Radiation Physics Note #58

Notes on Radiation Safety Aspects of Experiment P747

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P747 was a proposal[1] to search for fractionally-charged particles produced by 800 GeV protons incident on a mercury (Hg) target. The experiment involved the exposure of Hg, contained in four cylindrical vessels fabricated from carbon steel, to the PB proton beam in enclosure PE3 during the 1985 Tevatron fixed-target run. Fig. 1 is a sketch (not to scale) of the experimental arrangement. Fig. 2 shows a cylindrical module for containing the Hg. The experiment ended on May 16, 1985 after a total irradiation by 1.04×10^{15} protons during two periods of ∿192 hours (at an average rate of $\sim 1.3 \times 10^{9}$ sec^{-1}, or 7.6×10^{10} p-$pulse^{-1}$, 1 pulse-min^{-1}) and ∿109 hours (at a rate of $\sim 7.2 \times 10^{8}$ sec^{-1}), separated by about a week.

The radioactive cooling down of the Hg modules after the end of the run was monitored by surveying (on contact) both the upstream and downstream ends of each container with a Ludlum (Model 14C-1) G-M meter. The surveys started 338 hours after the end of the experiment and continued periodically until ∿3000 hours after shutdown. The results are shown in Table I. The ratio of upstream-to-downstream meter readings average 1 (±15%) for three out of the four modules (numbers 2, 3, and 5), but is equal to ∿0.3 for module 4, the first in-line module irradiated. A difference in exposure rate from the two ends of a module, due to differences in the number of interactions in the two end plates, would not be observed unless a large contribution arises from the radioactivity of the Fe end plates, since it is assumed that complete mixing in the Hg (a liquid) occurs. Exposure rates for the four modules based on downstream end measurements are shown in Figs. 3-6 as a function of cooling time.

The smooth curves are expected exposure rates calculated from the amount of radioactivity estimated to be in each module. The following assumptions were used in these estimates: (1) The Monte Carlo computer program CASIM[2] was used to follow the hadronic cascades that arise in the interactions of 800 GeV protons and predict the number of stars (inelastic events) produced in each module. (2) The number of radionuclides with half-lives longer than one day was set equal to 25% of the number of stars[3] from CASIM that occurred in each material (Hg, Fe) in each module. (See Table II). (3) Each radioactive decay produced a 1 MeV γ-ray; the conversion factor from energy-flux-to-exposure rate was taken[4] as 1.84 x 10^{-6} $R\text{-}hr^{-1}$ per $MeV\text{-}cm^{-2}\text{-}sec^{-1}$. (4) The buildup and decay of dose rates from each module was governed by $\dot{D}=b\Phi \ln[(t_i+t_c)/t_c]$, where Φ is the incident fluence, b is a material and beam dependent constant (determined as indicated below), and t_i and t_c are irradiation and cooling times such that t_c >12 minutes and (t_i+t_c) <500 days.[5]

The exposure rate on contact with the downstream end of each module was calculated as the sum of that due to a uniformly distributed 4-inch thick cylindrical source of Hg shielded by a 0.5-inch thick Fe plate plus that due to a 0.5-inch thick uniformly distributed cylindrical source of

Fe. The expression for the exposure rate due to a cylindrical radioactive source given by Foderaro[4] was used for these estimates. As seen in Figs. 3-6 the contribution due only to a cylindrical source of Hg shielded by an 0.5"-thick Fe plate is also plotted. Note that the contribution to the dose-rate from the Fe end plate is about twice as large as that due to the Hg; it should be mentioned, however, that buildup of radioactivity within the materials has been neglected in these calculations. Although the calculations are greater than the measurements, except for module 4, by factors of from three to eight, calculated values of the ratio of upstream to downstream exposure rates are approximately unity for modules 3 and 5 in agreements with the observations. For module 2 the calculated ratio is 0.83 compared to the average measured value of 1.1, and for number 4 it is 0.55 while that measured was $\sim$0.3. Furthermore, the slopes of the calculated curves are in approximate agreement with those measured. Very crude analysis suggest that the radioactive cooling can be represented by two principal isotopes that have half-lives of $\sim$11 and $\sim$175 days, although no specific nuclides can be identified with these values.

