N73-19476

FOR

OLD GAS ATTITUDE CONTROL JET VALVES

PHASE II FINAL REPORT

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

SPACE
SYSTEMS

70SD4285
November 1970

A SOLENOID FAILURE DETECTION SYSTEM
FOR
COLD GAS ATTITUDE CONTROL JET VALVES

PHASE II FINAL REPORT
COVERING THE PERIOD MARCH 1969 TO JULY 1970
UNDER CONTRACT JPL 952578

PREPARED FOR

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
4800 OAK GROVE DRIVE
PASADENA, CALIFORNIA 91102

1

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ABSTRACT

This report describes the second phase in the development of a solenoid valve failure detection system. The technique requires the addition of a radioactive gas to the propellant of a cold gas jet attitude control system. Solenoid failure is detected with an avalanche radiation detector located in the jet nozzle which senses the radiation emitted by the leaking radioactive gas. Measurements of ^{14}CO leakage rates through a Mariner type solenoid valve are presented as a function of gas activity and detector configuration. A cylindrical avalanche detector with a factor of 40 improvement in leak sensitivity is proposed for flight systems because it allows the quantity of radioactive gas that must be added to the propellant to be reduced to a practical level.

SECTION 1

INTRODUCTION

The active life of a Mariner type spacecraft, in the absence of failures, is determined by the life of the Reaction Control System, i.e., when the propellant is consumed the spacecraft starts tumbling in space reducing the efficiency of the communication links to the point that the spacecraft is considered lost. Loss of propellant after launch is almost exclusively associated with the jet valves, the thrust supply elements of the Mariner-type cold gas reaction control system, because a perfectly sealing jet valve is a technical improbability. Prior to launch the leak rate of each valve is quantitatively specified, however failure can occur during flight leading to propellant loss. The Mariner-type reaction control system includes a built-in redundancy to reduce the risk of such failure. The weight performance of this system is very poor because two propellant tanks are used; each serving half of the thrusters with each tank containing enough propellant to compensate for the torque supplied by an open valve failure. An alternate, more weight-effective configuration has been proposed (Reference 1). In this case the two half systems are linked to the same propellant tank through shut-off valves. As soon as an open failure occurs on one of the half systems, its feed line is shut off leaving the spacecraft in control of the other half system. This alternate system requires a failure detection system to control the feed line valve. This report deals with a two-phase development of a solenoid failure detection system that will allow each valve to be interrogated periodically during flight. The program culminated with leak tests performed on Mariner type solenoid valves with a prototype failure detection apparatus. The results of the Phase I feasibility study will be briefly reviewed, followed by the results of a comparative analysis of avalanche detector configurations presented relative to the design of an operational solenoid failure detection system.

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1. Roselli-Lorenzini, F.G., "Failure Detection System for Solenoid Actuated Gas Jet Valves," JPL Document No. SPS 37-61, Volume III.

SECTION 2

TECHNICAL DISCUSSION

In the initial phase of this program, measurements were made to determine the feasibility of detecting gas jet leakage in flight using a radioactive gas and a GE avalanche detector, a tiny, high gain, solid state radiation detector. In these experiments a radioactive gas ^{14}CO was mixed with N_2 and metered with a Vacoa metering valve through a test nozzle, into a vacuum chamber. The calibration of the metering valve is shown in Figure 2-1. With the test apparatus shown in Figure 2-2, it was possible to show that the radiation (beta particles) emitted by ^{14}C could be detected when the ^{14}CO was leaking at a rate of a few scc/hr. It was also shown that much greater sensitivity to leak rate was obtained when the detector was placed between the leaking valve and the nozzle as opposed to placing the detector outside the cone of the jet nozzle. At the end of the first phase of this program then the measurements had demonstrated the feasibility of measuring the 1 scc/hr leak rates typical of solenoid failure with a radioactive gas and an avalanche

