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DESIGN OF A CONTINUOUS DUTY CRYOPUMP

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CONTENTS

<u>Section</u>		<u>Page</u>
1	SUMMARY	1-1
2	INTRODUCTION	2-1
3	PROGRAM OBJECTIVE	3-1
4	BACKGROUND AND APPROACH.	4-1
5	DESCRIPTION	5-1
5.1	Cryopump	5-3
5.1.1	Deuterium Pumping Unit	5-3
5.1.2	Nitrogen Shield Assembly.	5-4
5.1.3	Louver Actuators.	5-8
5.1.4	Collector Pump	5-9
5.1.5	Coolant Distribution and Manifolds	5-10
5.1.6	Vacuum Chamber Cover.	5-12
5.1.7	Transfer Line	5-12
5.2	Cryopump Controller	5-14
5.2.1	Controller	5-14
5.2.2	Power Supply	5-20
5.3	Cryopump Control.	5-21
5.3.1	Events	5-21
5.3.2	Interlocks	5-21
5.3.3	Sequencer	5-22
5.3.4	Actuators, Sensors and Switches	5-25
5.4	Control System Software.	5-26
6	SUPPORTING ANALYSIS	6-1
6.1	Leakage Analysis	6-1
6.2	Thermodynamic Analysis.	6-4

CONTENTS (contd)

<u>Section</u>	<u>Page</u>
6.2.1 Analysis of Fixed Shielding	6-5
6.2.2 Analysis of Movable Louvers	6-5
6.3 Safety Analysis	6-10
6.3.1 Overpressure Protection	6-10
6.3.2 Hydrogen Limit	6-14
6.3.3 Collector Pump Regeneration	6-14
7 REFERENCES	7-1

Appendix

A	Requirements for a Continuous Duty Cryopump Control System . .	A-1
B	Instructions for Controller Operation	B-1
C	Control Program Description	C-1

ILLUSTRATIONS

<u>Fig.</u>		<u>Page</u>
4-1	Continuous Duty Cryopump	4-1
4-2	Prototype Regenerable Cryopump from Reference 6 (LLNL Photo)	4-2
4-3	Partial Assembly of Prototype Regenerable Cryopump of Reference 6 (LLNL Photo)	4-2
5-1	Cryopump Controller	5-1
5-2	Actuator Assembly for Louver Doors	5-2
5-3	Liquid Helium-Cooled Deuterium Pumping Panels.	5-3
5-4	Cryopump During Assembly.	5-5
5-5	Cryopump Shield Assembly Shown in Welding & Aligning Fixture .	5-7
5-6	View from Collector Pump Cavity into Pump Lower Shield Showing Door Lying Open	5-8
5-7	Layout Showing Arrangement of Louver Door Mechanism.	5-9
5-8	Collector Pump	5-10
5-9	Collector Pump Shown in the Cryopump.	5-10
5-10	Schematic of Helium Control Valves	5-11
5-11	Arrangement of Feedthroughs on the Vacuum Tank Cover.	5-12
5-12	Layout Showing Manual Control Valve for Helium Transfer Line . .	5-13
5-13	Layout Showing Remote Control Valve for Helium Transfer Line . .	5-13
5-14	Control Console	5-15
5-15	Control Panel Showing System Schematic	5-17
5-16	12 Vdc Power Supply.	5-20
5-17	Controller Program Logic Diagram.	5-27
5-18	Controller Program Flow Chart	5-29

ILLUSTRATIONS (contd)

<u>Fig.</u>		<u>Page</u>
6-1	Cryogenic Leakage Model, Side View Through Pump Segment . . .	6-2
6-2	Thermal Model for Fixed Shielding	6-6
6-3	Fixed Shielding Temperature Distribution	6-7
6-4	Movable Shielding Thermal Model	6-8
6-5	Effect of Hinge Conductance on Pumping Panel	6-9
6-6	Temperature Distribution for Foll-Only Hinge Configuration	6-11
 A-1	 Pump Valve Schematic & Sequencer Requirements	 A-3
C-1	Program Listing	C-4

TABLES

<u>Table</u>		<u>Page</u>
5-1	Event Descriptions	5-21
5-2	Default Valve/Actuator Positions	5-22
5-3	Binary Digits & Valve/Actuator Codes Relationship	5-23
5-4	Description of Actuators, Sensors & Switches	5-24
5-5	Actuator Types.	5-25
5-6	Microprocessor Display During Sequencer Operation.	5-25
6-1	Base Condition & Range of Variables	6-4
6-2	Effect of Cryopump Characteristics on Leakage & Pressure Compared to a Base Condition	6-4
A-1	Identification of Helium Valves	A-1
A-2	Cryopump System Schematic Indicating Lights.	A-7

1 - SUMMARY

A continuous duty cryopump system was designed and developed that comprises a self-contained cryopump for installation into a vacuum chamber, and a microprocessor controller for automatic operation. This deuterium pump has two units in a single housing, arranged so that one is pumping while the other is being regenerated. Liquid helium-cooled, finned sections in each unit pump deuterium by condensation, and a third pump integral within the cryopump housing collects the regenerated gas. A microprocessor unit controls distribution of liquid and gaseous helium, used for conditioning the pumping units, and operates remote actuators for the regeneration. Software provides fully automatic, timed sequencing of the repetitive cryopump events which include: cooldown of the pumping units, opening of the louvers isolating the unit from the vacuum chamber, closing of the louvers, and warming up of the unit for regeneration. Default values in the software can be reprogrammed by the operator through the keyboard in response to prompts displayed on the computer. An override allows the operator to control the cryopump manually by activating switches on a control panel. Interlocks to prevent cryogen lockup are included in the software.

The cryopump system was delivered at the end of this operating period to Lawrence Livermore National Laboratory for installation and performance testing.

2 - INTRODUCTION

Fusion power reactors and fusion experiments leading to commercialization of fusion power will produce large volumes of gas at low pressure, principally hydrogen isotopes and helium. The helium product of the fusion reaction is produced at the rate of more than 15 Torr-liters per second for each 1000 MW of fusion power. The amount of deuterium and tritium to be pumped depends on the efficiencies of the fusion process (fractional burnup) and of the particle injection devices. Deuterium and tritium quantities up to 10 times the helium quantity might have to be pumped in a power reactor.

The fusion power of near-term interim experiments and the concomitant helium production are projected to be significantly lower than will be produced ultimately by a fusion reactor; however, the amount of hydrogen isotopes that would have to be handled continuously is high. The near-term need then is for development of high-throughput continuous operation pumps for pumping hydrogen isotopes.

The program for developing the capability to pump the principal fusion exhaust products helium, deuterium and tritium, has been proceeding logically. Studies have evaluated helium pumping techniques that showed the most promise for handling helium at very high pump speeds. These evaluations considered the use of sorbents, such as artificial zeolite molecular sieves (Ref 1) and activated charcoal (Ref 2) and the use of trapping gases for pumping both helium (Ref 3) and mixtures of hydrogen and helium (Ref 4). Compound cryopumps were then developed for pumping both helium and hydrogen isotopes which featured the sorption and trapping methods previously evaluated (Ref 5). Afterward began the sequence leading to a cryopump that could operate continuously. A unit was developed (Ref 6) for pumping hydrogen (deuterium) which could be immersed in a vacuum chamber for efficient pumping and which could be regenerated without discharging the previously pumped gas back to the vacuum chamber. The unit demonstrated feasibility of the regeneration concept and was prototypical of the unit described in this report which adds the capability of continuous operation. The ability to pump helium and to co-pump helium and hydrogen can be retrofitted.

3 - PROGRAM OBJECTIVE

The program objective was to design and fabricate a deuterium cryopump which could be operated continuously, and mounted within the vacuum chamber to be pumped. In-cell cryopumps, typically, are regenerated by releasing pumped gasses back to the vacuum chamber to be roughed by a vacuum system appended to the chamber; this is an unacceptable condition for a continuously operated system.

The precursor of, and model for, the pump produced in this program is an in-cell pump (described in Ref 6 and referred to in this report as the "first" pump) which can be regenerated without mandatory back flow to the vacuum chamber. The objective of this previous program was to demonstrate reliability, repeatability, operational characteristics and feasibility of the regeneration feature. It was not necessary to show capability for continuous operation, nor was it an objective to optimize back-leakage to the vacuum chamber. These were objectives of the current program.

4 - BACKGROUND AND APPROACH

The continuous duty cryopump (Fig. 4-1) was evolved from the previously developed regenerable cryopump (Ref 2), and retained many of the first pump's proven design features to minimize technology risk. It is appropriate to describe the first pump briefly to allow an understanding of the technical base for this program. The regenerable pump (Fig. 4-2 and 4-3) developed at Lawrence Livermore National Laboratory (LLNL) is a manually operated device capable of pumping deuterium gas at approximately 63,000 liters per second. The pump featured a set of 13 liquid helium-cooled pumping panels for condensing the deuterium. These panels were thermally shielded by a series of Z-shaped double chevrons, where the ends of each "Z" were hinged to its center section. When the hinged portions (louvers) were opened, deuterium could pass to the pumping panels from two sides. For regeneration, the pumping surfaces were isolated from the vacuum chamber by closing the

Fig. 4-1 Continuous Duty Cryopump

Fig. 4-2 Prototype Regenerable Cryopump from Reference 6 (LLNL Photo)

Fig. 4-3 Partial Assembly of Prototype Regenerable Cryopump of Reference 6 (LLNL Photo)

hinged portions. Deuterium was dumped from the pumping panels by purging the liquid helium coolant into the cavity formed by the closed louvers. The gas was then pumped from the cavity by an appended collector pump, which was itself a helium-cooled unit. The collector pump was regenerated periodically into a roughing system. The gas throughput to the vacuum chamber had to be interrupted during pumping panel regeneration because this first pump was a single unit.

A comparison of the prototype regenerable pump and the continuous duty cryopump is shown below.

- Regeneration - The first pump was not required to demonstrate continuous operation and, therefore, was regenerated to the collector pump during a shutdown of the pumped gas throughput. The subject pump is regenerated without interruption of pumped gas flow.
- Operation - Control of the first pump's valves and louver actuator was done manually because regeneration was infrequent. Due to the continuous duty requirement of the current pump, the design features automatically controlled valves and actuators.

- Pumping Units - A single pumping unit was sufficient to satisfy the first pump's requirement to demonstrate capability for regeneration. The current pump features two identifiable pumping units, allowing one unit to operate while the second is being regenerated. Although this arrangement is prototypical of units which would satisfy a reactor's requirement of continuous operations, it is not optimum. The pump has 100% excess capacity over that required to satisfy the pumping need. A more appropriate excess capacity would be up to 20% (Ref 6) so that a typical reactor installation would feature pumping systems with six individual units capable of sequential regeneration.
- Pumping Speed - The pumping speed specified for the current pump is not in consequence of the speed required of the first, but is instead in response to the requirements and physical constraints of the vacuum chamber. The pump is designed to pump 0.124 Torr liter/second deuterium at a vacuum chamber pressure of 10^{-5} Torr. The first pump's speed was 63,000 liter/ second deuterium.
- Leakage During Regeneration - The first pump was not optimized for leakage back to the vacuum chamber, and indicated leakage was as high as 30%. The test results showed, however, how the condition could be improved. The current pump features close fitting louver doors and increased collector pump conductance to attain a leakage of 5%.

5 - DESCRIPTION

The continuous duty cryopump system consists of a cryopump (Fig. 4-1) which is self-contained for installation into a vacuum chamber, and a microprocessor controller (Fig. 5-1) for automatic operation. The pump consists of two units in a single housing, arranged so that one is pumping while the other is regenerating.

Fig. 5-1 Cryopump Controller

Liquid helium-cooled, finned sections in each unit effect pumping of deuterium by condensation. Liquid nitrogen-cooled shields, incorporating a Z-shaped chevron configuration, surround both units. The chevrons are equipped with hinged louvers so that the louvers are closed for regeneration and open for pumping. A single-mechanism assembly using a driver and reversing link (Fig. 5-2) operates all louvers so that those of one pumping unit are driven closed, while the other unit's louvers are opened simultaneously. A liquid helium-cooled collector pump, integral within the shields, recondenses the pumped gas as it is evaporated from each pumping unit during regeneration. Doors separate each unit from the collector pump. Gas released from the collector pump during its regeneration is pumped by a mechanical roughing system.

Fig. 5-2 Actuator Assembly for Louver Doors

The control of cryogenic and ambient helium distribution for cooling and warming the pumping units, and operation of remote actuators, are performed by a programmable microprocessor unit. Some valves on the collector pump, which is regenerated infrequently, are manually operated. The software provides for fully automatic, timed sequencing of the repetitive cryopump events, which are cooldown, operation and regeneration. Automatic valve commands and timing of the events can be reprogrammed through a keyboard. An override button allows the operator to interrupt automatic operation and to control helium valves, louvers and collector doors directly through a switch panel. Temperatures and pressures are monitored, and helium levels within the three pump reservoirs are held automatically.

