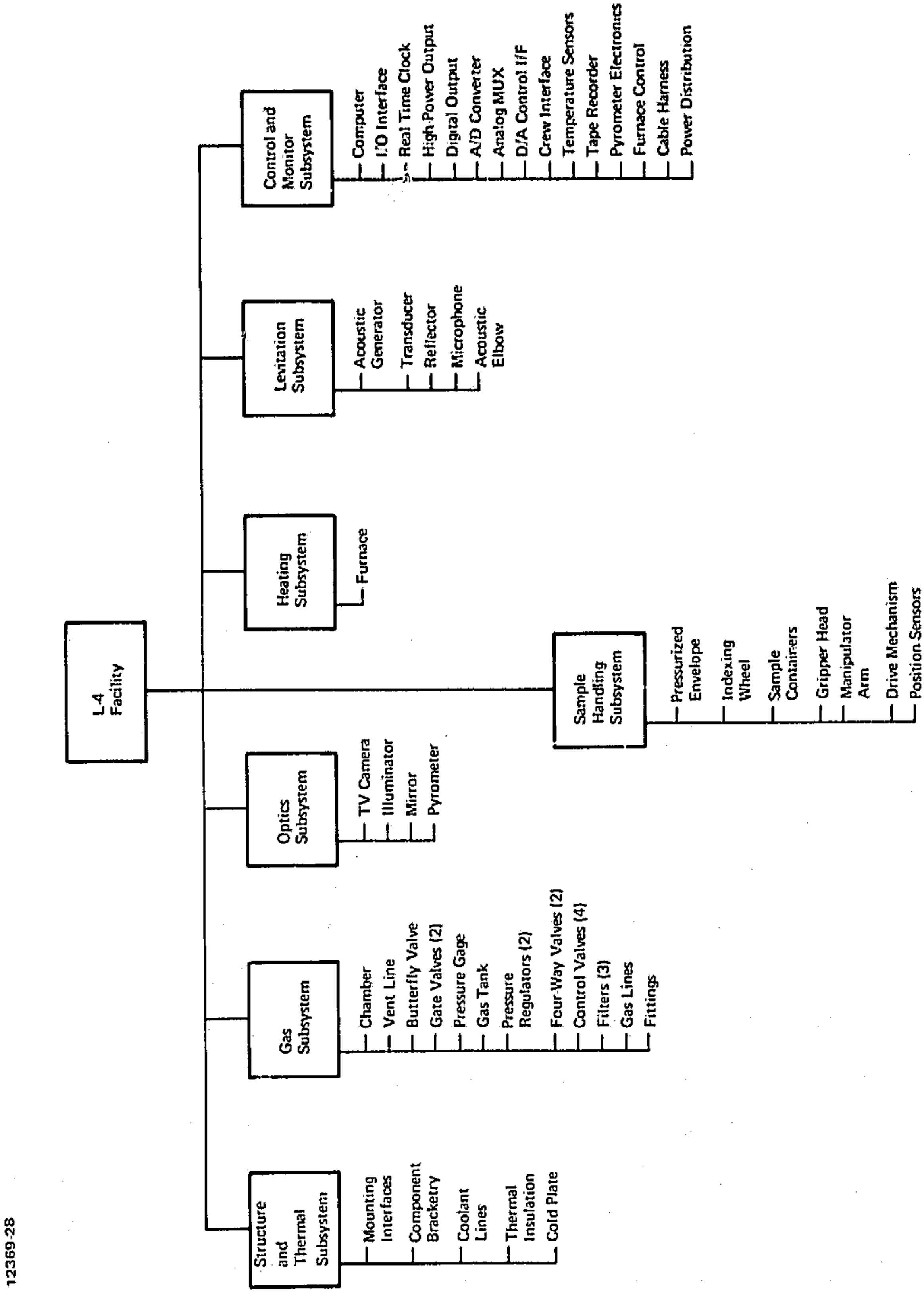

Figure 2-2 L-4 Facility Hardware Tree

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2.3 MULTIPLE HIGH-TEMPERATURE FURNACE FACILITY (F-1A) AND MULTIPLE LOW-TEMPERATURE FURNACE FACILITY (F-2A)

Furnace facilities F-1 and F-2 differ only in the temperature ranges for which they are designed, higher and lower than 1,200°C, respectively. Therefore, in this section, they are described together, with differences noted. Figure 2-3 is a hardware tree of the F-1 facility and Figure 2-4 is a hardware tree of the F-2 facility.

Six furnaces are mounted in a cluster, with provision for power, control, and thermal regulation. Typical furnaces used for design definition are, for F-1, the ARTCOR zirconia furnace, and for F-2, the Varian Marshall Model 1332. 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.

2.4 ZONE REFINING FACILITY (F-3)

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. Figure 2-5 is a hardware tree for the 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 vent tube, ion pump, and vacuum gage, or gas supply and pressure gage and controls. Provisions are also included for cooling fluids for furnace temperature control.

The electronic control system is similar to that described above for the F-1 and F-2 facilities.

2.5 ELECTROPHORESIS FACILITY (E-1)

The electrophoresis experiment preliminary design is based on prototype development work on a continuous-flow electrophoresis apparatus conducted for the Skylab Program. A hardware tree is shown in Figure 2-6. The system is

