LIGO-T880014

#07

List of 3/1/89

Boude Moore LIGO Internal Report 88-1 12/16/88

ASPECTS OF LEAK DETECTION IN LIGO BEAM TUBES

I. SCOPE

Two related sets of questions are discussed:

1. Can the existing leak rate in a 2 km beam tube be measured? If there is no significant leak, can this fact be established?
2. Can a leak in the beam tube be found? Once it is known that leaks exist, and the magnitude is measured, can reasonable procedures and equipment be used to find them?
   a) What quantitative pressure transients can be expected at a detector, from inputs of tracer gas through a leak? What is the time required for a signal to travel to the detector, and what is its amplitude?
   b) What leak detection equipment will be needed to measure the expected leaks? Will standard commercial equipment be satisfactory, or will special equipment need to be developed?

II. GENERAL/BACKGROUND

For this analysis the allowable air leak for a LIGO detector is assumed to be 1×10^{-9} torr liters/second. A tight vacuum system is needed for several reasons:

a) In order to maintain constant pressure. Small leaks can be temporarily blocked by solid particles or by liquid condensation.[1] A sudden change of 4×10^9 molecules (1×10^{-10} torr liters) within a 4 km arm would cause a false indication of a gravity wave.[2]

b) In order to reduce the risk of gas bursts from ion pumps, used extensively in the LIGO. A small air leak will, in time, cause argon to accumulate in the ion pumps. This argon will diffuse into any cavities, building up high pressures since there is no mechanism for escape. Thin films deposited in the presence of an argon glow discharge have shown surface craters and gas bursts.[3] There is a possibility that similar bursts could occur in ion pumps.

c) In order to ensure reliable leak-free vacuum over the 20-year life of the facility. Small leaks may grow with time due to corrosion and stress cycles. Subsequent leak testing and repair procedures would interfere with the operation of the observatory.

Helium is assumed to be the tracer gas. Other gases could be used, but they have lower molecular velocities so that the response time would be increased.

It is assumed that only a short pulse of helium will be admitted through the leak. This reduces the signal at the detector, but avoids filling the beam tube with helium which would then have to be slowly pumped away. Perhaps more important, it reduces the helium background caused by permeation in and out of elastomers, ceramics, etc.

III. MEASURE TOTAL LEAK RATE

Assume a mass spectrometer, equivalent to the Dycor, behind an LN_2 trap, installed on the beam tube. Also assume a leak valve to admit air to the beam tube, in order to confirm the air signature. Can this equipment detect a 10^{-9} torr liter/second air leak?

The water vapor will be pumped by the LN_2 trap. Only air and hydrogen will reach the mass spectrometer.

Partial Pressure of Air

With one turbo operating at a nominal 4000 L/S, a 10^{-9} T L/S leak would give a partial pressure of 2.5×10^{-13} torr. This is too low for reliable observations (unless a more sensitive unit, such as the UTI, Balzers, or EXTREL, is used, but these are less suitable for field work).

With a lower pump speed, the signal is increased proportionately. For example, at 40 L/S, the partial pressure due to the leak would be 2.5×10^{-11} torr, easily observable.

However, the simplest approach is just to valve off the pumps, and let the pressure rise. With a beam tube volume of 2.3×10^6 liters per 2 km section, and a leak of 10^{-9} T L/S, the rate of rise is 4×10^{-16} torr/second, 1.6×10^{-12} torr/hour, 3.8×10^{-11} torr/day. Any sorption effects (which would reduce the rate of rise) can be checked by recording the subsequent pumpdown.

Thus it would appear that a simple rate-of-rise test (with an LN_2 trap to remove water) is all that is necessary to establish the leak rate. However, there is a danger that the hydrogen pressure would rise so far that it would interfere with the measurement.

Hydrogen Partial Pressure

Assume:

Initial hydrogen content of steel = 1 ppm by weight
Time since steel manufacture = 3000 hrs (~ 4 mos)
Hydrogen outgassing rate @ 1 hr since mfg = 1.5×10^{-10} T L/S cm^2
Hydrogen outgassing rate @ 3000 hours since mfg = 2.7×10^{-12} T L/S cm^2
Surface area of 2 km tube = 7.7×10^7 cm^2
Hydrogen gas load = 2.1×10^{-4} T L/S
Volume of 2 km tube = 2.3×10^6 liters
Rate of rise, hydrogen = 9×10^{-11} torr/sec
= 3.3×10^{-7} torr/hour
= 8×10^{-6} torr/day

After a 1 day rate of rise, the hydrogen is approaching 10^{-5} torr, the typical upper limit for mass spectrometer operation. However, the air signature by this time is very clear.

It is concluded that it is feasible to measure air leak rates of 10^{-9} T L/S in the 2 km beam tube, using a simple and rugged type of mass spectrometer, such as the Dycor. (This will be confirmed by direct measurement when the VTF is operational.)

An alternate procedure to establish the total leak rate is to simply flood the tube housing with helium. This is more sensitive, but more costly.

IV. FLOW OF HELIUM FROM LEAK TO DETECTOR

Two kilometers is a long way for tracer gas to travel, and 2.3 x 10^6 liters is a large volume for it to fill. Quantitative calculations of the gas travel time and partial pressures are made in order to assess the feasibility of leak detection operations.