The program CASIM was also used to estimate the temperature rise in each Hg module due to beam heating. The energy deposited in each module (from CASIM for a Gaussian beam with FWHM $\approx$ 1-inch), and the heat gain and associated temperature rise are given in Table II. The heat gain H (cal-proton^{-1}) is related to the energy deposition ε (GeV-proton^{-1}) by

$$H = \varepsilon \times 3.82 \times 10^{-11},$$

and the temperature rise ΔT (°C) is obtained from this by use of

$$\Delta T = H/(mc_p),$$

where m is the mass of the Hg in each module and c_p is the specific heat which is taken as 0.033 $cal\text{-}g^{-1}\text{-}(°C)^{-1}$. The maximum value of H for one pulse of 10^{11} protons occurs in module 2. From the value shown in the Table, the normal operating (equilibrium) temperature based on convective and radiative heat transfer is found[6] to be 42°C. This value is in good agreement with measured temperatures of ~45°C during normal operations with average beams of ~1 x 10^{11} $protons\text{-}min^{-1}$.

The induced activity within the Hg was identified at the conclusion of the experiment by observation[7] of the γ-ray spectrum with a Ge(Li) detector. Table III lists the isotopes observed and the specific activity, decay corrected to the end of the run. The principal radioisotopes produced were, as expected, those with atomic numbers close to that of Hg. The existence of clearly identified Ag isotopes may arise from small Cd and Ag impurities within the Hg.

It should be recalled, however, that from the discussion above concerning exposure rates it is possible that radioisotopes produced from Fe bombardment (e.g., Mn, Co, and Cr isotopes) dominate the residual activity of each module. Unfortunately, no Ge(Li) spectra from the activated Fe end plates were obtained. For shipment, about four months after the end of the run, the Hg modules were packed in USA DOT 7A Type A 55-gal drums and sent as Low Specific Activity (LSA) material.

Other safety aspects of this experiment are mentioned in the Spill Control and Emergency Plan for Mercury Targets in Enclosure PE-3 included as an Appendix to this report.

References

1. The collaboration spokesmen were A.A. Hahn and G.L. Shaw from the University of California at Irvine. The liaison physicist at Fermilab was R. Tokarek.

2. Van Ginneken A. and Awschalom M., 1975, High Energy Particle Interactions in Large Targets, Vol. 1 (Batavia, IL: Fermi National Accelerator Laboratory).

3. Radiation Guide, Ch. 12 (Batavia, IL: Fermi National Accelerator Laboratory); Barbier M., 1969, Induced Radioactivity (North Holland Press).

4. Foderaro A., 1978, The Photon Shielding Manual, 2nd Edition (The Penn State Bookstore, McAllister Building, The Pennsylvania State University, University Park, PA. 16802).

5. Sullivan A.H. and Overton T.R., 1965, Health Physics 11, 1101.

6. Based on results of a preliminary engineering design study by Kurt Krempetz.

7. Thanks to Jay Baldwin and Rich Allen.

TABLE I

Exposure rates (in mR/hr) on contact with downstream (A) and upstream (B) ends of Modules containing Hg, as a function of time t_c (hr) after beam shutdown. For Module locations see Fig. 1.

Module →	2		3		4		5	
t_c	A	B	A	B	A	B	A	B
338	900	900	550	475	650	200	475	350
670	250	230	350	350	500	150	220	200
795	220	320(?)	270	340	270	100	180	180
1296	150	200	160	170	230	80	100	100
1798	115	175	120	120	155	42	80	80
2952	90	100	95	95	155	33	50	70

Table II

Heat gain H and temperature rise ΔT (per incident proton) based on CASIM calculations for energy deposition. Also shown are the interactions (stars) in the iron (upstream and downstream) end plates and the mercury.

Module Number	Stars-proton^{-1}			In Mercury		
	Hg	Fe (up)	Fe (down)	ε (GeV-proton^{-1})	H (cal-proton^{-1}) (x10^{-11})	ΔT (°C-proton^{-1}) (x10^{-11})
2	22.3±.7	1.92±.12	3.69±.16	29.1±.6	111.3	0.14
3	38.1±.8	4.47±.21	5.38±.13	23.5±.6	89.8	0.12
4	5.8±.3	.04±.005	1.49±.14	9.4±.4	35.9	0.046
5	37.8±.7	5.16±.15	5.06±.22	18.3±.2	69.9	0.091

Table III

Principal isotopes identified within the Hg modules after the end of the run.

Nuclide	Specific Activity (corrected to 5/16/85) (nCi/g)	$T_{1/2}$ (days)
^{203}Hg	333±13	46.6
^{198}Au	880±106	2.7
^{196}Au	379±16	6.2
^{188}Pt	143±12	10.2
^{188}Ir	48.9±8.1	1.75
^{185}Os	1.40±.07	94.
^{110m}Ag	.095±.017	250.
^{106m}Ag	3.92±.53	8.3
^{105}Ag	4.19±.23	41.3

Figure Captions

1. Sketch of experimental set up in Enclosure PE3.

2. Sketch of module, made from carbon-steel, that contained the Hg. It was filled with Hg to within 1" of the top, as shown.

