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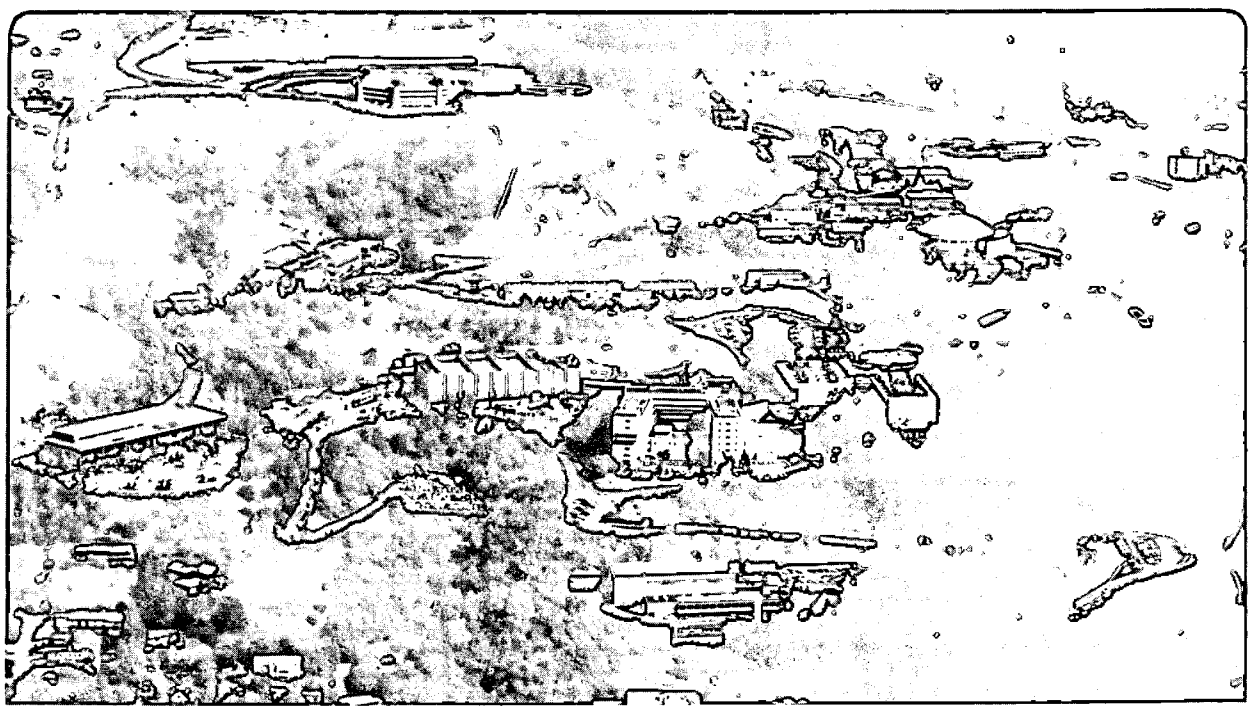

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ENGINEERING NOTE

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PROGRAM — PROJECT — JOB
NBSTF - TFTR
CRYOGENICS
TITLE
CRYOPUMP OPERATIONS

OPERATION OF THE NBSTF CRYOPUMP

R. Byrns/G. Newell

I. PROLOGUE

In January, 1977 the Lawrence Livermore and Berkeley Laboratories (LLNL/LBL) were commissioned to develop the prototype neutral beam line for the Princeton Plasma Physics Lab (PPPL) Tokamak Fusion Test Reactor (TFTR). Construction and installation proceeded during 1978-79 at Berkeley and cryosystem first cooldown was in July, 1979.

II. NEUTRAL BEAM SOURCE TEST FACILITY (NBSTF)

Design and construction have been described in earlier papers [1-6] and internal LLNL and LBL Engineering notes listed in the Appendix (including some operational notes). The beam line arrangement is shown in Figure 1. Three ion sources will be installed on each injector vessel at Princeton. The present source is rated at 120kV, 65A and 0.5 sec pulse length with 75% D^+ (20 MW for 3 sources).

Starting from the right side of Figure 1 a brief description of the process follows. For the three sources, the total deuterium gas flow is 100 Torr liter per second. In the source, electrons are stripped and the D^+ is accelerated to 120kV. The energetic beam travels through the dense gas ($\sim$ 300 mTorr-cm) gradient created by the D_2 source gas in the neutralizer and through charge exchange becomes neutral, D^o. The magnet permits the D^o neutrals to pass through and deflects the D^+ remaining ions into the ion dump. The beam then passes through the photo diode into the calorimeter, both used for beam measurements and tuning. With the calorimeter retracted, the beam can then pass through the duct, which models the entry into the tokamak through the magnetic field of the torus. With a

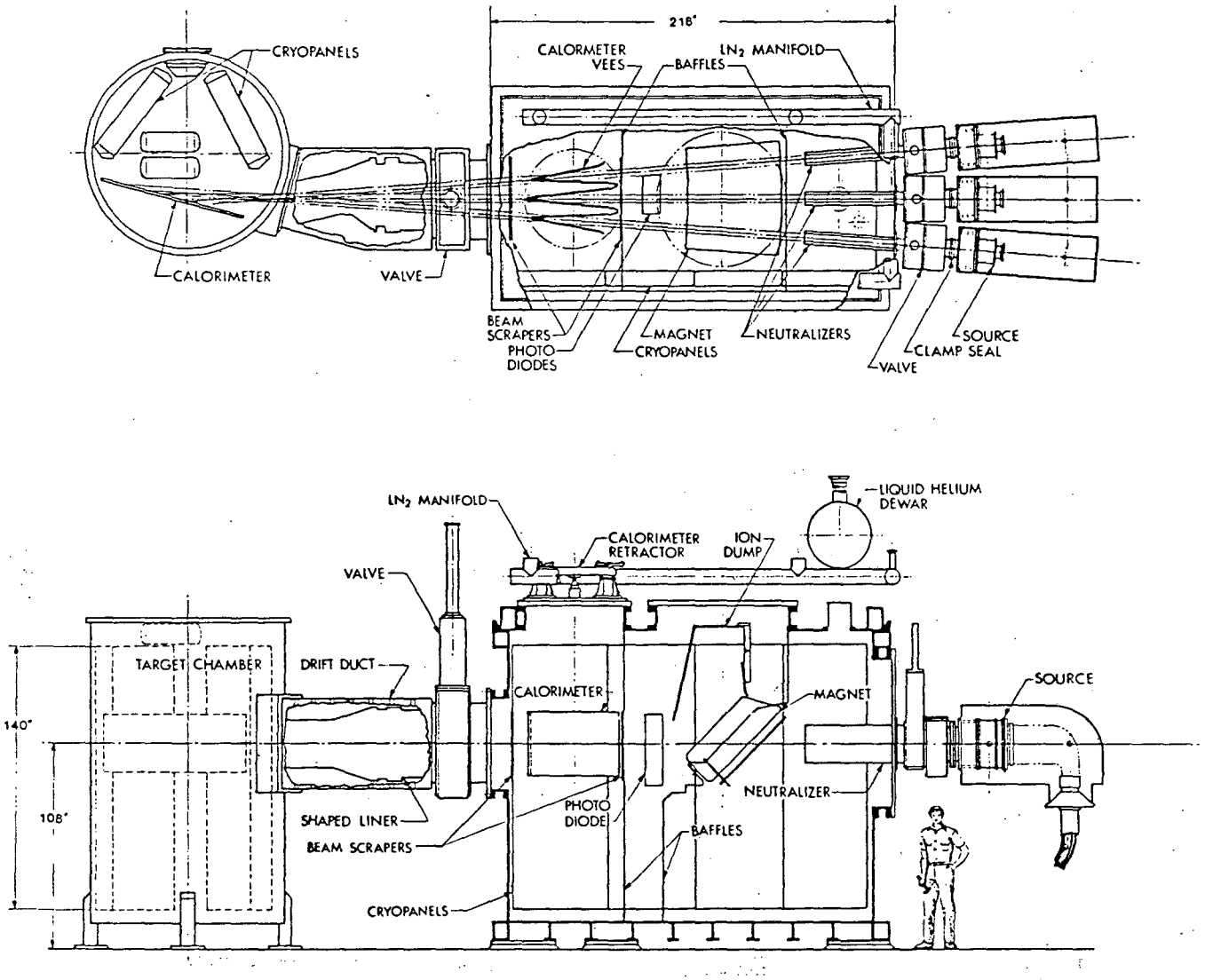

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Fig. 1. Neutral beam injector with target tank.