Diffusion Equation

The gas reflects diffusely from the tube surface, traveling in all directions at random. Its concentration will thus vary with Fick's laws of diffusion.

If an impulse of gas is admitted to an infinitely long beam tube, it will spread in accordance with: [4]

$$C = \frac{Q}{2(\pi DCt)^{1/2}} \times \frac{1}{LCM} \times e^{-x^2}/(4DCt)$$

where:

t = time, seconds, from the impulse
x = axial distance, cm, from the point where the gas is admitted
DC = diffusion coefficient, cm^2/sec (to be described below)
Q = quantity of gas admitted, torr-liters
LCM = tube volume, liters, per cm length = 11.6745 for 48" ID tube
C = torr

Diffusion Coefficient

The steady state diffusion of gas through a tube is matched to its molecular transmission (long tube formula), leading to:[5]

$$DC = \frac{dv}{3}$$

where:

DC = diffusion coefficient, $cm^2/second$
d = tube internal diameter, cm
v = average velocity of gas molecule, cm/sec
= 1.256 x 10^5 for helium at 25C

Flow Along Infinite Tube From Helium Pulse

A pulse of helium, 1×10^{-9} TL, is admitted to an infinitely long beam pipe. Its diffusion away from the admittance point is plotted on page A-1 for 100, 300, 1000, and 3000 seconds elapsed time. The maximum pressure is over 10^{-15} torr at 100 seconds, but drops into the 10^{-16} torr range for the longer times. Also at 100 seconds, the pressure profile is mostly confined to the space between ± 1 km. However by 3000 seconds, some of the gas has traveled 6 km.

Since the flow is molecular, the reflections from a tube end can be superimposed to find the pressure profile in finite tubes.[4]

Flow Along ± 1 km Tube From Helium Pulse

For this same pulse admitted to the midpoint of the 2 km beam tube, the pressure profile is plotted on page A-1. The 100 second profile is not much changed, but by 1000 seconds the profile is practically flat, i.e. the pressure is uniform throughout the tube.

For a distance, x, from the midpoint, the total pressure is the sum of the pressures from:

1. Direct flow (no reflections); distance = x.
2. One reflection from end 1, distance = 1 km + (1 km $-x$); = 2 x 10^5 cm $-x$.
3. One reflection from end 1 plus one from end 2, distance = 4 x 10^5 cm + x.
4. Two reflections from end 1 plus one from end 2, distance = 6 x 10^5 cm $-x$.

Further reflections will be negligibly small, as shown in the infinite tube plot.

Additional pressures come from:

5. One reflection from end 2, distance = 2 x 10^5 cm + x.
6. One reflection from end 2 plus one reflection from end 1, distance = 4 x 10^5 cm $-x$.
7. Two reflections from end 2 plus one reflection from end 1, distance = 6 x 10^5 cm + x.

The pressures are found for each of these seven distances and added to give the total pressure at the point x.

It has been assumed that this pulse spreads into a static volume, i.e. there are no vacuum pumps operating.

Pressure Transients

The leak detector is assumed to be at one end of the tube. The leak is placed at 250, 500, 1000, and 2000 meters from the end. Reflections from each end are added to find the total pressure at the end. The transients are shown on page A-2. The closest leak, 250 m, gives a quicker response and a larger signal. However, all the signals are in the 10^{-16} torr range.

In this plot, no vacuum pumps are operating.

The small magnitudes of these pressures suggest that concentration and accumulation procedures be used for leak detection.

Integrated Transients

A turbopump will collect gas at its inlet and compress it into the foreline. All gases except helium and neon are selectively pumped in the foreline. The helium pressure will build up in the foreline volume. The helium pressure transient at the turbo inlet is reduced in proportion to the quantity already pumped, as an initial correction for the pump speed.

The center figure on page A-2 shows accumulation with a small turbo, 100 L/S, and with a 3 liter foreline volume to allow space for the selective pump (cryopump or getter). The foreline pressure is raised to the 10^{-12} torr range. This is still too small for reliable detection. The compression ratio is a few times 10^4, about the limit for most turbos.

The bottom plot on page A-3 shows accumulation with a large turbo, 4000 L/S. It is backed by a second small turbo to provide adequate compression. The volume is reduced to 1 liter, since most of the non-helium gases are pumped in the space between the turbos. This plot shows pressures in the 10^{-10} torr range, a practical level for field operations.

The BASIC code listing for these calculations is given in pages A-4 through A- 6.

Leak Detector Equipment

Commercial leak detectors operate well in the range of 10^{-9} to 10^{-10} TL/S. Some are advertised for 10^{-11} and 10^{-12}. There is even one unit, built by Quantum Mechanics under license from Martin-Marietta, which claims a sensitivity of 10^{-15} (with a Balzers mass spectrometer).

Concentration is a well established procedure for leak detection. In the days when large chambers were pumped with diffusion pumps, it was conventional to provide a foreline fitting where the leak detector could be connected. The small partial pressures of helium in the chamber would be increased by several orders of magnitude in the foreline. The liquid nitrogen trap in the leak detector served as a selective gas pump.

Accumulation is also a well known procedure, but is seldom used. Most detectors provide a valve to close off the high vacuum pump, and allow the helium to accumulate at the mass spectrometer. Only two of the vendors are known to provide a getter pump for hydrogen, so that accumulation can continue for a reasonable time.