The cryopump is fully maintainable. It is suspended through thermal isolators from a vacuum chamber cover, allowing the pump to be removed from the chamber by lifting the cover. The pump can be knocked down to its basic elements by undoing screws and mechanical fasteners. The entire shield including panels, bulkheads, door actuators, doors, thermal isolators and structural supports can be disassembled to allow removal of the helium-cooled pumping panels and the collector pump for examination and modification as required. The valves, actuators, sensor feedthroughs, manifolds and electrical connections on top of the chamber cover are similarly mounted for ready replacement.

5.1 CRYOPUMP

The following sections provide a description of the cryopump elements. Supporting analysis is discussed in Section 6.

5.1.1 Deuterium Pumping Unit

Deuterium gas is pumped by condensation on the liquid helium-cooled aluminum 6061 alloy units shown in Fig. 5-3. Each of the two units designated No. 1 and No. 2 is made up of upper and lower cylindrical reservoirs connected to five fin-tube condensers. The

Fig. 5-3 Liquid Helium - Cooled Deuterium Pumping Panels

reservoirs are 2.0 in. (5.1 cm) diameter x 10 in. (25.4 cm) long and each condenser is made from 0.5 in. (1.3 cm) diameter tubing with two sets of 5/8 in. (1.6 cm) x 12 in. (30.5 cm) x 1/8 in. (0.32 cm) fins attached to provide the necessary pumping surface area. Two thin-walled 0.20 in. (0.51 cm) stainless steel tubes (1.0 in. (2.5 cm) diameter x 23.2 in. (59 cm)) welded to the upper reservoir using a bimetallic braze assembly provide a thermal standoff between the pumping section and the nitrogen shield, and serve as helium fill and vent passages, and as dump and purge passages, respectively, during regeneration.

The fin-tube in line with the helium fill line is extended through the interior of the upper reservoir and into the interior of the lower reservoir, so that when a transfer line is introduced into the fill passage, its length is extended effectively to a sump in the lower reservoir. This combination of extended tube and sump has proven effective in initially filling a dewar with liquid helium.

The complete deuterium pumping section is suspended from feedthroughs welded to the upper ends of the helium fill and vent passages. This arrangement minimizes conductive thermal losses to the contained liquid helium, by providing a 31 in. (79 cm) low thermal conductance path between the ambient temperature connection at the vacuum chamber cover and the pumping section upper reservoir. The feedthroughs incorporate knife-edge seals with Kapton gaskets to effect the vacuum seal at the cover.

The upper and lower reservoirs and fin-tube condensers make up a volume of 61.0 in.³ (1,000 cm³) so that each pumping section contains one liter of liquid helium which is purged for regeneration. Helium boiloff caused by thermal radiation to the 344 in.² (2219 cm²) of surface area is estimated to be one liter in over 6 hours.

5.1.2 Nitrogen Shield Assembly

The nitrogen shield assembly (Fig. 5-4) provides the thermal radiation barrier between the vacuum chamber walls and the liquid helium-cooled pumping units. It incorporates actuator linkages, and the movable louver doors which allow passage of the deuterium gas during operation and block passage during regeneration; the collector door assemblies, which are open for regeneration and closed for operation and cooldown; and thermal isolators which reduce thermal conduction to the pumping units and collector pump. The isolators are clamped to the fill and vent passages for support of the entire suspended shield assembly.

(a) VIEW SHOWING LANYARDS FOR COLLECTOR DOORS

(b) VIEW SHOWING THERMAL STANDOFF THROUGH THE TANK COVER

(c) VIEW SHOWING OFFSET ROUGHING DUCT

Fig. 5-4 Cryopump During Assembly

The shield assembly has three separate compartments: one each for the two pumping units isolated from each other by a space for the louver actuators, and one for the collector pump separated from the pumping section components by collector doors.

The shield assembly is cooled conductively by upper and lower liquid nitrogen reservoirs integral with the shield panels, and by 0.5 in. (1.3 cm) diameter tubes (a total of 12) connecting the two reservoirs. The tubes are incorporated in the fixed portion of the double chevron Z-shaped louvers so that heat transferred to the louver doors and fixed portions can be conducted to the liquid nitrogen in the tubes.

The pumping section upper reservoirs are housed in a rectangular upper shield that is 10.8 in. (27.4 cm) wide x 29.6 in. (75.2 cm) x 5.2 in. (13.2 cm) high. The upper shield includes the two segments, containing the helium reservoirs, which are part of the vacuum volume within the cryopump. A 2.8 in. (7.1 cm) long middle section between the two is reserved for the louver actuator linkage and is part of the chamber evacuated volume. The lower rectangular shield is similarly arranged around the lower helium reservoirs except that this shield is 16.0 in. (40.6 cm) wide to include the collector pump compartment.

The lower plate of the upper shield and the upper plate of the lower shield were held square and parallel in an aligning and welding fixture during manufacture to maintain a precise 12.00 in. (30.48 cm) between their faces (Fig. 5-5). This effort was undertaken to produce a minimal gap around the sealing edge of the louver doors. The parallel plates form the door upper and lower sealing edges and also provide the anchor for the door hinges. These plates are 3/8 in. (0.95 cm) thick aluminum compared to 1/8 in. (0.32 cm) thick aluminum for most of the shield assembly parts.

The shield assembly segment between the parallel plates contains the double chevron shields. Each chevron segment comprises a fixed portion (4 in. (10.2 cm) x 12 in. (30.5 cm)) and two movable louver doors (4 in. (10.2 cm)) x 11.97 in. (30.40 cm) except for the outer chevron shields which require a single door only. Doors are attached by free moving hinges. A thermal bridge of ten 3 mil (.0076 cm) thick aluminum foil sheets connects the fixed and moving chevron pieces, and forms the sealing edge for an adjacent door when the doors are closed.

The fin-tube sections of the pumping units are placed alternately between the fixed chevron portions so that all the liquid helium-cooled and liquid nitrogen-cooled tubes are in

Fig. 5-5 Cryopump Shield Assembly Shown in Welding and Aligning Fixture

a plane. A design alternative was to make the fixed chevron portions consisting of cooling tube, shield and hinge halves from extruded pieces. In deference to the possibility of warping during welding, a major subassembly which consisted of the 12 fixed chevron portions, the upper and lower liquid nitrogen reservoirs, and connecting 1/2 in. (1.3 cm) tubing is a welded unit. The placement and welding of the hinges, which was the most critical step, was done last using the parallel plates held in their proper positions by the welding fixture to assure accuracy.

A single thin-walled, one inch (2.5 cm) diameter stainless steel tube attached to the upper reservoir using a bimetallic braze assembly is the vent line for the thermal shield assembly. A 3/8 in. (0.96 cm) diameter transfer line inside this tube is the liquid nitrogen fill.

The outer edges of each set of five louver doors associated with a pumping panel are linked together (Fig. 5-2) to operate as a unit in the form of a four-bar linkage. The doors are fitted with brackets which attach through cam slots in the brackets to drive pins on a push rod. This feature permits adjustment of the door brackets at final assembly for best alignment of each door.

Each pumping panel is isolated from the collector pump by a collector door whose frame is bolted inside the rectangular lower shield. The collector door opening is 11.5 in. (29.2

cm) x 4.5 in. (11.4 cm), providing a door opening area to pumping panel projected area (the view into the louvers on both sides from the vacuum chamber) ratio of 0.18 compared to a ratio of 0.0045 for the first regenerable pump. The door is closed by a lanyard pull attached to the door (Fig. 5-6) which traverses to an automatically operated air cylinder mounted on the vacuum chamber cover, and is opened by a spring and a counterweight.

Fig. 5-6 View from Collector Pump Cavity into Pump Lower Shield Showing Door Lying Open

Thermal isolators, bolted to the rectangular upper shield and to the top of the collector pump compartment, shield the fill and vent lines. These 2 1/2 in. (6.3 cm) O.D. x 17.75 in. (45 cm) long aluminum tubes on the upper shield and 35.25 in. (89.5 cm) long tubes on the collector compartment are clamped to the fill and vent lines which, in turn, suspend the entire cryopump within the vacuum chamber.

5.1.3 Louver Actuators

The louver actuator assembly opens and closes the louver doors as required for pump operation and regeneration. The drive mechanism (Fig. 5-7) operates through an air cylinder actuator mounted on the vacuum chamber cover so that a single motion opens the louver doors of one pumping unit, while it simultaneously closes the doors of the other unit.

Two of the three arms on the drive shaft crank connect to the louver door sets on opposite sides of pumping panel No. 2. The third leg connects to a similar crank on the follower shaft to operate in reverse the door sets of pumping panel No. 1. The drive and follower shafts are guided by brass bushings in the upper and lower parallel plates. The

Fig. 5-7 Layout Showing Arrangement of Lower Door Mechanism

drive shaft which passes through a Wilson seal in the chamber cover has articulated sections to allow for any misalignment. Brass pinions on the connecting rods ride in the cam slots in the door brackets. The location of the door brackets, the position of the pinions on the connecting rods and the lengths of the linkages between the cranks and the doors are made adjustable to allow setting doors to produce relatively gas-tight volumes. The cranks, shafts, push rods and connecting rods are aluminum.

5.1.4 Collector Pump

Deuterium released from the pumping units during regeneration passes through the collector door opening to be pumped on the liquid helium-cooled collector pump (Fig. 5-8 and 5-9). It is an appendage to the pumping panel units and is housed in the lower rectangular shield.

The pump is a 3.0 in. (7.6 cm) diameter tube x 27 in. (68.6 cm) long providing 269 in.² (1735 cm²) of pumping surface. The pump is serviced by helium fill and vent lines

Fig. 5-8 Collector Pump

Fig. 5-9 Collector Pump Shown in the Cryopump

which are respectively dump and purge lines during regeneration. These thin-walled one-inch (2.5 cm) diameter stainless steel tubes provide a 50 in. (127 cm) low conductance path to the ambient vacuum chamber wall. The complete unit is suspended from feedthroughs welded to the upper ends of the two lines. Helium boiloff caused by thermal radiation is estimated to be one liter in more than 4.5 hours. For the collector pump regeneration is approximately once every 8 hours.

5.1.5 Coolant Distribution and Manifolds

Liquid nitrogen and liquid helium are coolants for the cryopump shields and pumping units, respectively. Valves and manifolds mounted on the vacuum chamber cover provide the means of automatically or manually controlling the flow of coolants.

The nitrogen manifold consists of a one inch (2.5 cm) stainless steel cross that accepts the liquid nitrogen facility supply line in its top leg. A 3/8 in. (0.95 cm) diameter transfer line, which extends the supply line to the pump's upper reservoir, is an integral part of the manifold. The lateral legs of the cross house an unrestricted vent and a liquid level sensor feedthrough. A remotely operated cryogenic nitrogen valve in the facility supply line is operated from the controller.

The collector pump and the two pumping units are each provided with two manifolds mounted on top of the cover. Figure 5-10 shows the arrangement schematic. The fill/dump manifold is a one inch (2.5 cm) stainless steel tee that accepts the transfer line in its top leg. This leg has a one inch manual ball valve to shut off the top port when the transfer line is withdrawn. The transfer line and the vertical passage of the tee form an annular passage which is a helium-coolant dump path during regeneration. The lateral leg of the tee has a dump valve which, for the pump sections, is a remotely controlled valve and is a manually operated valve on the collector pump.

Fig. 5-10 Schematic of Helium Control Valves

The vent/purge manifold is a one inch (2.5 cm) diameter stainless steel unit with three interconnected legs. One leg has a vent valve which is open during pump operation and closed during regeneration. A second leg has a relief valve set at 10 psig (0.17 MPa) for protection against thermal runaway, and a purge valve which supplies ambient helium to the pump dewar during regeneration. The purge valve is closed during operation. The third leg houses a feedthrough for the liquid level sensors which control operation of the fill valve mounted on each helium transfer line. The vent and purge valves on the pumping units are automatic. Those on the collector pump are manual.

5.1.6 Vacuum Chamber Cover

A 1.5 in. (3.8 cm) thick aluminum cover (Fig. 5-11) is the support for the cryopump suspended inside the vacuum chamber and for the manifolds, valves and actuators mounted outside. The coolant feedthroughs (six helium and one nitrogen) connect to thermal isolators on the tank cover to form the vacuum seal. The rotary seal for the louver actuator, two linear-motion-bellows seals for the collector doors, and the related air cylinders and pilot valves mount directly on the cover. Temperature sensor leads connect to a 55-pin vacuum-tight connector and pressure-sensing lines pass through bulkhead fittings on the cover.

Fig. 5-11 Arrangement of Feedthroughs on the Vacuum Tank Cover

5.1.7 Transfer Line

Helium stored in 500 liter dewars is pressure-fed to the collector pump and the two pumping units. Each U-shaped transfer line is a 1/4 in. (0.64 cm) O.D. stainless steel tube which is wrapped with multilayer superinsulation within a coaxial, evacuated sheath. A charcoal trap in the annular space assures high vacuum when the transfer line is in use. The transfer line feed end is inserted in the fill/vent manifolds and becomes a permanent part of the installation during operation. The supply end which features a combination fill valve and bayonet (Fig. 5-12) penetrates to the bottom of the storage dewar. An adapter kit (Fig. 5-13) converts the fill valve from manual to automatic for operation through the controller.