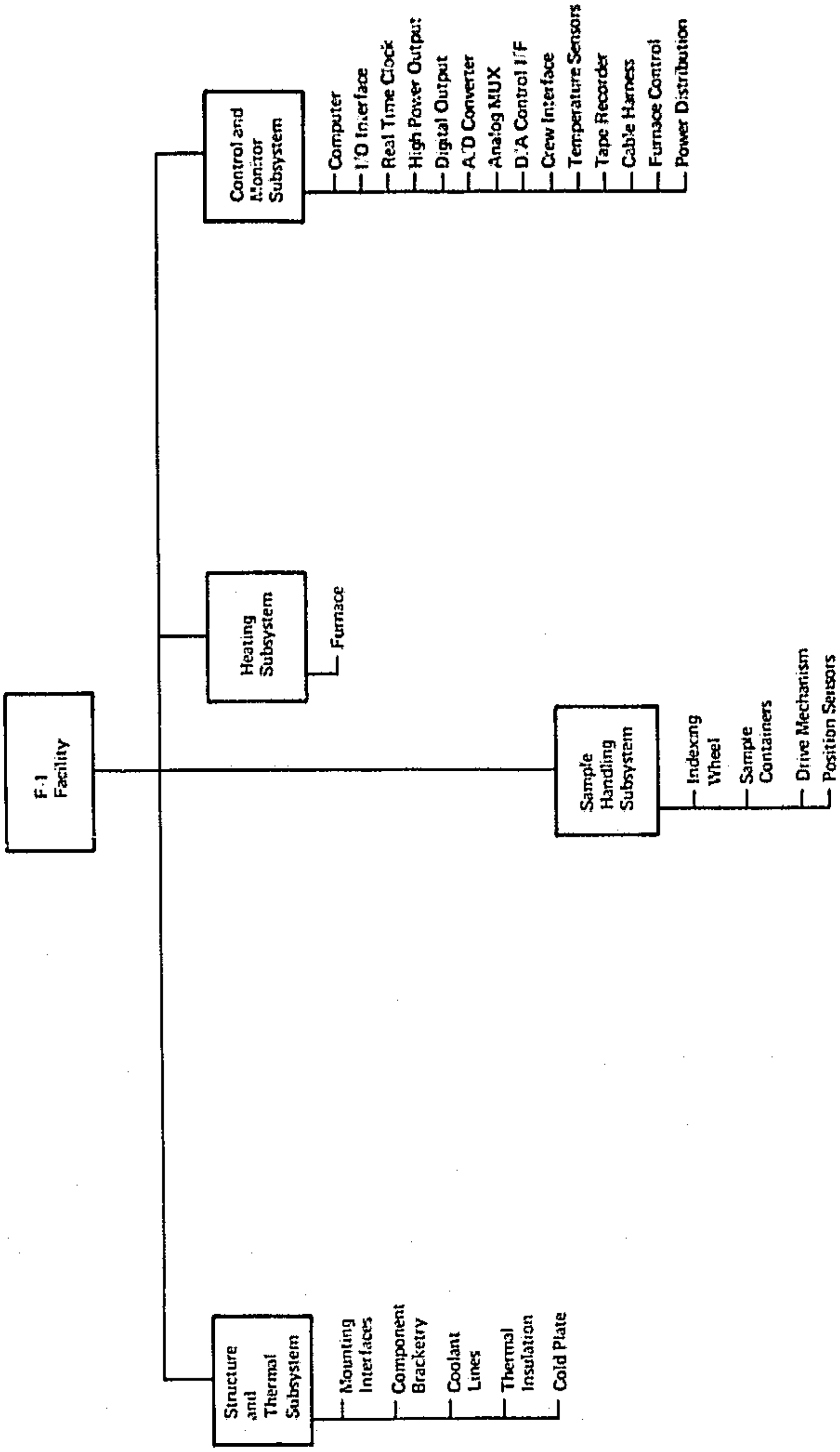

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Figure 2-3 F-1 Facility Hardware Tree

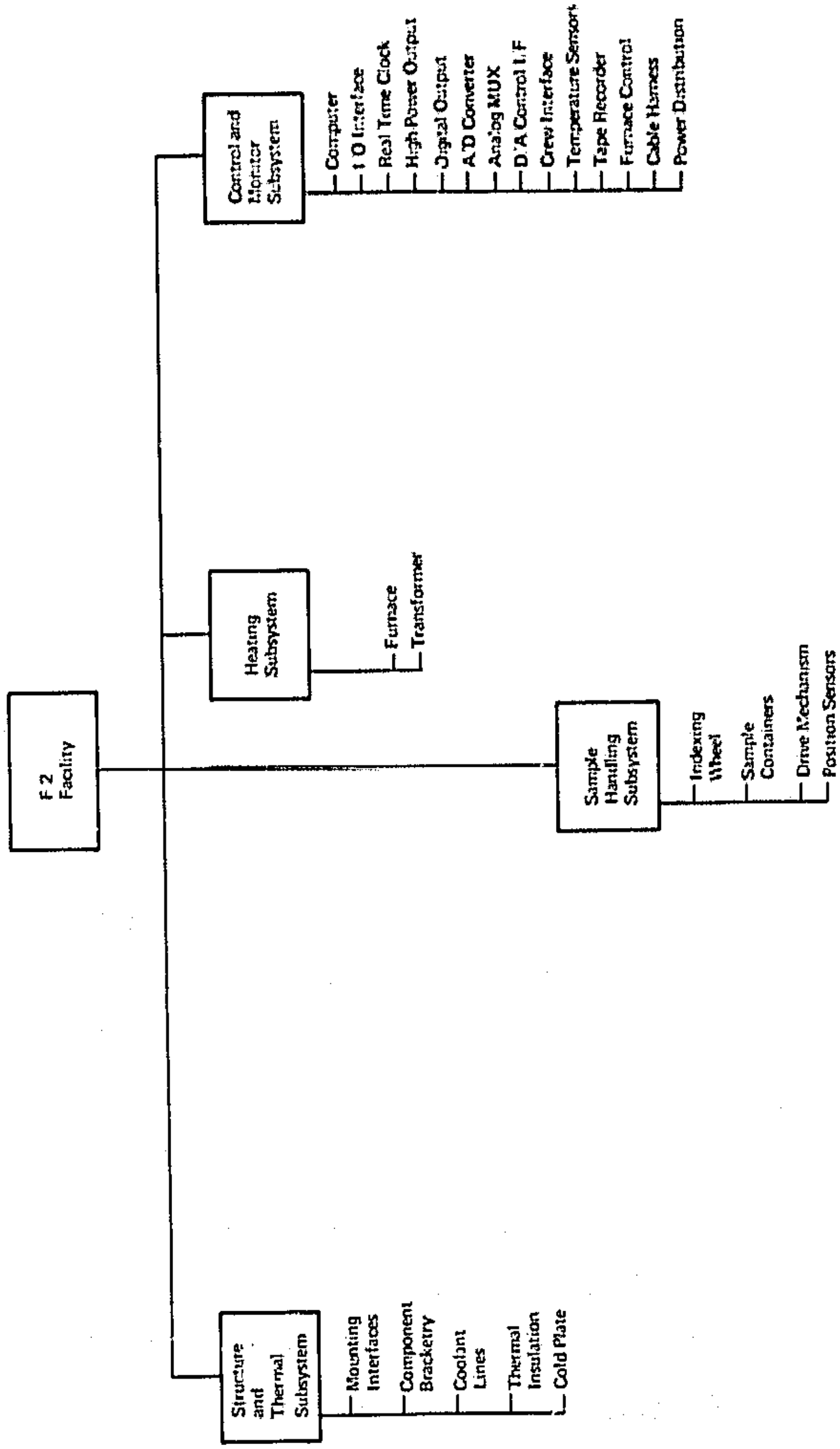

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Figure 2-4 F-2 Facility Hardware Tree