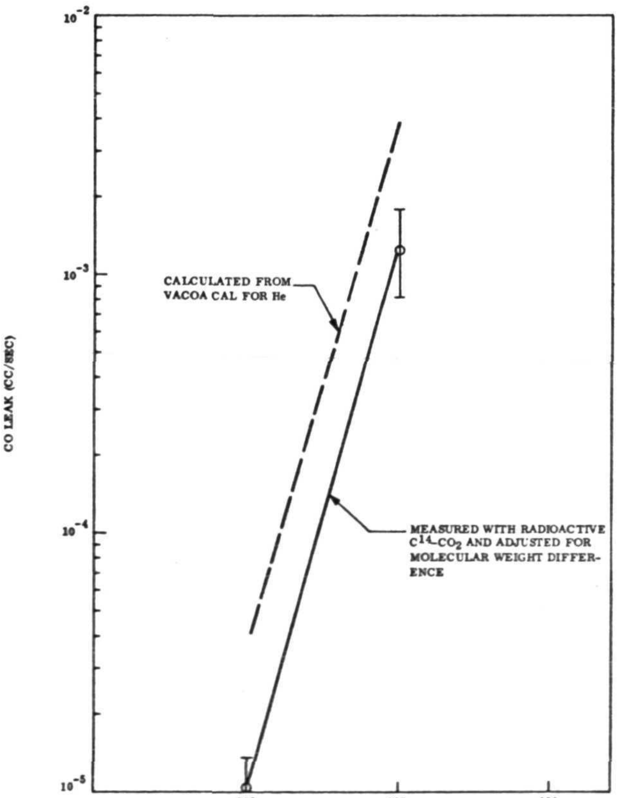


Figure 2-1. Metering Valve Calibration

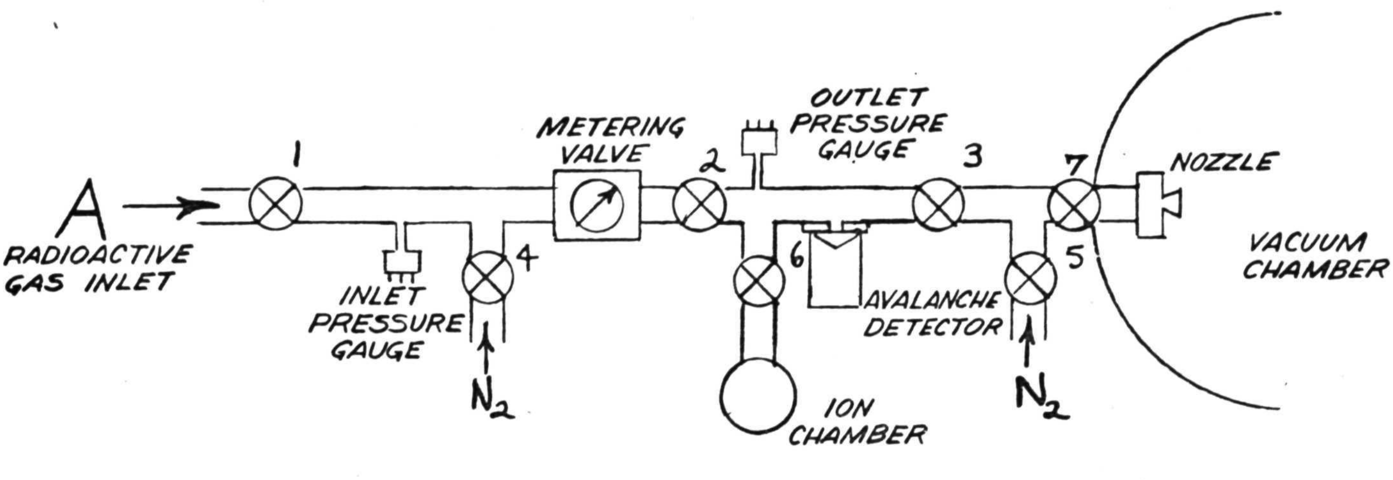


Figure 2-2. Test Apparatus Schematic

radiation detector. It was also discovered that the best approach to an in-flight system required a tiny detector to be placed between the seat of the solenoid valve and the gas jet nozzle. Thus, the second phase of this program began with an evaluation of several avalanche detector configurations to determine which could be adapted to the problem, so that a practical in-flight system could be developed.

2.1 DETECTOR CONFIGURATION

An avalanche detector consists of a silicon avalanche diode and its tunnel diode amplifier. The silicon avalanche diode is a PN junction device with a "contoured" N region. This physical shaping of the back side of the device presents a high electrical field to the incoming radiation. The polarity of the field is such that each time radiation is absorbed the electrons released from the ionized silicon atoms are accelerated, striking and ionizing other atoms in the crystal resulting in a cascade of electrons toward the back contact of the avalanche diode. The tunnel diode amplifier monitors this cascade of charge and triggers when the number of electrons exceeds a preset level.

Of all solid state radiation detectors internal gain or amplification is only inherent in the avalanche detector. It is this gain that prompted the use of avalanche detectors in this application because no other device could be made small enough to fit inside a jet nozzle without interfering with normal gas flow and still have sufficient sensitivity to detect ^{14}C beta particles. It should be remembered that ^{14}C labelled carbon monoxide was selected as the tracer gas to be mixed with the nitrogen propellant because the CO has the same molecular weight as N_2, thus they will both leak at the same rate.

Initially three detector configurations were evaluated as shown in Figure 2-3. The first was the plane or wafer shaped avalanche diode which would be mounted in close proximity to the solenoid valve seat and the aperture of the jet nozzle. The other two configurations required developmental diodes; one an annular avalanche diode which would be mounted where the solenoid valve "seats" with the jet nozzle. The other was a cylindrical avalanche diode which would be mounted in the nozzle such that its active surface had the same internal dimensions as the jet nozzle.

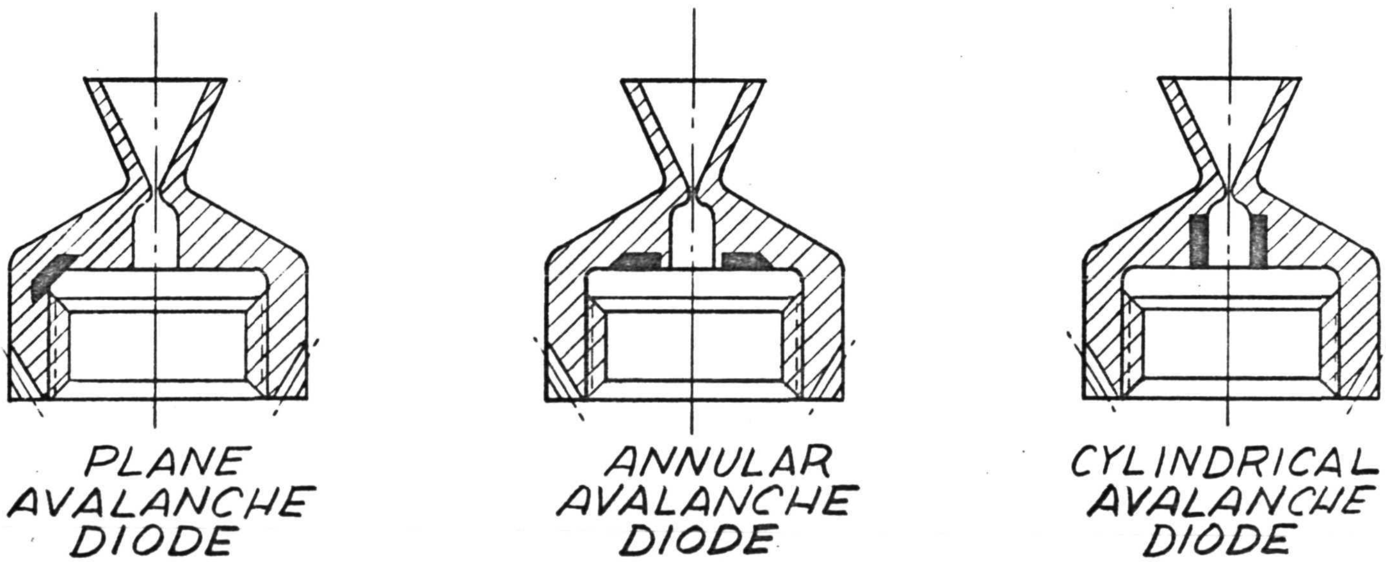


Figure 2-3. Leak Detector Configurations

Theoretically it turns out that the cylindrical diode configuration should be nearly 40 times more sensitive to leak rate than the wafer and 10 times more sensitive than the annular configuration primarily because it is a 4π detector; i.e., it can detect any ^{14}C beta emitted in any direction as it passes through the jet nozzle. Sample calculations of the leak sensitivity of the plane, annular and cylindrical avalanche diodes are presented below.

SAMPLE DETECTOR SENSITIVITY CALCULATIONS

A. PLANAR CONFIGURATION

$$\text{Outlet Detector Count Rate (0.125 in active dia)} = \frac{\text{Inlet leak rate} \cdot \text{Inlet Activity per unit vol.}}{4\pi} \times \frac{\text{Outlet Detector Area}}{\text{Distance to leak}} \times {}^{14}\text{C Detection Efficiency}$$

$$= \frac{1.6 \times 10^4}{4\pi}\ \text{d/sec}\ (0.22)\ (0.2)$$

$$= 44\ \text{counts/sec} \quad @\ 1\ \text{cc per hour}$$

B. CYLINDRICAL CONFIGURATION

$$\text{Outlet Detector Count Rate (0.100 in inside dia)} = \frac{\text{Inlet leak rate} \cdot \text{Inlet Activity per unit vol.}}{1} \times \frac{\text{Outlet Detector Area}}{\text{Distance to leak}} \times {}^{14}\text{C Detection Efficiency}$$

$$= 1.6 \times 10^4\ \text{d/sec}\ (1)\ (0.1)$$

$$= 1600\ \text{counts/sec} \quad @\ 1\ \text{cc per hour}$$

C. ANNULAR CONFIGURATION

$$\text{Outlet Detector Count Rate (I.D. 0.280 cm) (O.D. 0.460 cm)} = \frac{\text{Inlet leak rate} \cdot \text{Inlet Activity per unit vol.}}{4\pi} \times \frac{\text{Outlet Detector Area}}{\text{(Distance to leak}} \times {}^{14}\text{Carbon Efficiency}$$

$$= \frac{1.6}{4\pi} \times 10^4\ \text{d/sec}\ (1)\ (0.2)$$

$$= 200\ \text{c/sec}$$

Note: Count rates are calculated independent of gas transit time through detectors sensitive volume.