Fig. 5-12 Layout Showing Manual Control Valve for Helium Transfer Line

Fig. 5-13 Layout Showing Remote Control Valve for Helium Transfer Line

5.2 CRYOPUMP CONTROLLER

The cryopump controller (Fig. 5-14) meets the requirements specified in Appendix A. It contains the instrumentation and control elements for remotely monitoring and controlling the cryopump system. The principal element in the controller is a programmable microcomputer which commands all remotely operated valves and actuators. The controller operates in either of two modes named sequencer or direct. In the sequencer or programmed mode, the computer performs control functions based on preprogrammed, elapsed-time events that sequence the cryopump through its repetitive control cycle. In the direct mode, the system is under manual control allowing relays for valves and actuators to be turned on and off, based on activation of the associated switches. The controllers operating instructions are given in Appendix B.

Sensor outputs are read on the displays during control operations so that elapsed time between events can be changed by the operator based on the readings. The data acquisition system has 10 temperature sensors (7 LN₂, 3 LHe), two pressure gages, three LHe level gages and one LN₂ level gage.

Silicon diode sensors measure cryogenic temperatures of the helium reservoirs and the LN-cooled shielding. A single cryogenic thermometer unit with digital display is used for all 10 sensors. A switch enables selection of any one, and potentiometers in series with each sensor allow calibration in the laboratory using helium in the storage dewars as reference.

The pressure gage system (Baratron) measures the condition within the collector pump compartment and the pumping unit compartment. The value is displayed on a digital read-out unit.

Three liquid-helium and one liquid-nitrogen-level sensor system maintains the liquid level between limits which are preset in the nitrogen system, and settable in the helium system. The helium system has a control override signal to prevent automatic sequencing during regeneration. The status of the fill valve and an analog display of percent remaining are displayed for each helium sensor system.

5.2.1 Controller

The controller housed in an upright cabinet contains the electrical, electronic and computer systems, and interfaces necessary to provide the manual and automatic control capa-

Fig. 5-14 Control Console

bilities for the cryopump. The front of the cabinet (Fig. 5-14) contains the cryopump controls and displays above the integral desk top for the microcomputer and the cassette recorder/player. The electrical subsystems are accessible for maintenance through a rear door. All electric power control is centralized within the cabinet for the cryopump operations. The two cryopump system on-off switches are located on the lower power distribution chassis which is accessible from the rear of the cabinet. One switch powers a 120 Vac convenience strip and the other powers the control equipment. To activate the cryopump, these two switches and the one located on the right hand side of the computer keyboard are in the "ON" position.

The front of the cabinet consists of six panel areas:

- Temperature sensor selector and digital cryogenic thermometer panel
- Ten (10) temperature sensor calibrating potentiometers and LN_2 level control panel
- Display and control panel - The display panel (Fig. 5-15) consists of a schematic diagram of the cryopump system, with light emitting diodes (LEDs) mounted adjacent to the valve symbols. When a particular valve or actuator is activated either manually from the switches located to the left of the schematic diagram, or automatically through the microcomputer, the associated LED lights indicate that the particular valve has received a 120 V activating signal from a solid-state relay rack. (The controller circuitry was specifically designed to give an end-to-end check of the automatic sequencing operation, without valve positional feedback information, since the position of cryogenic valves can be readily observed for visual corroboration)
- 60 Hz 120 Vac outlet phono plug, helium control panel - The electrical power outlet on the panel is a convenience outlet for furnishing power to the cassette recorder. The color coded phono plugs are internally wired to the microcomputer so that the cassette recorder can be readily used for program loading or storing
- Storage space and desk top - A storage space is provided in the cabinet (with a panel) so that the microcomputer and recorder can be housed within the cabinet when they are not needed, leaving the full area of the desk top available for other purposes
- Blank panels - Located below the desk top, forming cover panels for the internal controller wiring.

Fig. 5-15 Control Panel Showing System Schematic

5.2.1.1 Temperature Suite - The cryopump temperature suite basically consists of three Lakeshore Cryotronics Inc. units:

- Model DRC-80, Digital Cryogenic Thermometer
- Model SW-10, 10-Sensor Selector Switch
- Model DT-500K, 10 Silicon Diode Sensors.

Ten (10) external one Mohm trimpots are mounted on the left side of the second panel, for calibrating the individual diode sensors. Resolution is 0.1°K .

The cryopump temperature suite is a completely self-contained system providing direct digital readout in Kelvin temperature units. It displays temperature to 0.1°K over its operating range of 1 to 400°K for normal operation. In the scale expanded mode, the resolution is 0.01K below 30°K and 0.05K from 30°K to 100°K .

5.2.1.2 LN₂ Level Gage Suite - The LN₂ level control suite basically consists of two Johns Cryogenics units:

- Model SN1-6, level control unit
- Upper and lower sensors.

A minor modification made to the vendor-delivered units does not affect its operation as an independent unit. To facilitate using the SN1-6 control unit in the cabinet, two plugs are mounted on the back of the unit and the wiring for the upper and lower sensor units are routed through the sensor cable to the cryopump. The remote valve outlet is used to activate the LN₂ fill valve.

5.2.1.3 Display and Control Panel - The display and control panel is a pictorial representation of the cryopump system with discrete "Dialight" type 9175 and 9176 LEDs used to indicate valve status. The right side of the panel contains three buttons.

- **Emergency Stop** - This button is a maintain-maintain switch located on the upper right side of the schematic panel. It interrupts sequencer operation and unpowers all valves/actuators when pushed in. A subsequent push resets the button, but the unpowered valve/actuator condition remains until the operator enters keyboard instructions (see Appendix B, Section 3), or pushes the Auto/Direct button
- **Stop** - This button is a maintain-maintain switch located below the Emergency Stop button. It holds the valves/actuators in their current positions when pushed in. A subsequent push resets the button, but the valve/actuator positions are held until instructions are entered (see Appendix B, Section 3) at the keyboard or the Auto/Direct button is pushed
- **Auto/Direct** - This is a color-coded, maintain-maintain switch. With the blue and amber button in the extended position the computer is in automatic (sequencer) mode. The computer performs the control function based on preprogrammed elapsed time events that sequence the cryopump through its repetitive cycles. With the button in the depressed position, the system is under manual or direct control, allowing the relays for the valves and actuators to be turned on and off based on the commands (activation) of the appropriate switches on the left side of the panel.

5.2.1.4 LHe Level Controller Suite - The cryopump liquid-helium-level control suite consists of three systems manufactured by American Magnetics, Inc. Each system has a Model KE-101A controller and a LHe level sensor which is a very fine filament of superconductive NbTi wire inside a rugged 1/4 in. diameter tube. When the sensor is energized with a

small current (70 mA), the length of wire above the liquid helium becomes resistive while the wire below the liquid remains superconducting. Consequently, the resistance of the sensor varies linearly with the depth of the liquid helium.

The level controller supplies a constant current to the sensor and measures the resulting voltage across it. This voltage is scaled, inverted and offset to indicate the helium level on a panel meter scaled from 0 to 100%. The output is also accessible on the controller rear as a 0 to 100 mV recorder output.

Low and high limit set points are provided for performing control functions with the level controller. When the liquid helium level drops below the low limit set point, a relay closes and the low limit indicator light is illuminated. Similarly, when the liquid helium level rises above the high limit set point a second relay closes and the high limit indicator light is illuminated. Outputs from both of these relays are at the rear.

A 117 Vac (optional 220 Vac) socket is on the rear panel of the off-the-shelf instrument for directly controlling automatic fill systems. When the helium level drops below the low set point, the socket is energized and remains energized until the helium rises to the high limit set point. The socket is then deenergized until the liquid helium level falls to the low limit. For the continuous duty cryopump operation the above feature has been disconnected so that a no-voltage signal can be provided to the microcomputer.

5.2.1.5 Computer Suite - The Rockwell AIM-65 microcomputer is used as the controller for all remotely operated valves and actuators. The microcomputer system, which can be programmed readily in either Basic or Assembler language, consists of:

- A65-420 - AIM 65 with 4K RAM, monitor, Basic and Assembler
- A65-006 - AIM 65 power supply and enclosure
- RM65-7008(E) - 8 slot card cage
- RM65-7104(E) - Adapter/buffer
- RM65-3132(E) - 32K dynamic RAM module
- RM65-5223(E) - Multi-function peripheral interface (MPI) module
- CTR-60 - Radio Shack "Realistic" cassette recorder
- PB16 - "Gordos" 16 position I/O unit (Opto-22 makes an exact equivalent)
- OAC5 - "Gordos" ac output module (Opto-22 makes an exact equivalent).

The AIM-65 has a 20-column thermal printer, a 20-character alphanumeric display, and a full-size terminal style keyboard. The software control program (Subsection 5.4) developed

for the cryopump application is in Basic. The cassette recorder provides the permanent storage medium used for program loading and recording.

A PB-16 mounting rack provides the interface mounting station for the solid state relays. The 16 valves/actuators are commanded through the solid state relays both in the sequencer (automatic) and the direct (manual) modes.

To activate the computer for automatic operation, or to control the valves/ actuators manually, the switch located on the right hand side of the computer keyboard and the two switches located on the power panel must be in the "ON" position.

5.2.2 Power Supply

An external +12 Vdc, 3 amp regulated power supply for the 8-slot card cage was built and is housed in the chassis located on the lower left hand cabinet wall. It has an external knob controller that can be used to vary the voltage from 0 to 30 Vdc. Since overvoltage may damage the control system, this voltage should be carefully adjusted to 12 ± 1 Vdc for the cryopump use (Fig. 5-16). A stop is provided at the 12 Vdc output position. The power supply is a standard full-wave rectifier design consisting of:

- Transformer 120 V-P-24 V-S
- Full-wave bridge rectifier 400 PIV
- Adjustable regulator, LM 317T 1.2 to 37 Vdc .
- Standard electronic components as indicated.

Fig. 5-16 12 Vdc Power Supply

5.3 CRYOPUMP CONTROL

The control system for the cryopump uses the digital microprocessor computer to set the positions of the automatic valve and louver actuators in the pump. The operator controls the position of the pump valve and door actuators at the computer console (Fig. 5-14). He/she operates the actuators automatically with commands entered through the computer keyboard or manually using switches on the schematic panel. Automatic (sequencer) or manual (direct) operation is selected by pushing the Auto/Direct and Stop buttons. These buttons which are activated only in the automatic mode, allow the operator to interrupt cryopump actuator sequencing. Temperature and cryogenic liquid-level instrumentation is mounted on the console. Liquid helium level is displayed and the high and low level quantities can be set for the two pumping units and the collector pump. Descriptive information about the computer program and the associated pump nomenclature is provided below.

5.3.1 Events

A particular arrangement of valve and louver actuator positions held for a specified time is termed an event. There are six events preprogrammed into the control system software as described in Table 5-1.

Table 5-1 Event Descriptions

EVENT	DESCRIPTIONS
1	PUMPING UNIT NO. 1 PUMPING, PUMPING UNIT NO. 2 REGENERATING
2	PUMPING UNIT NO. 1 PUMPING, PUMPING UNIT NO. 2 COOLING DOWN
3	PUMPING UNIT NO. 1 REGENERATING, PUMPING UNIT NO. 2 PUMPING
4	PUMPING UNIT NO. 1 COOLING DOWN, PUMPING UNIT NO. 2 PUMPING
5	COLLECTOR PUMP REGENERATING
6	COLLECTOR PUMP COOLING DOWN
R85-0718-031G	

In addition to the preprogrammed events, the control system allows the operator using the microprocessor keyboard to enter valve and louver actuator positions of his/her own choosing for any or all of the events.

5.3.2 Interlocks

To prevent the pump from being improperly operated, there are interlocks on certain valves. The use of interlocks is optional and is set by the response to a microcomputer prompt: "Do you want interlocks". The interlocks operate as follows:

- If, for a particular pumping unit, its fill and dump valves are closed, then its vent valve will be commanded open
- If a fill valve is open, then the corresponding purge valve is commanded closed.

5.3.3 Sequencer

The microprocessor control software has a built-in sequence of events which will be followed when the program is in the sequencer (automatic) mode. The valve/actuator positions for each event, the length of time for each event, and then the number of pump cycles between collector regenerations may be set by the operator. The valve/actuator positions have default values in the software as described in Table 5-2. These valve positions will be commanded unless they are altered by the operator.