A conceptual leak detector schematic is shown on page A-3. The 5000 L/S turbo connecting to the beam pipe is the facility pump used for beam tube and chamber roughing. (There is also a Varian 9000 L/S pump available.) A small backing turbo is required to increase the compression ratio for helium. The mass spectrometer is on the foreline of the backing turbo, together with a getter. This volume is kept small, less than 1 liter, to increase the sensitivity. A clean-up turbo pumps out the accumulation volume on command. Most of the gas flow through the 5000 L/S turbo is collected by the cryopump (with no charcoal) and by hydrogen getters in the turbo foreline. Only helium and neon pass through to the backing turbo. The RGA/MS is a rugged unit suitable for field use, such as the Dycor. The entire leak detector will fit comfortably on a cart, so it can be moved easily.

The helium pressure transient at the inlet of the 5000 L/S turbo is shown at the top of page A-2, for various leak locations. With the valve to the cleanup turbo OPEN, the RGA/MS will see the same transient (except the pumpdown at 11 min/decade has been added), but at 100 times higher pressure (the ratio of the turbo speeds.). With this valve CLOSED, the helium will accumulate as shown at the bottom of page A-2.

It is likely that most leak testing will involve searching for leaks much larger than 10^{-9} T L/S. For these operations this valve is left OPEN to avoid saturating the system with helium.

Helium Background

When helium enters the beam tube through a leak, the helium pressure will, in time, rise to a level where the smallest leaks can no longer be detected. The helium must then be pumped away. The valve to the mobile cart is closed, that to the 600 CFM roughing pump is opened, and the beam tube is pumped from both ends. With a nominal effective speed of 8000 L/S from the two large turbos, the 2.3 x 10^6 liter volume is pumped down at a rate of 11 minutes/decade. At the same time, the valve to the cleanup turbo is opened, and the accumulated helium in the leak detector is pumped away.

These pumpdowns continue until the helium background level is reached. In the beam tube, the helium has permeated into the elastomer seals on the two 48" gate valve seats, one at each end, and into the two or four 20" valve seats at the turbopumps. (No O-ring can be exposed to atmosphere on one side and vacuum on the other, since permeation of atmospheric helium would create excessive background.) It also has permeated into the ceramic feedthroughs of the ion pumps and of any gages or mass spectrometers—but at a much lower rate than into the elastomers. As the helium pressure is reduced, the helium will come back out of the elastomers and ceramics, but very slowly, so that a sustained helium partial pressure is maintained in the beam tube. Leak detection can continue, as long as this background does not become so large that the small leaks cannot be observed.

Similar permeation takes place in the turbopump forelines, where helium has access to the oil in the bearings, and to the electrical insulation in the motor windings. This is likely to cause a higher background than the elastomers and ceramics.

It would be helpful in planning the leak test procedures and operations, to have quantitative guidelines on how much background is added by various pressure levels of helium and times of exposure. This information is not usually given to operators, but they develop a feel for the problem with experience. However, in this case, the helium partial pressure levels are smaller than usual, so that more care must be used to avoid helium saturation. It would seem reasonable to seek this information from the several manufacturers of turbopumped leak detectors. It would also be possible to investigate the rate of helium saturation of the 50 L/S turbopump on the VTF.

If severe helium saturation occurs, leak test operations are shut down for the day, while the equipment is baked out. This frequently happens during leak testing, but is unnecessary. It can be avoided by forethought and careful operation.

V. SUMMARY AND RECOMMENDATIONS

1. The total air leak into a 2 km beam tube is assumed to be 10^{-9} T L/S or less. This would assure reliable, leak-free operation of the LIGO over its 20 year life.
2. This total air leak can be directly measured using rate-of-rise techniques, a liquid nitrogen trap for water vapor, and a rugged mass spectrometer suitable for field use.
3. The travel time of the helium tracer gas from a leak to the detector is acceptably short. Even for a 1 kilometer separation, a measurable signal develops in 5 minutes.
4. The helium pressure from a 10^{-9} TL impulse is low, in the 10^{-16} torr range. Thus, as is frequently done in large chambers, the helium may be concentrated by pumping through turbo pumps.
5. A practical concentration procedure for the LIGO is to use two turbopumps in series. This provides sufficient compression ratio for the helium. It is necessary to selectively pump the water vapor, hydrogen, and air, so that they do not swamp the mass spectrometer.
6. An accumulation of helium in a 1 liter volume provides pressures in the 10^{-10} torr range in response to the 10^{-9} TL impulse (nominal small leak). This is well within the useable range of the rugged mass spectrometers, such as the Dycor, suitable for field use.
7. The high sensitivity of this leak detector concept can be useless if a high helium background is allowed to develop. Detailed and quantitative operating procedures will be helpful. Further work is needed to define the helium background to be expected as a function of helium exposure.

VI. REVIEWER'S COMMENTS

The reviewer's comments of 7/21/88 and 12/1/88 are attached.

VII. REFERENCES

1. Burrows, G, *Flow Through and Blockage of Capillary Leaks*, Trans. Instn. Chem. Engrs, **39**, pp. 55–63, 1961.
2. Weiss, R., *Vacuum Test Facility Plan*, Memo 62188, dated June 21, 1988.
3. Kay, E., *Impact Evaporation and Thin Film Growth in a Glow Discharge*, in Advances in Electronics and Electron Physics, **17**, p. 308, ed. L. Marton, Academic Press, 1962.
4. Crank, J., *The Mathematics of Diffusion*, 1956.
5. Hayashi, C., *Role of Adsorption in Production and Measurement of High Vacuum*, in Vacuum Symposium Transactions, pp. 13–26, 1957.