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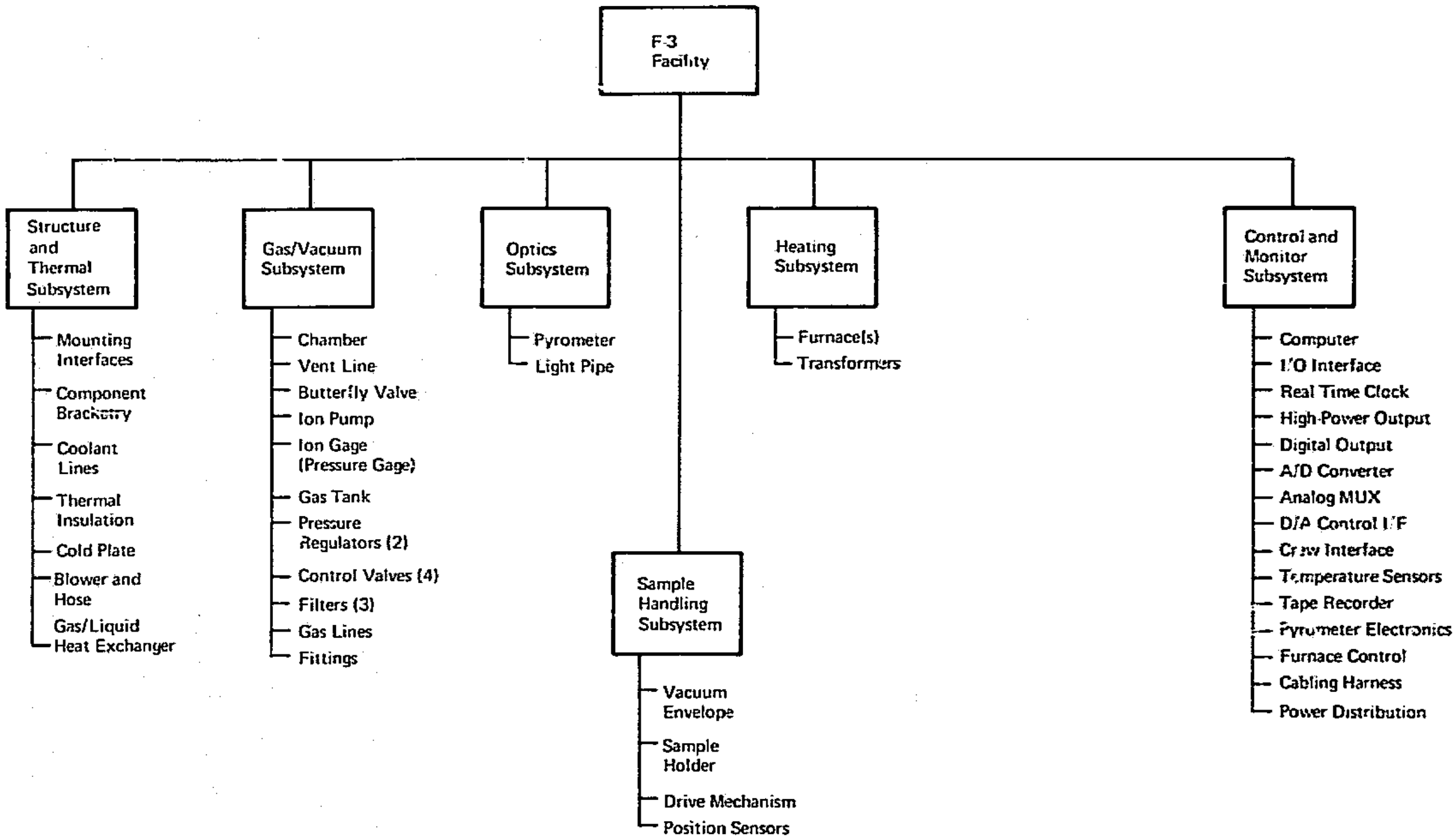

