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AUTOMATIC CONTROLS FOR FACILITIES AND MERCURY ION THRUSTERS IN DURABILITY TESTING

by C. R. Nichols and S. J. Obloy
Lewis Research Center
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TECHNICAL PAPER proposed for presentation at Fourth Propulsion Joint Specialist Conference sponsored by the American Institute of Aeronautics and Astronautics
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AUTOMATIC CONTROLS FOR FACILITIES AND MERCURY ION THRUSTERS IN DURABILITY TESTING

by C. R. Nichols* and S. J. Obloy†

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

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ABSTRACT

For the last three years durability tests of electric thrusters at Lewis Research Center have resulted in changes to several vacuum chamber systems. This and the use of thruster control circuits permitted operation with reduced support manpower. The vacuum chambers range in size from 1.5 to 7.6 meters in diameter with 8.5 to 850 cubic meters in volume. These chambers use normal roughing, oil-diffusion and cryopumping systems. Chamber pressure, with thrusters operating, is typically in the 10^{-7} torr range. Changes to these facilities are described which provide for automatic shutdown during unattended operation. Thruster controls are described that allowed continuous testing of ion thrusters for almost three months with only one man per shift. Additional thruster controls and tank modifications now permit unattended durability testing.

INTRODUCTION

Extensive ground testing of ion thrusters is required to evaluate performance for space flight programs such as SERT I and SERT II.[1,2] These tests are made in vacuum tanks that simulate altitudes of about 100 miles or higher. Some of the tests are several thousand hours long.

The ground testing facilities at the Lewis Research Center range in size from 1.5 to 7.6 meters diameter and 8.5 to 850 cubic meters volume. They are evacuated by conventional oil diffusion pumping systems.

Operation of both facility and thruster imposed a heavy demand on personnel. To minimize this demand a program was completed to eliminate operating personnel. Unattended durability tests have been conducted successfully in two facilities. Both ion and plasma thrusters have been operated for several hundreds of hours in these unattended durability tests. The thruster and facility controls necessary for this unattended operation are described.

7.6-METER DIAMETER TANK

Ion thruster performance tests have been conducted in the Lewis 7.6-meter diameter, 850 cubic meter environmental chamber since its completion in 1963. These tests were made with thrusters utilizing a condensable propellant. The chamber is constructed with a mild steel outer shell and a 1/8-inch clad stainless steel liner. It has a conventional oil diffusion pumping system and a liquid nitrogen cooled propellant condenser.[3] It has been successfully operated, with ion thrusters varying in size from 0.15 to 1.5 meters at pressures in the 10^{-7} torr range.[4,5]

The facility is supported by liquid nitrogen, vacuum, water, and air systems. The liquid nitrogen system is shown in Fig. 1. It is a combination of manual, remote manual and automatic control. The nitrogen is supplied from the 56,000 gallon storage dewar to the chamber either by gravity or from the 100 gpm pumps. The propellant condenser is operated as a flooded system with the level controlled automatically within the separation tank. The diffusion pump baffles and the vacuum foreline traps are supplied from the same system and may be operated in either a single or two phase mode depending on whether the system is gravity or pump fed. Routing of the liquid nitrogen and operation of the pumps is strictly a manual operation.

The vacuum system is a conventional remote operated manual system with oil diffusion pumps and rotary two-stage backing.[3] All valves are sequenced to a fail-safe mode (closed) in event of a power failure. The foreline traps were installed at a later date to prevent mercury, the normal thruster propellant, from contaminating the roughing system.

The water system is shown in Fig. 2. Cooling water from the diffusion pumps is returned to the first section of a divided pit where it is pumped, as a coolant, to the ion beam target, and returned to second section of the pit where it is cooled by mixing with overflow water from the first section. This mixture is then pumped through the head shield and returned to a storm sewer. In event of pump failure, domestic water may be introduced to cool both the propellant target and the head shield. This interchange is manual.

The air supply system is separate from the main laboratory system. It is rated at 108 CFM with a 0.3 cubic meter surge and storage tank. In this facility it is used to actuate manual remote valves and controls. Some redundancy has been built in with a connection to the adjoining facility.

Facility and thruster performance are dependent on the reliability of the vacuum and cryopumping systems. The record of repairs and service is shown on table 1. Failure of the oil diffusion pump heater is the most serious of the failures shown, since this could degrade the vacuum level beyond the acceptable thruster operation range of 2×10^{-5} torr. Operation of the adjacent 4.6-meter diameter tank required the system to be changed from a gravity fed, two-phase mode to a pump fed, single-phase mode. Original construction used a single-phase flow system to the diffusion pump traps. When the system is operated in a two-phase mode the vent return system becomes marginal. This requires manual control of the feed and vent system.

*Head, Research Facilities Section.
†Head, Electronics Section.

Air compressor maintenance was necessary because the flow requirements for this facility had increased to the capacity of the compressor. This increase, along with minor mechanical design deficiencies necessitated frequent service. Since then, a second compressor has been added to reduce the load.

The 7.6-meter facility was installed with manual operation and control. The remote manual controls and indication for both thruster and facility were grouped in two separate locations in the control room adjacent to the chamber. Hence it was assumed that each would have personnel in constant attendance. An annunciator alarm system gave visual and audible notice of a system failure. The main events were low water pressure, low air pressure, low nitrogen level in separation tank, and loss of liquid nitrogen dewar insulating vacuum. Because of the manual mode of operation, these events did not shut the facility down. Loss of power would automatically place all equipment in a fail-safe mode to preserve vacuum integrity.

7.6-METER DIAMETER TANK AUTOMATIC SHUTDOWN

With the advent of durability testing of ion thrusters in this chamber it became desirable to provide automatic "shutdown" controls for unattended tank operation. Shutdown here denotes that under certain abnormal conditions the pumping system is turned off and certain valves are closed to preserve tank vacuum if at all possible. A simplified logic diagram for shutdown is shown in Fig. 3.