During this program experimental verification of diode sensitivity could only be performed with the plane diode configuration because both the annular and cylindrical diode configurations had not advanced beyond the prototype stages of development. Near the end of this program significant progress had been made toward developing cylindrical detectors (see Appendix A). However, no operational devices were produced during this contract period, as a result all experimental results pertain to the plane diode configuration.

2.2 LEAK TEST PROCEDURE

Mariner type solenoid valves were used to demonstrate the sensitivity of the solenoid failure detection scheme. A test nozzle was designed to hold a plane avalanche diode in proximity to the "seat" between the valve and the nozzle aperture.

A mechanical drawing of the detector's position in the test nozzle is shown in Figure 2-4. It should be noted that the internal dimensions of the test nozzle closely approximate those of a "Mariner" jet nozzle. The completed test nozzle avalanche detector and "Mariner" solenoid valve are shown in Figure 2-5. This test nozzle connects to the leak test apparatus below the metering valve as shown in Figure 2-6. Briefly, the radioactive gas, a mixture of Carbon-14 tagged carbon monoxide and nitrogen is contained in a reservoir bounded by valves 1 through 7. With the Mariner solenoid valve open the test nozzle was evacuated and sealed off from the vacuum pump and the gas mixture was then metered in through the Vacoa metering valve, 7, in Figure 2-6. The count rate measured by the detector was then tabulated as a function of leak rate and the activity of the gas. After calibrating the detector inside the test nozzle, the Mariner solenoid valve was then closed and again the radioactive gas was allowed to flow into the solenoid valve through the by-pass valve, 5, in Figure 2-6. The count rate was then tabulated and the leak rate defined relative to the activity of the gas in the reservoir. The complete test procedure is described in detail in Appendix B.

2.3 TEST RESULTS

Using the apparatus and test procedure described above, the following tests were performed:

1. The detector mounted in the test nozzle was calibrated as a function of gas activity. The results are shown in Table 2-1.

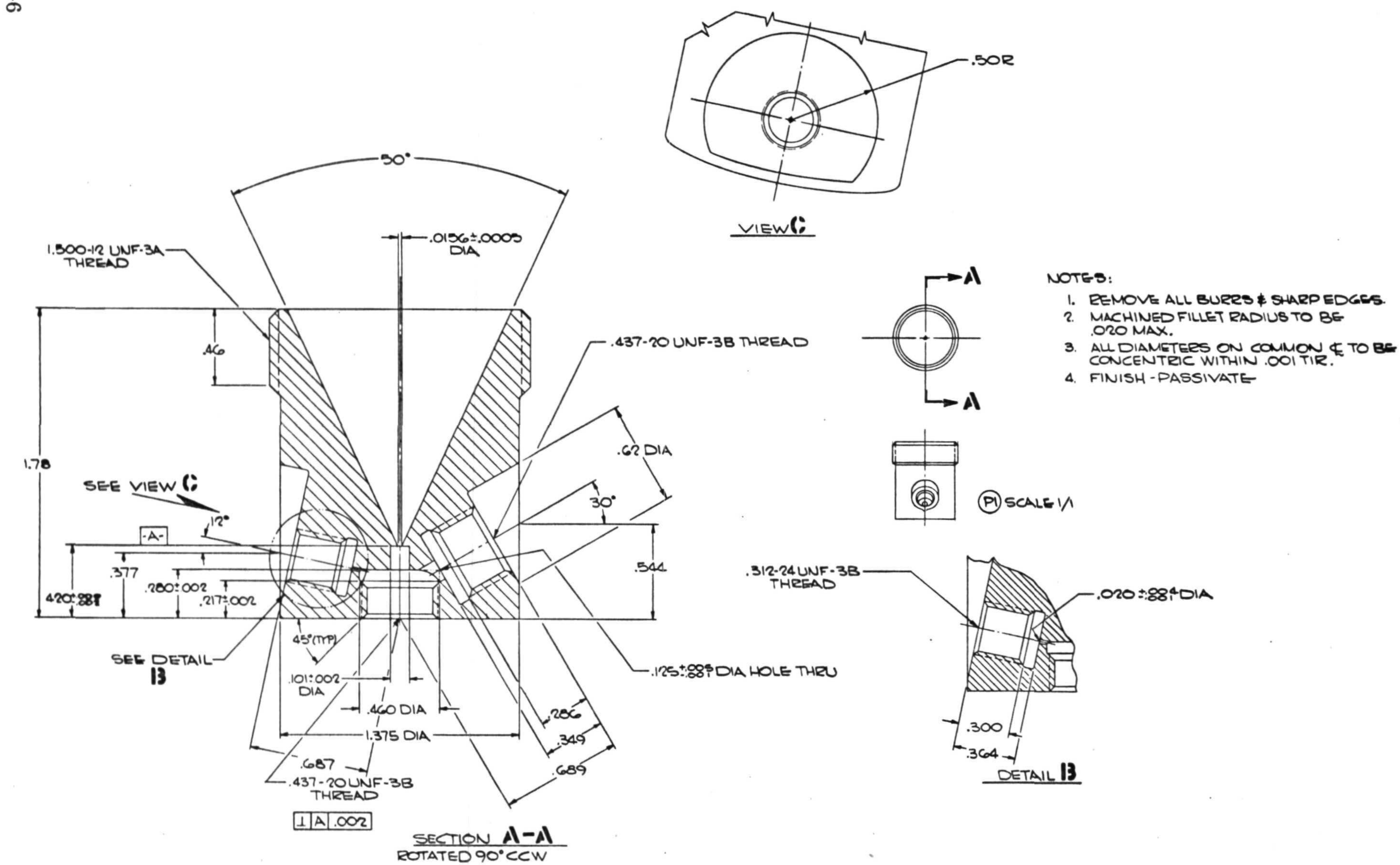


Figure 2-4. Test Nozzle "A"