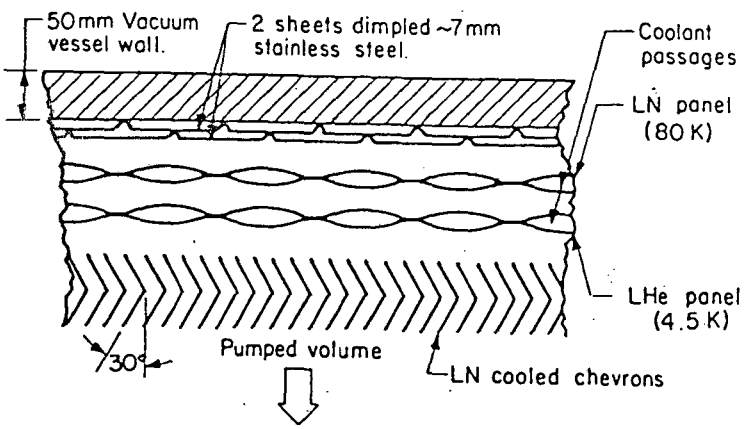

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Fig. 2. Cryopanel assembly section.

TABLE I NBSTF Cryopump System Equipment List

1. Injector Vacuum Vessel, 18 ft. long x 13 ft. high x 10 ft. wide, Type 316 stainless steel. Gas volume (less enclosed apparatus) 50,000 liters. Vessel weight, 66,000 lbs. Lid weight, 38,000 lbs.

2. Mechanical Vacuum Pumps.

   a) One Stokes Model 1722 two-stage consisting of a 1300 CFM rotary dry lobe high vacuum booster and a Model 412 300 CFM oil-sealed rotary pump.

   b) One Stokes Model 412 300 CFM oil-sealed rotary pump.

   c) One Leybold-Heraeus turbomolecular pump. 3500 ℓ/sec (air) backed by a Leybold 26 ℓ/sec rotary oil-sealed pump.

3. Eight cryopanels, each module 48" (1.2m) x 144" (3.6m); total effective active pump area 30 m^2, design pump speed on $D_2 \sim 2.5 \times 10^6$ ℓ/sec at 4.5°K.
   Mass of one LHe quilt ∿ 200 lbs , 8 ≃ 1600 lbs.
   Volume of one LHe quilt ∿ 15 liters, 8 ≃ 120 liters LHe.
   Weight of one module ∿ 1300 lbs. , 200 lbs each quilt, (2), 900 lbs frame & chevron.

Heat Load to Panels	LBL (8 meas.)	PPPL (1 and 8 meas.)[8]	LLNL Design[1]
One panel LHe	3.8 ℓ/hr	4 ℓ/hr	
Eight panels	30 ℓ/hr	32 ℓ/hr	
	21 W	23 W	45 W
One panel LN_2		11 ℓ/hr	
Eight panels	75 ℓ/hr	80 ℓ/hr (est.)	104 ℓ/hr (4700 W)

   Mass to be cooled to LN_2-temp. ≃ 5900 Kg, includes 1070 Kg to LHe and requires minimum of 3500 ℓ LN_2; 210 ℓ LHe. (1)

4. One 750 ℓ LHe dewar, with LN shield, forty layers of superinsulation to 80K, ten to 4.5K, vacuum insulated. One internal diverter valve.

5. One LN dewar 12m long of 20 cm dia tube, (∿380ℓ), vacuum insulated.

6. One Sullair oil lubricated helical screw compressor, displacement, 880 CFM delivery 700 CFM (55 gm/sec), 18 atm discharge, 3600 RPM, 300 kW, 2 pole induction motor.

7. One coldbox CCI (Cryogenic Consultants, Inc.) 400W at 4.5K with one dry (20K) expander engine and one wet (6K) engine. 250W with only the dry engine.

8. External LHe distribution system,[8] 72m of separate supply and return 2.5 cm dia. vacuum insulated transfer line with 40 layers of superinsulation (18 W), 20 bayonet connections (25 W) and 4 broken stem valves (3 W) for flow control to the NBI and target tank. A 9 kW heater tied to GHe storage provides for warm-up/cooldown transients.

pure neutral, D^0 beam, linear passage through the magnetic toroidal field and entry into the plasma is possible. Any ions, D^+, would only be deflected. At LBL the beam terminates on a water-cooled beam dump in the target tank. The neutral deuterium beam provides fuel and heating for the fusion reaction plasma.

The extremely high gas flow required for optimum ion source performance, coupled with the proper neutralizer gradient and the very low gas density (high vacuum) downstream to prevent beam loss present a unique design challenge. This can be solved with cryopumping and conductance baffling.

III. AUXILIARY VACUUM SYSTEM

The injector vessel is a rectangular box of austenitic stainless steel (304 and 316) 18 ft long x 13 ft high and 10 ft wide. Gas volume, allowing for the equipment inside, is 50,000 liters.

Two mechanical pumps are used to rough-pump the vessel. One is a Stokes Model 1722 two-stage unit consisting of a rotary oil-sealed 300-cfm Model 412 vacuum pump backing a 1300-cfm rotary lobe dry high-vacuum booster. The second vacuum pump is also a Stokes Model 412 300-cfm vacuum pump. The roughing line has a refrigerated copper wool trap to prevent oil migration from the mechanical pump. From atmospheric pressure the injector vessel can be rough-pumped to 100 mTorr within an hour, at which time the turbo pump is valved in, taking the vessel to its uncryopumped base pressure in the high 10^{-7} Torr region.

The cryopanels in both the injector and the target tank have been augmented by Leybold-Heraeus turbomolecular pumps, 3500 liter/second (air) each backed by a Leybold-Heraeus 26 ℓ/s oil-sealed rotary piston pump. The turbo pumps are compact and easily operated. They provide clean vacuum, handle large gas loads at desired base pressures and have been reliable with minimal maintenance.

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To minimize pump-down the vessel may be returned to atmospheric pressure by first or partially letting up to dry nitrogen gas, followed by filtered air. For people access to the vessel safeguards are taken to provide full ventilation and insure oxygen content is kept above minimum levels.

In order to give a minimum or lowest possible pressure at the duct entry to the tokamak, the vessel is divided into three chambers by the baffles as seen in Figure 1. This provides a staged or cascade pumping system between the high gas flow from the source end and the desired low pressure at the duct by conductance limiting each chamber.

IV. CRYOSYSTEM DESCRIPTION

Eight modular cryopanels, each module approximately 48"w x 120"h x 10"t line both sides of the injector vessel, four panels to a side. In addition, two cryopanel modules are installed in the target tank. Panel construction, see Figure 2, consists of a quilted stainless-steel assembly holding LN_2 facing the vessel outer wall, another quilt holding LHe and an LN-cooled copper chevron assembly with ~ 27% transmission facing the vessel centerline. The quilts are fabricated from .060" sheet stainless steel, with spot welds on approximately 4" centers, sealed by edge welding and hydroformed at 400 psi.