Table 5-2 Default Valve/Actuator Positions

VALVE/ACTUATOR	NOMENCLATURE	EVENT					
		1	2	3	4	5	6
PURGE 1	P1	C	C	O	C	C	C
VENT 1	V1	O	O	C	O	O	O
FILL COLLECTOR	FC	O	O	O	O	C	O
FILL 1	F1	O	O	C	O	O	O
DUMP 1	D1	O	C	C	O	C	C
DUMP 2	D2	C	C	C	C	C	C
FILL 2	F2	C	O	O	O	O	O
PURGE 2	P2	O	C	C	C	C	C
VENT 2	V2	C	O	O	O	O	O
LOUVER 2	L2	C	C	O	O	C	C
COLLECTOR DOOR 1	CD1	C	C	O	C	C	C
COLLECTOR DOOR 2	CD2	O	C	C	C	C	C
NOTES: LOUVERS 1 AND 2 ARE CONNECTED SO THAT ONE IS OPEN WHILE THE OTHER IS CLOSED O = OPEN; C = CLOSED R85-0718-032G							

The length of time spent in each event is set by an internal loop in the control program and thus is directly controlled by the CPU clock. Alternatively, the event time for each event may be specified in response to the question, "Do you want to initialize event times?". The default value is approximately 0.1 min per event for any event time not inputted. The event times input are in minutes.

The sequencer will cycle the pump a number of times (each pass through Events 1 to 4 constitutes a loop) before the collector is regenerated (Event 5). The number of loops may be input by the operator. The default value is three.

The sequence in which events are commanded by the control software is shown as follows:

2-3-4-1-2-3-4-1-2-3-4 additional (1-2-3-4) cycles to satisfy the specified number of loops -1-2-5- manually operated collector pump regeneration if desired -6-3-4-1-2-3-4- etc.

Note: (1) The first loop omits Event 1 so that pumping unit 2 is not regenerated immediately following initial cooldown of the pump.

(2) Numerals refer to the events described in Table 5-1.

The computer display shows the status of the louver door and valve actuator positions as typified by the following:

1 BVS 164 AVS 213

This sample display shows status during Event 1 which arranges the actuators for pumping unit No. 1 to be pumping the vacuum chamber, while pumping unit No. 2 is being regenerated (Table 5-1). The actuator command signals are represented by a decimal equivalent of two eight-digit binary numbers, which are translated by the computer as signals to relays for powering and unpowering the actuators. The sample numbers in their binary form are:

164: 10100100 for BVS (valve set B)

213: 11010100 for AVS (valve set A)

Each digit in the sixteen binary terms represents a signal to a valve/actuator to the powered (0) or to be unpowered (1). The relationship between the binary digits and the valve/actuator codes is as shown in Table 5-3.

Table 5-3 Binary Digits & Valve/Actuator Codes Relationship

BVS								
BINARY DIGIT	1	0	1	0	0	1	0	0
VALVE ACTUATOR	P1	V10	V1C	FC	F1	D10	D1C	D20
AVS								
BINARY	1	1	0	1	0	1	0	0
VALVE ACTUATOR	D2C	F2	P2	V20	V2C	L2	CD1	CD2
R85-071B-033G								

The nomenclature is described in Table 5-4. The "O" or "C" following the nomenclature for a vent or dump valve, e.g., V10 or D1C indicates a command is required to open or to close the valve, respectively. For the given example, the relationship between the computer signal represented by the binary code and the positions of the louvers doors and valves is shown in Table 5-5.

Table 5-4 Description of Actuators, Sensors & Switches

ACTUATORS			
DESCRIPTION	CODE	ACTUATOR TYPE*	FUNCTION
COLLECTOR FILL VALVE	FC	AUTO/NC	LIQUID HELIUM IN
COLLECTOR VENT VALVE	VC	MANUAL	COLD GAS HELIUM OUT
COLLECTOR PURGE	PC	MANUAL	AMBIENT HELIUM IN
COLLECTOR DUMP	DC	MANUAL	CRYOGENIC HELIUM OUT
FILL VALVE NO. 1	F1	AUTO/NC	LIQUID HELIUM IN
VENT VALVE NO. 1	V1	AUTO/POPC	COLD GAS HELIUM OUT
PURGE VALVE NO. 1	P1	AUTO/NC	AMBIENT HELIUM IN
DUMP VALVE NO. 1	D1	AUTO/POPC	CRYOGENIC HELIUM OUT
FILL VALVE NO. 2	F2	AUTO/NC	LIQUID HELIUM IN
VENT VALVE NO. 2	V2	AUTO/POPC	COLD GAS HELIUM OUT
PURGE VALVE NO. 2	P2	AUTO/NC	AMBIENT HELIUM IN
DUMP VALVE NO. 2	D2	AUTO/POPC	CRYOGENIC HELIUM OUT
LOUVER 1	L1	AUTO/NO	LOUVER DOORS
LOUVER 2	L2	AUTO/NO	LOUVER DOORS
COLLECTOR DOOR NO. 1	CD1	AUTO/NO	PUMP-TO-COLLECTOR DOOR
COLLECTOR DOOR NO. 2	CD2	AUTO/NC	PUMP-TO-COLLECTOR DOOR
SENSORS & SWITCHES			
DESCRIPTION	FUNCTION		
EMERGENCY STOP BUTTON	PANEL CONTROL TO STOP AUTOMATIC SEQUENCER AND UNPOWER OPERATORS		
STOP BUTTON	PANEL CONTROL TO STOP AUTOMATIC SEQUENCER AND LEAVE OPERATORS IN THEIR LAST POSITIONS		
DIRECT/AUTO SWITCH	ALLOWS SELECTION OF AUTOMATIC SEQUENCER OR MANUAL CONTROL OF OPERATORS		
COLLECTOR FILL HELIUM SENSOR	HELIUM LEVEL SENSOR IN COLLECTOR		
FILL NO. 1 HELIUM SENSOR	HELIUM LEVEL SENSOR IN PUMPING UNIT NO. 1		
FILL NO. 2 HELIUM SENSOR	HELIUM LEVEL SENSOR IN PUMPING UNIT NO. 2		
* NC = NORMALLY CLOSED; NO = NORMALLY OPEN; POPC = POWERED OPEN, POWERED CLOSED			
R85-0718-034G			

Table 5-5 Actuator Types

BINARY CODE	1	0	1	0	0	1	0	0	1	1	0	1	0	1	0	1
ACTUATOR	P1	V10	V1C	FC	F1	D10	D1C	D20	D2C	F2	P2	V20	V2C	L2	CD1	CD2
TYPE	NC	PO	PC	NC	NC	PO	PC	PO	PC	NC	NC	PO	PC	NC	NO	NO
POSITION	C	O	O	O	C	O	O	C	O	C	O	C	C	C	C	O

NOTE:
 NC = NORMALLY CLOSED; NO = NORMALLY OPEN;
 PC = POWER TO CLOSE; PO = POWER TO OPEN
 R85-0718-035G

The default positions for all events as shown on the computer display, are shown below in Table 5-6.

Table 5-6 Microprocessor Display During Sequencer Operation

EVENT	BINARY CODE			
	BVS	164	AVS	213
1	BVS	165	AVS	44
2	BVS	75	AVS	42
3	BVS	165	AVS	40
4	BVS	181	AVS	44
5	BVS	165	AVS	44
6	BVS	165	AVS	44

NOTE:
 TABLE 5-2 SHOWS THE CORRESPONDING VALVE/ACTUATOR POSITIONS
 R85-0718-036G

5.3.4 Actuators, Sensors and Switches

The cryopump is equipped with a number of actuators (valves, louvers and doors), level sensors and switches which allow the the controller or the operator to operate the pump. These are described in Table 5-4 and in the following sections:

5.3.4.1 Level Sensors - The microprocessor scans each of the level sensors and uses the information returned to control the operators. The input to the microprocessor is the output signal from a level controller which is commanding fill valve actuation (close at high level, open at low level). The fill valve opens only when the level controller and the microprocessor sequencer provide "open valve" commands simultaneously.

5.3.4.2 Emergency Stop Button - When this button is activated all valves/actuators will be unpowered. The vent and dump valves will be left in the position they were in when the Emergency Stop was activated. The collector doors will open and the louver doors on pumping unit No. 2 will close. Purge and fill valves will close or remain closed.

5.3.4.3 Stop Button - When this button is activated, the Stop command stops program execution but leaves the valves and doors powered in the positions they were in prior to Stop activation.

5.3.4.4 Sequencer Stop - Sequence Stop is a stop which is activated by typing an "S" while the computer is executing an event. When the event is complete the computer will stop, leaving all valves powered in the positions of that event.

5.3.4.5 Auto/Direct Button - When this button is activated to the Direct position the operator can operate the valve and door actuators directly using the control switches (Subsection 5.3.4.6). In the Auto position, the sequencer mode commands the valve/actuators.

5.3.4.6 Control Switches - When a switch (Fig. 5-15) is in the up position, the corresponding valve or door is commanded to open. When the switch is in the down position, the corresponding valve is commanded closed. The lower door switch operates from side to side. When this switch is pointing to the right, louver No. 2 is open and No. 1 is closed. When to the left, No. 1 is open and No. 2 is closed.

5.4 CONTROL SYSTEM SOFTWARE

The automatic sequencing of the cryopump is controlled by an AIM-65 microprocessor programmed in AIM-65 Basic language. A complete program listing is provided in Appendix C.

The overall program flow is shown in Fig. 5-17. After program initiation, the operator has the options of selecting the positions of any or all of the valve and louver actuators for each event, the event times (the time duration of each event), and the number of pumping cycles (loops) between collector regenerations. He/she must then select a mode of operation which may be "Sequencer Start", "Direct" or "Reinitialize". Selection of "Direct" allows the operator to control the actuators directly, and selection of "Reinitialize" causes the above options to be reoffered. If "Sequencer Start" is selected, the program starts on the selected sequence of events, holding each event for the proper time.

The program loops through the pumping Events 1, 2, 3, 4 (starting with Event 2 on the first pass) for the designated number of cycles. It then executes Events, 1, 2 and 5 and then pauses waiting for the operator to complete collector regeneration and cooldown,

Fig. 5-17 Controller Program Logic Diagram

which is a manual operation. After cooldown the operator signals to continue. When this signal is received, Events 6, 3 and 4 are executed. This is followed by a return to the Events 1, 2, 3, 4 sequence.

The basic routine of the sequencer program is subroutine 500 which acts on input data, sets valve positions and checks external button positions and sensor controller commands. It has an internal loop which causes the subroutine to be accessed 140 times multiplied by the value set for that particular event time. Because it takes approximately one minute to complete 140 loops through the subroutine, execution of the program statements acts as the sequencer clock.

Figure 5-18 provides a more detailed program flow chart. It will be noted that throughout the program, checks are made on the status of the Emergency Stop, Stop, and Auto/Direct buttons. When the program detects that any button has been pushed, it will branch to an appropriate subroutine to effect the desired sequencer termination.

Valves may be in positions other than those commanded by either the operator or by a level sensor. If a valve is directed to a position in violation of the interlock rules, then the interlocks will prevail (Subsection 5.3.2). Each fill valve is subject to command of both the programmed position and the fill sensor. If either the programmed position or fill sensor commands a fill valve to close, then the valve will close. The valve will open only if both signals are "open" commands.

Fig. 5-13 Controller Program Flow Chart (1 of 10)

Fig. 5-18 Controller Program Flow Chart (3 of 10)

Fig. 5-18 Controller Program Flow Chart (4 of 10)

R85-0718-014 (5/10)

Fig. 5-18 Controller Program Flow Chart (5 of 10)

Fig. 5-18 Controller Program Flow Chart (6 of 10)

Fig. 5-18 Controller Program Flow Chart (7 of 10)

Fig. 5-18 Controller Program Flow Chart (8 of 10)

Fig. 5-18 Controller Program Flow Chart (9 of 10)

Fig. 5-18 Controller Program Flow Chart (10 of 10)

6 - SUPPORTING ANALYSIS

This section provides a summary of analyses performed in support of the cryopump design. In many cases the design evolved from similarity to the first pump (Ref 6). These items included louver design, thermal isolation methods, feed and dump line sizing, temperature and pressure instrumentation selection, roughing line size and transfer line design. A structural analysis was performed to verify the design for the low thermal stresses and low operating pressures projected for the cryopump. Adequate margin was verified for all containers particularly at points of penetration between reservoirs and connecting tubes. The structural analysis is filed in the Grumman Advanced Energy Systems group.

6.1 LEAKAGE ANALYSIS

Deuterium is pumped on to the liquid helium-cooled pumping units while the louver doors are open to allow passage from the vacuum chamber. The collector door is closed to isolate the pumping units from the collector pump. To effect regeneration the positions of the doors are reversed; the louver doors are closed and the collector door is open. Liquid helium is purged from the pumping panel, allowing the panel to warm up sufficiently to release the deuterium. The released gas is then captured on the collector pump. During the regeneration the pump is subject to back-leakage to the vacuum chamber during the gas transfer from the pumping unit to the collector pump. Low conductance gaps between the movable louver doors and the fixed portions of the pump shielding control the back-flow.