3-6. Radioactive cooling curves of exposure rate as a function of time (in hours) after end of experimental run for each module. The smooth curves were calculated as described in the text.

SKETCH OF EXPERIMENT (not to scale)

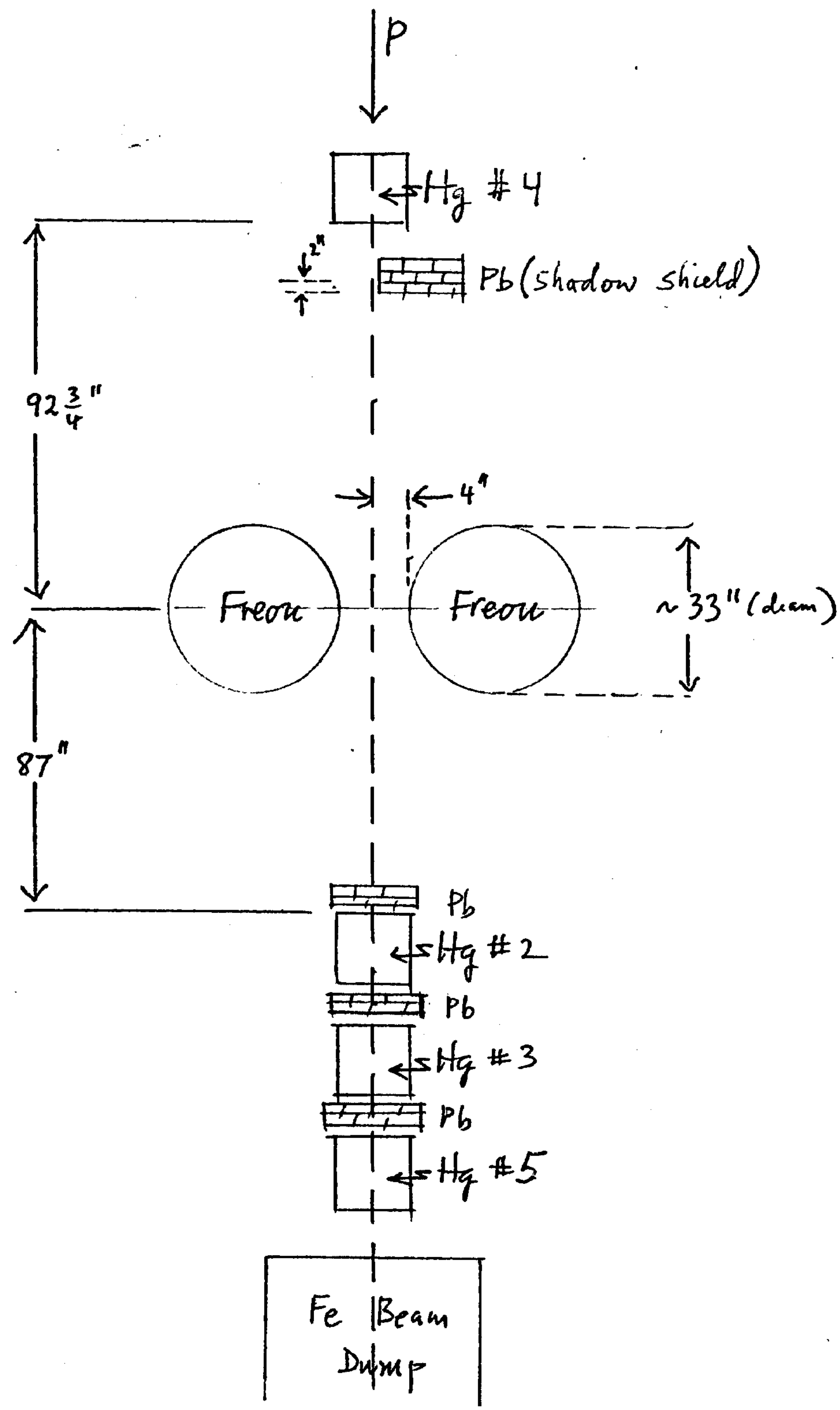