Both LN and LHe cryopanels are fully instrumented with Cu-Co thermocouples for the 300 - 80K range, and with top, mid and lower level carbon glass resistors (CGR) for each He panel. Temperature on all panels is read on the graphic display in the Control Room.

Black hole speed for air is 75 ℓ/sec in^2 = 11.5 ℓ/sec cm^2. Speed for deuterium is then:

$$S_{D_2} = 11.5 \sqrt{\frac{28.4}{4}} \cdot \sqrt{\frac{300°}{300°}} = 30.6 \text{ ℓ/sec cm}^2 \text{ at ambient}$$

Chevron transmission of ~27% and ambient temperature gas gives S_{D_2} = 8.3 ℓ/sec cm^2 (9 ℓ/sec cm^2 measured at LLNL)[6]. The 30m^2 of pump area thus can provide an installed capacity of 2.5 x 10^6 ℓ/sec pump speed for deuterium.

A LHe dewar, 750 ℓ capacity, is located on the vessel lid and feeds the cryopanels by gravity. The dewar has a coaxial bayonet on both top and bottom. The top connection is for supply and return LHe from the coldbox and the lower bayonet is for LHe circulation to the panels. The dewar is vacuum insulated with an LN shield, 40 layers of superinsulation to 80K, 10 layers to 4.5K. The dewar contains a 30 micron bronze filter acting as a phase separator on the coldbox supply line at the top. The other three dewar connections are combined in the diverter valve.

The diverter valve, Figure 3, is a single package removable from the dewar as a unit. It is capable of remote operation by electric motors from the control room console. The valve combines four valve functions and includes a phase separator for return flow from the panels. The diverter valve has three modes: cooldown from 300K where cold helium gas flow is forced through the cryopanel bottom; circulation, where phase separation occurs in the 750 ℓ dewar and the cryopanels are gravity fed; regeneration where the panels are emptied of LHe, warmed by gas conduction in the vessel, the administrative limit of 12 Torr ℓ/ℓ (in the 50,000 ℓ volume = 600,000 Torr-ℓ) deuterium is sublimed and pumped out and LHe is then tranferred back to the panels for rapid cooldown.

The external LHe distribution system consists of 72m of vacuum insulated (plus 40 layers of superinsulation) LHe transfer lines. The separate supply and return lines extend from the coldbox to the distribution box which contains valves for flow control to the 750 ℓ LHe dewar and the target tank cryopanels. A 9 kW heater tied to the GHe storage system is included for warmup/cooldown transients.

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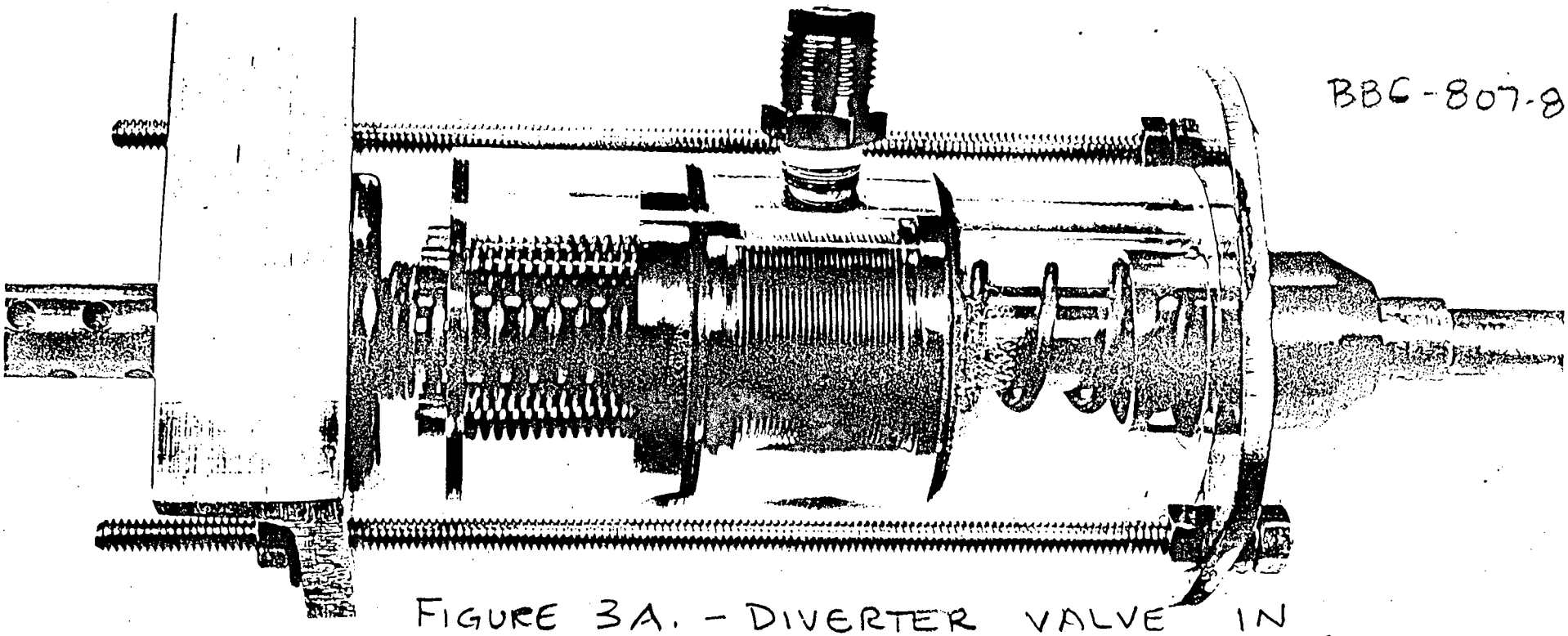

FIGURE 3A. - DIVERTER VALVE IN LUCITE TEST HOUSING - (V-1, V-2, V-3)