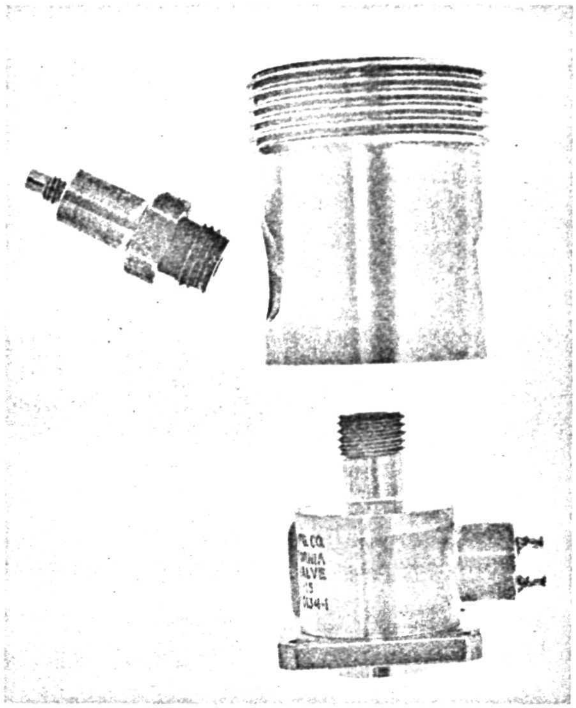


Figure 2-5. Test Nozzle, Detector and Solenoid Valve

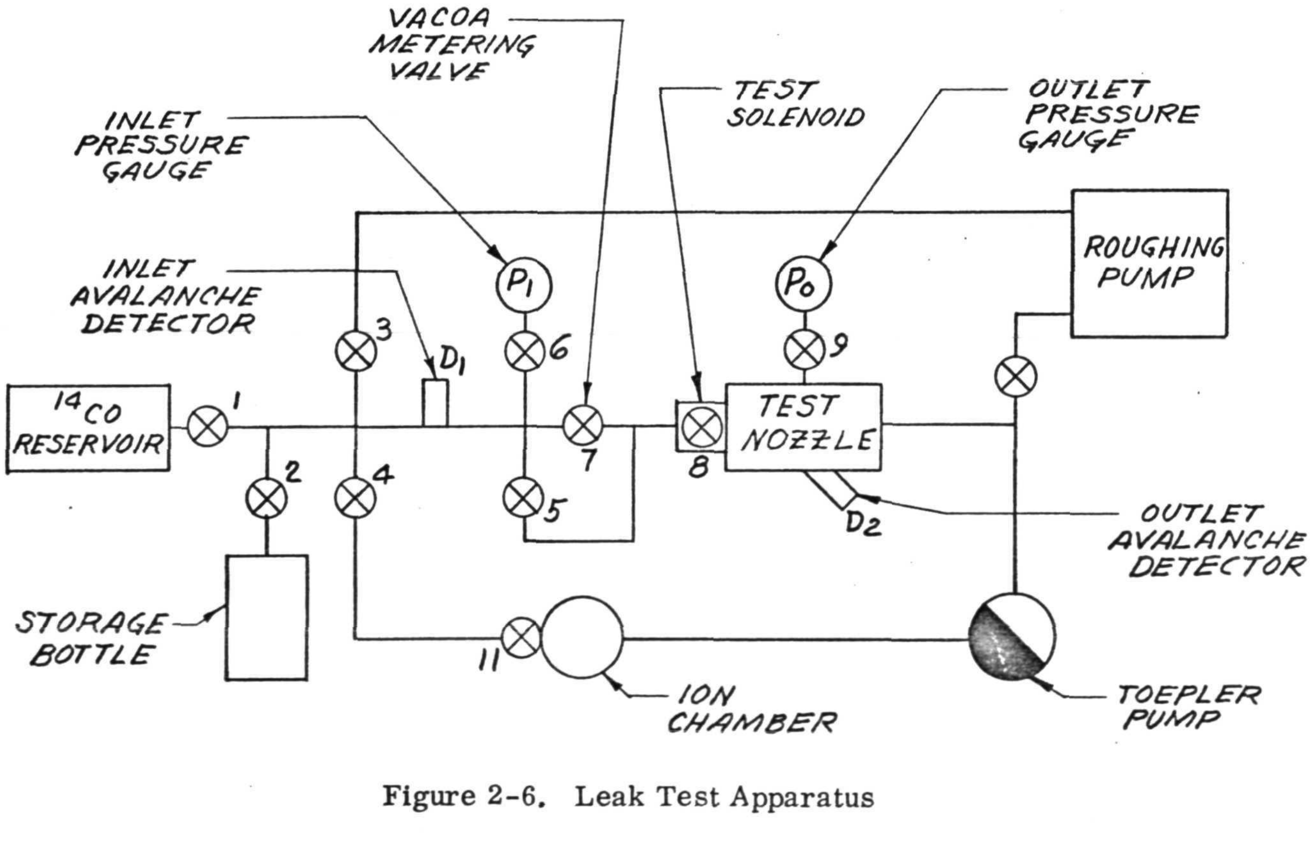


Figure 2-6. Leak Test Apparatus

2. The detector mounted in the test nozzle was also calibrated as a function of flow rate, metering valve turns units (Table 2-2).

3. The solenoid valve leak rate was measured with the calibrated detector as shown in Table 2-3.

4. Tests were performed to determine the feasibility of recirculating the radioactive gas mixture.

Table 2-1. Effect of Diluting Radioactive Gas

Metering Valve Setting (units)	Inlet Pressure (psi)	Inlet Detector Count Rate (counts/sec)	Gas Activity (microcuries/ cm^3)	Outlet Pressure (mm Hg)	Outlet Detector Count Rate (counts/10 sec)
200	15	1100	50	10	270
		1200			265
		1100			279
		1030			280
	5.0	120	2		25
		108			22
		115			27
		110			25
		105			29
	5.0	25	0.08		2
		29			3
		31			1
		25			3
		28			2

The gas dilution results in Table 2-1 were obtained by increasing the total volume of the gas mixing reservoir up to 300 cm^3 and letting air in which reduced the number of microcuries of ^{14}C per cm^3 of air. In this way it was possible to detect less than 0.1 microcuries $^{14}C/cm^3$.

The detector calibration data of Table 2-2 indicated that count rate dropped off at the higher leak rates. This seems likely in view of the fact that the probability of detecting the radioactive molecules of the gas is less likely when they are rapidly moving past the sensitive volume than when they are dwelling in it for longer periods.

It is important to note here that the use of cylindrical detectors should reduce the effect of flow rate on detection sensitivity because, the radioactive gas will dwell within the sensitive volume of the cylindrical device longer thus increasing the probability of detecting it. For example the following relationship

$$t_f = \frac{\ell A}{Q} (3.6 \times 10^3)$$

gives the time t_f (sec) it takes for a gas flowing at rate Q (cm^3/hr) to flow through cylinder ℓ centimeters long and active area A (cm^2). Using this it can be seen that a cylinder 0.1 cm long and 0.25 cm inside diameter has a dwell time of several seconds at a flow rate of 1 cm^3/hr.

The leak rate data of Table 2-3 obtained with Mariner solenoid valve #2 shows considerable repeatability within the statistical error of the measurement. As shown in Figure 2-7, the average values of these data fall on the detector calibration curve between 3 and 5 cc/hr. The corresponding JPL calibration was 4 cc/hr.