The abnormal conditions which initiate shutdown are:

(1) Loss of service air pressure
(2) Loss of cooling water
(3) High tank pressure
(4) Loss of electrical power

Service air is used to operate tank valves through solenoid control valves. Enough air is stored in the system to operate the valves at least once. Cooling water is used in both the roughing pump systems and the oil-diffusion pumps.

Normal tank pressure with thrusters operating is in 10^{-7} torr range. Pressure is measured with a hot cathode ionization gauge. The readout circuit has two independent preset pressure limits useful for control and alarm functions. When for any reason the pressure rises to 10^{-6} torr range, it is shown in an annunciator-alarm system. Further increase in pressure to 10^{-5} torr range starts a 0-15 minute preset timer. If the gas leak into the tank is rapid and pressure rises to 10^{-4} torr range before the preset time interval expires, the tank goes into "emergency" shutdown. If 10^{-4} torr is reached anytime after the preset time interval, the tank goes into a normal shutdown.

In emergency shutdown, the oil diffusion pumps are turned off, quick cool water is started, and the valves between the oil-diffusion and the second stage or blower forepumps are closed, all occurring at the same time. After a delay of a few seconds the blower forepumps shut off and the valves between the two stages of roughing pumps close. Finally after another short delay the first stage roughing pumps shut off.

In a normal shutdown the quick cool water is not turned on. The roughing stages are not shut off until about 1 hour after the oil diffusion pumps are shut off to let the vapor jets collapse in them. All shutdowns of the tank are normal except for fast pressure rise or electrical power failure. Pushbutton switches permit manual shutdown in normal or emergency modes. An override switch is used to bypass the pressure readout limit controls during pumpdown of the tank. A recorder gives a continuous trace of tank pressure. The shutdown sequence for the various conditions is shown in table 2.

Two sets of twelve annunciators each indicate off-normal conditions. The first off normal event in each set displays a red light, all others are white. One set consists of those events, any one of which initiates a shutdown. The other set consists of those events that may lead to a shutdown, and thereby help diagnose the problem. Events in each set are cited here.

Set 1:

- Low air pressure
- Low water pressure
- 480 V power failure
- 120 V power failure
- Tank pressure 5×10^{-4} torr

Set 2:

- High foreline pressure
- Loss of LN_2 dewar vacuum
- Oil diffusion pump heater failure
- Tank pressure 1×10^{-6} torr
- Tank pressure 2×10^{-5} torr
- Blower forepump off
- Roughing pump off
- LN_2 valves closed
- Thruster beam current off limit
- Thruster impingement current high

The first off-normal event on either annunciator set will alert plant protection via a telephone wire pair. Plant protection will telephone for help from a qualified personnel list. Override switches are provided for each roughing pump and for each quadrant of oil diffusion pumps to prevent an alarm when the system is operated without one or more of the pumps.

The system is also set to shut off electrical power to the thruster under test if tank pressure is in 10^{-5} torr range, or any preselected thruster parameter is outside the desired limits. Figure 4 shows the instrument rack with annunciators, recorder, and control panel.

Each of the 22 oil diffusion pumps has 3 pairs of heaters, one pair per electrical phase. Two modes of operation are available, "high" and "low" heat. With none defective, all heaters operate on high heat, and on low heat two pairs are used. Low heat is sufficient to maintain vacuum. Therefore the system normally operates on low heat. A control system automatically switches a diffusion pump to high heat when one of its heaters fails, thereby maintaining pumping capacity until repairs can be made.

This automatic tank shutdown system was developed for unattended durability testing of ion thrusters. In addition it is now possible to do research in the tank without the need for tank operators. Also, it is now possible to carry on research for two work shifts, leave this large tank at vacuum unattended during the third shift, and then continue the research program at the start of the first shift the next day. The time made available for additional research by eliminating shutdown and restart amounts to 4 hours each day of research. The installation of this automatic shutdown system was completed in a three-month period.

AUTOMATION OF OTHER VACUUM TANKS

Several other vacuum facilities at the Lewis Research Center are operating in an automatic mode. These tanks range in size from 1.5 to 3.0 meters diameter and 8.5 to 30.6 cubic meters. Pictures of two of these tanks are shown in Figs. 5 and 6. They differ from the 7.6 meter tank in that they can be operated automatically in both startup and shutdown modes. Selection of mode is manual and initiation of the operations by pushbutton. Pictures of the flow panels are shown in Figs. 7 and 8.

All events are sequenced and controlled by either interlocks or timing mechanisms. Either mode may be interrupted manually or by the automatic sensing of an abnormal condition. These conditions are the same as previously described except that the abnormal pressure sensing is at a higher point. This point automatically shuts down the second stage blower, with a subsequent shutdown of the diffusion pumps. After an interruption the cycle may be continued manually or a restart made from the beginning if it is desired to continue automatically.

These systems may be converted easily to unattended operation with the existing or additional sensing elements as future requirements dictate.

One of the 1.5 meter diameter tanks has operated unattended with a plasma thruster for more than 500 hours continuously.

THRUSTER CONTROLLERS

In mid 1965, control circuits were developed to (a) recycle the screen and accelerator high voltage supplies, (b) maintain constant beam current, and (c) maintain constant discharge current. These were on-off devices that operated motor driven auto-transformers. They permitted the durability testing of up to four thrusters in the 7.6 meter diameter vacuum chamber with only two men in attendance.[4,6,7] For about the last 3000 hours of this 5000 hour test, only one man was used per work shift. Hourly data was recorded automatically in digital form for one thruster.

In March 1968, two 0.15 meter mercury ion thrusters were operated in the 7.6 meter diameter vacuum chamber for several hundred hours completely unattended. One thruster used power conditioning equipment provided by a contractor; the other operated with equipment designed and built at Lewis Research Center. Figure 9 shows the Lewis power conditioning and recording equipment. Figure 10 is the block diagram of this mercury ion thruster control system.