FIG. 1

Hg MODULE

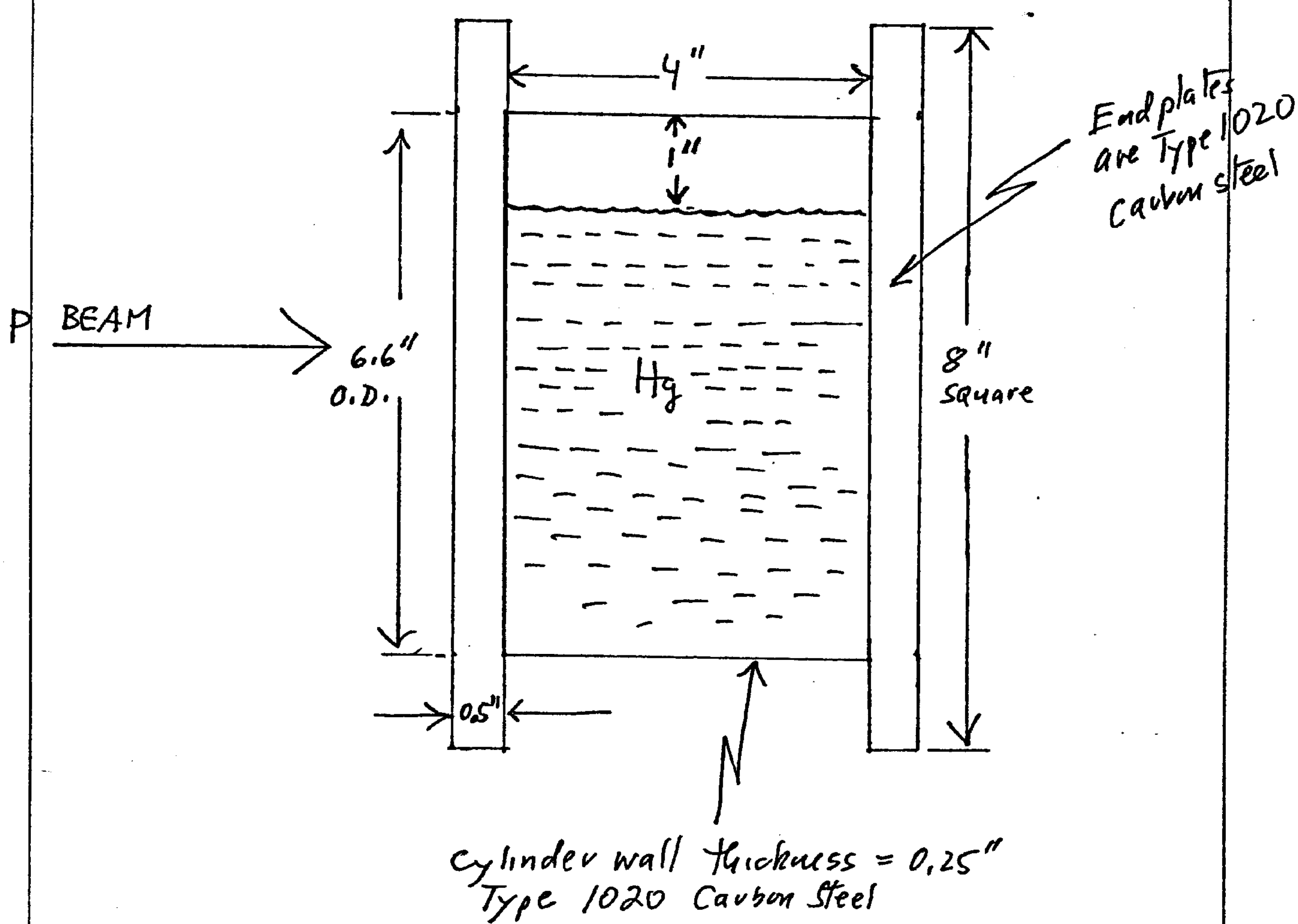


FIG. 2

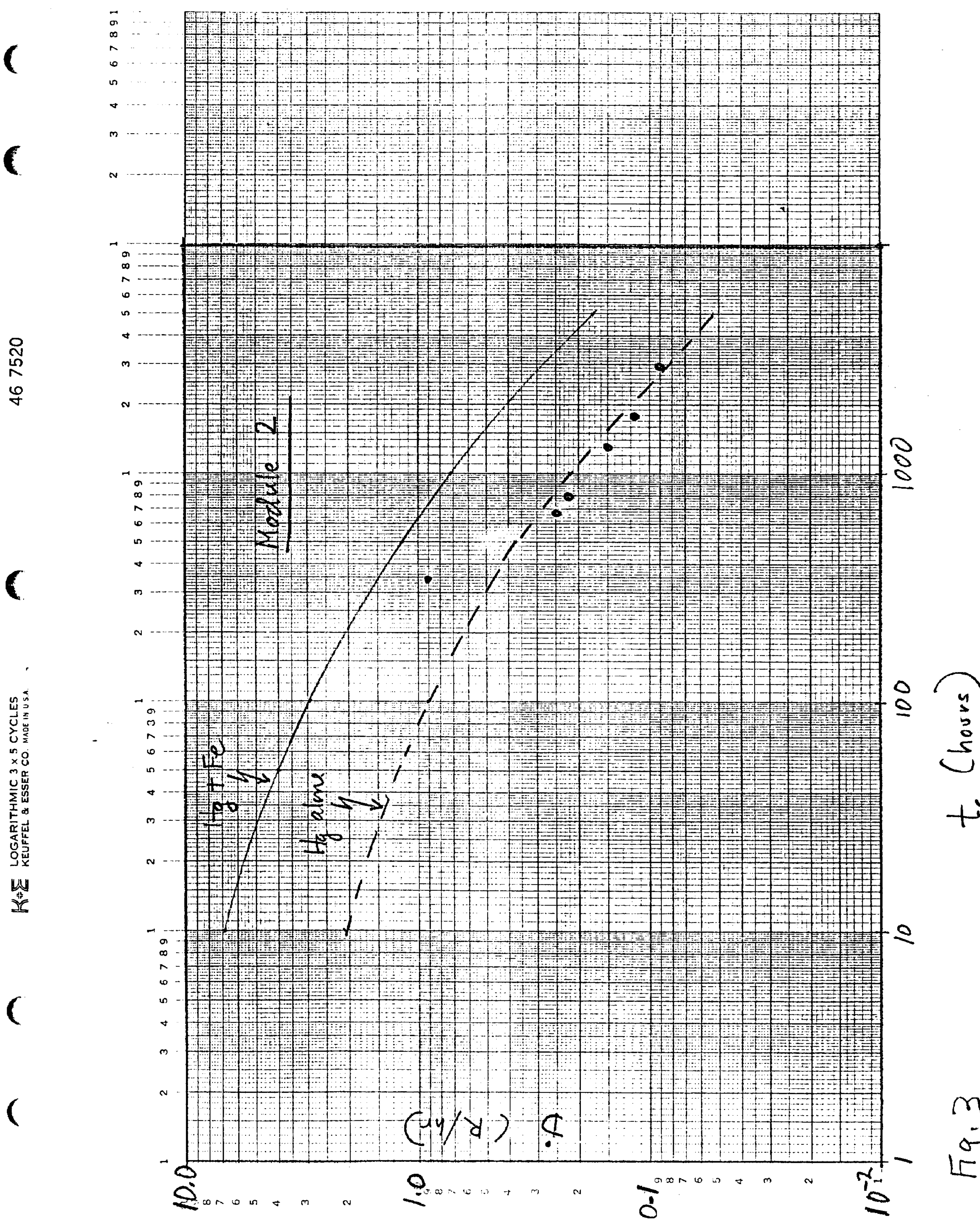

Module 2
Hg + Fe
Hg alone
D (R/hr)
10.0
1.0
0.1
10^{-2}
1
10
100
1000
t_c (hours)
K+E LOGARITHMIC 3 x 5 CYCLES KEUFFEL & ESSER CO. MADE IN U.S.A.
46 7520