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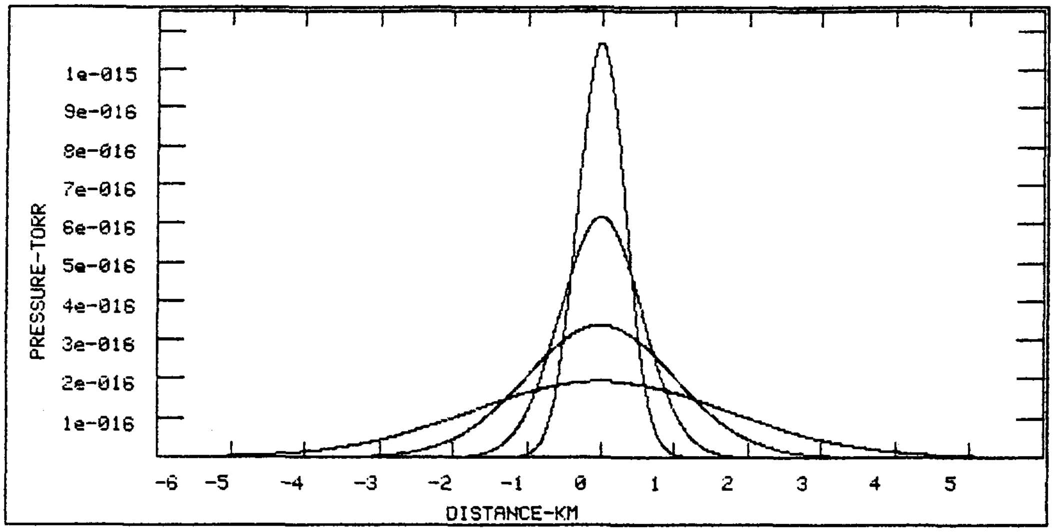
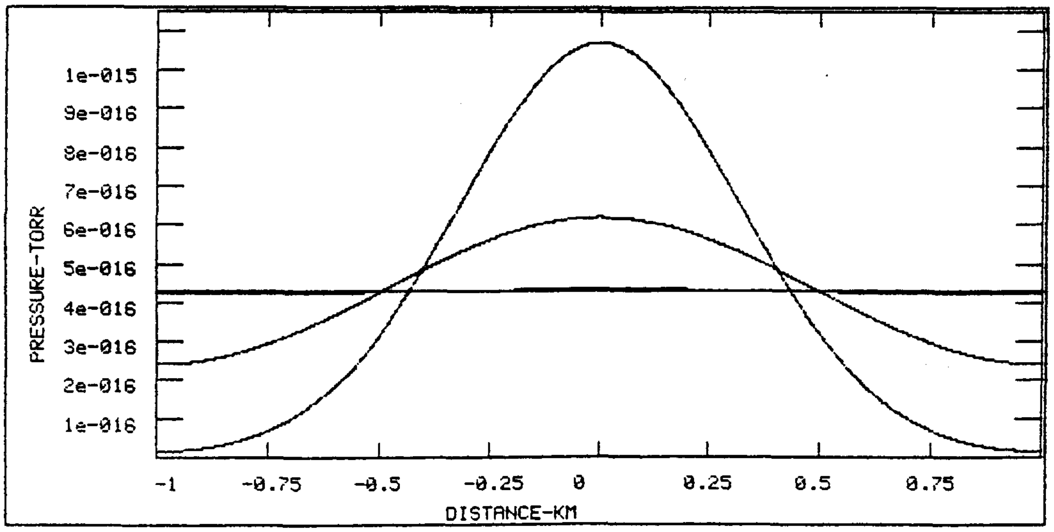
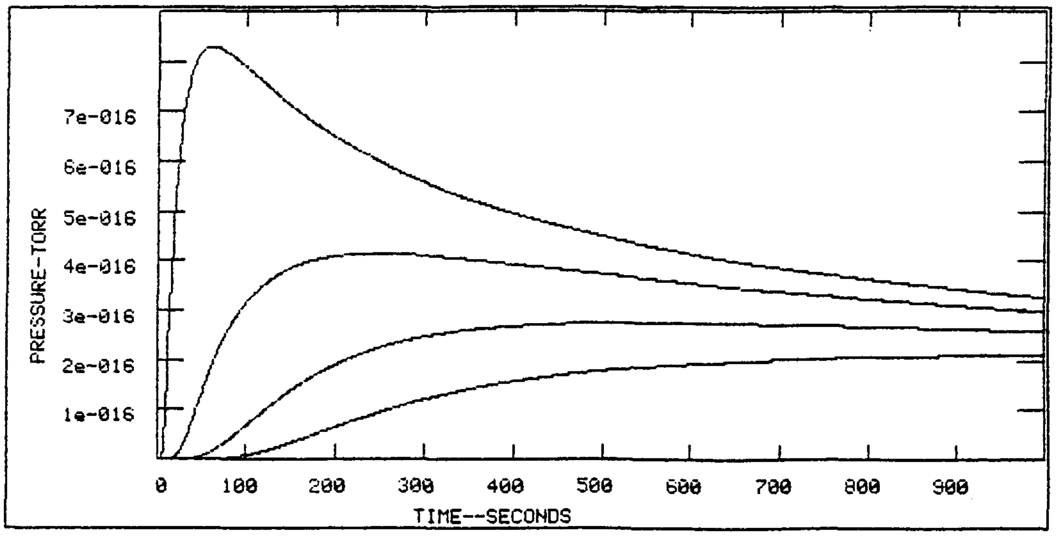
LIGO BEAM TUBE--HELIUM LEAK PULSE PATTERN        /GW/LIGO_LEAK_T_DIFF   88/04/21   09:44:42