The screen and accelerator high voltage power supplies are automatically controlled so that on current overload, that is, voltage breakdown, both supplies will shut off. Within seconds, the output voltage control will be reduced to a minimum value, the supply will be restarted, and the voltage returned to its original value. This sequence is used to minimize the high-voltage transients associated with turning on these large laboratory supplies at a high value, which frequently causes repeated breakdowns. If the number of voltage breakdowns exceeds a preset value within a given time interval, both high voltage power supplies will shut off and will remain off until restarted manually.

Another controller maintains a constant beam current by varying the main mercury vaporizer heater power. A deviation in beam current becomes an error signal which, after amplification, is fed into a solid state proportional controller that adjusts the main vaporizer heater power to maintain a preset beam current.

A constant current supply is used in the discharge circuit where this current is maintained constant by varying the discharge voltage. This variation is sensed and compared with a preset reference. The resultant amplified error signal is the input to a solid state proportional controller which adjusts the power to the cathode vaporizer heater. The discharge voltage of 30 to 50 volts is at a high common mode voltage of 1000 to 5000 volts d.c. Current sensors are available which detect the variation in discharge voltage and convert it to a voltage signal at or near ground potential. This resultant signal is proportional to the measured parameter and can be used with a controller, recorder, meter or data logger.

A hollow cathode is used through which mercury vapor is fed. Electrons, extracted from this mercury vapor, ionize the main mercury beam. A similar but smaller hollow cathode is used as the main ion beam neutralizer. A controller maintains the neutralizer vaporizer at a constant temperature.

The neutralizer and high voltage supplies generally float at less than 50 volts above ground. For safe operation, when this voltage reaches 100 volts, this part of the circuit is automatically clamped to ground and must be reset manually.

Meter relays are used to shut down the thruster for any one of the following conditions:

(1) High discharge current
(2) High accelerator current
(3) High or low neutralizer emission current

Other situations, such as the loss of any vaporizer heater power supply or a controller, will produce one or more of the shutdown conditions listed above. A high or low beam current is reflected in the neutralizer emission current and if the limits are exceeded, the thruster will shut down. Also, if the neutralizer and high voltage power supplies are clamped to ground, the neutralizer emission current drops to its low set point and the thruster shuts down.

On voltage breakdown between screen and accelerator, the accelerator current could momentarily increase beyond its high limit set point causing shutdown of the thruster. To prevent this, a timer (0 to 60 seconds) is used. If the abnormal condition still prevails at the end of a preset interval, the thruster will shutdown: otherwise normal operation will continue. Timers are also provided for the high and low limits of the neutralizer emission current meter relay to prevent thruster shutdown by a momentary fluctuation in this parameter.

These controls when properly set will maintain a thruster operational for extended periods of time and will safely shut off the power should a fault occur in the thruster or power conditioning equipment. The thruster must be restarted manually.

CONCLUDING REMARKS

Prior to tank conversion, automatic thruster controls were developed. These allowed up to 3000-hour tests of two or more thrusters with only one man per shift. After conversion unattended ion and plasma thruster durability tests were successfully conducted in vacuum tanks ranging in size from 1.5 to 7.6 meters in diameter. These tests were several hundreds of hours long.

Automation of the facility controls has produced the additional benefit of increasing the available research testing time by eliminating the shutdown and startup operation between successive work shifts.

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System	Item	Frequency per month	
		Repairs	Services
Vacuum	Diffusion pump heater replacement	4	
	Roughing pumps		4
	Pressure measurement	7	
Liquid nitrogen	Flow adjustments		8.5
	Leak	0.4	
Water	Low pressure		0.3
Air	Compressor repair	3.7	

TABLE 1. - 7.6-METER TANK SYSTEMS REPAIRS AND SERVICE RECORD

Off-normal fault	Tank shut down	Diffusion pump power		LN_2 valves		Quick cool water		75 Min. delay		Valves second stage		30 Sec. delay		Roughing or blower forepumps (second stage)		Valves first stage		30 Sec. delay		Roughing pumps (first stage)		Thruster		Tank shutdown and annunciator	Annunciator only
		On	Off	Open	Closed	On	Off	Yes	No	Open	Closed	Yes	No	On	Off	Open	Closed	Yes	No	On	Off	On	Off		
Tank press. at 1×10^{-6} torr	None	X		X			X	--	--	X		--	--	X		X		--	--	X		X			X
Tank press. at 2×10^{-5} torr	None	X		X			X	--	--	X		--	--	X		X		--	--	X			X		X
Tank press. at 5×10^{-4} from 2×10^{-5} in more than 5 minutes	Normal		X		X		X	X			X	X			X		X	X			X		X	X	
Air press. low	Normal		X		X		X	X			X	X			X		X	X		X			(a)	X	
Water press. low	Normal		X		X		X	X			X	X			X		X	X			X		(a)	X	
480 V power failure (blower forepumps)	Normal		X		X		X	X			X	X			X[b]		X	X			X		(a)	X	
120 V power failure (valves)	Normal		X		X	X		X			X[b]	X			X		X[b]	X			X		(a)	X	
Manual "normal shut down" button	Normal		X		X		X	X			X	X			X		X	X			X		(a)	X	
Accelerator current high for 30 sec. continuously	None	X		X			X	--	--	X		--	--	X		X		--	--	X			X		X
Discharge current high or low for 1 minute continuously	None	X		X			X	--	--	X		--	--	X		X		--	--	X			X		X
Tank press. at 5×10^{-4} from 2×10^{-5} in 5 minutes or less	Emer.		X		X	X			X		X	X			X		X	X			X		X	X	
480 V power failure first stage roughing pumps	Emer.		X		X	X			X		X		X		X		X		X		X[b]		(a)	X	
120 V power failure (control power)	Emer.		X		X	X			X		X		X		X		X		X		X		(a)	X	
Manual "emergency shut down" button	Emer.		X		X	X			X		X	X			X		X	X			X		(a)	X	
Diffusion pump heater failure, foreline press. high, LN_2 dewar press. high, blower forepump out, first stage roughing pump out																									X

[a]Thruster off at 2×10^{-5} torr.
[b]Off or closed after fault with no delay.