Figure 2-5 F-3 Zone Refining Facility Hardware Tree

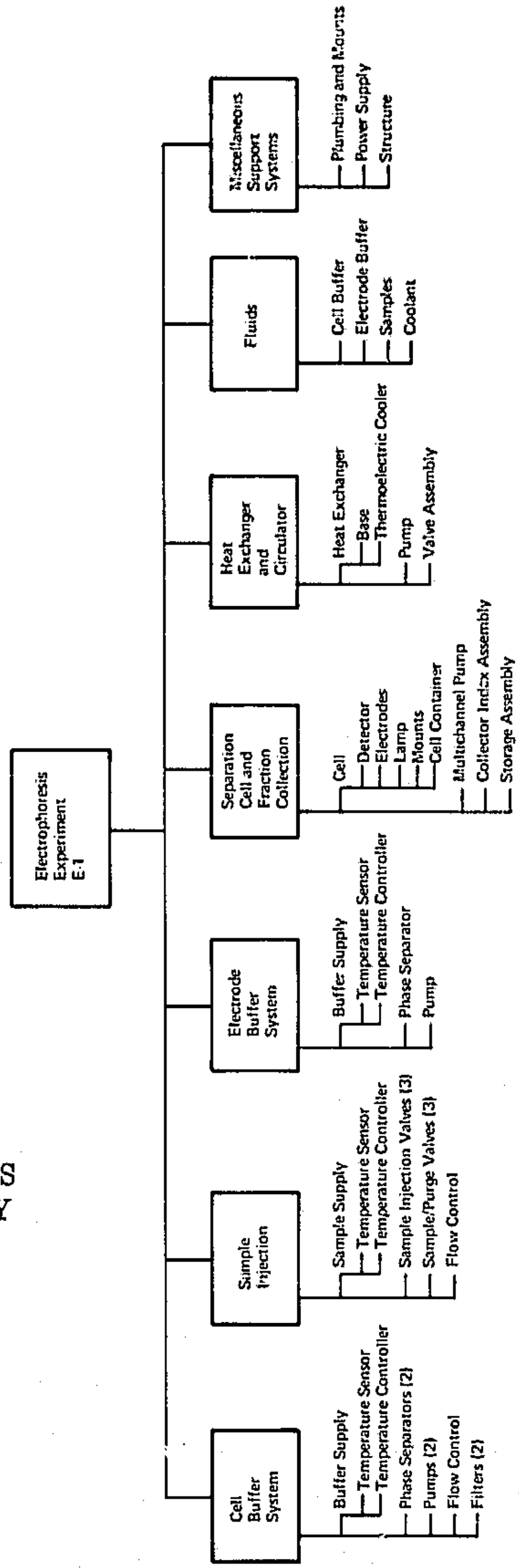

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Figure 2-6 E-1 Electrophoresis Hardware Tree designed to accept three separate samples and collect and maintain the fractions produced by the electrophoresis operation. The cell electric field strength is a constant voltage (5 to 50 V per cm). The buffer temperature in the cell is controlled within the range of 15 to 25^{o}C (288 to 298^{o}K). There is one sample inlet port located at one side of the separation cell so as to allow maximum deflection for the separated fractions. The buffer inlet is made up of multiple ports to allow uniform inlet and flow through the cell. Forty-six product fraction collection ports span the width of the cell. The ports are spaced to provide separate collection of adjacent product fractions more than 1 mm apart. The product fraction collection containers are 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 takes place between processing of the individual samples.

The collected fractions are stored between 0 and 5^{o}C (273 and 278^{o}K) for return to the Earthbound laboratory. Data collected includes cell electrode voltage, flow-rates, and detection of separated fractions. Operation is automatic, except for initial switching. Caution and warning displays are included to indicate the need for shutdown in case of hazardous operation.

2.6 CORE FACILITIES

A Common Operations Related Equipment (CORE) facility is required to operate each of the facilities. However, in establishing various combinations of facilities for different payloads, a common core unit may be utilized. 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.

The core unit 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 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.

SECTION 3

DEVELOPMENT SCHEDULES

The development schedule for a typical facility (electromagnetic levitation, L-1) is shown in Figure 3-1. This schedule shows a hardware development and flight unit delivery time requirement of approximately 20 months. The schedule assumes that conceptual and preliminary design studies (Phases A and B) and supporting research and technology (SR&T) tasks in critical areas have been completed prior to the initiation of hardware development. The 20-month schedule represents only L-1; other facilities will require more or less time, as indicated in Table 3-1, depending on the relative complexity of the facility and its test program.

Table 3-1

Facilities Development Summary for Shuttle Flights 3, 6, 8, and 10

Space Processing Automated Facility	Development Time (Months)	Units
Electromagnetic Levitation Facility (L-1)	20	2
Acoustic Levitation Facility (L-4A)	19	1
Multiple High-Temperature Furnace Facility (F-1A)	17	2
Multiple Low-Temperature Furnace Facility (F-2A)	17	2
Zone Refining Facility (F-3A)	17	2
Electrophoresis; Continuous Flow (E-1)	21	2
Electrophoresis; Static Column	18	1
General-Purpose Facility	22	1
Core Unit	20	3