The remaining data shown in Table 2-4 was taken to evaluate the feasibility of transferring the gas that had leaked from the reservoir through the metering valve, through the solenoid valve, into the test chamber by returning it to the reservoir via a piston type recirculating pump. The data of Table 2-4 was taken with a Toepler pump which uses a mercury piston

Table 2-2. Outlet Detector Calibration Tests versus Leak Rate (Metering Valve Turns)

Time hrs	Metering Valve Setting	Leak Rate scc/hr	Inlet Pressure psi	Inlet Detector count/Rate count/10sec	Ion Chamber Current amps	Outlet Pressure mm Hg	Outlet Detector Count Rate count/10 sec
				TEST #3			
1040	0	0	5.6	522	$4x10^{-9}$	7	0
				489			
				484			
				472			
1044	200	7.2		504		8	3
				534			3
				457			1
				493			5
1049				481		9	4
				469			7
				489			4
				511			5
1054			5.58	498		10	6
				490			8
				519			4
				497			4
1059			5.56	483		11	3
				463			7
				484			5
				484			4
1104	200	7.2	5.54	450		12	2
				558			3
				472			6
				492			1
1109			5.52	485	$3.9x10^{-9}$	13	5
				469			5
				470			3
				489			11
1113			5.50	472		14	2
				544			3
				488			7
				515			6
1117			5.48	460		15	8
				495			5
				457			6
				482			5

Table 2-2. Outlet Detector Calibration Tests versus Leak Rate (Metering Valve Turns) (Cont'd)

Time hrs	Metering Valve Setting	Leak Rate scc/hr	Inlet Pressure psi	Inlet Detector count/Rate count/10sec	Ion Chamber Current amps	Outlet Pressure mm Hg	Outlet Detector Count Rate count/10 sec
1121			5.46	435 491 462 450		16	6 6 5 4
1125			5.45	496 504 457 493	3.9×10^{-9}	17	4 5 7 5
1150	0	0	RECIRCULATION				
1160	0	0	5.60	490 489 500 465	4.0×10^{-9}	5	0 0 0 0
				TEST #4			
(Seconds)							
0	0		11.7	225 220 238 255	8.6×10^{-11}	9	0 0 0 0
105	195	5.4		230 240 229 250		10	1 3 7 5
220				240 235 228 250		11	7 1 2 4
330			11.65	249 249 236 240		12	11 15 3 13
430				268 228 238 250	8.55	13	5 7 1 5
540			11.60	245 255 238 229		14	3 9 13 7
660	195	5.4	11.60	236 250 236 240	8.5	15	3 11 5 3

Table 2-2. Outlet Detector Calibration Tests versus Leak Rate (Metering Valve Turns) (Cont'd)

Time hrs	Metering Valve Setting	Leak Rate scc/hr	Inlet Pressure psi	Inlet Detector count/Rate count/10sec	Ion Chamber Current amps	Outlet Pressure mm Hg	Outlet Detector Count Rate count/10 sec
NO RECYCLE PUMPED OUT TEST NOZZLE							
0	0		11.60	265	8.5	10	0
				245			0
				260			0
				241			0
39	200	7.2	11.55	250		11	5
				248			9
				260			5
				239			6
79			11.50	250		12	11
				240			7
				275			5
				242			5
116			11.45	240	8.45	13	3
				238			9
				261			7
				245			4
151			11.40	248		14	13
				246			9
				254			5
				239			7
191			11.35	254	8.4	15	5
				250			5
				251			7
				240			6
NO RECYCLE – PUMPED OUT TEST NOZZLE							
0	0		11.35	250	8.4	8.5	0
				248			0
				239			0
				240			0
42	225	18.0 (Extrapolated)	11.30	240		10	5
				235			3
84			11.25	229	8.3	11	7
				254			3
122			11.20	250		12	4
				242			5
162			11.15	234	8.2	13	3
				240			1
200			11.10	239		14	3
				240			3
240			11.05	229	8.1	15	3
				238			5

Table 2-2. Outlet Detector Calibration Tests versus Leak Rate (Metering Valve Turns) (Cont'd)

Time hrs	Metering Valve Setting	Leak Rate scc/hr	Inlet Pressure psi	Inlet Detector count/Rate count/10sec	Ion Chamber Current amps	Outlet Pressure mm Hg	Outlet Detector Count Rate count/10 sec
NO RECYCLE - PUMPED OUT TEST NOZZLE							
0	0		11.05	229	8.1	9	0
21	250	40 (Extrapolated)		235 220		10	3 5
40				240 220		11	3 3
59	250		10.90	235 230	7.9	12	3 5
78				231 250		13	3 2
97				230 225		14	5 5
116			10.70	228 235	7.7	15	7 6
ION CHAMBER CALIBRATION							
4.39×10^{-12} amps/microcurie							

Table 2-3. Solenoid Valve #2 Leak Test

Time hrs.	Metering Valve Setting	Inlet Pressure psi	Inlet Detector Count Rate count/10sec	Ion Chamber Current amps	Outlet Pressure mm Hg	Outlet Detector Count Rate counts/10 sec
1105	0	10.7	220	$7.7x10^{-11}$	10.4	0
			210			0
			198			0
			224			0
			190			0
1120	Bypassed		210			1
			198			0
			195			0
			225			1
			221			0
1135			225			1
			195			3
			190			0
			221			1
			220			1
1150			221		10.6	1
			225			1
			198			3
			215			1
			202			0
1330	RECYCLED					
1345	0	10.7	210	$7.7x10^{-11}$	10.4	0
			221			0
			195			0
			219			0
			208			0
1400	Bypassed		219			1
			195			0
			201			1
			198			0
			210			1
1415			198			0
			190			1
			210			1
			225			0
			195			1
1430			210			1
			210			1
			218			0
			298			1
			190			1
1445			201			1
			225			3
			198			1
			190			1
			225			0
1500	RECYCLED					