TUBE DIAMETER, D, CM        1.21920E+02    HELIUM VELOCITY, U, CM/SEC    1.25600E+05    HELIUM PULSE, Q, TORR LITERS  1.00000E-09
DIFFUSION COEFF., DC, CM^2/S  5.10438E+06  TUBE VOL., LITERS/CM LENGTH   1.16745E+01
```

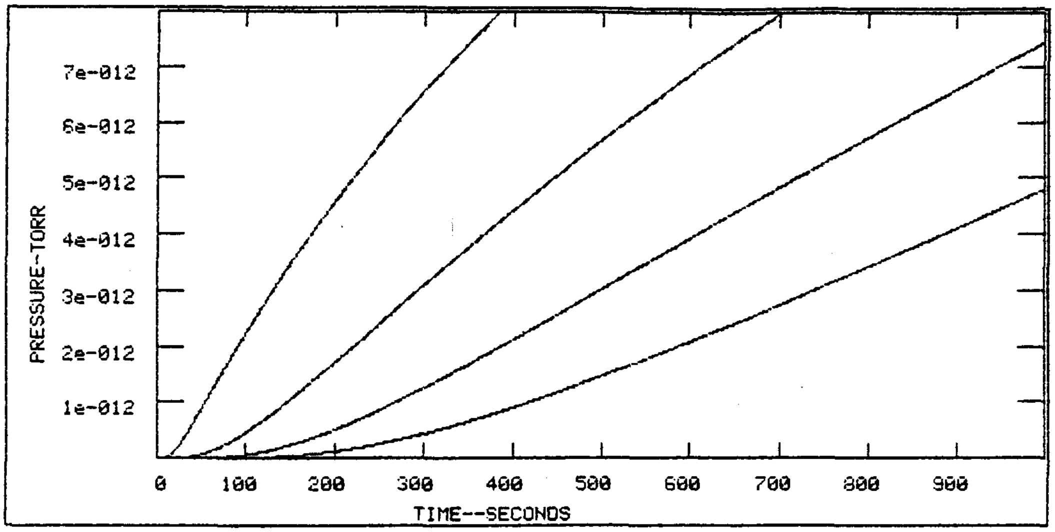

HELIUM IMPULSE OF 1E-9 TL INPUT TO INFINITELY LONG BEAM TUBE, 4 FEET ID
PRESSURE PROFILES AFTER 100, 300, 1000, AND 3000 SECONDS


HELIUM PULSE OF 1E-9 TL, INLET AT MIDPOINT OF 2 KM BEAM TUBE
PRESSURE PROFILES AT: 100, 300, 1000, AND 3000 SECONDS--INCLUDING REFLECTIONS FROM ENDS

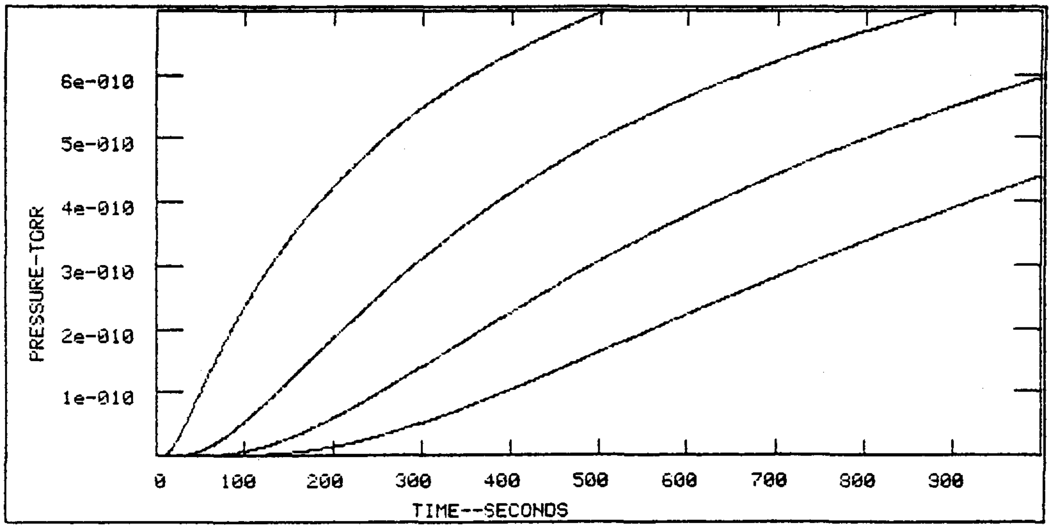
PRESSURE TRANSIENTS AT END, DUE TO IMPULSE INLET AT 250, 500, 1000, AND 2000 M FROM END
NO VACCUM PUMPS OPERATING



ACCUMULATION OF PRESSURE TRANSIENTS ABOVE. GAS IS COMPRESSED INTO A FIXED VOLUME BY A TURBOPUMP
TURBOPUMP SPEED= 100 L/S, AND ACCUMULATION VOLUME=3 L

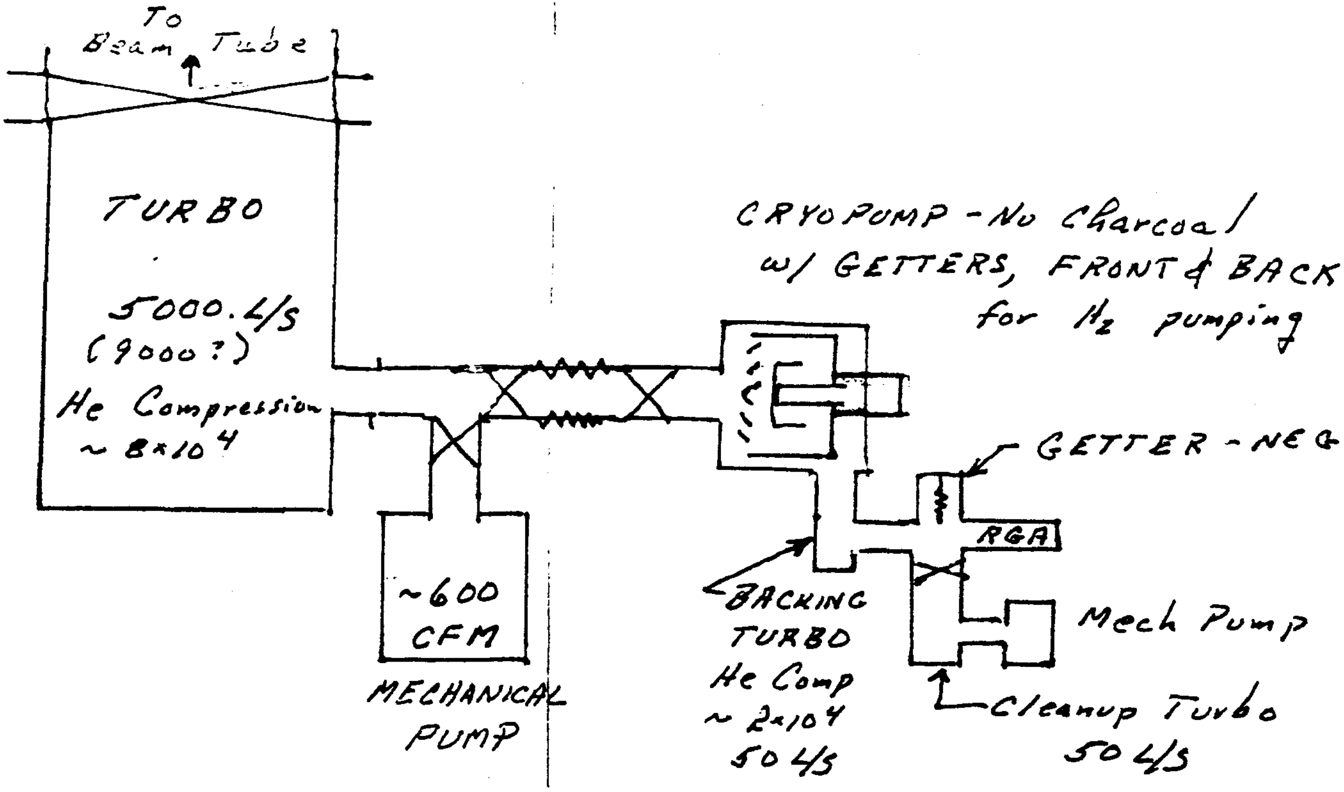


SAME ACCUMULATION WITH TURBO SPEED=4000 L/S AND 1 L ACCUMULATION VOLUME



FIXED INSTALLATION
@ EACH CHAMBER

MOBILE LEAK DETECTOR
2/LIGO FACILITY



1. All metal values, except 16" valve over 5000 l/s Turbo

2. < 1. Liter Accumulation Volume @ RGA

3. Options for Selective H_2 pump
   a) Ti on 40K surface of crya
   b) NEG getter
   c) Hot Palladium surface/turbo

4-12-88

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10 !GAS DIFFUSION FROM LEAK THROUGH LIGO BEAM TUBE
20 DIM F$[50]
30 F$="/GU/LIGO_LEAK_T_DIFF"
40 !PRINTER IS 2,142
50 !PRINT CHR$(27)&"&k2S" !COMPRESSED PRINT
60 !PRINT CHR$(14) !BOLD PRINT
70  OPTION BASE 1
80 DIM LT(4,1000),P(4,1000) !TOTAL LENGTH, KM & PRESSURE, TORR
90 DIM X$[30],Y$[30]
100 CRT IS 1,160
110 D=48*2.54 !TUBE DIA, ;CM
120 V=125600 !HELIUM AVERAGE VELOCITY, CM/SEC, DUSHMAN
130 Q=1e-010*10 !LEAK OF E-10 TL/S * 10 SEC
140 DC=D*V/3 !DIFFUSION COEFF.
150 LCM=PI*D^2/4/1000 !LITERS VOLUME/CM LENGTH OF PIPE
160 PRINT TAB(30);"LIGO BEAM TUBE--HELIUM LEAK PULSE PATTERN";"          ";F$;"   ";DATE$;"   ";TIME$