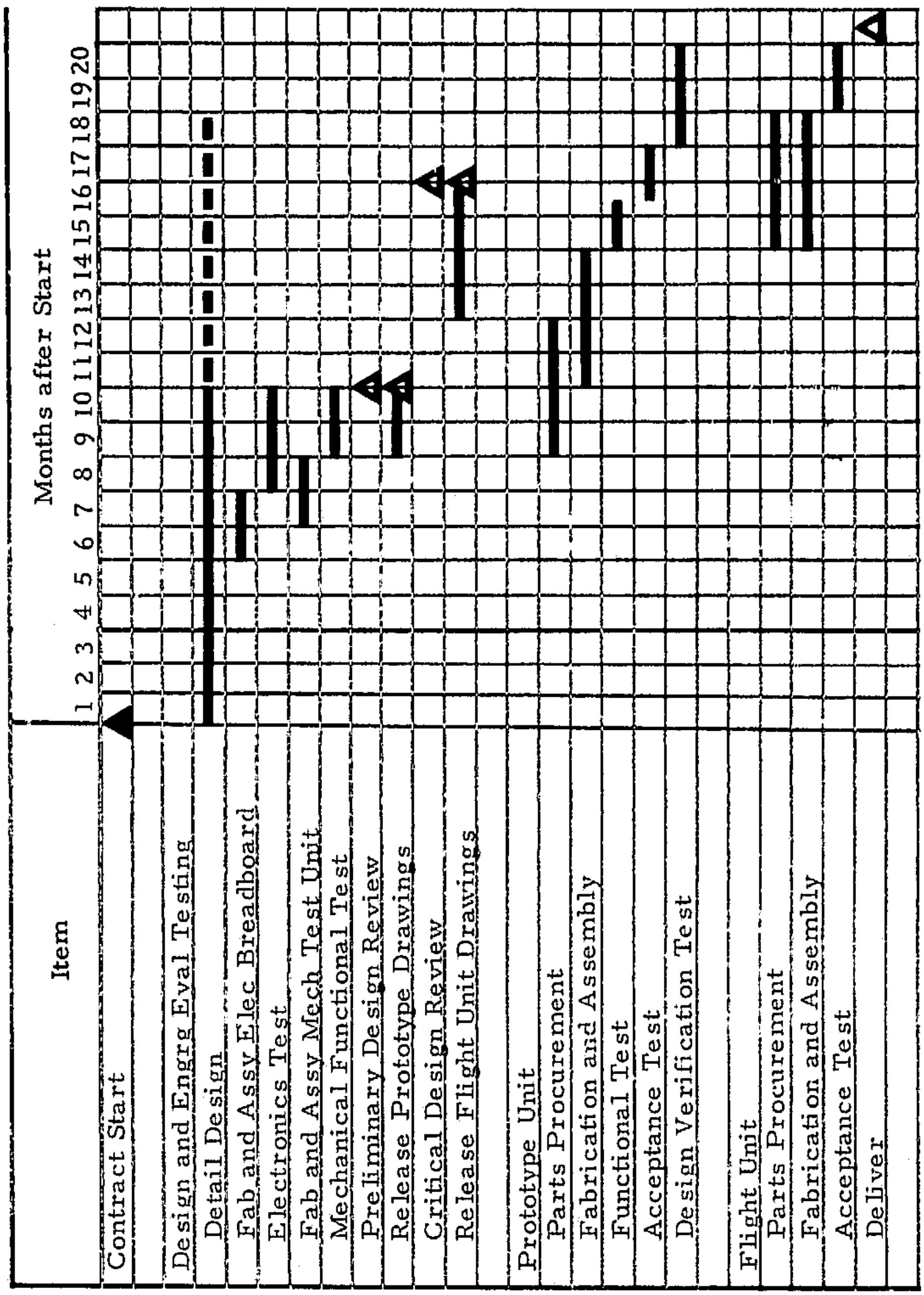

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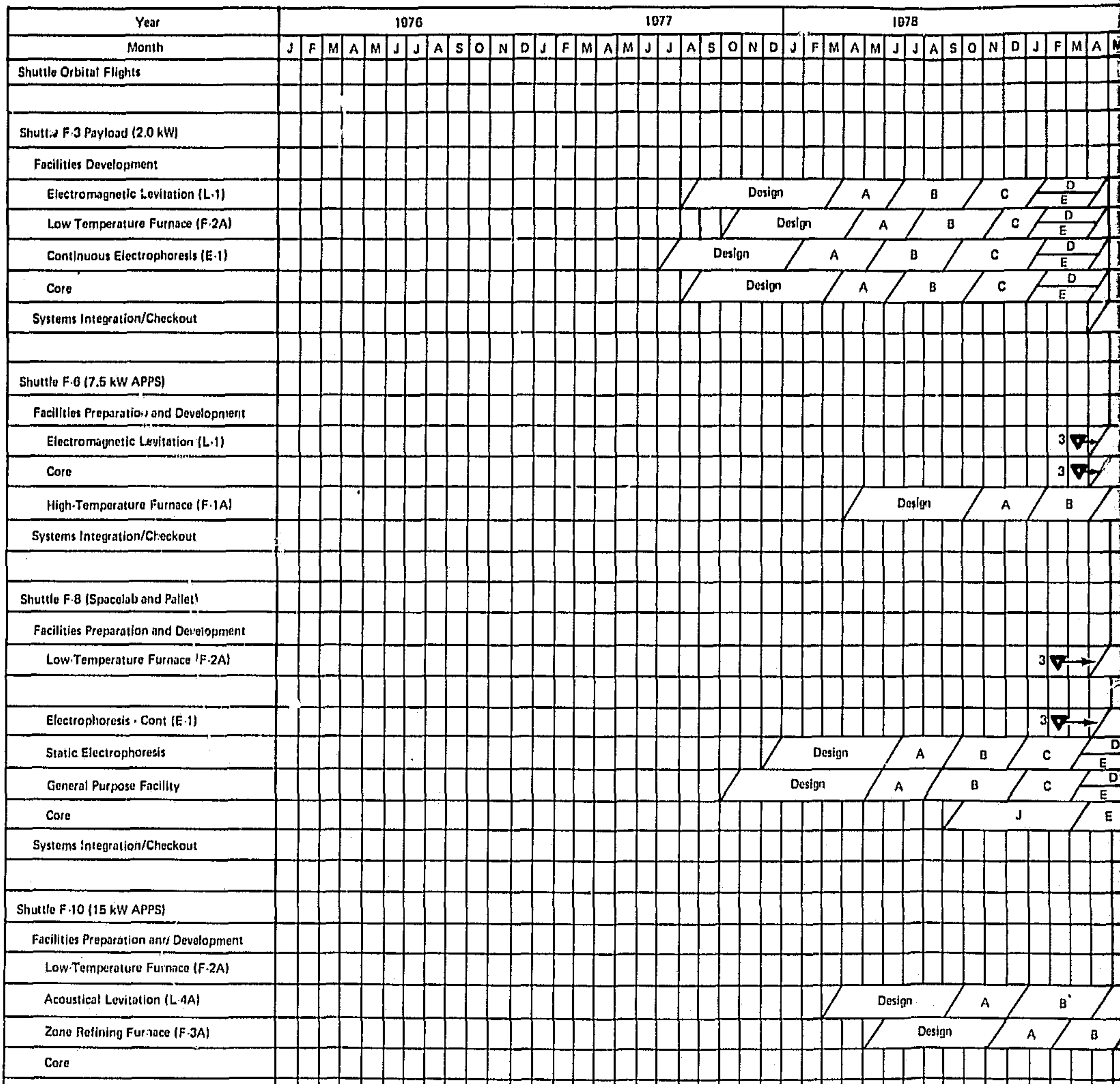
Figure 3-1 Single Facility Typical Development Schedule

Figure 3-2 shows the lead time required for development and the flow of space processing applications hardware among Shuttle Flights 3, 6, 8, and 10. The schedule indicates that automated facilities could also be made available for integration with the Spacelab on Flight 8 in the event the decision is made to include automated equipment in addition to the semi-automatic facilities developed for operation by the scientist-astronauts in the Spacelab.

A flyable prototype and a flight model will satisfy the requirement for numbers of units for all facilities with the exception of the core unit, which will require two flight units. Note that on completion of prototype design verification testing, the unit is refurbished prior to being made available for integration for flight.