An analytical model was prepared to evaluate the effect of pump geometry and operating conditions on the percentage of total pumped gas that returns to the vacuum chamber, and to predict the effect on pressure within the pump cavity. The model evaluates conditions over small time increments Δt so that the final conditions of a time increment become the initial conditions of the succeeding time. The model represents one pump segment; namely, a single pumping panel consisting of a liquid helium-filled tube with 1.75 in. (4.5 cm) x 1/8 in. (0.32 cm) fins attached, and 2 in. (5.1 cm) lengths each of the upper and lower helium reservoirs of the collector pump and collector door opening. The segment is bounded by two adjacent fixed louver panels, by one pair of louver doors, and a 2 in. (5.1 cm) length of the liquid nitrogen-cooled thermal shielding. The leakage path back to the

vacuum chamber is the gap between the upper and lower edges of each louver door and the fixed shielding; and between the door face and the adjacent door hinge which forms a door-stop.

The pressure P in the pump segment volume V results from a balance of gas flows within the segment. As the liquid helium is purged from the pumping panel during a time increment Δt , the panel area ΔA that is uncovered releases its gas charge Q_{in} into the volume. A quantity Q_1 is repumped on to the remaining cold portion of the panel, a quantity Q_{leak} leaks back to the vacuum chamber, and a quantity Q_2 enters the collector cavity to be pumped (Fig. 6-1). The cavity pressure change $(P - P_i)$ in a time increment is

$$P - P_i = (Q_{in} - Q_1 - Q_2 - Q_{leak})/V$$

Fig. 6-1 Cryogenic Leakage Model, Side View Through Pump Segment

The quantity Q_{in} released depends upon the prior accumulation of condensed gas on the panel that is on the pump throughput q , and the total pumping time T before regeneration.

$$Q_{in} = qT\Delta A$$

The quantity Q_1 redeposited on the remaining cold area of pumping panel A_{cold} , that is the area of panel surface backed by liquid helium is

$$Q_1 = P S_S A_{cold} \Delta t$$

where S_S is the specific pumping speed of the helium-cooled panel. The amount Q_2 of gas deposited on the collector pump surface area A_{coll} during a time increment is affected by the collector door conductance C and the specific pumping speed S_{sc} of the collector pump.

$$Q_2 = P(1/(S_{sc} A_{coll}) + 1/C)^{-1} \Delta t$$

The collector pump speed and the pumping panel speed during regeneration are difficult to assess because of the uncertainty of gas temperature and because of the rapid transition through different pressure regimes. The pumping speeds are treated as variables in the evaluation.

The amount leaked back to the vacuum tank Q_{leak} is

$$Q_{leak} = (P - P_{tank}) C_{leak} \Delta t$$

The slit between the louver door edge and the fixed portion of the shield has a conductance C_{leak} . When the leakage through the slit is measurable, the vacuum tank pressure is negligible compared to the pressure in the pump, and is taken as zero.

Defining the pumping speed or conductance for the pumping panel, the collector pump and the leak path as $Z_1/\Delta t$, $Z_2/\Delta t$ and $Z_3/\Delta t$ then the pump cavity pressure is

$$P = (qT\Delta A + VP_1)/(V + Z_1 + Z_2 + Z_3)$$

A set of conditions was picked as a basis for comparison to determine the sensitivity of leakage and pressure to changes in key parameters. The base condition and the range of the variables are shown in Table 6-1.

Table 6-1 Base Condition & Range of Variables

PARAMETER	BASE CONDITION	RANGE
SEGMENT WIDTH	5.1 cm	1
PUMPING PANEL AREA	694 cm ²	1
LOUVER DOOR HEIGHT	30.5 cm	1
COLLECTOR PUMP AREA	131 cm ²	1 to 1.8
COLLECTOR DOOR HEIGHT	11.9 cm	0.13 to 1
LOUVER DOOR GAP	0.1 cm	0.5 to 5
COOLANT PURGE RATE	4 cc/s	0.5 to 1
TOTAL PUMPING TIME	480 sec	1 to 2
COLLECTOR STICKING COEFFICIENT	1	0.5 to 1
PANEL STICKING COEFFICIENT	1	0.5 to 1

R85-0718-037G

The results in Table 6-2 predict significant reduction in leakage back to the vacuum chamber if the slit area around the louver door is reduced to a practical minimum and if the collector door area is increased to a practical maximum, as projected in Ref 6. In each case the base conditions (0.1 cm slit and 11.9 cm high collector door) were targeted for design.

Table 6-2 Effect of Cryopump Characteristics on Leakage & Pressure Compared to a Base Condition

PARAMETER	PARAMETER RATIO	LEAKAGE RATIO	PRESSURE PEAK RATIO
LOUVER GAP	5	4.31	0.80
LOUVER GAP	0.5	0.51	1.03
PUMPING TIME	2	1.01	16.4
COLLECTOR DOOR AREA	0.5	1.65	12.7
COLLECTOR DOOR AREA	0.25	2.80	18.2
COLLECTOR DOOR AREA	0.13	4.72	23.1
HELIUM PUMPING SPEED	0.5	1.28	6.42
COLLECTOR PUMP AREA	1.8	0.85	0.81
COOLANT PURGE RATE	0.5	1.00	0.51

R85-0718-038G

6.2 THERMODYNAMIC ANALYSIS

Steady state thermal analyses were performed on the shielding around the helium pumping units and the collector pump. Steady state temperature distributions were determined for the fixed shielding, and for the movable shielding which allows control of the pumped gas flow into the helium-cooled elements.

The problems were modeled on a workhorse thermal analyzer computer program which uses a "lumped parameter" or nodal presentation of the design. The nodes are thermally connected by discrete conduction, convection and radiation couplings analogous to an electrical circuit. This method has shown a close correspondence to real heat transfer processes.

6.2.1 Analysis of Fixed Shielding

A two-dimensional steady state thermal model of the pumping units and the upper and lower fixed shields was constructed. The model consists of an assembly with the uniform cross section shown in Fig. 6-2. The shielding material is aluminum 6061. A temperature-dependent thermal conductivity is based on Ref 7 data. The nitrogen-cooled shielding radiates to a 300°K stainless steel vacuum vessel externally and to 4°K aluminum helium-cooled units internally. The emissivities of the aluminum and stainless steel are 0.1 and 0.4, respectively. A contact resistance of $50 \text{ BTU hr}^{-1} \text{ ft}^{-2} \text{ F}^{-1}$ ($284 \text{ W m}^{-2} \text{ K}^{-1}$) is used between all fastened (non-welded) interfaces. The collector door is assumed to have a temperature equal to its lower connection and is assumed to be detached at its upper edge.

Figure 6-3 presents the steady-state temperature distribution in the shielding. The upper helium reservoir absorbs $.025 \text{ W}$ ($.209 \text{ W m}^{-2}$) from the shielding. The lower helium reservoir absorbs $.027 \text{ W}$ ($.233 \text{ W m}^{-2}$) and the collector pump reservoir absorbs $.088 \text{ W}$ ($.488 \text{ W m}^{-2}$).

The analysis shows that the shielding maximum temperature is predicted to be 117°K and the maximum heat transfer rate on the helium units is $.488 \text{ W m}^{-2}$.

6.2.2 Analysis of Movable Louvers

A two-dimensional thermal model of the movable louver assembly was constructed. The analysis was performed with the louvers in an open position. A cross section of the assembly is presented in Fig. 6-4. The louver and pumping panel material is aluminum 6061. The length of the louvers is 30.5 cm. The movable portion of each louver is blackened to reduce the vacuum vessel radiation from reaching the pumping panel surface. Because the cryopump operates in a vacuum environment, the only modes of heat transfer are radiation and conduction.

The model was run for a variety of hinge conductive couplings. The maximum louver temperature and pumping panel flux density were determined as a function of hinge conductive coupling. The results are presented in Fig. 6-5.

A similar louver assembly was tested at Lawrence Livermore National Laboratory (Ref 6). The experimental results indicate a maximum louver temperature of 200°K for an assembly with a hinge attaching the louver. This corresponds to a hinge conductance of $.014 \text{ WK}^{-1}$ and a pumping panel flux density of 8.2 W m^{-2} (Fig. 6-5). To increase the conduction

NOTE: ALL DIMENSIONS ARE IN cm

R85-0718-006G

Fig. 6-2 Thermal Model for Fixed Shielding

Fig. 6-3 Fixed Shielding Temperature Distribution

Fig. 6-4 Movable Shielding Thermal Model

Fig. 6-5 Effect of Hinge Conductance on Pumping Panel Flux Density and Maximum Louver Temperature

across the hinge, a thermal shunt was added. The shunt comprised 10 layers of .003 in. aluminum foil. The calculated conductive coupling value for the foil shunt was $.204 \text{ WK}^{-1}$. The hinge and foil conductive couplings are in parallel and produce a total coupling of $.218 \text{ WK}^{-1}$. This coupling corresponds to a maximum louver temperature of 90.5°K from Ref 6. The addition of the foil reduced the pumping panel flux density from 8.2 to 2.75 Wm^{-2} . The pumping panel flux density in this range of hinge conductances is insensitive to relatively large changes in hinge conductance. Further improvements to the hinge design to increase its conductance would cause no significant reduction in the pumping panel heat load.

A hinge was incorporated into the design which would be easier and less expensive to manufacture. The new hinge mounts to the movable louver in only three places. The conductance through the hinge becomes negligible and the total conductive path is provided by the foil only. The total hinge conductance is reduced to $.204 \text{ WK}^{-1}$. This does not affect the pumping panel flux density significantly; therefore, the new design is found acceptable. Figure 6-6 presents the temperature distribution for the louver assembly with the foil-only hinge configuration. Note that the major temperature drop still occurs across the hinge.

6.3 SAFETY ANALYSIS

The pump design was analyzed to verify safe function in case of inadvertent off-nominal operation. The conditions which were evaluated were:

- Overpressure of the helium pumping unit or collector pump
- Release of pumped hydrogen back to the main chamber
- Regeneration of collector pump with roughing system inoperative.

6.3.1 Overpressure Protection

The flow of helium for the pumping panel is controlled on its inlet side by the fill valve mounted on the transfer line. It is controlled on its outlet side by the vent valve which allows boil-off vapor to be returned to the refrigeration unit, and by the dump valve which allows the cryogenic helium to be returned during regeneration.

The cryopump controller provides interlocks to prevent all three valves on each pumping unit from being closed simultaneously. Valves on the outlet of the collector pump are manual and are set by the operator. To provide redundancy in an event such as a controller or valve failure, each pumping unit and the collector pump unit have mechanical relief valves installed in their outlet manifolds to protect against overpressure. The relief valves

Fig. 6-6 Temperature Distribution for Foil Only Hinge Configuration

are set at 10 psig (0.17 MPa) and will restrict the trapped helium pressure to 25 psia (0.17 MPa) if all ports are closed during normal pumping operation.

The relief valves also provide protection in case the pressure in the main vacuum tank is allowed to increase to a value in the transition pressure range which is conducive to thermal runaway. Convective heat transfer in the confined space between the pump's thermal shield and the helium filled containers is estimated conservatively at $10^{-2} \text{ W cm}^{-2}$, so that for the pumping unit with an exposed surface area of 2219 cm^2 , the total heat load Q is 22.2 W. The pumping unit internal volume V_i including fill and vent systems is 1632 cm^3 containing 61% liquid helium, so that when the helium pressure increases to 2.5 atm (0.25 MPa) (selected as the relief pressure for analysis), the energy added to the helium is 717 Ws. This pressure therefore is reached in 32 s.

The pressure trend following relief valve unseating was evaluated using a time increment calculation which determined pressure of the contained helium as a function of the energy in and the flow out. Critical flow, $\dot{W}$ through the relief valve orifice is

$$\dot{W} = AP (g\gamma/RT(2/(\gamma + 1))^{(\gamma + 1)/(\gamma - 1)})^{1/2} \quad \text{where}$$

A = relief valve effective orifice

P = helium pressure

T = helium temperature

γ = helium specific heat ratio

The helium mass in the pumping unit W after an increment of time Δt is

$$W_2 = W_1 - \dot{W}_1 \Delta t$$

where the subscripts 1 and 2 refer to the state of the helium prior to and following a time increment.

The heat incident on the cryogenic surfaces causes a temperature change $T_2 - T_1$ in accordance with

$$T_2 - T_1 = Q \Delta t / (W C_{p1})$$

where

C_p = helium specific heat.

The container pressure P is defined by

$$P_2 = k_2 W_2 T_2 / V_i$$

where

$$k = P/\rho T$$

is derived from the NBS helium thermophysical properties manual (Ref 8), which was the source for all helium properties required in this analysis.

The conditions for the pumping unit at the time of relief valve opening are as follows:

- Relief diameter - 0.5 inch ($C_D = 0.25$)
- Temperature - 5.33°K
- Pressure - 2.5 atm (0.25 MPa)
- Constant heat load - 22.2 W
- Volume - 1632 cm³
- Helium mass - 136.2 g.

The pressure in the pump unit decreases after the opening of the relief valve and reaches a pressure of 70% initial value within one second. Additional cases, in which the relief area was reduced to 25% and in which the energy deposition rate was increased four times, likewise produced no overpressure.