Fig. 3

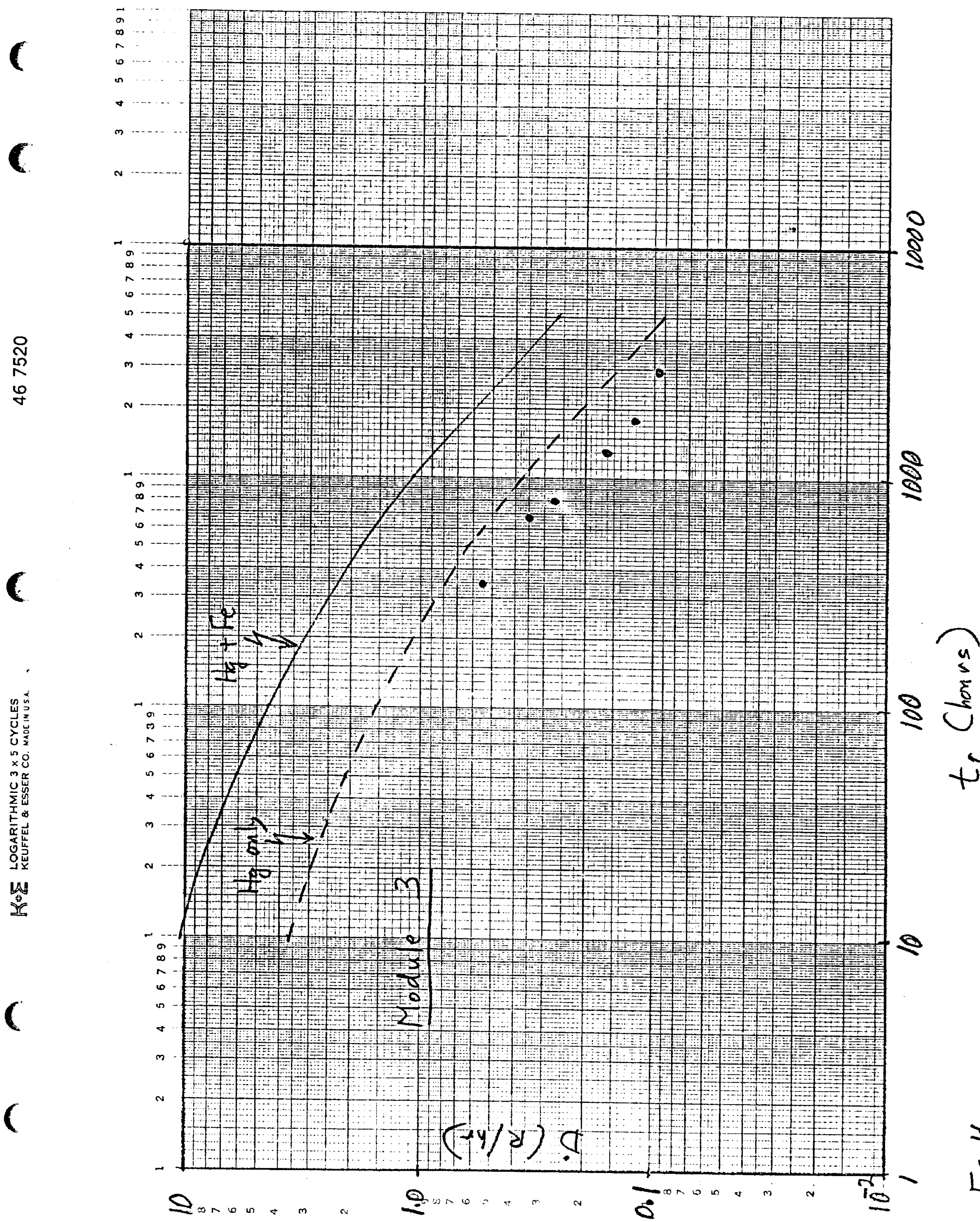

Hg + Fe
Hg only
Module 3
$\dot{D}$ (R/hr)
t_c (hours)
10
1.0
0.1
10^{-2}
1
10
100
1000
10000
LOGARITHMIC 3 x 5 CYCLES
KEUFFEL & ESSER CO. MADE IN U.S.A.
46 7520