TABLE 2. - UNATTENDED TANK OPERATION SHUTDOWN SEQUENCE

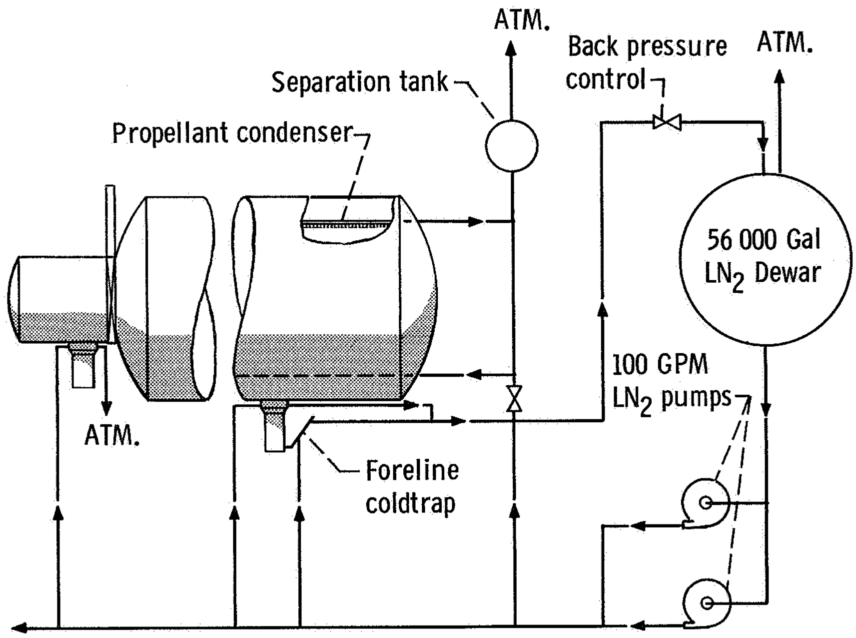

Figure 1. - 7.6 Meter tank liquid nitrogen system.

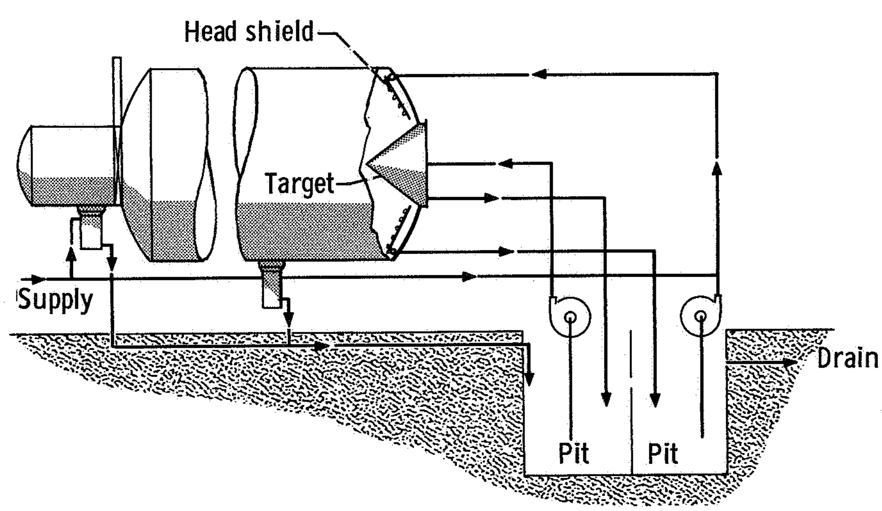

Figure 2. - 7.6 Meter tank cooling water system.