The collector pump was similarly analyzed. It has an exposed surface area of 1733 cm², so that the total heat load is 17.3 W. Its volume including fill and vent systems is 3854 cm³ containing 73.8% liquid. A relief valve set at a pressure of 2.5 (0.25 MPa) atm would open in 33.7 s. As in the case of the pumping unit, pressure decreases upon relief valve opening, and is down to 72% after one second. For a condition in which the relief valve area was reduced to 12.5% from the nominal 0.5 in. diameter ($C_d = 0.25$), pressure increased slightly to 2.51 atm before starting to drop within 15 s.

Based on these results, a relief valve was installed on each pumping unit and on the collector pump. The orifice was 0.5 in. diameter and the relief setting was 10 psig (0.17

MPa), which decreased the relief pressure from the analyzed value of 2.5 atm (0.25 MPa) for added margin.

6.3.2 Hydrogen Limit

The cryopump accumulates hydrogen (deuterium) on its collector pump until it is regenerated by releasing its gas load to the roughing system. This accumulated amount constitutes a potential combustion source if its partial pressure in air puts it in a flammability range for hydrogen-air. If the hydrogen pressure resulting from an inadvertent release into the vacuum chamber is less than 12 Torr, then no combustion is expected from subsequent mixing with air (Ref 9).

A 12 Torr pressure in the vacuum chamber which has a free volume of 2490 liters corresponds to a deuterium gas mass of 6.4 g. Based on the cryopump throughput of 0.124 Torr liter/sec, which is $2.65 \times 10^{-5} \text{ g s}^{-1}$, the prescribed pressure limit would be attained in 67 hours. This time is far in excess of the regeneration cycle time for the pump whose collector pump will be regenerated daily.

6.3.3 Collector Pump Regeneration

The collector doors between the compartments containing the collector pump and the pumping units are closed during collector pump regeneration. Gas released into the collector compartment will cause a slight differential pressure across the collector doors. The collector compartment is 25.1 liter. More than 11 hours of operation between regenerations combined with a closed roughing system would be required to exceed the door design pressure limit of 1 psia (52 Torr). The selected collector door design is satisfactory.

7 - REFERENCES

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APPENDIX A

REQUIREMENTS FOR A CONTINUOUS DUTY CRYOPUMP CONTROL SYSTEM

APPENDIX A INTRODUCTION

The continuous duty cryopump control system provides the means of remotely monitoring and controlling the cryopump system. The control system is defined as the equipment and software required to satisfy the requirements defined herein. This includes but is not necessarily limited to a microcomputer, a switch panel, temperature sensor, and level sensor controllers. The programmable microcomputer (MPU) is the controller for all remotely operated valves and actuators. The controller operates in the sequencer mode (auto), and performs the control function based on preprogrammed lapsed time events (sequence) that command the cryopump valves and actuators through repetitive control cycles. The event currently being commanded is concurrently displayed on the MPU. In the direct mode, the system is under manual control, allowing valves and actuators to be turned on and off based on positioning of switches on the switch panel.

Each measurement can be read on displays provided with the sensors. The control system has 10 temperature sensors (for example 7 LN₂, 3 LHe) two pressure gages (Baratron) including one provided by LLNL, 3 LHe level gages and one LN₂ level gage.

The control system provides the capability of operating one cryogenic nitrogen valve (Appendix A, Section 1), nine helium valves (Section A2; See Table A-1), one louver actuator (Subsection A3.1), and two collector door actuators (Subsection A3.2).

Table A-1 Identification of Helium Valves

IDENT	VALVE NOMENCLATURE
P1	PUMPING UNIT 1 PURGE
V1	PUMPING UNIT 1 VENT
DC	COLLECTOR PUMP DUMP (MANUAL)
FC	COLLECTOR PUMP FILL
F1	PUMPING UNIT 1 FILL
D1	PUMPING UNIT 1 DUMP
PC	COLLECTOR PUMP PURGE (MANUAL)
D2	PUMPING UNIT 2 DUMP
F2	PUMPING UNIT 2 FILL
VC	COLLECTOR PUMP VENT (MANUAL)
P2	PUMPING UNIT 2 PURGE
V2	PUMPING UNIT 2 VENT

R85-0718-039G

A1 CRYOGENIC NITROGEN VALVE (1)

Capability to open/close the cryogenic nitrogen valve (identified as valve "LN" in Fig. A-1) is provided by a signal from a liquid level sensor. The high level signal closes the valve, and the low level opens the valve. The valve is powered to open, and unpowered to close.

A2 HELIUM VALVES (NINE AUTOMATIC AND THREE MANUAL)

The pump coolant is liquid helium. The helium valves (identified Fig. A-1) provide the capability of supplying liquid helium through a fill valve, discharging the vapor boiled off through a vent valve, introducing ambient gas helium through a purge valve for pump regeneration, and discharging the cold helium during regeneration through a dump valve. The helium valves are identified in Table A-1. Valves DC, PC and VC are manually operated valves and require no control operations.

A2.1 FILL VALVE (3)

Capability in the sequencer mode to open/close each fill valve is provided by a signal from a liquid level sensor (3) and a sequencer in accordance with the following matrix:

If the signal from the level sensor is:	and the signal from the sequencer is:	then the fill valve is commanded:
close	close	closed
open	close	closed
close	open	closed
open	open	open

The valve is powered to open and unpowered to close. The capability in the direct mode is provided to override the function of the above paragraph so the valve can be opened/ closed regardless of the level sensor and sequencer signals.

A2.2 VENT VALVE (2)

Capability in the sequencer mode to open/close each vent valve (except valve VC) is provided by a signal from a sequencer. The valve is powered while closing and while opening. It is unpowered in the closed and open position.

ACTUATOR		SEQUENCER PROGRAM PROFILES																			
EVENT	NAME	P1	V1	DC	FC	F1	D1	PC	D2	F2	VC	P2	V2	L1	CD1	CD2	R	CRYOPANEL No. 1		CRYOPANEL No. 2	
1		C	O	C	O	O	C	C	O	C	O	O	C	O	C	O	C	PUMPING		REGENERATING	
2		C	O	C	O	O	C	C	C	O	O	C	O	O	C	C	C	PUMPING		COOLING DOWN	
5		C	O	O	C	O	C	O	C	O	C	C	O	O	C	C	O	[COLLECTOR PUMP REGENERATING]			
6		C	O	C	O	O	C	C	C	O	O	C	O	O	C	C	C	[COLLECTOR PUMP COOLING DOWN]			
3		O	C	C	O	C	O	C	C	O	O	C	O	C	O	C	C	REGENERATING		PUMPING	
4		C	O	C	O	O	C	C	C	O	O	C	O	C	C	C	C	COOLING DOWN		PUMPING	

*SEE SUBSECTION A2.1

- NOTES:
- C - CLOSED; O - OPEN
 - COMMANDS TO VALVES FC, F1 & F2 SUBJECT TO CONDITIONS OF SUBSECTION A2.1
 - VALVE LN IS NOT OPERATED BY SEQUENCER
 - VALVES DC, PC, VC AND R ARE MANUAL VALVES (NOT OPERATED BY SEQUENCER)
 - EVENTS 1, 2, 3 AND 4 CONSTITUTE ONE CYCLE
 - EVENTS 5 AND 6 DO NOT OCCUR DURING EACH CYCLE BUT OCCUR DURING EACH *Nth CYCLE (N IS PROGRAMMABLE).

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Fig. A-1 Pump Valve Schematic & Sequencer Requirements

Capability in the direct mode is provided to override the function of the above paragraph allowing the valve to be opened/closed regardless of the sequencer signal.

Interlock is provided in the sequencer mode so that the vent valve cannot be closed while both the corresponding fill valve is closed (F1-V1, F2-V2, per Section A2) and the corresponding dump valve is closed (D1-V1, D2-V2, per Section A2).

A2.3 PURGE VALVE (2)

Capability in the sequencer mode is provided to open/close each purge valve (except valve PC) with a signal from a sequencer. The valve is powered to open and unpowered to close.

Capability is provided in the direct mode to override the function of the above paragraph so that the valve can be opened/closed regardless of the sequencer signal.

Interlock is provided in the sequencer mode so that the purge valve cannot be opened while the corresponding fill valve is open (F1-P1, F2-P2, per Section A2).

A2.4 DUMP VALVE (2)

Capability in the sequencer mode to open/close each dump valve (except valve DC) is provided by a signal from a sequencer. The valve is powered while opening and powered while closing. It is unpowered in the closed and open position.

Capability is provided in the direct mode to override the function of the above paragraph so that the valve can be opened/closed regardless of the sequencer signal.

A3 ACTUATORS

The continuous duty cryopump has three pneumatic actuators operated by electric pilot valves. These electric valves are controlled by signals from the sequencer.

A3.1 LOUVER ACTUATOR (1)

Capability in the sequencer mode to open/close the louver-actuator pilot valve (Valve "L1" in Fig. A-1) is provided by a signal from a sequencer. The valve is powered to open (position 2) and unpowered to close (position 1). (Position 2 means that pumping unit 2 is open; position 1 means that pumping unit 1 is open.)

Capability is provided in the direct mode to override the function of the above paragraph allowing the valve to be opened/closed regardless of the sequencer signal.

A3.2 COLLECTOR DOOR ACTUATOR (2)

Capability in the sequencer mode to open/close each collector door actuator pilot valve, (identified as CD1 and CD2 in Fig. A-1), is provided by a signal from a sequencer. Each valve is powered to close a door, and unpowered to open a door. (Valve CD1 operates the door for pumping unit 1 and valve CD2 operates the door for pumping unit 2.)

Provide the capability in the direct mode to override the function of the above paragraph so that each valve can be opened/closed regardless of the sequencer signal.

A4 VACUUM ROUGHING VALVE

A single roughing valve (valve R) provided by LLNL isolates the collector pump from the vacuum roughing system. This valve is a manually operated valve and requires no control operations.

A5 PROGRAMMABLE MICROPROCESSOR UNIT

The programmable microprocessor unit (MPU) is the controller for all remotely operated valves described in Section A2, and the actuators described in Section A3. The MPU accepts operator commands to a software program (sequencer) by means of a keyboard.

A5.1 SEQUENCER

A software program (sequencer) and necessary relays in the MPU are incorporated to control the remotely operated valves and actuators in accordance with the profiles shown in Fig. A-1 and the requirements of Subsection A2.1 through A3.2.

The sequencer program will repeat the standard cycle consisting of Events 1, 2, 3 and 4 except that for each nth cycle and each multiple of nth cycle, the cycle will consist of Events 1, 2, 5, 6, 3 and 4 (regeneration cycle). A Stop command will automatically follow Event 5. The value "n" is to be determined by test during the cryopump development program at LLNL. The time durations of each event (1, 2, 5, 6, 3, 4) are to be determined during development testing at LLNL. The sequencer program will provide the capability of varying the value of "n" and the duration of the events by keyboard entry. The event currently being commanded will be displayed on the MPU.

The sequencer program will respond to the following commands inputted at the keyboard.

- Start - The Sequencer Program Profiles (Fig. A-1) will start by keyboard command at the beginning of Event 2 and repeat the standard cycles and/or regeneration cycles, defined in Subsection A5.1, until another command is entered
- Stop - Sequencer Program Profiles will be interrupted by a keyboard command or switch, which will hold the valves and actuators at their positions at the time of interruption. This condition will prevail until another command is entered. The provisions of Subsection A2.1 will remain in effect
- Emergency Stop - The Sequencer Program Profiles will be interrupted by a keyboard command or switch and all valve and actuator power will be switched off (unpowered). Instrumentation power will not be interrupted. This condition will prevail until another command is entered
- Sequencer Stop - This keyboard command causes the Sequencer Program Profiles to continue to the end of the event within which the Sequencer Stop command is given and then to stop and hold
- Resume - The Sequencer Program Profile will resume from the point of interruption resulting from a "Stop" "Emergency Stop" or "Sequencer Stop" command. The cycles will repeat until another command is entered.

A5.2 FAULT CONDITIONS

Fault conditions requiring automatic shutdown have not been identified. The MPU will respond to the shutdowns (Subsection A5.1) effected by the operator.

A5.3 STATUS DISPLAY

The capability to read the following information is provided.

A5.3.1 Cryopump System Schematic

Indicating lights are provided on a cryopump system schematic which will be "on" to indicate the conditions shown in Table A-2.

A5.3.2 MPU Display

The event being performed by the Sequencer Program will be displayed concurrently when the Sequencer Program is in effect. This display will be shown automatically without operator input.

**Table A-2 Cryopump System Schematic
Indicating Lights**

VALVE/ACTUATOR	CONDITION
PURGE 1	OPEN
VENT 1	OPEN
FILL COLL	OPEN
FILL 1	OPEN
DUMP 2	OPEN
FILL 2	OPEN
PURGE 2	OPEN
VENT 2	OPEN
PANEL NO. 1	PUMPING
PANEL NO. 2	PUMPING
COLLECTOR DOOR NO. 1	OPEN
COLLECTOR DOOR NO. 2	OPEN
R85-0718-040G	

APPENDIX B
INSTRUCTION FOR CONTROLLER OPERATION

APPENDIX B

CONTROLLER OPERATION

Operator instructions for the cryopump controller are entered through the microprocessor keyboard. The computer program stored on a cassette is entered into computer memory prior to operation. Once automatic sequencing of the valves and actuators has begun, the operator has options for interrupting the sequence.