Fig 4

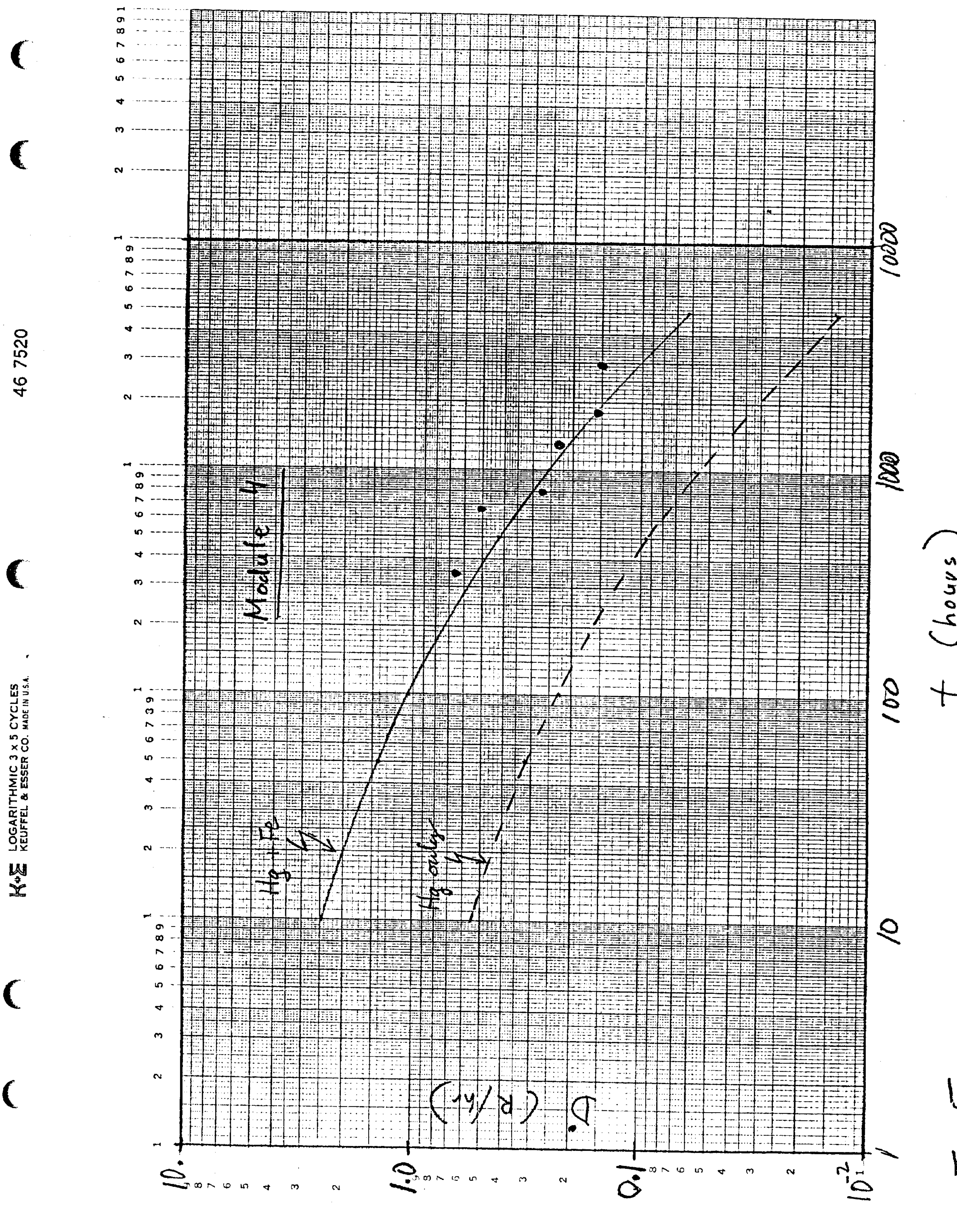