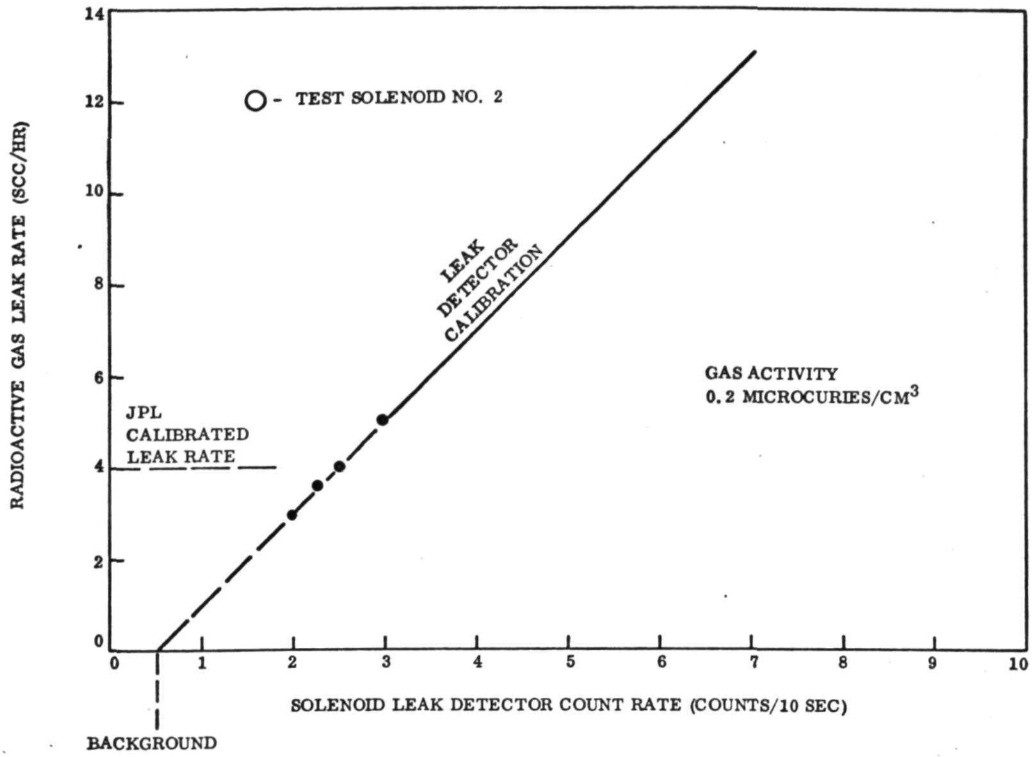


Figure 2-7. Leak Test Results Solenoid Valve No. 2

and float valves to open and close the input and output to the piston chamber. The data clearly indicates the feasibility of this pumping scheme because it was possible to restore the original conditions within a few minutes after each test as long as there was no leakage around the joints and valves of the apparatus.

Table 2-4. Vacuum System Stability and Recycle Tests

A. Stability test performed with all external valves closed after evacuation

Time	Pressure Inlet (psi)	Pressure Outlet (mm Hg)
1100	0.15	12.3
1200		15.0
1330		18.9
1500		22.9
1700		27.3
Recycled 10 times------------		
	0.15	7.5

B. Recycling test

Recycle Number	Inlet (psi)	Outlet (mm Hg)
Initial	1.2	3.0
After bleed in	0.2	25.0
After 1st cycle	0.4	15.0
2nd	0.6	10.0
3rd	0.8	8.0
4th	1.0	6.0
5th	1.1	5.0
6th	1.2	3.0

SECTION 3

CONCLUSIONS AND RECOMMENDATIONS

The test results showed that an avalanche detector could be placed in a jet nozzle and have sufficient sensitivity to detect leak rates typical of the Mariner type solenoid valves used in these tests. The accuracy and precision of the measurements have improved considerably over the first feasibility tests carried out in this program. Based on these results the configuration recommended for an operational solenoid failure detection system should be the cylindrical detector because of the factor of 40 improvement in sensitivity. This would require less radioactive gas to be added to the propellant reservoir and would improve the precision and accuracy of the measurement considerably. It was also shown that ground testing of solenoid leakage could be performed practically by incorporating a recirculating pump; however, it is recommended that the apparatus use welded joints as opposed to the use of fittings.

APPENDIX A

CYLINDRICAL AVALANCHE DETECTORS

The actual fabrication of cylindrical type detectors for internal gas counting requires the development of several additional process steps not needed for normal plane detectors. It is extremely important that the silicon surface damage be kept to a minimum during the various drilling, lapping and etching operations.

The starting material for a cylindrical detector is, typically, a 50 ohm-cm silicon slug, 3/8" long, cut from a 1/4" diameter rod grown in the (111) direction. This slug is drilled out along its axis, to a diameter of 1/8".

Several different methods are being investigated for making the axial hole in the slug: lapping, ultrasonic drilling, diamond core drilling, and combinations of these techniques. The basic requirement is that a maximum damage region of 1 mil (0.001") is allowed on the inner surface of the hole.

The hollow slug is subjected to a deep gallium diffusion ($\sim$ 3.8 mil junction depth). After diffusion, the outer surface is lapped to remove the diffused region, and the ends of the cylinder are lapped with a conical lapping tool to achieve the required surface contouring angle. When all lapping operations are completed, the device is cleaned and etched to remove all damage regions (1 mil is etched off).

Mechanical mounting of the detector will depend on the specific application. A typical mounting for a gas (or liquid) flow detector is shown schematically in Figure A-1. The detector is mounted onto a tube at each end, using conductive silver epoxy to assure a good electrical contact to the p-region of the detector. The gas or liquid to be counted flows in through one tube and out the other. The entire detector assembly can be encapsulated, the exact configuration depending on the location and space available.