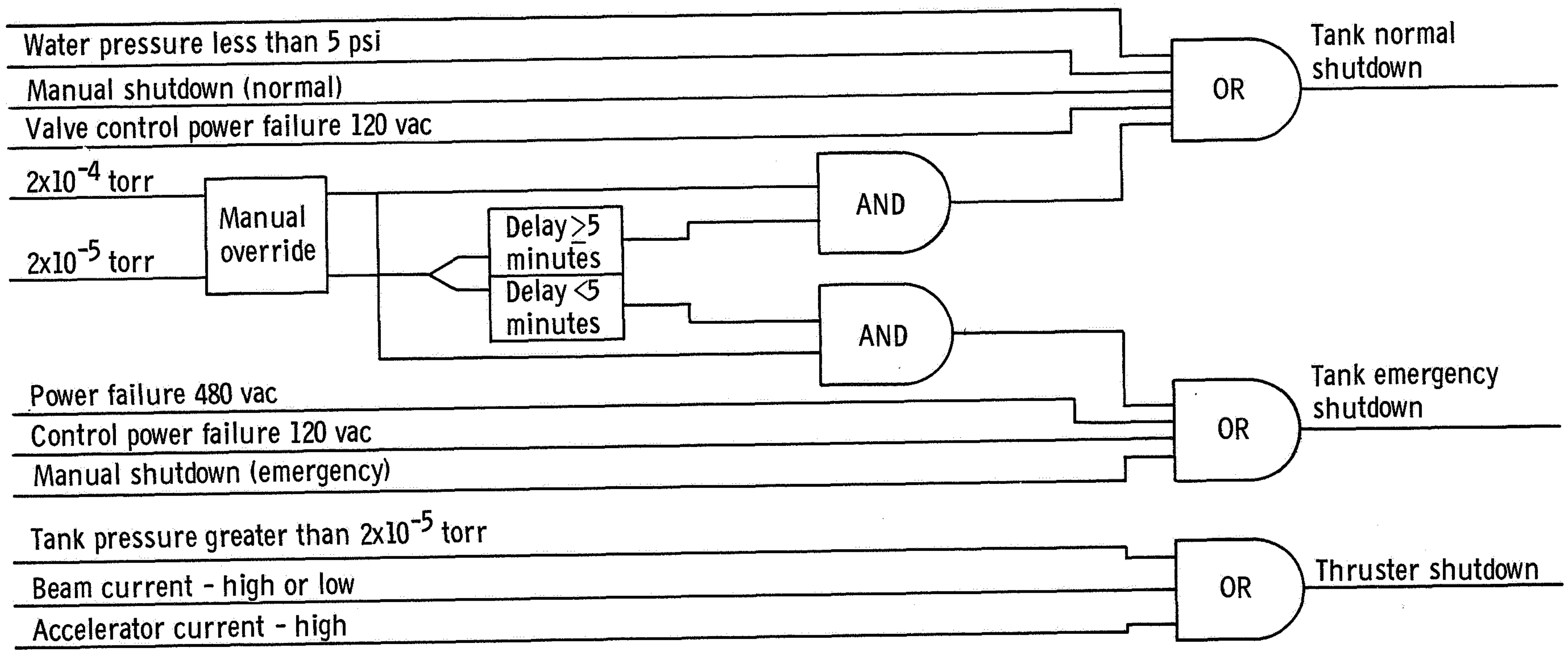

Figure 3. - Facility shutdown logic diagram.

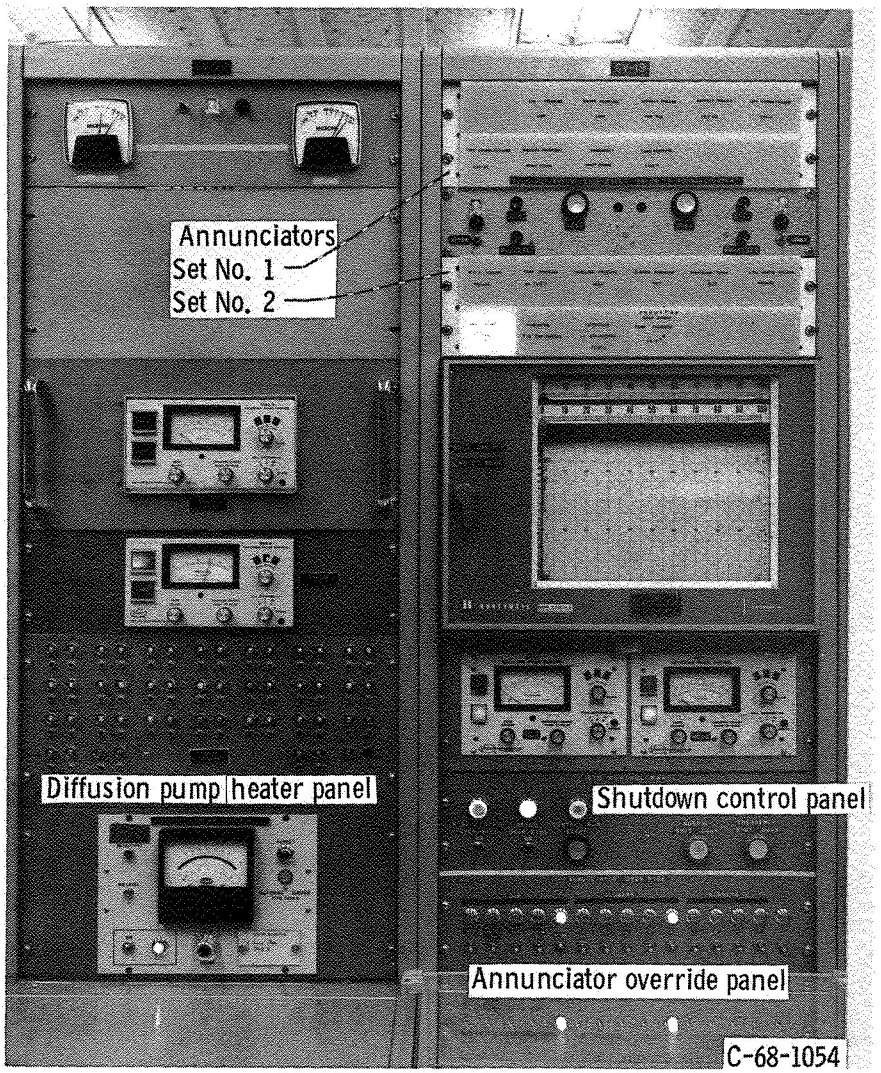

Figure 4. - 7.6 Meter tank automatic shutdown control panel.