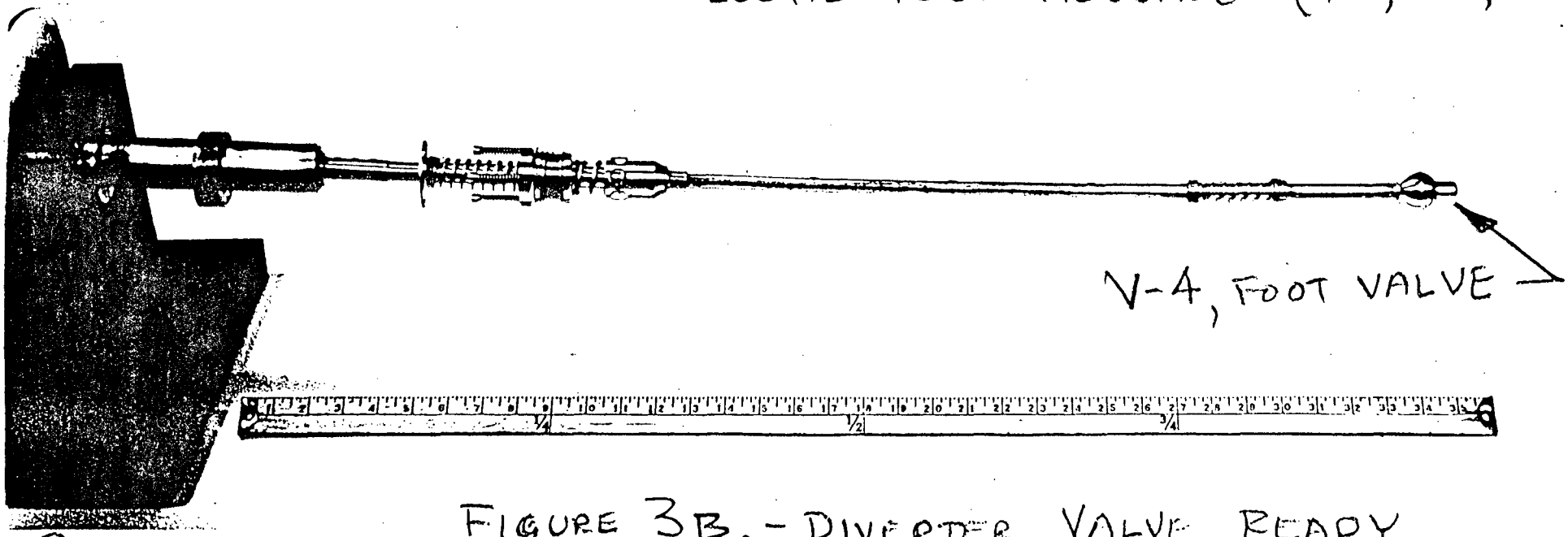

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FIGURE 3B. - DIVERTER VALVE READY TO INSERT IN LHe DEWAR

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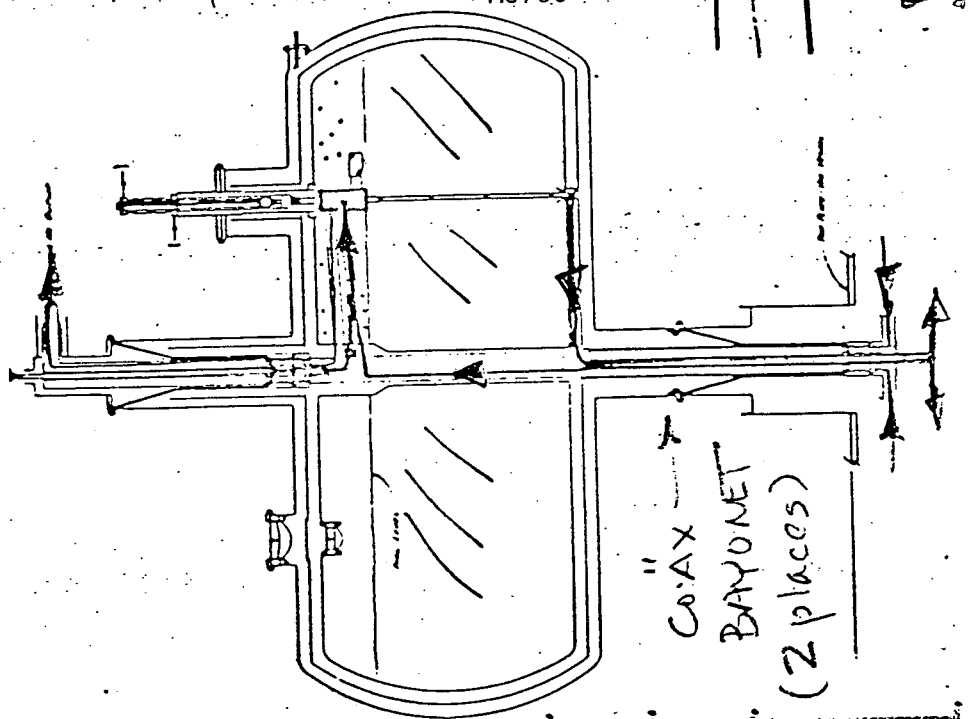

FIG 3C - DIVERTER VALVE IN LHe Dewar

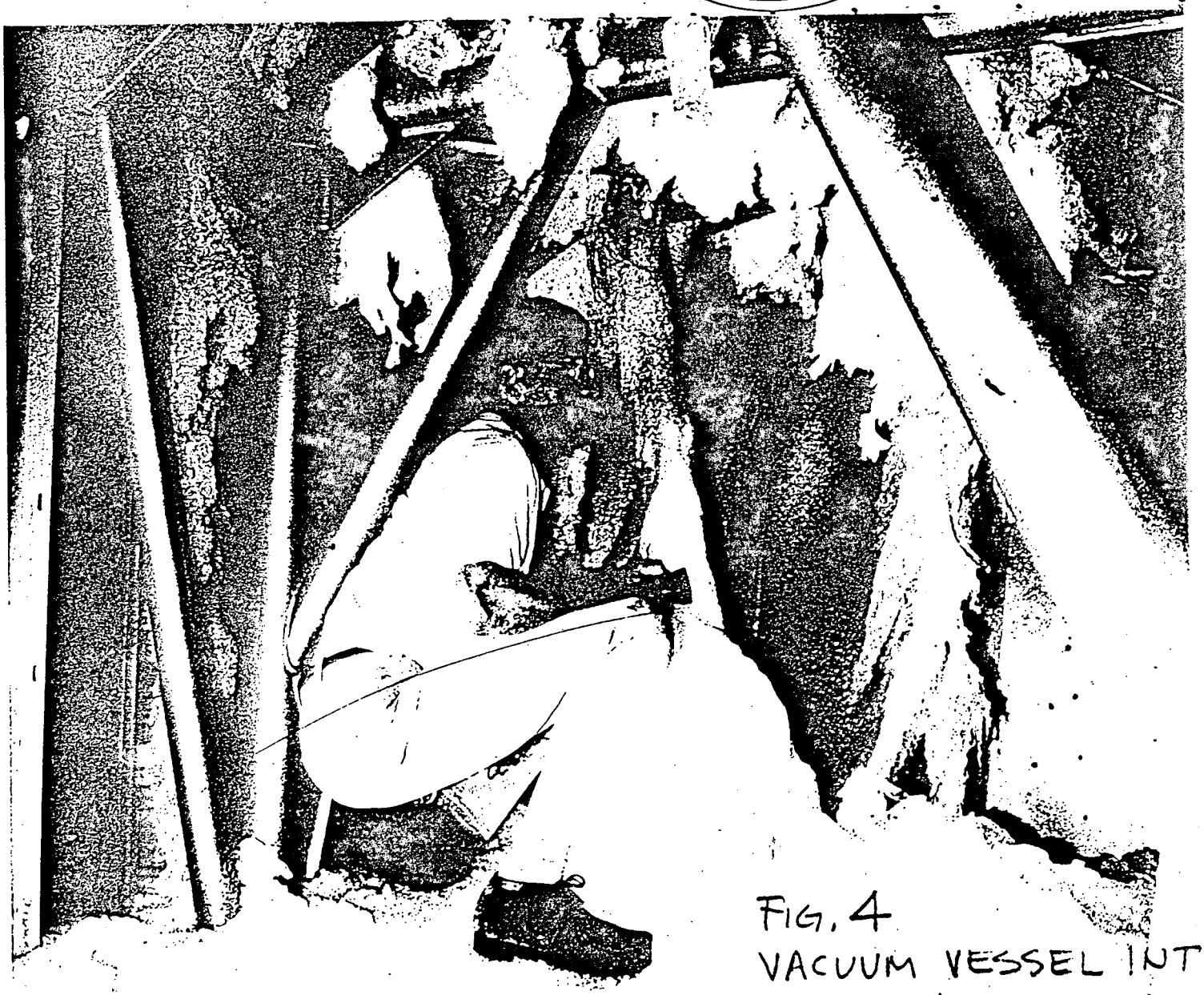

FIG. 4
VACUUM VESSEL INTERIOR AFTER WATER LINE BURS

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The LN manifold, approximately 12m of 20 cm dia. pipe, is essentially a long low profile dewar, feeding and venting each module individually. The external LN system is supplied from a 4,000 gallon supply dewar and distributes to the injector vessel, target tank and coldbox via vacuum-insulated transfer lines.