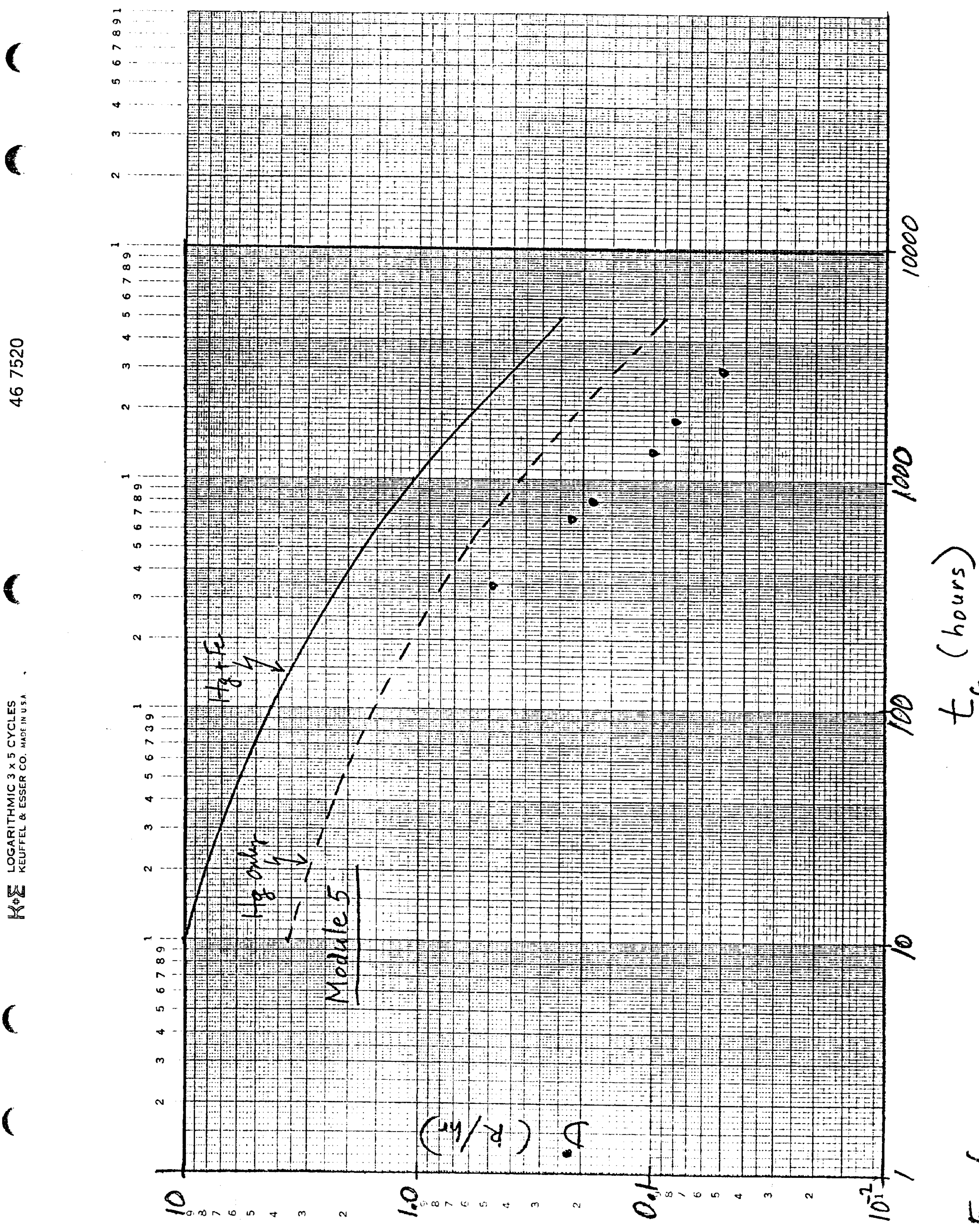