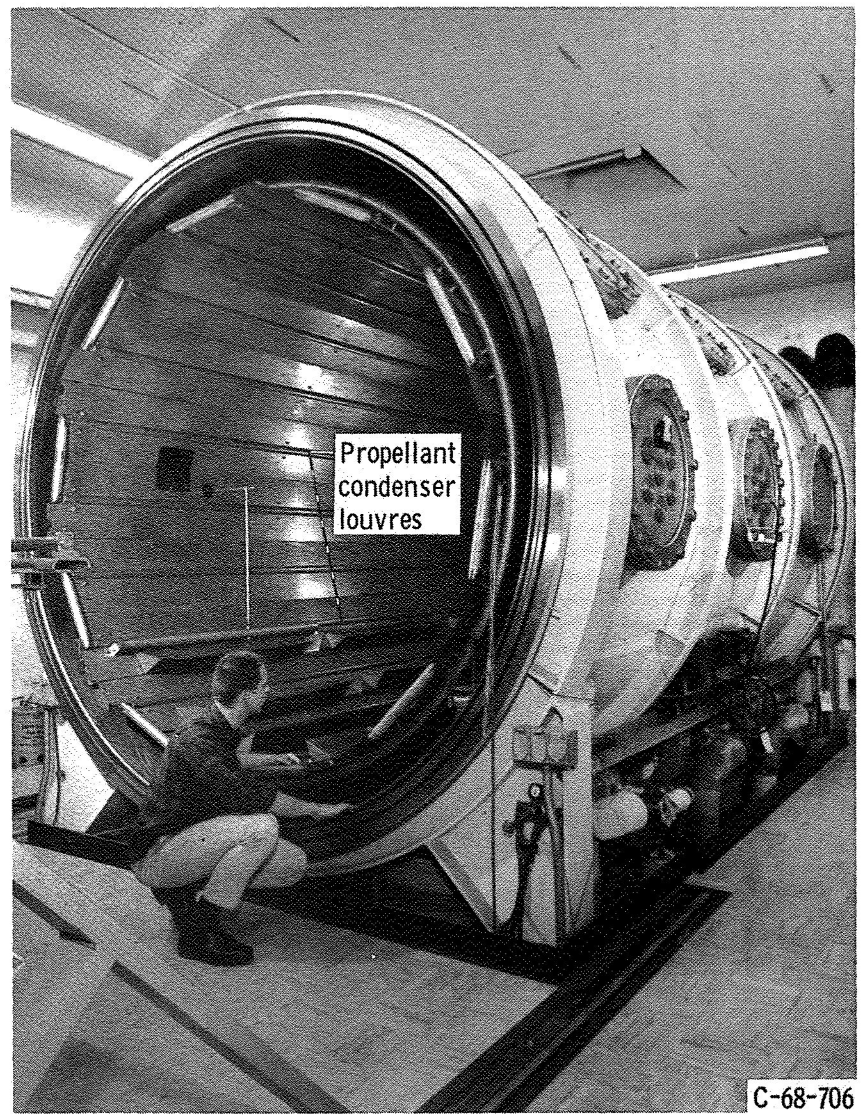

Figure 5. - 3.0 Meter diameter tank.

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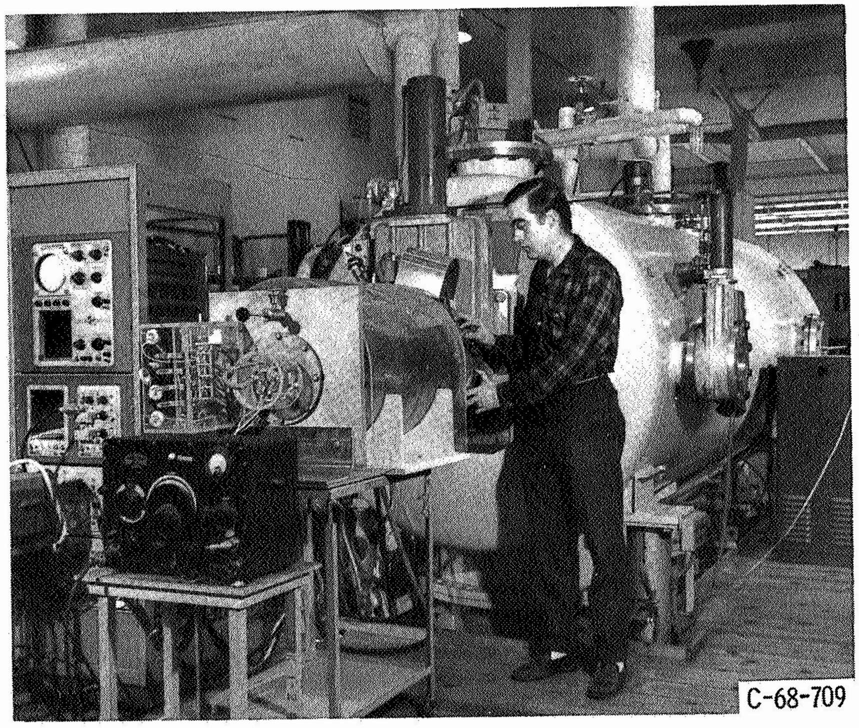
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Figure 6. - 1.5 Meter tank.