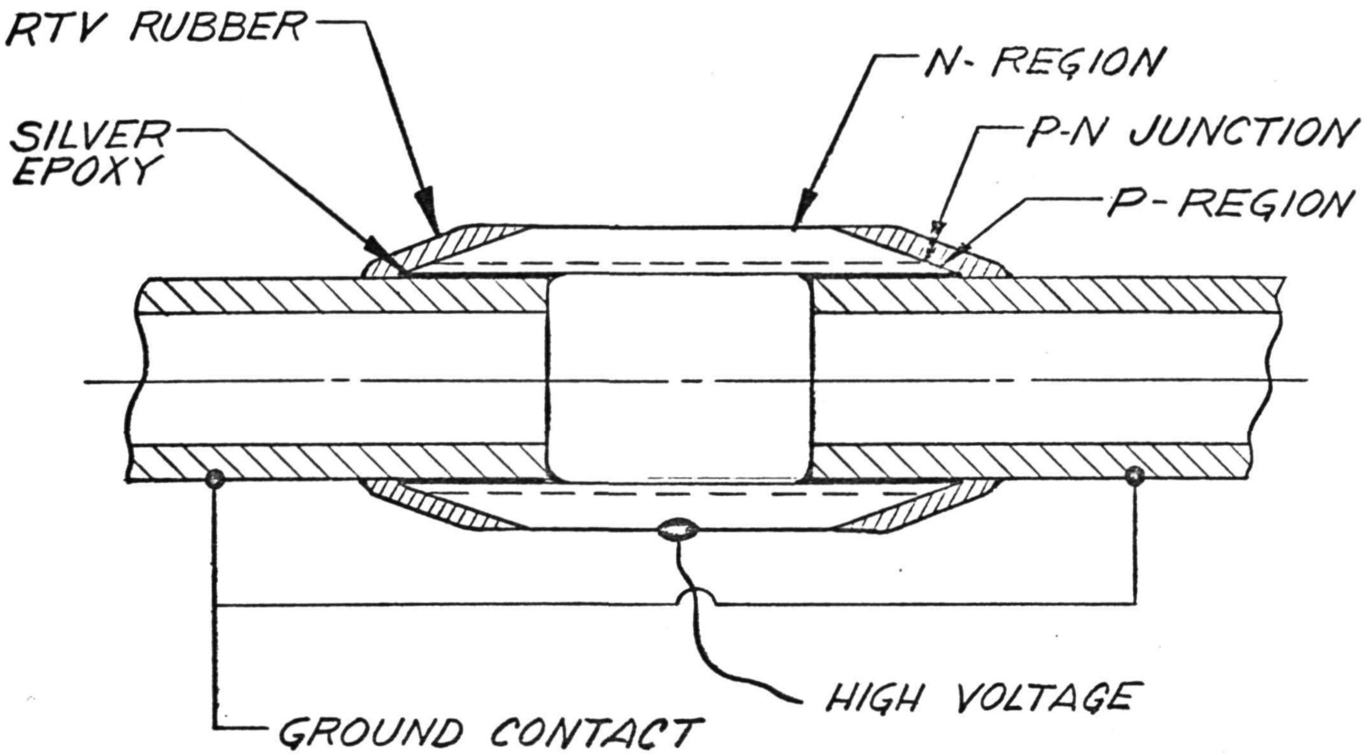


Figure A-1. Flow Detector Schematic

Two slugs of silicon have been drilled out, diffused and lapped. The drilling was done by an ultrasonic process. One of the cylinders cracked during the contouring process. The other was contoured at a 45° bevel angle and subsequently etched which is shown in Figure A-2. The contouring angle was shown to be too large by electrical tests, and a recontouring is being performed. Additional silicon slugs are being prepared for drilling and diffusion. Several different drilling methods are being studied, and successful use has been made of ultrasonic drilling and of lapping. Diamond core drilling will also be evaluated.

Figure A-2. Initial Cylindrical Diode Configuration

APPENDIX B

OPERATING INSTRUCTIONS FOR THE SOLENOID VALVE LEAK TEST APPARATUS

1. Assemble system according to Figure 2-6 in the text.

2. Make sure all valves are closed before turning on roughing pump.

3. Open all valves and evacuate entire system including both upper and lower halves of Toepler pump (be sure bleed valve on Toepler pump controller is closed).

4. When system is evacuated close all valves again and open valve #1. The radioactive gas will then transfer into the section bounded by valves #1 through #7 (see Figure B-1.a).

Test Nozzle Calibration

5. Turn on avalanche detector counting system which monitors test nozzle detector count rate. Turn discriminator knob clockwise until continuous counts are obtained on the display, then turn the discriminator knob back one-quarter turn. Repeat this procedure with the avalanche gain control knob. This maximizes the sensitivity of the unit.

6. Energize the solenoid #8, then turn the metering valve, #7, (see Figure B-1.b) and tabulate detector count rate versus metering valve setting. This calibrates the test nozzle detector according to the metering valve calibration as shown in Section 2, Figure 2-1.

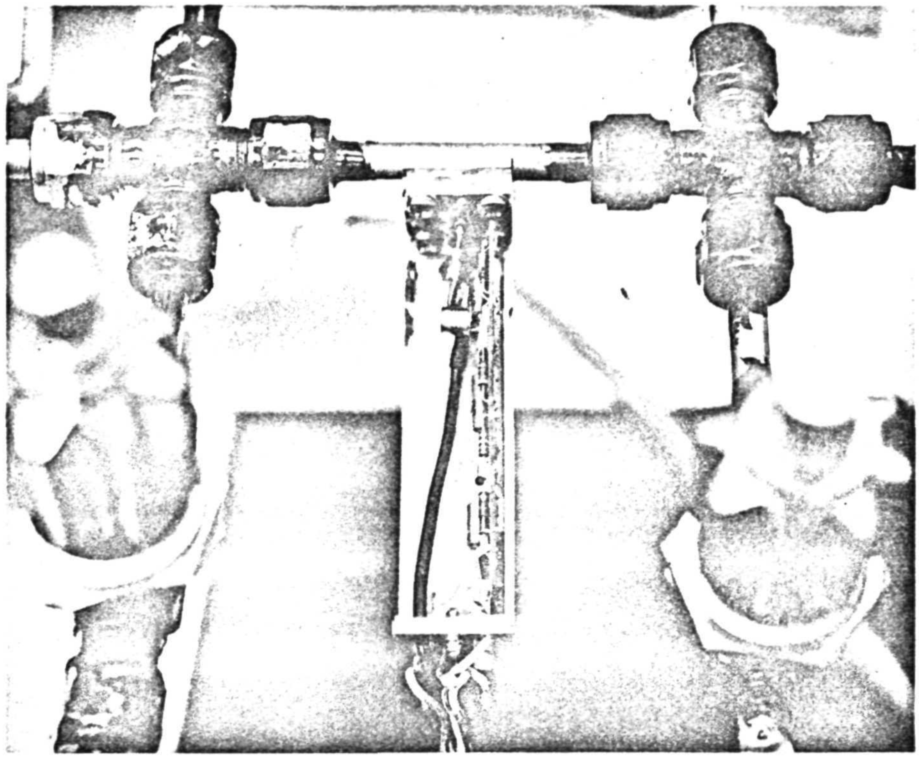
7. After calibration, close #7.

8. Turn off roughing pump. Open Toepler pump controller bleed valve carefully and leave it open. The mercury piston will begin to fill the upper chamber of the pump (Figure B-1.c) forcing the radioactive gas through the outlet tube back into the storage line. When the mercury reaches the top contact the relay in the controller will start the roughing pump again which draws the mercury back down into the lower chamber (See Figure B-4.d).When the mercury touches the lower contact points the controller shuts off the roughing pump again causing the piston to force more radioactive gas through the outlet. In practice this process continued automatically as long as the pressure in the storage line didn't exceed 8 psi. Normally about 10 cycles were required to force the gas back into the storage line.

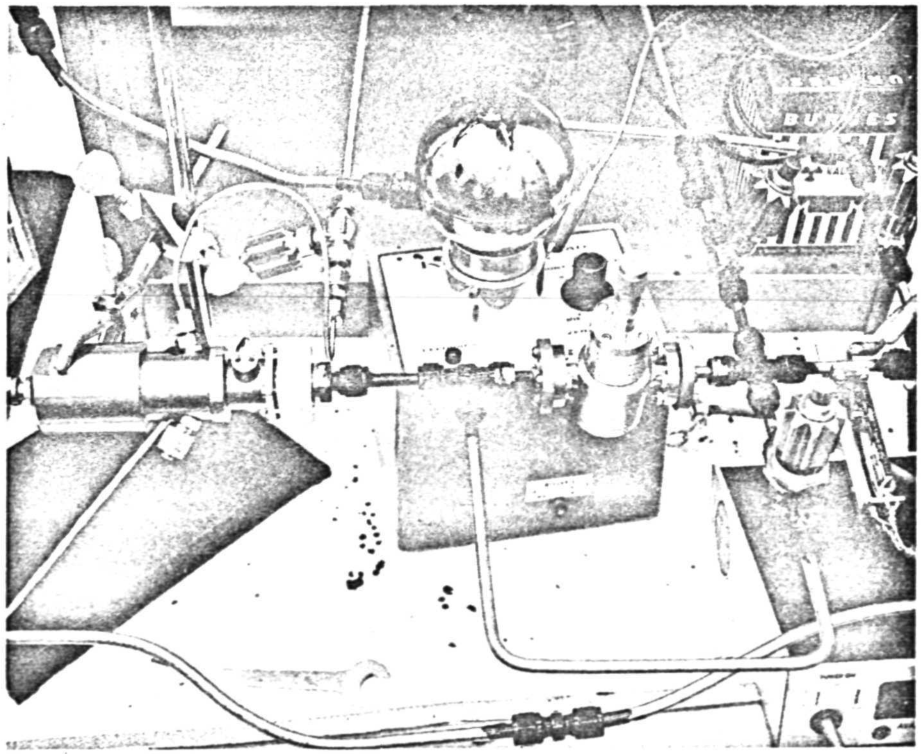
9. De-energize the test solenoid valve and with the electronic counter bias controls set the same as for the nozzle calibration, open valve #5 and monitor count rate versus time.