170 IMAGE 30A,D.5 De,5X,30A,D.5De,5X,30A,D.5 De
180 IMAGE 30A,D.5 De,5X,30A,D.5De
190  PRINT @ PRINT USING 170 ; "TUBE DIAMETER, D, CM";D,"HELIUM VELOCITY, V, CM/SEC";V,"HELIUM PULSE, Q, TORR LITERS";Q
200 PRINT USING 180 ; "DIFFUSION COEFF., DC, CM^2/S ";DC,"TUBE VOL., LITERS/CM LENGTH ";LCM @ PRINT
210 !*****
220 !DIFFUSION IN INFINITE PIPE
230 !*****
240  K=1 @ T=100
250 GOSUB 5000 !FIND PRESSURE PCROFILE AT GIVEN TIME
260  K=2 @ T=300
270 GOSUB 5000 ! FIND L & PLOT
280  K=3 @ T=1000
290 GOSUB 5000
300  K=4 @ T=3000
310 GOSUB 5000
320 PRINT @ PRINT @ PRINT @ PRINT
330 PRINT TAB(30);"HELIUM IMPULSE OF 1E-9 TL INPUT TO INFINITELY LONG BEAM TUBE, 4 FEET ID"
340 PRINT TAB(30);"PRESSURE PROFILES AFTER 100, 300, 1000, AND 3000 SECONDS"
350 GOSUB 2500 ! DRAW GRAPH
360 FOR K=1 TO 4
370 MOVE LT(K,1),P(K,1)
380 FOR J=2 TO 1000
390 DRAW LT(K,J),P(K,J)
400 NEXT J
410 MOVE -LT(K,1),P(K,1)
420 FOR J=2 TO 1000
430 DRAW -LT(K,J),P(K,J)
440 NEXT J
450 NEXT K
460 BEEP @ PAUSE
462 !*****
464 !DIFFUSION IN 2 KM TUBE
466 !*****
470 PRINT @ PRINT @ PRINT
480 PRINT TAB(30);"HELIUM PULSE OF 1E-9 TL, INLET AT MIDPOINT OF 2 KM BEAM TUBE"
490 PRINT TAB(30);"PRESSURE PROFILES AT: 100, 300, 1000, AND 3000 SECONDS--INCLUDING REFLECTIONS FROM ENDS"
500 X1=-1 @ X2=1 @ X4=0.25
510  K=1 @ T=100
520 GOSUB 6000 !FIND PRESSURE PCROFILE AT GIVEN TIME
530  K=2 @ T=300
540 GOSUB 6000 ! FIND L & PLOT
550  K=3 @ T=1000
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560 GOSUB 6000
570  K=4 @ T=3000
580 GOSUB 6000
590 GOSUB 2600 ! DRAW GRAPH
600 FOR K=1 TO 4
610 MOVE LT(K,1),P(K,1)
620 FOR J=2 TO 1000
630 DRAW LT(K,J),P(K,J)
640 NEXT J
650 MOVE -LT(K,1),P(K,1)
660 FOR J=2 TO 1000
670 DRAW -LT(K,J),P(K,J)
680 NEXT J
690 NEXT K
700 BEEP @ PAUSE
710 PRINT CHR$(12)
712 !*****
714 !PRESSURE TRANSIENT AT DETECTOR
716 !*****
720 FOR K=1 TO 4 !4 POSITIONS, 250, 500, 1000, & 2000 M AWAY FROM END