The 400 W CCI helium refrigerator is equipped with a large full flow charcoal adsorber (∿ 80 lbs.), a warm (20K) expander engine and a wet expander (6K). The oil lubed screw compressor (55 gm/sec or 700 SCFM, 18 atm, 300 kW) contains a full oil removal system and slide valve. The slide valve and discharge pressure control permit an infinite number of pressure and mass flow combinations, minimizing power draw for varied operating modes. The gas management system has medium pressure (16 atm) GHe storage equal to about 300 ℓ LHe. A recently developed simple automatic control system allows long periods of unattended operation.[9]

V. CRYOSYSTEM OPERATIONS

Prior to cooldown the injector vessel has had insulating vacuum established. Normally with a reasonably clean vessel and minimal water vapor the pressure comes down to 100 mTorr within one hour; a few more hours on the turbopump bring it into the 10^{-6} range. The helium circuit has been pumped to less than 100 mTorr and purged with GHe, a minimum of three times $(10^{-3}\ \text{atm})^3$ leaving parts per billion impurities in the He circuit. All water circuits within the vessel have been prepared and interlocked for full flow or else blown dry. Should water flow stop after cooldown, frozen and burst tubing may occur, dumping large amounts of water into the vessel on warmup or during operation. (Figure 4) Ideally the LN circuit should be purged dry and filled with GN_2 prior to coldown.

A. Cooldown

Cooldown starts with LN_2 flow into the manifold, the LHe dewar

shroud and the injector tank guard lines. From the manifold it gradually works down the fill line to the bottom of each module. As soon as the fill line is cold with liquid at the bottom, LN cooling proceeds rapidly and flow stability occurs very soon. The cryopanel modules are supported from the vessel lid by prestressed short diagonal tension struts. Because of the supports and the possibility of excess stress due to shrinkage differential in the module frame, the cooling rate from 300K to 80K has a maximum rate set at 50C/hr. In practice the rate is much more conservative than this, closer to 30C/hr maximum, so the time to 80K is 8 to 10 hours. Cooling rate is closely monitored by thermocouples and carbon glass resistors (CGRs). During the first cooldowns strain gages mounted on the struts were also closely watched, but after safe rates were established, the strain gages are no longer used.

The LHe quilt starts cooling by radiation very soon after the LN circuits are filling. Because of its low mass (200 lbs) the LHe quilt can approach ∿ 200K after 40 hours of LN cooling. Therefore, it is desirable to have it full of GHe backed by a regulated supply. The diverter valve must be in the "cooldown" position to start the GHe cooldown. This forces cold GHe from the coldbox through the LHe dewar (and its inlet phase separator) out through the bottom foot-valve, down through the LHe cryopanel bottom, up the panel and out through the diverter valve and return to the coldbox. (Figure 5)

In some part of the circuit, a valve is needed to return or bypass hot gas back to compressor suction, as the gas initially leaving the panel is rather hot, say 300K. At LBL we have two options for our "overboard" circuit: one is the bypass cooldown valve (B.C. valve) at the top of cryopanel 4L and 4R and the other is in the coldbox return line at Bayonet 11 before entering the coldbox. Both of these valves return GHe to compresso

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reached 50K the "overboard" - either Bayo 11 or B.C. valves are closed, shunting all return flow through the coldbox. Within another hour or so LHe starts forming in the panels and dewar. Each panel holds 15 ℓ so all eight hold ∿ 120 liters. When the panels are full and LHe starts coming up on the LHe dewar level gage, the diverter valve is switched to the "circulating' mode. Supply flow (50% LHe) into the dewar phase separates, LHe goes to the dewar, GHe to return, and LHe feeds the panels via gravity through the foot valve. GHe from the panels returns through the diverter valve to dewar ullage and exits to the coldbox.

Required time (including coldbox cooldown) 300K to 80K, is 8 - 10 hours; 80K to 4.5K has been 10 - 12 hours. Faster time is possible to 4.5K if the dewar is full initially, as in the "REGEN" mode. Cryogen amounts required for cooldown have not been measured (but can be calculated).[1] We normally make enough LHe for 10-30% dewar fill, as this amount is within our GHe storage capacity (∿ 300 ℓ).

B. Warmup

Warmup is essentially the reverse of the cooldown process. The diverter valve is put into the "cooldown" position and the "overboard" B.C. valves 4L and 4R are cracked open. Then small amounts of warm GHe can be brought into the dewar from the distribution box valving after first permitting normal boil-off for a short time. Within a few (3 - 5) hours all the GHe can be recovered from both the LHe dewar and the cryopanels, as well as the coldbox. The only way to warm the LN panels is to cut off the supply as soon as possible and permit normal boil-off. The LN panels are not arranged for easy forced warm-up. One possible improvement would be to add electrical heaters to the LN modules. The standard method is to let the vessel up to ∿ 500 mTorr of GN_2, after the panel temperatures are above ∿ 50K. Then within 24 - 36 hours the system is close to ambient and ready to let up to air for work access.

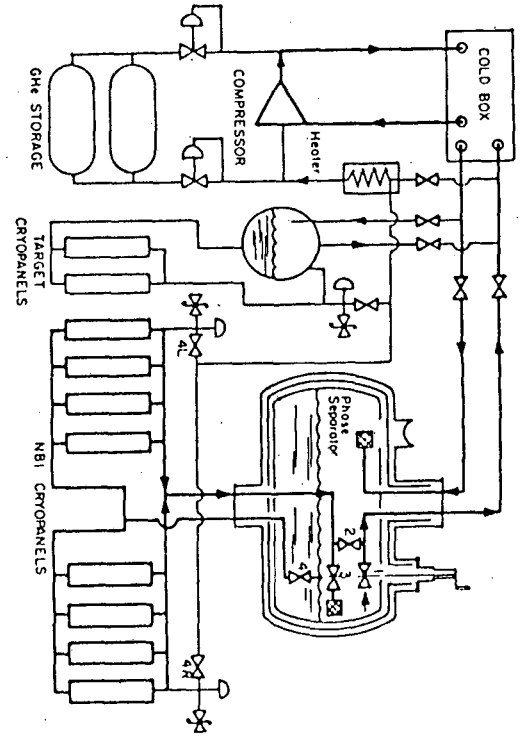

Fig. 5 Helium system schematic. For cooldown V-1 is closed, V-2 is open, V-3 acts as 4 psi relief. For circulate V-1 is open, V-2 as 4 psi relief, V-3 is open. For regenerate V-1 is open, V-2 as a 10 psi relief, V-3 closed, and V-4 closed acts as a 5 psi relief.

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C. Steady State

The steady state operation is maintained with the diverter valve in the "circulate" mode. The level in the LHe dewar is established 10 - 30% by cutting off makeup GHe at the proper time and balancing the refrigerator. This balance is achieved by mass flow and capacity manual adjustments, dropping output from liquefaction into the refrigeration range of the automatic controller.[9] The control holds the suction pressure within a narrow (± 1%) range and hence the temperature on the cryopanels.

There have been no noticeable effects on the reefer system by any variations in heat load due to beam pulse/non-pulse or D_2/H_2. There have been indications the base pressure of the vessel is directly related to compressor suction pressure. For pressure between 1 and 3 psig, temperature varies between 4.2 - 4.4K. (Bldg. 6, LBL is at 750 ft. elevation, 1 atm = 14.3 psi) Adding another 1 psi or so for pressure drop through the heat exchanger boosts temperature to 4.3 - 4.5K. Vessel base pressure is in the low 10^{-8} Torr region. For D_2 operation, pressure at the duct is in the mid 10^{-7} range.[7] For regeneration tests the panels were loaded with up to 4000 Torr-ℓ H_2 and pressures held in the mid 10^{-6}, low 10^{-5} Torr region.[10] D_2 was loaded 10 pulses of 30 Torr-ℓ/s at 100 sec each and pressures held in the mid 10^{-6} Torr in the duct area, up to 2×10^{-5} Torr in the neutralizer area.