The instructions for preparing the computer for operation from an unpowered condition, for using the automatic sequencer, and for interrupting sequencer operation are provided in these sections:

B1 COMPUTER STARTUP

The power switch for the AIM-65 computer is located on the right hand side of the unit. When the power is on, the computer will display "ROCKWELL AIM 65". A less-than sign (<) will appear on the left of the display, meaning the computer is waiting for a response to designate the operating language.

The system has been set up for Basic language, therefore type 5. The computer will respond with "MEMORY SIZE". Press the Return key because there is no limit needed in memory storage. The computer will respond with "WIDTH". Once again press the Return key because the field width need not be specified. The computer will display "36334 BYTES FREE" "AIM 65 BASIC V1.1".

The next step is to check memory location 41993 to make sure it contains the number 80. This memory location specifies how a cassette tape will be read into memory. Type: ? PEEK (41993) and the computer will display a number. If it is anything but 80, 80 will have to be put into memory. To do this type: POKE 41993,80. (If the operator wishes, he may just type POKE 41993,80 before loading from a cassette. No harm is done if 80 was already in memory.)

The next step is to turn the printer off. To do this press the control key (CTRL) and the PRINT key at the same time. If the printer is on when a program is being loaded an

error will occur. The computer is now ready to be loaded. Rewind the tape, and set the cassette volume and tone controls to about 9.

Type in Load and hit the Return key.

<u>Computer Display</u>	<u>Typed in Response</u>
IN =	T
F =	FPUMP
T =	1

Hit the Return key.

Press the recorder Play button. The computer will start to display program lines. The printer must be off at this time. After the program is loaded, stop the cassette, then rewind. After rewind is finished, stop the cassette, remove it and store in a safe place. The controller program is now ready for operation, and will start when the operator types RUN and hits the Return key.

B2 PROGRAM EXECUTION

A guide to operation of the sequencer is presented here. (Note: A dash (-) in response column means "hit Return key.")

<u>Computer Display</u>	<u>Typed in Response</u>
Type "B" to begin	RUN - B -
Do you want to initialize valve positions Y-Yes N-No	Y or N -
Do you want to initialize event times Y-Yes N-No	Y or N -
Do you want to initialize collector regeneration loop Y-Yes N-No	Y or N -

Typed in
Response

Computer Display

(If the response to initialization of valve positions is yes then the computer will display the following. If not, it tests the event times question, by skipping the following display)

Do you want event descriptions?

Y-Yes N-No

Y or N -

(If the response is yes, the following display is shown)

There are 6 events which correspond to modes of operation for cryo-1, cryo-2 and the collector

Events for cryo-1 and cryo-2 are;

- 1 Pumping - Regenerating
- 2 Pumping - Cooling down
- 3 Regenerating - Pumping
- 4 Cooling Down - Pumping

Events for collector regeneration are:

- 5 Collector is regenerating
- 6 Collector is cooling down

Do you want interlocks

Y-Yes N-No

Y or N -

Input the number for the corresponding event

-

O-Open C-Closed

O or C -

Purge 1

O or C -

? O or C

Vent 1

O or C -

? O or C

Computer Display

Typed in
Response

Fill collector

O or C -

? O or C

Fill 1

O or C -

? O or C

Dump 1

O or C -

? O or C

Dump 2

O or C -

? O or C

Fill 2

O or C -

? O or C

Purge 2

O or C -

? O or C

Vent 2

O or C -

? O or C

Louver

O or C -

? O or C

(Note: The question refers to the position of the louver door for
pumping unit No. 2)

Collector door 1

O or C -

? O or C

Collector door 2

O or C -

? O or C

Computer Display

Typed in

Response

Do you want to change valve positions for another event

Y-Yes N-No

Y or N -

(Following a no response, if time changes are desired the output is as follows. If not the regeneration frequency question is tested next.)

Input the event for the time change

1 or 2 or ... or 6

1, 2, 3, 4, 5, 6

What is the new time?

(In minutes) -

Are there any other time changes:

Y-Yes N-No

Y or N -

(Following an N response, if the frequency of collector regeneration is to be initialized the output is as follows: If not, the computer skips to start of sequencer.)

How many times will the cryopumps cycle
before the collector operates

-

The sequencer is ready to start,
please type

SS - Start

R - Reinitialize

Go to direct control by typing

"G" - and pressing the direct control switch

SS or R or G -

- If SS is typed in, the computer starts to control the valves as specified by the operator or as specified by the computer's data

- If R is typed in, all previous initializations are lost. The computer asks for initializations. If none are given, the computer uses its internal data to control the valves
- If G is typed in and the Auto/Direct button is pressed, direct control is given to the operator. The computer resets (all previous initializations are lost), and "Type B to begin" is displayed on the computer.

B3 EXECUTION STOP

The operator can stop the sequencer operation using one of several options. He can push and reset the Emergency Stop button (Subsection 5.3.4.2) or Stop button (Subsection 5.3.4.3) on the schematic panel of the controller, he can type the "S" key on the computer to cause a Sequencer Stop (Subsection 5.3.4.4) or he can push the Auto/Direct button to enter the direct mode (Subsection 5.3.4.5). The sequencer is automatically stopped following Event 5 (Subsection 5.3.3)

Following an execution stop caused by one of the first three options (Emergency Stop button, Stop button, "S" key) the computer offers the operator three alternative means of continuing:

1. Continue automatic operation of the cryopump at the point where operation was interrupted.
2. Reinitialize valves. This option allows the operator to change the event parameters (Subsection 5.3.1) and to resume the automatic operation of the pump at Event 2 as shown in Subsection 5.3.3.
3. Go to direct control. This option allows the operator to go to direct control, by typing the proper response (specified in the program) into the keyboard and pressing the Auto/Direct button. After direct control is activated, all previous initializing of events made during automatic operation will be lost and the program will resume from the beginning when sequencer mode is reselected.

When the execution is stopped by pushing the Auto/Direct button the computer displays "type "B" to begin". This prompt is obeyed only when a return to the sequencer mode is desired. The required operation is (1) Push the Auto/Direct button to reset it to the Auto position, and (2) Type "B". If a "B" is typed before the button is in the Auto position, the computer will display "reset D-C switch", requesting a reset to Auto.

When the program execution is stopped automatically in Event 5 the operator resumes the sequencer mode by typing "C" to continue. The sequencer proceeds to Event 6 (see Subsection 5.3.3). Alternatively, the operator can choose one of the three options as are available after an Emergency Stop, or an additional option of ending the computer program. With this last option the program is exited and requires a Run command to restart. The relays hold the valves/actuators in the Event 5 position.

The operator can take over direct control of the valves/actuators using the Auto/Direct button and the panel switches at any time that the computer and the controller power is on.

B4 KEYBOARD FUNCTION KEYS

- **ESC** - Escape key should not be pressed during program execution. If it is, it will command the computer to leave its present mode of operation and wait for a new command to specify what language the computer will operate in. If this key was pressed during program execution, type 6. This will put the computer back into Basic without erasing memory. After typing a 6, type RUN and the program will be ready to run again, but any previous utilization will have been erased
- **F1** - If the F1 key is pressed during program execution, execution will stop. The computer will display "BREAK in XXX" where XXX signifies the line at which program execution was at the time the F1 key was pressed. To restart program execution type RUN. Once again all previous initialization has been lost
- **RETURN** when a response is required - If an input is required by the computer and the operator hits the RETURN key without typing the specified response, program execution will be stopped. To restart program execution, press CTRL PRINT to turn off the printer, then type RUN and the program will start from the beginning. All previous initialization will have been lost.

APPENDIX C
CONTROL PROGRAM DESCRIPTION

APPENDIX C

CONTROL PROGRAM DESCRIPTION

The controller computer program listing is presented in Fig. C-1. A description of the program is presented below, with reference to the lines in the program:

- Lines 0-5
 - Data Direction Registers and Data Control Registers are initialized to specify input and output peripheral ports
 - Peripheral ports controlling the Gordos are initialized to unpower the valves
 - Event times are initialized to 0.1 min each. $T(I)$ is the variable for the event times
 - Cycling loop is initialized at 3. The variable for the loop is AB. Variable NAR is used when the loop is initialized to some number other than 3
 - Line 5 initializes A(I) to -5. A(I) is an array of 6 elements. A(I) is the valve position of Purge 1 in Event 1, A(2) is the valve position of Purge 1 in Event 2, etc. A(I) can have the values 0, 1, or -5. If valve and door positions are initialized by the operator, A(I) will have the value 0 or 1. A test will be made during program execution so that, if A(I) is not equal to -5, the data for the event 1 in the computer's memory won't be used. Instead, the values for A(I), B(I), C(I), D(I),... P(I) will be used to control valve positions
- Lines 6-7
 - This is a subroutine which reads data specified in the program
- Lines 10-16
 - This is a subroutine which is called if an improper response is typed into the computer. For example, if a N or Y is the specified response and M is typed in by mistake, this subroutine is called and the operator is asked to reenter the proper response
- Lines 20-276
 - This subroutine deals with initializing door and valve positions for specified events. The interlock option is found in this subroutine. If the interlock option is chosen, lines 252 to 258 make tests on particular valves. If a test fails, the correction is automatically made within the subroutine. Each vent and

dump valve is powered to open and powered to close. The operator has the option of having each vent or dump valve to be opened or closed, and the computer will specify where power is to be sent

- Lines 280-294

- This subroutine looks at the peripheral port which is associated with Emergency Stop, Stop, and Auto/Direct buttons. If it detects a button has been pushed, the subroutine associated with that button is called

- Lines 296-350

- This subroutine is associated with the buttons. If the Emergency Stop is pushed, the subroutine is called from line 300. Lines 300 to 304 unpower all actuators. Line 312 checks the Emergency Stop button. If it is depressed, the computer will display "Reset Switches". Similarly, if the Stop button is pushed the subroutine is called from line 296. If Sequencer Stop is called by holding "S" on the keyboard, the subroutine is called from line 320

- Lines 360-378

- These lines are data lines. They represent valve/door positions for individual events. The order of the events is 1, 2, 3, 4, 1, 2, 5, 6, 3, 4 where line 360 is Event 1, line 362 is Event 2, etc

- Lines 400-436

- This subroutine is associated with the initialization of event time. Variable EN is the event variable and NT(EN) is a variable array for event times specified by the operator

- Lines 450-466

- This subroutine is associated with the amount of times the pumping units will cycle before the collector regenerates. Variable NAR is the number of times the pumps will cycle before collector regeneration

- Lines 500-598

- This subroutine controls the actual events. The test on line 500 checks to see if event times have been initialized. If they were, the initialized time would be used instead of the programmed time. The next test made is on line 503. this test checks to see if the valve/actuator positions for the particular event have been initialized. If they were, the initialized positions would be used instead of the programmed valve/door positions. Lines 524 to 536 check the Emergency Stop, Stop, and Auto/Direct button. If they are pushed, the program will go to the corresponding subroutine. Lines 538 to 580 check the helium level sensors and take the appropriate actions. Lines 588 to 590 are associated with Sequencer

Stop. If Sequencer Stop is activated, the variable m is set equal to 2. Line 596 checks the value of m, and if $m = 2$ then sub 320 is called

- Lines 650-672
 - This subroutine gives event descriptions. The subroutine is called when the valves are being initialized and the operator wants event descriptions
- Lines 1900-1945
 - These lines ask the operator to start program execution by typing a "B"
- Lines 2000-2058
 - These lines are initialization options. The operator is asked whether or not valve positions, event times, and collector regeneration frequency are to be initialized or not. Line 2000 checks the Auto/Direct. If the button is in the direct mode, the computer displays "Reset D-C switch"
- Lines 2060-2081
 - These are options given to the operator which will either start the sequencer, allow for reinitialization, or go to direct control depending on what the operator wants
- Line 2082
 - This is a test to see if collector regeneration frequency was initialized. If it were, the new frequency would be used
- Lines 2086-2126
 - This loop allows for Events 1 to 4 to operate for the amount of times specified by the collector regeneration frequency
- Lines 2140-2142
 - This is a dummy read statement which allows the computer to skip the first four lines of data
- Lines 2150-2178
 - This is the segment of the events where the collector will go through regeneration. After Event 5 the computer will stop, allowing the operator to manually regenerate the collector. To continue the program, the operator types in "C". If the Emergency Stop or Stop button is pushed, the computer takes the appropriate action. The operator then has the option to resume execution, reinitialize, switch to direct control, or end the program
- Lines 2179-2180
 - This restores the data and returns the computer to line 2082
- Line 2181
 - Program end.