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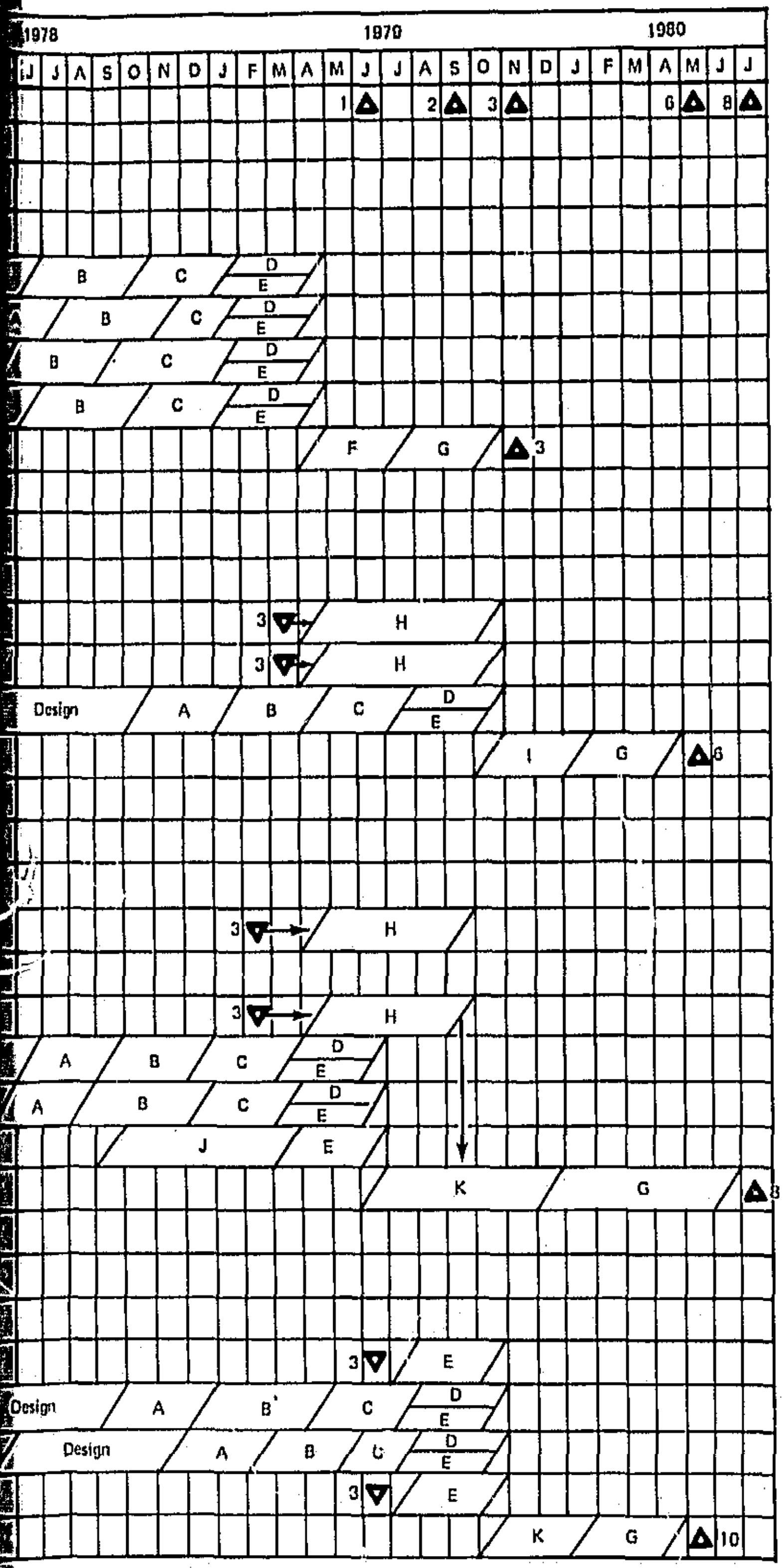

Legend:

A. Breadboard and Mechanical Test Unit Tests
B. Prototype Fabrication and Assembly
C. Prototype Acceptance Test
D. Prototype Design Verification Test
E. Flight Acceptance Test
F. Payload Integration
G. Orbiter Integration and Test
H. Refurbish Prototype and Acceptance Test
I. APPS Integration and Test
J. Fabricate and Assemble Second Flight Unit
K. Spacelab Integration and Test

Figure 3-2 Automated Space Processing Facilities Development Schedule

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SECTION 4

DEVELOPMENT COSTS

Costs have been developed for the six facilities and a related core unit described in Section 2. The assumptions and ground rules used in this cost development are:

1. Costs are generated on the basis of a separate development contractor for each facility. This results in a higher overall program cost than would be realized if a single contractor were selected for the overall program or if facilities having common requirements were developed by one contractor (e.g., L-1 and L-4 or F-1 and F-2).

2. Costs do not include facility integration into a payload, payload integration into the spacecraft, or launch and mission support services.

3. A typical development program, allowing 20 months to flight hardware delivery, is used (see Figure 3-1).

4. Facilities are not in a stand-alone condition; i.e., each facility requires operation in conjunction with a core unit.

5. The work breakdown structure is shown in Figures 4-1 and 4-2. Cost packages are:

   a. Project Management

      Cost includes the project manager, project control and scheduling, documentation support, and all project travel costs.

   b. System Engineering

      Cost includes top level systems engineering, including interface coordination and preparation of the facility specification. Also included is the preparation of all test plans and procedures, project quality and reliability engineering, and preparation and coordination of preliminary and critical design reviews.