The cryosystem heat loads were roughly measured on the first cooldown 7/79.[11] The best and most recent measurements at LBL (3/81) are 30.3 ℓ/hr (21 watts) LHe by a 5-hour level decay in the LHe dewar (3.8 ℓ/hr per panel) with no source operations. Manifold LN losses were measured (three times) by level decay at 75 ℓ/hr ± 4%. Independent measurements of boiloff gas by Garzotto[8] at PPPL for a single panel (3/81) were 4 ℓ/hr LHe and 11 ℓ/hr LN_2 and 32 ℓ/hr LHe for 8 panels (6/81). The design number [1] for LHe

was 45 watts; 30 watts of it radiation load. The LN design heat load was 4700 watts = 104 ℓ/hr.

Measured LHe heat loads at LBL (30 ℓ/hr) and PPPL (32 ℓ/hr) are about half the LLL design value of 45 watts (64 ℓ/hr). Added heat loads are imposed by the target tank cryopanels, the external distribution system and the transfer lines. Measured LN use at LBL 75 ℓ/hr and PPPL 11 ℓ/hr per panel = 88 ℓ/hr (includes module side loss) compare well with LLL design of 4700 W = 104 ℓ/hr.

VI. DIVERTER VALVE OPERATIONS

Because of combustion hazards of frozen deuterium and hydrogen build-up on the panels, as well as pumping speed decay, it is necessary to de-rime the panels. This is accomplished by the "REGEN" mode with the diverter valve.

Diverter valve operation for regeneration of the cryopanels is critically dependent on dedicated craftsmanship, careful valve seat lapping and alignment and precise flow, pressure and electrical measurements before final installatio The diverter valve was installed for the 7/79 operation and was satisfactory fo cooldown and circulation (steady-state) but failed for regeneration. Referring to Figure 5, the foot valve V4 must seal LHe against 5 psi, dewar vent valve #1 is open, #2 valve GHe return from panels acts as a 10 psi relief valve and develops pressure on top of the panel liquid to push it back up through the foo valve, V4, into the dewar. Valve #3 is closed. Valve sealing is critical, must seal and prevent LHe in the dewar from feeding into the cryopanels. Valve #2 must seal cold GHe with enough pressure to transfer LHe from the panels into the dewar.

After putting the diverter valve into the "REGEN" mode and closing the turbopump valve, sufficient heat must be added to the panels to generate enough GHe to make the LHe transfer and empty the panels, then to raise their

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temperature to at least 15K to sublime the frozen D_2. The first regen test[10] 8/27/80 Figure 6 used frozen H_2 and required 15 minutes after valve closing to initiate the cycle. Panel temperature went to 60K and vessel pressure went to 1000 mTorr after which the pumps were valved in. Pressure recovered in ∿ 20 minutes and diverter valve was put into "circulate" mode, panel temperature went to 4.5K in seconds and pressure dropped within minutes. The next run on D_2 8/28/80 Figure 7 required almost an hour for the cyle to start. Since then we have done many "REGEN" tests with H_2, D_2 and He for initiation of panel de-rime. These plots of temperature, pressure and pertinent operating actions versus time are in Reference 10. Skill and experience have developed a technique for operating at an optimum efficiency and timing. The preferred technique (2/26/81) for handling the administrative[13] limit (13 Torr @ 273K) D_2 is to admit 12 T-ℓ of He gas to the vacuum. Response is within 10 minutes, temperature goes to 66K, pressure goes to 4 Torr, pumps are valved in, foot valve (V4) is opened and pressure drops to 10^{-7} Torr, all within 35 minutes (Figure 8).

If large amounts of tritium* (T_2) are handled and must be recycled, then the addition of GHe may contaminate the T_2 recycle system. Therefore the addition of electrical heaters to the LHe panel bottom feed line may be advisable.

VII. SAFETY COMMENTS

General safety considerations for the system have included the up-to-air vacuum break. For the panels the LN has sufficiently large heat of vaporization that film boiling does not create pressures much greater than 1 atm in the LN system. It normally vents at 1 atm. We have noted that on some high Torr vacuum pressures on "REGEN" the LN gushes out rather rapidly.

*Tritium, a radioactive hydrogen isotope with 12 year half-life

For the LHe system burst discs inside the vessel were eliminated and the single panel up-to-air test[5] demonstrated the peak pressure rise was ∿ 150 psi. The external burst disc relieved at 75 psi and the pressure spike only lasted about ∿ 250 msec denoting a rather low energy level. Interestingly, a retard gage (check valve with bourdon tube pressure gage) was also connected to the system and registered 0 psi after the test, again indicating the small energy dissipation. The LBL system has large 1" dia. lower set (30 psi) relief valves installed in parallel with the burst discs, for a safer more reliable system. Recent experience with another system indicates complete elimination of burst discs may be desirable. A flat spring-loaded plate permits pressure relief and also on-line recovery by clamping and warm-up, eliminating the problems of on-line burst disc replacement.

The vessel lid is only held down by gravity and vacuum pressure. In the remote event of a sudden burst of dumped cryogen liquid into the vessel from a ruptured LHe or LN system the vessel lid lifts off at about 1 psi to vent any pressure rise.

Explosive and other hazards connected with the accumulated frozen H_2, D_2 or T_2 have been discussed elsewhere[13] and the administrative limit set at 12 T-ℓ/ℓ or 600,000 T-ℓ D_2 gas, after which "REGEN" is required. Hydrogen handling from early Bubble Chamber experience might also be considered to extend this limit.

Cryogenic, pressure, seismic and other standard LLL/LBL safety practices have been applied to the system. Suffocation hazard with N_2 gas in the enclosed injector vessel is carefully monitored.

VIII. VACUUM PUMPING SYSTEM

Design values for the 30 m^2 of cryopanel were 2.5×10^{-6} liter/sec pump speed using a specific speed of 8.3 ℓ/sec cm^2 for deuterium.[1] This can be compared with experimental data[6] of 9 ℓ/sec cm^2. For a gas load