10. After the leak test close #5 and recycle the radioactive gas.

Figure B-1. Solenoid Valve Leak Test Apparatus

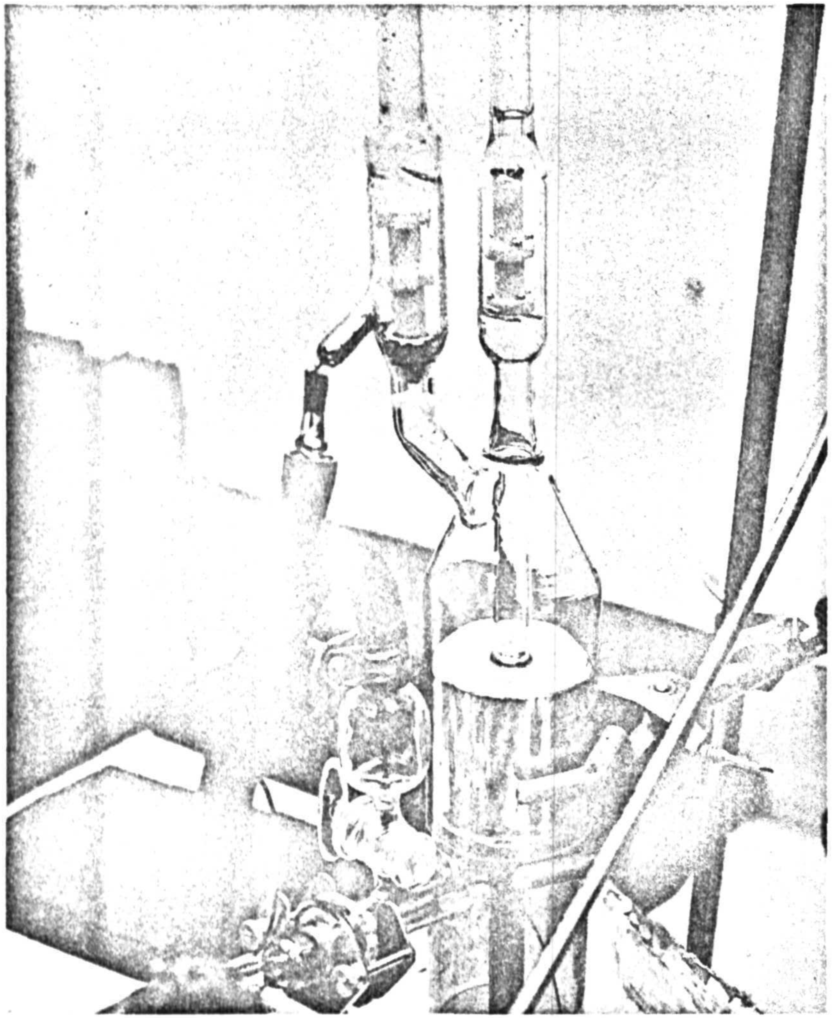


a.

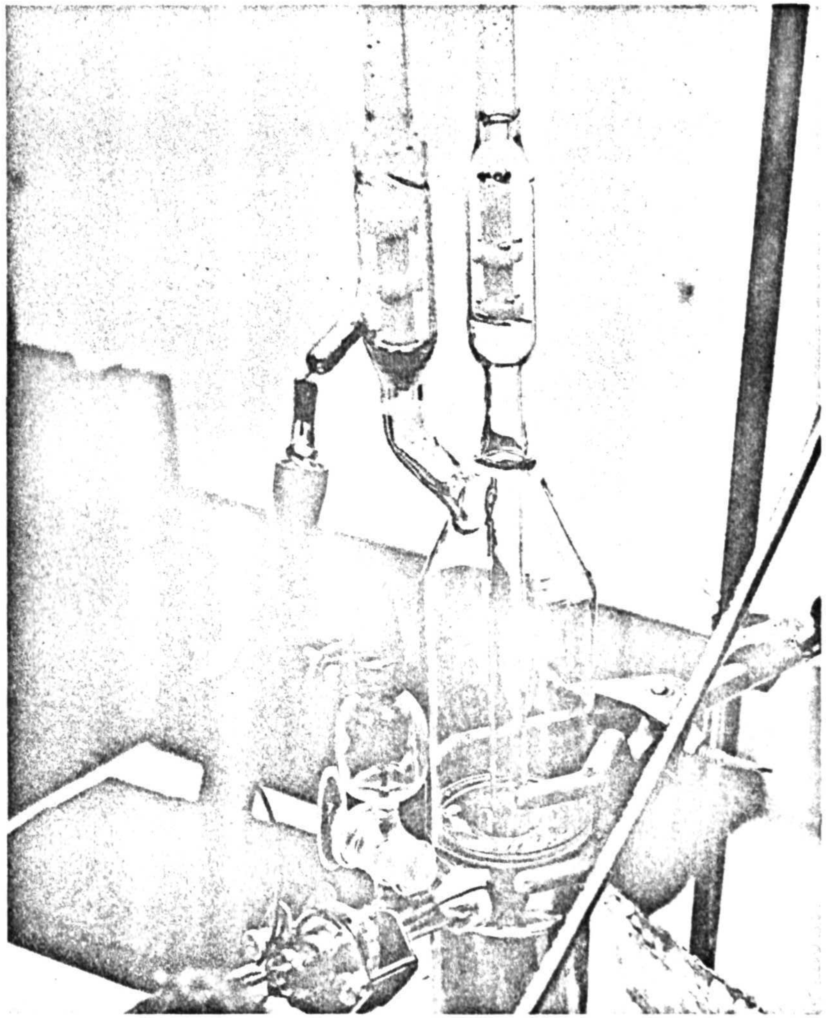


b.

Figure B-1. Solenoid Valve Leak Test Apparatus (Cont)



c.



d.