730 X=250*100*K !DISTANCE IN CM
740 GOSUB 7000 !FIND PRESSURE VS TIME FOR GIVEN X
750 NEXT K
760 X1=0 @ X2=1000 @ X4=100 @ N1=2 @ X$="TIME--SECONDS" !SETUP GRAPH
770 Y2=9e-016 @ Y4=1e-016 @ N2=3
780 PRINT TAB(30);"PRESSURE TRANSIENTS AT END, DUE TO IMPULSE INLET AT 250, 500, 1000, AND 2000 M FROM END"
790 PRINT TAB(30);"NO VACCUM PUMPS OPERATING"
800 GOSUB 2600 !DRAW GRAPH
810 FOR K=1 TO 4
820 MOVE 0,0
830 FOR J=1 TO 1000
840 DRAW J,P(K,J)
850 NEXT J
860 NEXT K
870 BEEP @ PAUSE
872 !*****
874 !INTEGRATED PRESSURE--SMALL TURBO
876 !*****
880 PRINT TAB(30);"ACCUMULATION OF PRESSURE TRANSIENTS ABOVE.  GAS IS COMPRESSED INTO A FIXED VOLUME BY A TURBOPUMP"
890 PRINT TAB(30);"TURBOPUMP SPEED= 100 L/S, AND ACCUMULATION VOLUME=3 L"
900 Y2=8e-012 @ Y4=1e-012 @ N2=3
910 GOSUB 2600
920 SP=100 !PUMP SPEED, L/S
930 VOL=3 !ACCUMULATION VOLUME, L
940 GOSUB 1040 !PLOT INTEGRATED PRESSURE
950 BEEP @ PAUSE
952 !*****
954 !INTEGRATED PRESSURE--LARGE TURBO
956 !*****
960 PRINT TAB(30);"SAME ACCUMULATION WITH TURBO SPEED=4000 L/S AND 1 L ACCUMULATION VOLUME"
970 Y2=7e-010 @ Y4=1e-010 @ N2=3
980 GOSUB 2600
990 SP=4000 !PUMP SPEED, L/S
1000 VOL=1 !ACCUMULATION VOLUME, L
1010 GOSUB 1040 !PLOT INTEGRATED PRESSURE
1020 BEEP @ PAUSE
1022 !*****
1024 !END
1026 !*****
1030 END
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1032 !*****
1034 !SUBROUTINE TO PLOT INTEGRATED PRESSUR
1040 FOR J=1 TO 4 !PLOT PRESSURE TRANSIENTS
1050 MOVE 0,0
1060 PMS=0 !PRESSURE AT MASS SPEC
1070 FOR K=1 TO 1000
1080 PMS=PMS+P(J,K)*SP/VOL*(Q-PMS*VOL)/Q !SP=PUMP SPEED
1090 !PUMP THRUPUT=ITS INLET PRESSURE, P(J,K)  X PUMP SPEED, SP.  THIS GAS QUANTITY IS COMPRESSED INTO THE ACCUMULATION VOLUME, VOL
1100 !THE INLET PRESSURE IS REDUCED BY THE QUANTITY ALREADY PUMPED, AS A FRACTION OF THE INLET QUANTITY, Q
1110 DRAW K,PMS
1120 NEXT K
1130 NEXT J
1140 RETURN

4990 !*****
4992 !SUBROUTINE TO FIND PRESSURE GIVEN X--INFINITE PIPE