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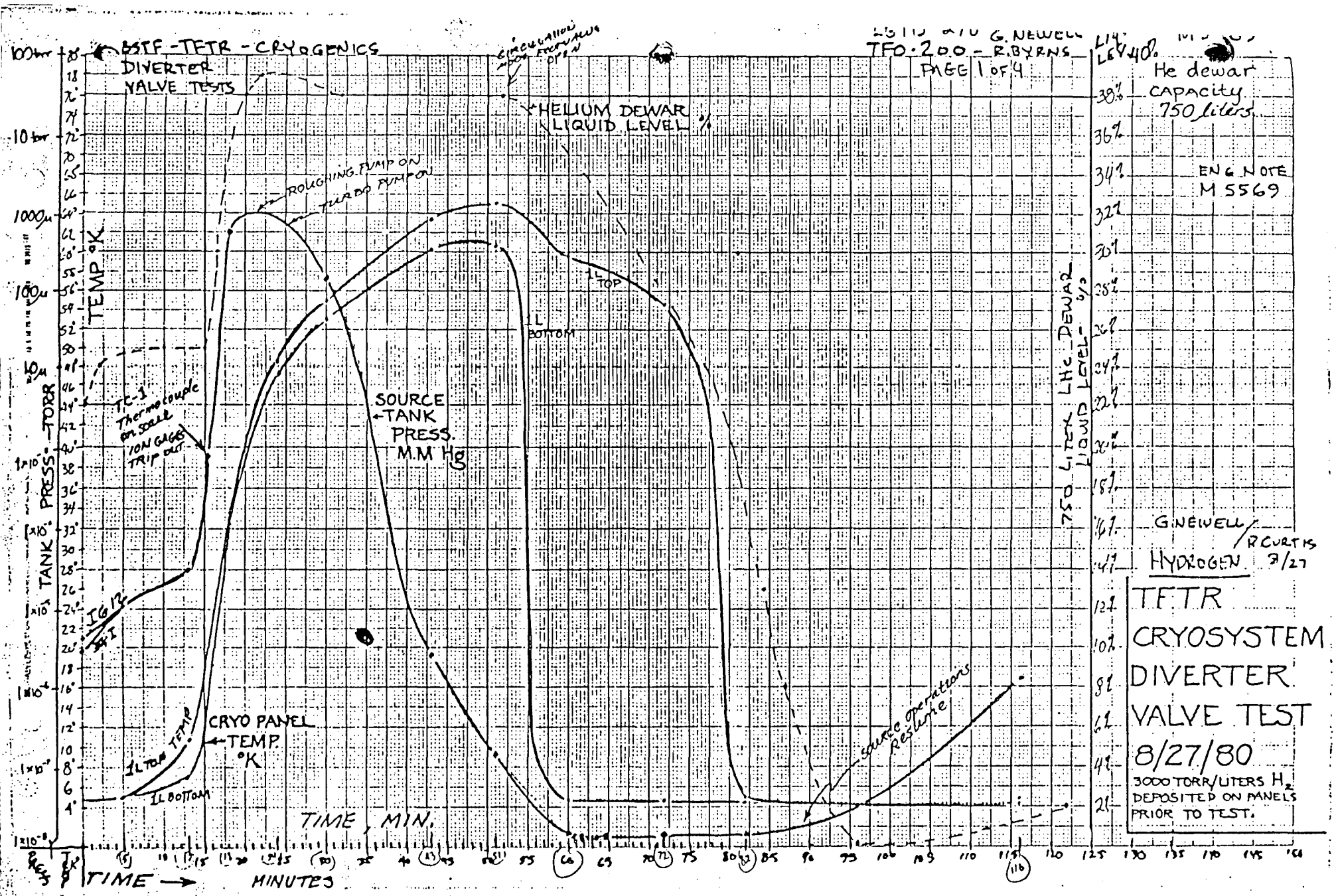

FIGURE 6 FIRST REGEN TEST

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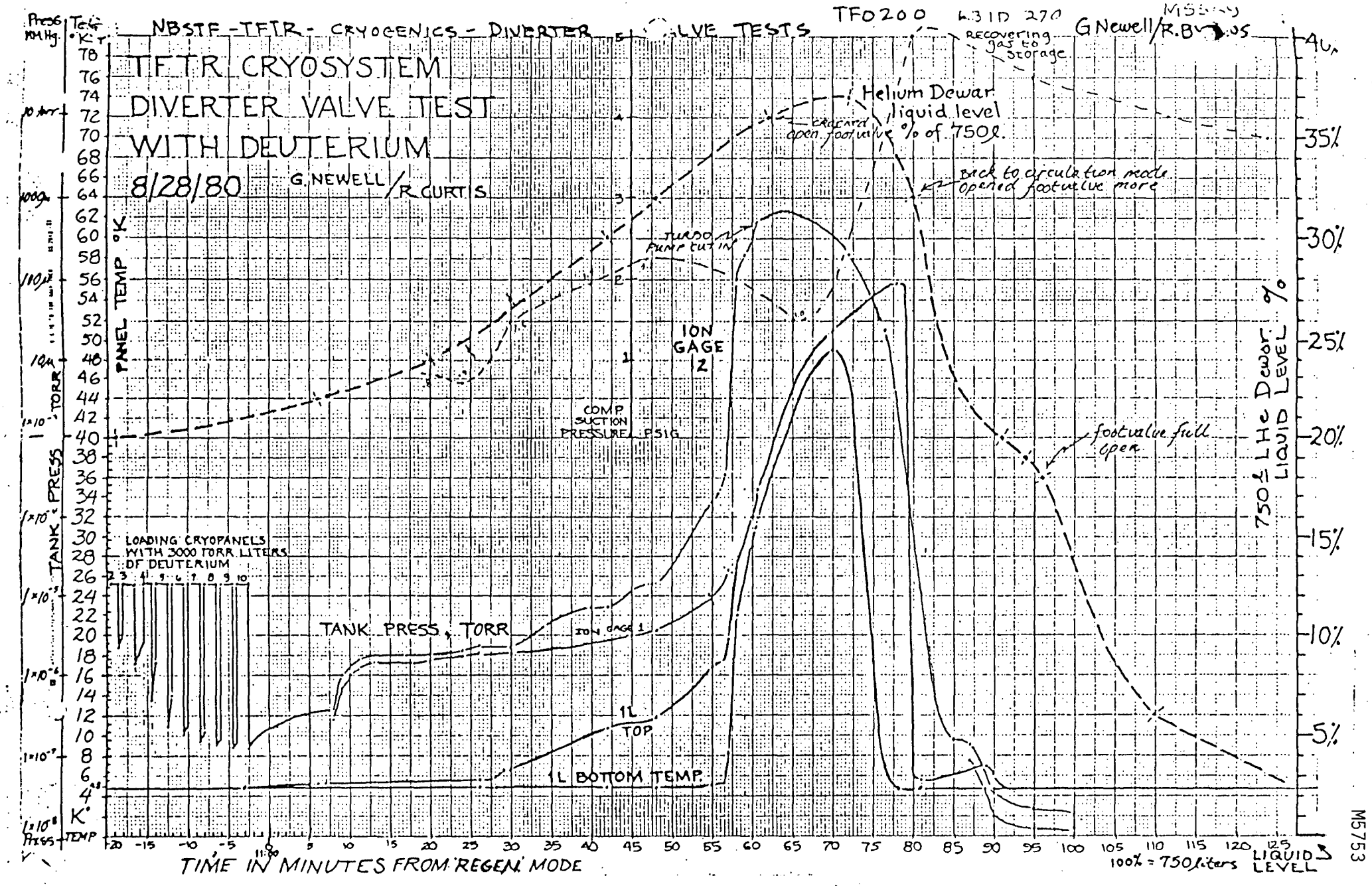