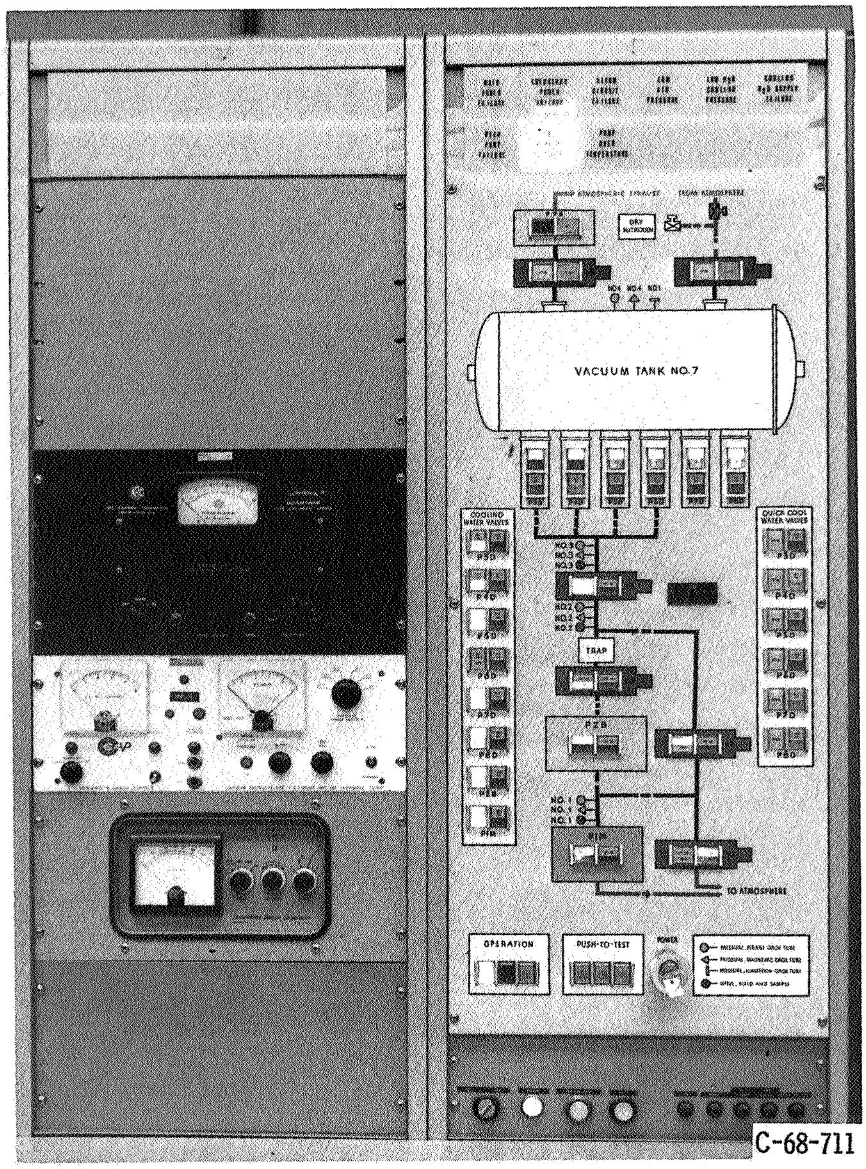

Figure 7. - 3.0 Meter tank flow and control panel.

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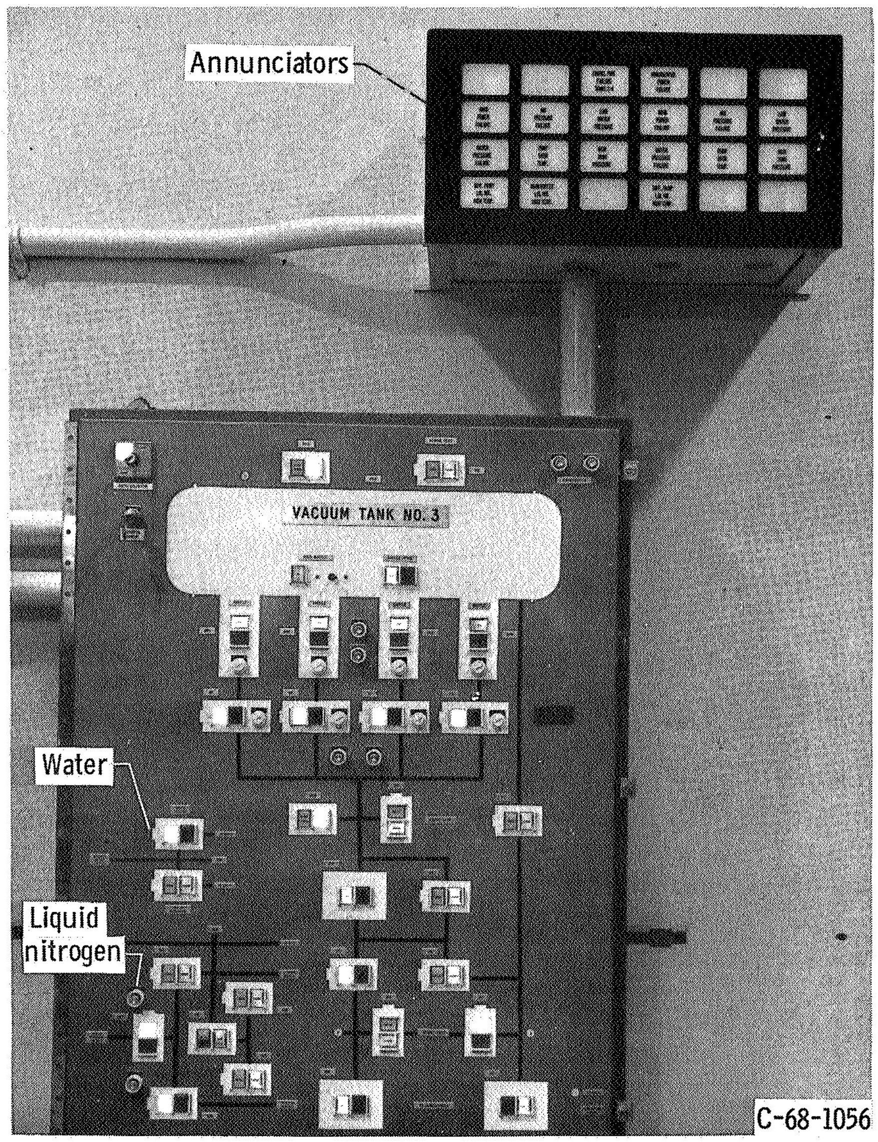

Figure 8. - 1.5 Meter tank flow and control panel.