4994 !*****
5000 FOR J=1 TO 1000 !START SUBROUTINE--PRESSURE PROFILE, NO REFLECTIONS
5010 X=J*600 !X DISTANCE DOWN PIPE, 6  METER STEPS
5012 LT(K,J)=X/100000 !CONVERT CM TO KM & SAVE
5020 P=Q/LCM/2/(PI*DC*T)^0.5*EXP((-X^2)/(4*DC*T))
5022 P(K,J)=P
5030 NEXT J
5060 RETURN
5990 !*****
5992 !SUBROUTINE TO FIND PRESSURE GIVEN X--2 KM PIPE, CENTER LEAK INLET
5994 !*****
6000 FOR J=1 TO 1000 !START SUBROUTINE--PRESSURE PROFILE, ENDS @ +- 1 KM, REFLECTING
6010 X=J*100 !  DISTANCE DOWN PIPE, 1  METER STEPS
6012 LT(K,J)=X/100000 !CONVERT CM TO KM & SAVE
6013 DT=4*DC*T !COEFFICIENT FOR EXPONENTIALS BELOW
6014 EA=EXP((-X^2)/DT) !FIRST PASS, NO BOUNCE
6015 EB=EXP((-(200000-X)^2)/DT) !SECOND PASS, BOUNCE OFF 1 KM WALL
6016 EC=EXP((-(400000+X)^2)/DT) !THIRD  PASS, BOUNCE OFF 1 KM WALL, THEN OPPOSITE WALL
6017 ED=EXP((-(600000-X)^2)/DT) !FOURTH PASS, BOUNCE OFF 1 KM WALL, THEN OPPOSITE WALL, THEN OFF FIRST WALL AGAIN
6018 EE=EXP((-(200000+X)^2)/DT) !OPPOSITE END, BOUNCE OFF 1 KM WALL
6019 EF=EXP((-(400000-X)^2)/DT) !OPPOSITE, TWO BOUNCES
6020 EG=EXP((-(600000+X)^2)/DT) !OPPOSITE, THREE BOUNCES
6021 P=Q/LCM/2/(PI*DC*T)^0.5*(EA+EB+EC+ED+EE+EF+EG)
6022 P(K,J)=P
6030 NEXT J
6060 RETURN
6990 !*****
6992 !SUBROUTINE TO FIND PRESSURE GIVEN X--2 KM PIPE, VARIOUS LEAK LOCATIONS
6994 !*****
7000 FOR J=1 TO 1000 !START SUBROUTINE--TIME PROFILE, 1 SECOND/STEP
7010 T=J !TIME IN SECONDS
7013 DT=4*DC*J !COEFFICIENT FOR EXPONENTIALS BELOW
7014 EA=EXP((-X^2)/DT) !FIRST PASS, NO BOUNCE
7015 EB=EXP((-(400000+X)^2)/DT) !SECOND PASS, DOWN PIPE & BACK. DETECTOR @ END
7016 EC=EXP((-(800000+X)^2)/DT) !THIRD PASS, TWO TRIPS DOWN TUBE & BACK
7017 ED=EXP((-(400000-X)^2)/DT) !OPPOSITE WAY, DOWN TUBE & BACK
7018 EE=EXP((-(800000-X)^2)/DT) !OPPOSITE WAY, TWO TRIPS DOWN TUBE & BACK
7021 P=Q/LCM/2/(PI*DC*T)^0.5*(EA+EB+EC+ED+EE)
7022 P(K,J)=P
7030 NEXT J
7060 RETURN
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