FIGURE 7 SECOND REGEN TEST ON DEUTERIUM -

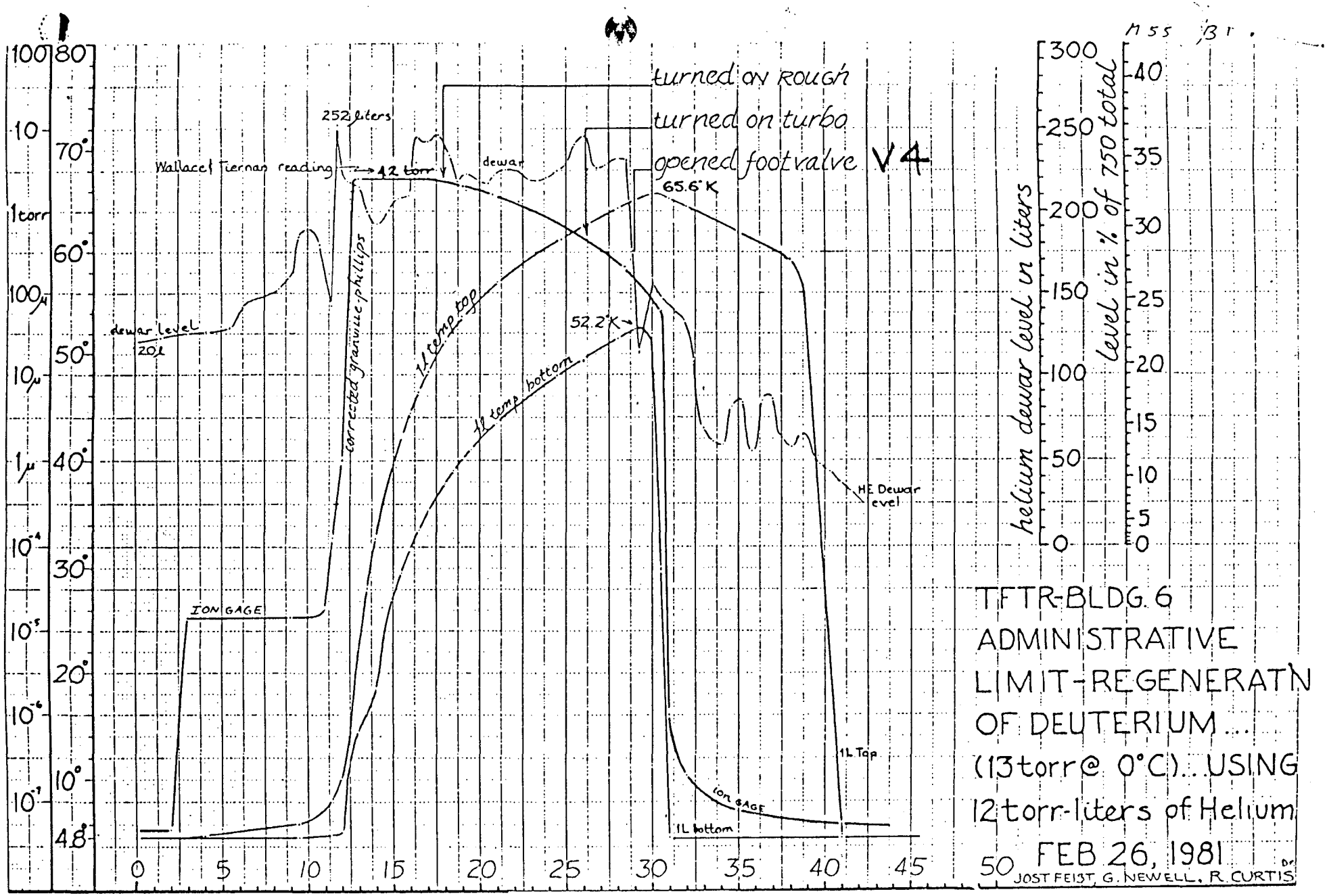

FIG 8

Cryopanel regeneration with diverter valve.
12 Torr-liters GHe injected to remove 13 Torr

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of 100 Torr ℓ/sec, average pressure would be 4×10^{-5} Torr. To minimize pressure at the delivery to the Tokamak the beam line vessel is divided into three sections for a differentially pumped or staged system. The baffles, shown in Figure 1, made of stainless steel sheet metal, block each section except for beam passage apertures at the magnet and the end section. Pressure gradient or line density to minimize beam loss is of more importance than pumping speed per se. Thus conductance and cryopanel locus are critical and can be optimized.

The gas loading has been calibrated on vessels of known size by pressure rise differences. Pressure measurements are made with a Baratron in the source end and Varian ion gages located in the first chamber (neutralizer), second chamber at the ion dump and photo diode, third chamber below the calorimeter, in the drift duct and the target chamber. Thus pressure-time history, beam on and beam off and pressure gradients can be measured during gas pulses, but conduction and pump speed must be calculated. Dynamic pump speeds can be measured. ($P = P_0 e^{-st/v}$.)

During gas loading of the cryopanels for the de-riming tests,[10] hydrogen gas pulses up to 40 Torr ℓ/sec for periods up to 100 sec were injected. Pressures at the neutralizer rose from 2×10^{-5} to 5×10^{-5} Torr and at the exit end remained constant at 2×10^{-5} Torr. Similar pulses for D_2 of 300 Torr-ℓ gave 2×10^{-6} Torr (from 1.5×10^{-7} Torr) at the exit end, with rise to 5×10^{-5} Torr and return to 2×10^{-7} Torr at the neutralizer. These values seem consistent with H_2/D_2 vapor pressures, and show the cryosystem meets the design criteria for beamline pressure gradient.

The cryopump vacuum performance has been carefully examined by J. Feist[7] (Max Planck Institute Plasma Physics, Garching) and will be reported later.

IX. REFRIGERATOR AND HEAT LOADS

The initial refrigerator capacity selection was based on:

1) The estimate of about 100 W for the NBI plus external distribution system.

2) Simultaneous test operation of the General Atomic Doublet III injector.

3) Added cryopanel loads for a target tank on the end of the NBI.

With this in mind, and multiplier factors of ε or π, something like the well-advanced Fermilab satellite refrigerator[15] seemed of about the right size. It was modular construction and could be increased from about 250 W to 400 W with addition of a wet expander. The first specification[16] called for 400 W or 80 ℓ/hr, but was lowered to 300 W/80 ℓ/hr to permit all bidders to quote. Four firms quoted in 1977 and Cryogenic Consultants, Inc. of Allentown, Pa. was low bidder at $300,000. The package included a 400 W cold box, an 80K adsorber, two expander engines and an oil lubed screw compressor with oil clean-up and controls.

The helium compressor was installed in July of 1978, and first run in September. The coldbox and expansion engines were installed in November, 1978, and liquid helium made in early December. Testing of the various components was carried out thru May of 1979, and the first cooldown of the crypanels occurred in July.

Both LBL and PPPL[8] measured the heat load at 22 W for eight cryopanels and the 750 ℓ LHe dewar. Considering the $30m^2$ pump area or $60m^2$ of 4.5K surface looking at 80K, the 22 W/$60m^2$ or 0.36 W/m^2 indicates an empirical value for emissivity. ($\varepsilon < 0.2$)

External heat loads were calculated[14] at 46 W, and included 72m of 2.5 cm dia. vacuum insulated line with 40 layers of superinsulation at 18 W, 20 bayonet connections at 25 W and a distribution valve box with 4 broken stem cold valves. The target tank cryopanel system heat load is estimated at 6 W

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when on-line. Total heat load is then estimated at 68 - 74 W.

The refrigerator has delivered 85 ℓ/hr while holding the 68 W static heat load, with 47 g/s mass flow at 18 atm. On this basis, performance should be in excess of 475 W or 95 ℓ/hr, and easily meets the original specification of 400 W or 80 ℓ/hr. The Fermilab satellite refrigerator performance[15] is 623 W or 126 ℓ/hr with 57.5 g/s mass flow at 20 atm.

The refrigerator is usually run at maximum capacity for cooldown, and LHe filling of the cryopanels and dewar. Filling of eight panels at 120 ℓ and another 200 ℓ in the dewar matches the warm gas storage capacity of 300 ℓ and requires about 4 hours. Then the refrigerator is backed down to a flow of 21 g/s at 12 atm. and the compressor draws about 150 kW. The helium system as of Aug., 1981 has about 4100 clock hours and only requires occasional operator time. While 4100 hours is only ∿ 25% of total hours (17,000) since cryosystem start-up, much of the initial source work only required the turbo-pump and the LN system. The gas load from one source is small. More recently source performance seems better with the helium system on. The simplified control system[9] consisting of a standard industrial controller (Barber-Colman) and a suction pressure transducer (Gulton Corp.) coupled to a discharge pressure control valve (Grove) permits long periods of night and week-end unattended operation.

The excess refrigerator capacity has been a real boon providing rapid cooldown and liquefaction, great operating time economy, and enhanced system reliability due to a wide margin for error. The screw compressor with its slide valve and pressure controls together with the cold box reciprocating expanders permit an infinite number of pressure and mass flow combinations, minimizing power draw for various operating modes.

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