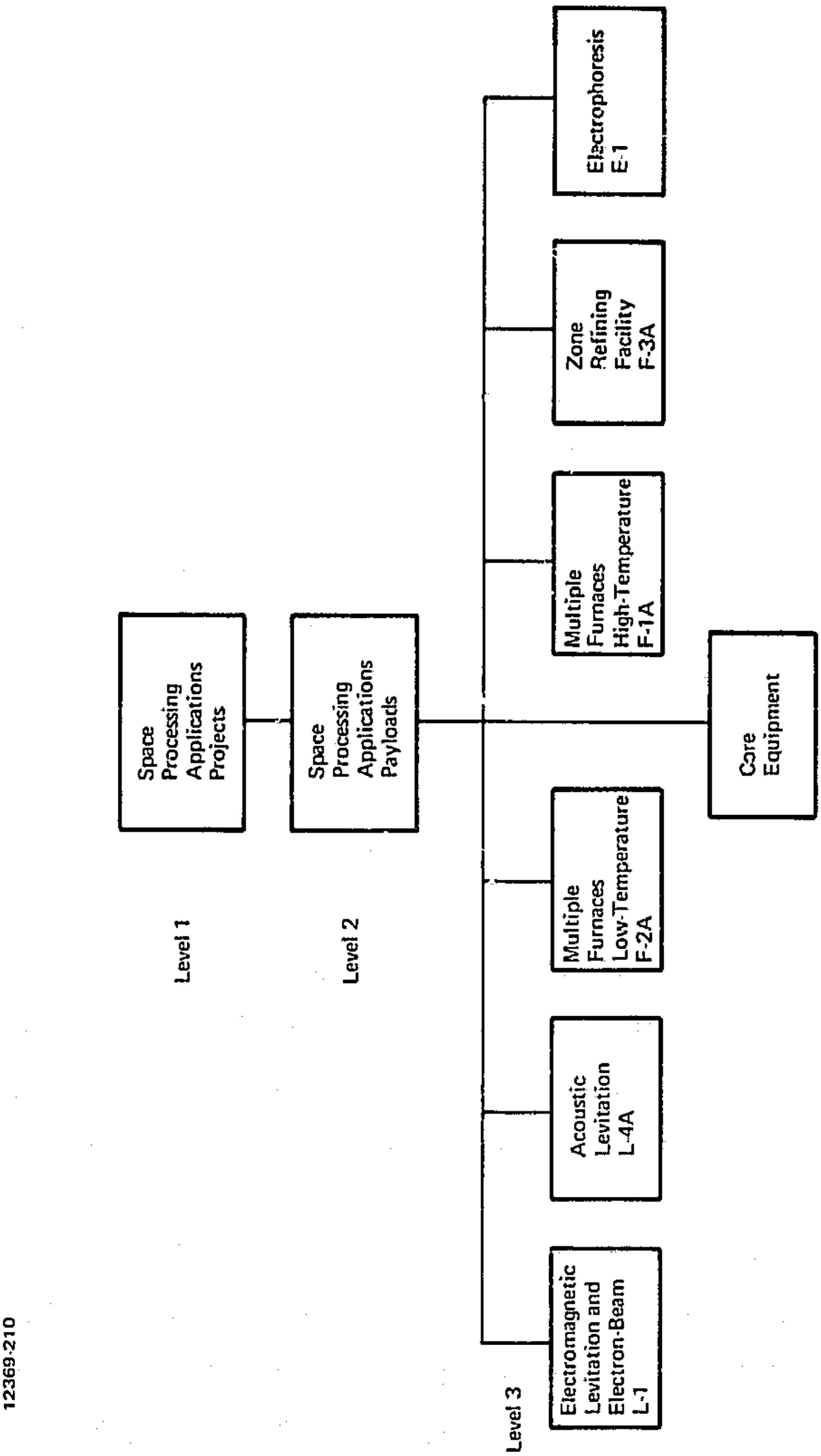

Figure 4-1 Work Breakdown Structure

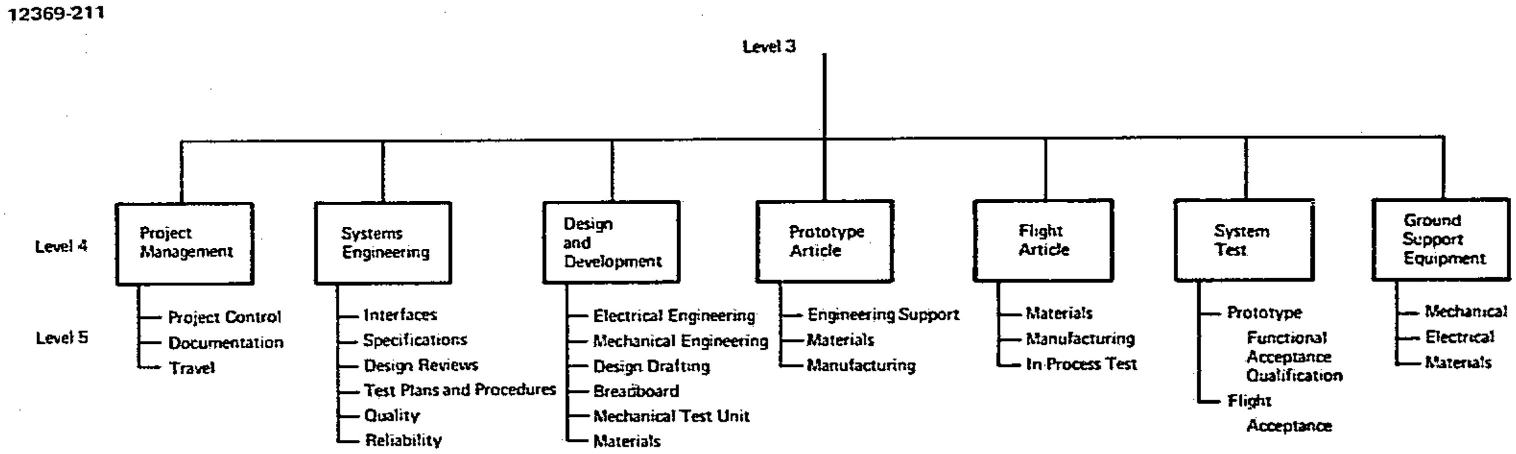

Figure 4-2 Work Breakdown Structure

c. Design and Development

This cost includes mechanical and electrical engineering, design drafting, and fabrication and test of an electronics functional breadboard and a mechanical test unit, which includes mechanisms, fluids, as required, and structure.

d. Prototype Article

This item includes materials, fabrication, assembly, and engineering support costs of the prototype article.

e. Flight Article

This item includes materials, fabrication, and assembly costs of the flight article and the in-process tests required during the flight article buildup. For the core unit, two flight units are required to comply with the overall program schedule, as described in Section 3.

f. System Test

System test hardware includes the prototype unit; which undergoes functional, flight acceptance, and qualification tests; and the flight article, which undergoes an acceptance test. For the core unit, acceptance test of the second flight article is included.

g. Ground Support Equipment

This item includes electrical test equipment, mechanical handling equipment, and other specialized equipment to exercise the facility during test and checkout.

h. Prototype Refurbishment

Costs of 50% parts replacement plus assembly and acceptance tests.

6. Costs are in 1975 dollars.

7. Where commercial equipment items are used, it has been assumed that the cost will be four times the standard catalog costs to harden the equipment sufficiently for the shuttle environment (Refer to Analysis of Commercial Equipment and Instrumentation for Spacelab Payloads; Contract NAS8-30541; 16 Sept 1974; Space Div. Rockwell International).

8. Materials costs include 50% for factory spares for prototype and flight hardware.

Table 4-1 is the cost summary as developed for the six facilities and the core unit.