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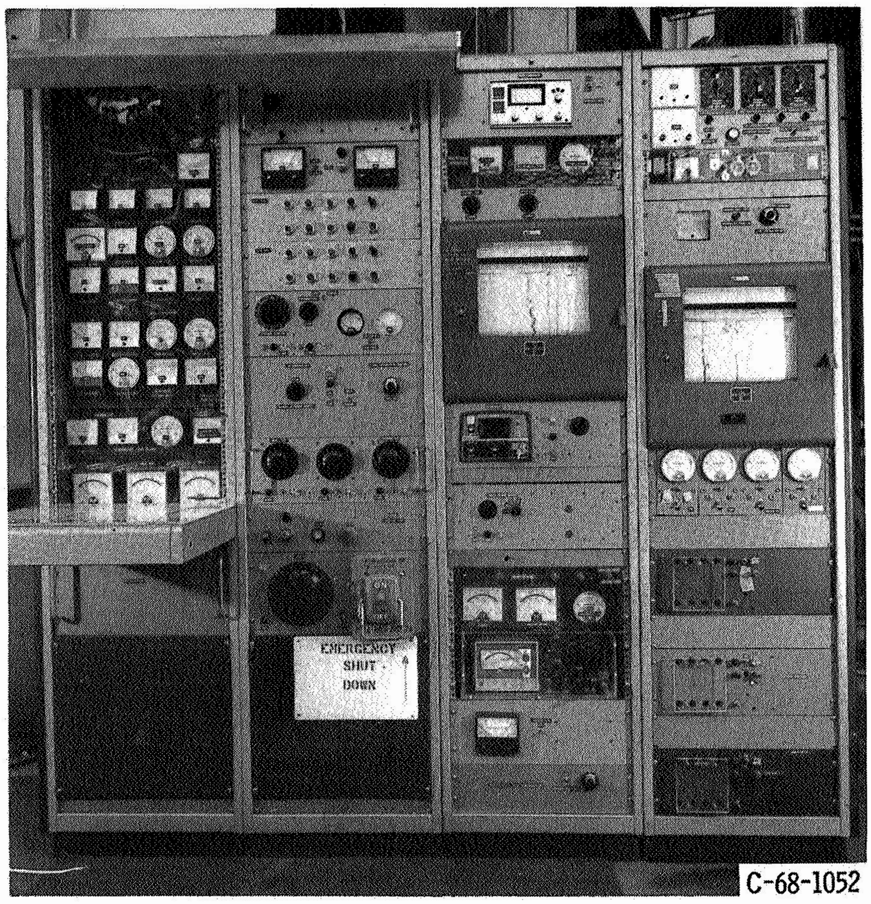

Figure 9. - Thruster power conditioning and recording equipment.

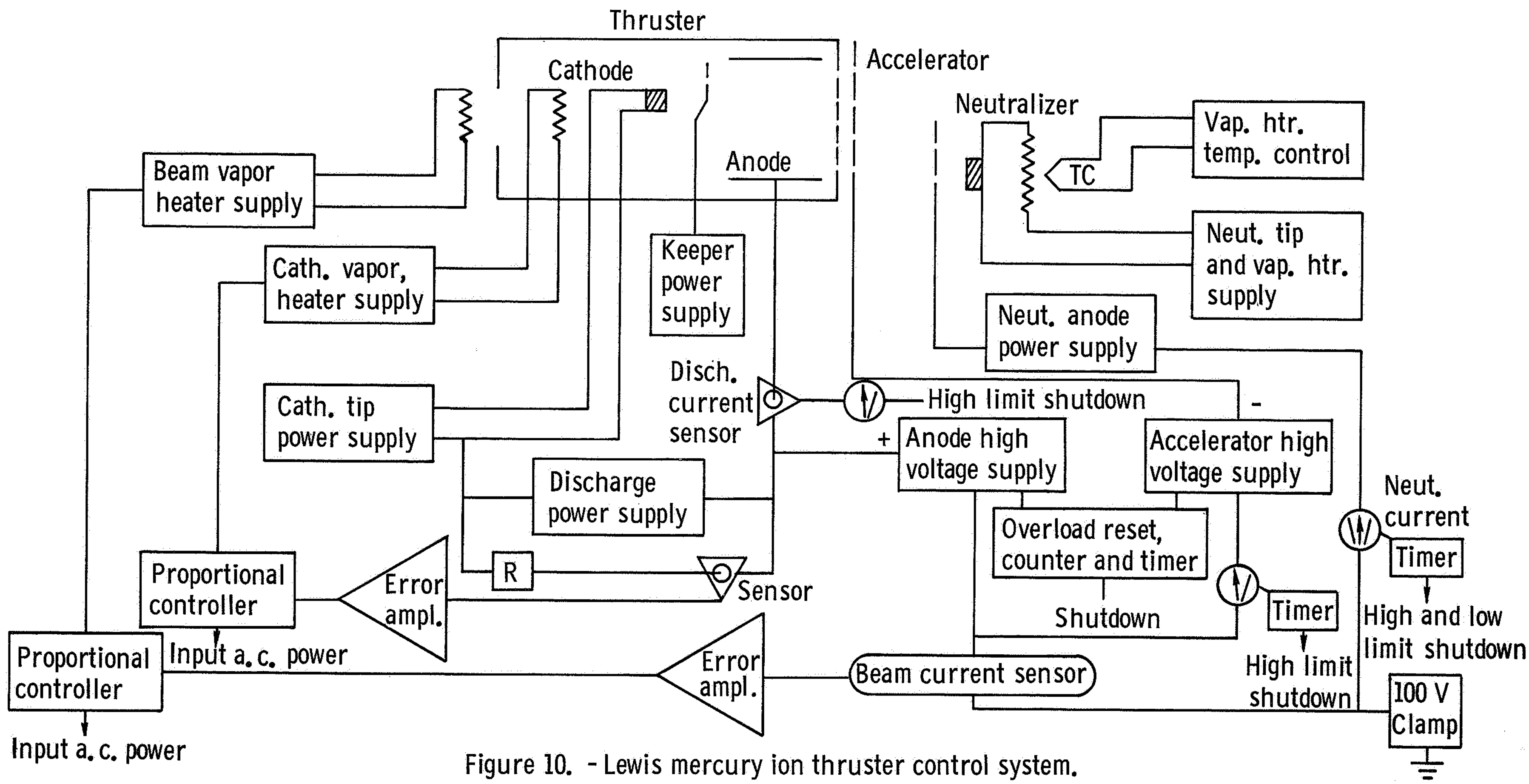

Figure 10. - Lewis mercury ion thruster control system.