K83-6718-04, 6 (1/4)

C-4

<pre> N)=0 204 IFL\$="C" THEN N(N)=1 206 PRINT:" COLLECT OR DOOR 1" 208 INPUT:CD1\$ 210 IF CD1\$<>"0" AND C D1\$>"0" GOT0214 212 GOT0216 214 GOSUB10: GOT0208 216 IF CD1\$="0" THEN O (EN)=1 218 IF CD1\$="C" THEN O (EN)=0 220 PRINT:" COLLECT O R DOOR 1" 221 PRINT "" 222 INPUT:CD2\$ 224 IF CD2\$<>"0" AND C D2\$>"0" GOT0228 226 GOT0230 228 GOSUB10: GOT0222 230 IF CD2\$="0" THEN P (EN)=1 232 IF CD2\$="C" THEN P (EN)=0 250 IFL\$="N" GOT026 0 252 IF E(EN)=1 AND F(N)=1 THEN E(EN)=0 AND C (EN)=1 254 IF J(EN)=1 AND H(N)=1 THEN E(EN)=0 AND M (EN)=1 256 IF E(EN)=0 THEN A(EN)=1 258 IF J(EN)=0 THEN N(EN)=1 260 PRINT:" DO YOU W ANT TO CHANGE VALVE POSITIONS " 262 PRINT:" FOR ANOT HER EVENT" 264 PRINT:" Y-YES N- NO" 265 PRINT:" " 266 INPUT: \$ 268 IF A\$<>"Y" AND A\$< <"N" GOT0272 270 GOT0274 272 GOSUB10: GOT0266 274 IF A\$="Y" GOT040 276 RETURN 280 MM=PEEK(36865) 282 IF MM=128 GOT028 </pre>	<pre> 6 284 GOSUB300: GOT028 0 286 MM=MM-128: IF MM) =64 GOT0290 288 GOSUB296 GOT028 0 290 MM=MM-64: IF MM) =32 GOT0294 292 RESTORE: GOT00 294 RETURN 296 PRINT:" A PROGRA M STOP HAS BEEN ENEC UTED" 298 GOT0312 300 POKE 36880,255 POKE 36881,255 304 POKE 36882,255 POKE 36883,255 308 PRINT:" EMERGENC Y STOP HAS BEEN ACTI VATED" 310 PRINT:" " 311 PRINT:" ALL VALV ES HAVE BEEN UNPOWER ED" 312 IF PEEK(36865)= 192 GOT0320 314 PRINT:" RESET BUT TON" 316 GOT0312 320 PRINT:" WOULD YO U LIKE TO " 322 PRINT:" 1-RESUM E PROGRAM EXECUTION" 324 PRINT:" 2-REINI TIALICE" 325 PRINT:" GO TO DI RECT CONTROL" 326 PRINT:" BY TYPIN G A " C " AND" 327 PRINT:" PRESSING RETURN THEN" 328 PRINT:" PRESSING THE DIRECT" 329 PRINT:" CONTROL SWITCH ON THE PANE L" 330 IF FLAG=1 THEN PRI NT:" 4-END PROGRAM" 331 INPUT:IES 332 IF ES<>"1" AND ES< AND ES<0 GOT0334 333 FLAG=0: GOT0338 334 IF FLAG=1 AND ES< </pre>	<pre> 460 GOT0336 335 FLAG=0: GOT0345 336 GOSUB10: GOT0331 338 IF ES=16 GOT0350 339 RESTORE 340 IF ES=20 GOT02000 342 LL=PEEK(36865)- 192 343 IFLC=31 AND LL)= 0 GOT00 344 GOT0342 345 PRINT:" THE PROG RAM HAS ENDED, TO RE START TYPE 'RUN'" 346 END 350 CFLAG=1: RETURN 360 DATA 1,0,1,0,0,1 ,0,0,1,1,0,1,0,1,0,1 ,0,0,1,0,1,0,0,1 ,0,1,0,0,1,0,1,1,0,0 ,0,1,0,0,1,0,0,1,0 ,1,1,0,0,1,0,1,0,1, ,0,1,0,0,1,0,0,0,0 ,0,0,1,1,0,1,0,1,0,1 ,0,1,0,0,1,0,1,0,0 ,0,1,0,0,1,0,1,0,0 ,0,1,0,0,1,0,0,1,0 ,0,1,0,0,1,0,0,1,0 ,1,1,0,0,1,0,1,0,1,0 ,0,1,0,0,1,0,0,0,1 ,0,1,0,0,1,0,1,0,0,0 400 PRINT:" INPUT TH E EVENT FOR THE TIME CHANGE" 402 PRINT:" 1,2,3,4, 5,6" 404 INPUT:EN: GOSUB28 0 406 IF EN<1 AND EN>C2 AND EN>C3 GOT0410 408 GOT0416 410 IF EN>C4 AND EN>C5 AND EN>C6 GOT0414 412 GOT0416 414 GOSUB10: GOT0404 416 PRINT:" WHAT IS THE NEW TIME" 418 INPUT:NT(EN) 422 PRINT:" ARE THER </pre>
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R85-0718-041G (2/4)

Fig C-1 Program Listing (Sheet 2 of 4)

E ANY OTHER TIME CHAR-
GES"

424 PRINT:" Y-YES N
-NO"

426 INPUT#

428 IFA#<C"Y"AND#<
C"N"GOTO432

430 GOTO434

432 GOSUB10 GOTO426

434 IFA#="Y"GOTO400

436 RETURN

450 PRINT:"HOW MANY
TIMES WILL THE CRYO
PUMPS CYCLE"

452 PRINT:"BEFORE T
HE COLLECTOR OPERATE
S"GOSUB280

454 INPUT#

456 IF#<0 THEN GOTO
460

458 GOTO466

460 PRINT:"THIS IS
NOT A POSSIBLE LOOP
FREQUENCY"

462 PRINT:"PLEASE R
EENTER THE DESIRED F
REQUENCY"

464 GOTO454

466 RETURN

500 IF#<1 OR#>5 THEN
PRINT:"NT-1"

501 FOR I=1 TO 140+T
I

502 BVS=0 AVS=0 L=0
LY=0

503 IFA I=-50 GOTO51
0

504 L=128*#*(I)+64*B
I)+32*G I)+16*D*(I)+
8*E(I)

505 BVS=J+4*F(I)+2*
G(I)+H(I)

506 J=128*0*(I)+64*J
(I)+32*K(I)+16*L(I)+
8*M(I)

507 AVS=J+4*N(I)+2*
O(I)+P(I)

508 GOTO524

510 BVS=128*A+64*B+
32*C+16*D+8*E+4*F+2*
G+H

512 AVS=128*Q+64*J+
32*K+16*L+8*M+4*N+2*
O+P

R85-0718-041G (3/4)

524 LL=PEEK(36865)

526 IFLL=128 GOTO53

0

528 GOSUB300 GOTO52

4

530 LL=LL-128 IFLL<
=64 GOTO534

532 GOSUB296 GOTO52

4

534 LL=LL-64 IFLL<=
32 GOTO538

536 RESTORE GOTO0

538 LL=LL-32 IFLL<=
16 GOTO542

540 PRINT:"NITROGEN
LEVEL IS LOW" LL=LL+
16

542 LL=LL-16 IFLL<=
8 GOTO554

544 IFA I=-50 GOTO55
0

546 IFD I/=0 THEN BVS
=BVS+16

548 GOTO552

550 IFD=0 THEN BVS=BV
S+16

552 LL=LL+8

554 LL=LL-8 IFLL=4
GOTO558

556 IFA I=-50 GOTO56
2

558 IFE I/=0 THEN BVS
=BVS+8

560 GOTO564

562 IFE=0 THEN BVS=BV
S+8

564 LL=LL+4

566 LL=LL-4 IFLL=2
GOTO578

568 IFA I=-5 THEN GO
TO574

570 IFJ I/=0 THEN AVS
=AVS+64

572 GOTO576

574 IFJ=0 THEN AVS=AV
S+64

576 LL=LL+2

578 LL=LL-2

579 IFLL=1 GOTO582

580 PRINT:"NITROGEN
PRESSURE IS HIGH"

582 GETG\$ K\$=G\$

584 IFK\$="S" THEN GOTO

0588

586 GOTO592

588 PRINT:"SEQUENCE
STOP ACTIVATED"

590 M=2

592 FORK=6880:BVS:P
OKE36881:AVS

593 IF I=1 THEN PRINT
I:"BVS",BVS,"AVS",AV
S

594 NEXT I

596 IFM=2 THEN GOSUB3
20

597 M=0

598 RETURN

650 PRINT:"THERE AP
E 6 EVENTS WHICH COR
RESPOND TO MODES OF"

652 PRINT:"OPERATIO
N FOR CRYO-1,CRYO-2,
AND THE COLLECTOR"

654 PRINT:" "

656 PRINT:"EVENTS F
OR CRYO-1 AND CRYO-2
ARE:"

658 PRINT:"1 PUMPIN
G-REGENERATING"

660 PRINT:"2 PUMPIN
G-COOLING DOWN"

662 PRINT:"3 REGEN
ERATING-PUMPING"

664 PRINT:"4 COOLIN
G DOWN-PUMPING"

666 PRINT:"EVENTS F
OR COLLECTOR REGENER
ATION ARE "

668 PRINT:"5 COLLE
CTOR IS REGENERATING
"

670 PRINT:"6 COLLE
CTOR IS COOLING DOWN
"

672 RETURN

1900 PRINT:"TYPE 'B
' TO BEGIN"

1910 INPUT#

1915 IFB#<"B"GOTO1
925

1920 GOTO1940

1925 GOSUB10 GOTO19

10

1940 IFB#="B"GOTO20
00

```

1945 GOTO1900
2000 LL=PEEK(36865)
-192
2001 IFLL<=31ANDLL>
=0GOTO2004
2002 GOTO2015
2004 PRINT"RESET D-
C SWITCH"
2006 GOTO2000
2015 PRINT"DO YOU
WANT TO INITIALIZE V
ALVE POSITIONS"
2018 PRINT" Y-YES
N-NO"
2020 INPUTIV$
2024 IFIV$<>"N"ANDI
V$<>"Y"GOTO2028
2026 GOTO2030
2028 GOSUB10 GOTO20
20
2029 PRINT" "
2030 PRINT"DO YOU
WANT TO INITIALIZE E
VENT TIMES"
2031 PRINT""
2032 PRINT" Y-YES
N-NO"
2034 INPUTIT$
2036 IFIT$<>"N"ANDI
T$<>"Y"GOTO2040
2038 GOTO2042
2040 GOSUB10 GOTO20
34
2041 PRINT" " GOSU
B200
2042 PRINT"DO YOU
WANT TO INITIALIZE T
HE COLLECTOR REGENER
ATION LOGS"
2044 PRINT"Y-YES N
-NO"
2045 PRINT""
2046 INPUTOL$
2048 IFOL$<>"N"ANDC
L$<>"Y"GOTO2052
2050 GOTO2054
2052 GOSUB10 GOTO20
46
2054 IFIV$="Y"THENG
OSUB20
2056 IFIT$="Y"THENG
OSUB400
2058 IFCL$="Y"THENG
OSUB450
2060 PRINT"THE SEQ
UENCER IS READY TO S
TART PLEASE TYPE"
2062 PRINT" SS-STA
RT"
2064 PRINT" R-FEI
NITIALIZE"
2066 PRINT"GO TO D
IRECT CONTROL BY TY
PING G AND "
2067 PRINT" CSSIN
G THE DIRECT CONTRO
L SWITCH"
2068 FE=C INPUTA$
2070 IFH$<>"SS"ANDH
$<>"R"ANDH$<>"G"GOTO
2074
2072 GOTO2076
2074 GOSUB10 GOTO20
68
2076 GOSUB200
2078 IFH$="SS"GOTO2
082
2079 IFH$="R"GOTO0
2079 LL=PEEK(36865)
-192
2080 IFLL<=31ANDLL>
=0GOTO0
2081 GOTO2079
2082 IFHARDK=5THENA
B=NAF
2086 FORI=1TO8
2090 FORI=FETO4
2095 GOSUB6
2096 IFPE=2THENGOSU
B6
2098 FE=1
2100 GOSUB500
2122 NEXTI
2124 RESTORE
2126 NEXTX
2130 RESTORE
2140 FORI=1TO4
2142 READA.A.A.A.A
.A.A.A.A.A.A.A.A.A
A NEXTI
2150 FORI=1TO12
2152 GOSUB6
2154 GOSUB500
2156 NEXTI
2160 FORI=5TO6
2161 GOSUB6
2162 GOSUB500
2164 IFI=6GOTO2172
2165 PRINT"READY F
OR COLLECTOR REGENER
ATION" CFLAG=0
2166 PRINT"FOR COL
LECTOR COOLDOWN. TYP
E C FLAG=1
2167 IF I IFH$="C"
GOTO2170
2168 GOSUB200 IFCL
AG=100TO1165
2169 GOTO2167
2170 FLAG=0 NEXTI
2171 FORI=1TO4
2172 GOSUB6
2174 GOSUB500
2176 NEXTI
2177 RESTORE
2180 GOTO2092
2181 END

```

R05-0718-041G (4/4)

Fig. C-1 Program Listing (Sheet 4 of 4)