Table 4-1

Facility Development Cost Summary
(Thousands of Dollars)

	L-1	L-4	F-1A	F-2A	F-3A	E-1	Core
Project Management	297	297	297	297	297	297	297
System Engineering	335	335	335	335	335	335	335
Design and Development	1,115	959	805	758	922	1,486	1,383
Prototype Article							
Engineering Support	46	46	26	26	46	46	46
Manufacturing	193	172	86	86	116	161	173
Materials	190	85	103	101	59	84	257
Flight Article							
Manufacturing	172	142	63	63	94	138	230
In-Process Test	30	22	14	14	22	40	86
Materials	190	85	103	101	59	84	514
System Test							
Prototype	172	172	172	172	172	172	172
Flight Acceptance	52	52	52	52	52	52	104
Ground Support Equipment							
Mechanical	66	66	55	55	55	81	20
Electrical	143	88	69	69	69	144	150
Materials	37	25	20	20	20	38	60
Refurbish Prototype	173	179	98	98	124	125	338
Totals	3,211	2,788	2,298	2,247	2,441	3,283	4,165

SECTION 5

SUPPORTING RESEARCH AND TECHNOLOGY

This section describes the SR&T work recommended as a result of the detailed evaluation of the facility preliminary design concepts.

5.1 ENVIRONMENTAL CHAMBER FOR MATERIAL PROCESSING AND SUPPORTING INSTRUMENTATION

Establish requirements and design for a general purpose chamber for processing a wide variety of materials in a vacuum (10^{-6} Torr or less) and inert atmospheres (inert gases to 10 atmospheres). Design definition includes size, shape, materials, finishes, cooling/heating provisions, port sizes, wall thicknesses, mounting interface, and thermal isolation. Determine vent line and vacuum pump requirements and applicable equipment. Establish instrumentation requirements for partial pressure measurements and internal viewing instrumentation.

5.2 SAMPLE STORAGE AND MANIPULATION MECHANISMS

Develop mechanisms for storage of sample and automatic positioning and manipulation in electromagnetic and acoustic levitation facilities. Mechanisms to be compatible with levitation schemes and range of materials to be handled.

Develop mechanisms for storage and loading of cartridges or raw samples into high-temperature and low-temperature furnace facilities.

5.3 ELECTRON-BEAM GUN

Develop continuous duty cycle (continuous adjustment power range to 4.5 kW) gun cathode. Develop thermal control system compatible with liquid coolant loop operation. Develop interlock system for gun control (to preclude operation if specimen is not levitated).

5.4 PYROMETER DEVELOPMENT

Investigate non-contact temperature measurement techniques for measurement to 3,500°C. Investigate compatibility of light pipes, beam splitters, and other optical schemes with the measurement technique employed. Detail feasible precision of measurements. Develop calibration techniques.

5.5 PARTIAL PRESSURE AND RESIDUAL GAS INSTRUMENTATION

Investigate requirements for partial pressure and residual gas measurements in process control applications. Compare requirements and existing instrumentation capabilities. Define instrument modification for sampling techniques and computer or process control interface and software requirements.

5.6 IMAGE RECORDING TECHNIQUES

Establish equipment requirements and specifications for image recording of processing operations. Requirements shall include lighting provisions and auxiliary records of time, temperature, pressure, etc. Evaluate film camera versus electronic imaging techniques for various processing requirements.

5.7 SOLID STATE RF GENERATOR DEVELOPMENT

Develop solid state RF generator for frequencies up to the state-of-the-art limit (presently 100 kHz), with power output up to 5 kW. Generator should be compatible with cold-plate and liquid-coolant-loop thermal control mechanisms. Develop required transformers, matching networks, and work coils.

5.8 HIGH FREQUENCY RF GENERATOR DEVELOPMENT

Develop vacuum tube RF generator technology for frequencies between about 100 kHz and 20 MHz and 5 kW output compatible with flight conditions, including liquid-coolant-loop thermal control techniques. Develop required transformers, matching networks, and work coils.

5.9 ACOUSTIC LEVITATION

Develop optimum chamber and transducer size and acoustic power and frequency for given sample specimen characteristics. Define transducer characteristics and specifications. Develop control techniques for frequency, power, and sample positioning.

5.10 IMAGE HEATER AND FURNACE

Develop 5 kW image heating system compatible with zone refining requirements. Define characteristics and requirements for equipment compatible with various materials. Define overall furnace system, including fluid cooling mechanism, cable and hose restraints, and furnace control system.

5.11 ELECTROMAGNETIC LEVITATION SAMPLE DETECTOR

Develop a "sample present" detector based on the loading of the energized work coil by the sample. Positive identification of sample presence for a wide range of sample sizes and material characteristics is required. Output of the detector circuit shall be level-shift signal to the computer on a single line.

5.12 ELECTROPHORESIS SAMPLE DETECTION AND COLLECTOR

Develop devices to automatically collect and store sample fractions. Develop automatic control techniques for operation of electrophoresis apparatus systems, including static and continuous flow.

5.13 FURNACE SAMPLE PROCESSING CHAMBERS

Develop a standard line of sealable instrumented cartridges for performing material processing in high-temperature and low-temperature furnace systems. The line should include simple melting crucibles, special-purpose capsules for Czochralski crystal growing experiments, and other comparable processes.

5.14 ZONE REFINING TRANSPORT MECHANISM

Develop mechanisms for traversing zone refiner compatible with various heating schemes and techniques. Develop position monitor and speed control for the mechanisms and specify the associated computer or controller interface. Define the required thermal protection.

5.15 HEATER MATERIALS FOR HIGH-TEMPERATURE FURNACES

Identify heater materials and heater element construction that can potentially withstand temperatures to 3,000°C, acceleration stresses of launch and boost, and the acoustic environment. Define additional requirements for shock-mounting furnaces incorporating these elements. Define proportional control techniques compatible with the heater element and furnace design. Develop a furnace controller.

5.16 PROCESS CONTROLLER INTERFACE

Define the peripheral electronics required for a general purpose subsystem, e.g., an analog-to-digital converter and multiplexer, power distribution switches, digital-to-analog converters for heating and motion control, crew interface panels, a real time clock, data recording, and control and data input interfaces. Specify required hardware. Include investigation of centralized versus distributed controllers for automated process functions. Develop software for interface controls.