46 7520
K+E LOGARITHMIC 3 x 5 CYCLES
KEUFFEL & ESSER CO. MADE IN U.S.A.
Module 4
Hg + Fe
Hg only
D (R/h)
10
1.0
0.1
10^{-2}
1
10
100
1000
10000
t_c (hours)

Fig. 5



46 7520
K+E LOGARITHMIC 3 x 5 CYCLES
KEUFFEL & ESSER CO. MADE IN U.S.A.
Hg + Fe
Hg only
Module 5
D (R/hr)
t_c (hours)
1
10
100
1000
10000
10
1.0
0.1
10^{-2}

Fig. 6

APPENDIX

March 12, 1985

FERMILAB PROPOSED EXPERIMENT P-747

SPILL CONTROL AND EMERGENCY PLAN FOR MERCURY TARGETS IN ENCLOSURE PE-3

1. INTRODUCTION

This experiment involves the exposure of four mercury targets to the PB proton beam. This will take place in enclosure PE-3, just downstream of the PE target box. The incident beam will be at an intensity of 1E11/minute up to a total exposure of approximately 1E15 protons. Calculations have indicated that the equilibrium temperature of the warmest target in the series will be approximately 61 degrees C. A "single pulse" accident of 1E13 protons would produce a temperature rise of about 23 degrees C. Therefore the temperatures of the targets will be continuously monitored during the exposure. If a temperature of more than 110 degrees C is exceeded, the critical devices for the PB beam will be tripped off, in order prevent an overpressure condition from developing in any of the targets. This is done to prevent a release of this toxic and (after irradiation) radioactive material which would present an immediate hazard to personnel and a risk of contaminating the enclosure. Fig. 1 shows a view of these targets as they are housed in sheet metal vapor shields. The purpose of these shields is to contain the major portion of the mercury in the unlikely event of a release. The mechanical design of the mercury vessels has been approved for the desired operating conditions by the Mechanical Safety Subcommittee. The temperature monitor chassis is located in the PS-4 service building. The remainder of this document will specify the procedures to be followed in the event of interlock trips due to the temperature monitors. While these targets have been designed to minimize the risk of a release of the mercury, all concerned should be informed that if a release were to occur, the atmospheric concentrations of mercury vapor (especially near the targets) can easily exceed the exposure limits. The targets will also become radioactive, near the end of the proposed run the contact dose rates will approach 1500 mR/hr. Therefore, all the usual precautions applicable to radioactive targets apply here.

2. OPERATIONS DEPARTMENT RESPONSE PROCEDURE (Note: all problems with these targets must be reported to Gerardi, Butala, Cossairt, Scherr or Sarlina at the time that they occur.)

In case of the interlocks tripping off the PB beam due to a suspected overtemperature condition on one or more of these targets, Operations personnel should:

A. Proceed immediately to PS-4 and record the 4 target temperatures (chassis # 2, temperaures 1 through 4). If any target exceeds 110 degrees C, proceed to step B. Otherwise, log the incident as a false alarm and proceed with operation of the beam.

B. If any target temperature exceeds 110 degrees C, determine whether a mercury vapor survey meter is available by consulting instructions from Roger Tokarek. If such a meter is available go to step C, if not go to step D.

C. Measure the mercury vapor levels at the points listed below (in order). If at any point the levels exceed Ø.1 mg/m^3, leave the area immediately and proceed to D. Disposable protective clothing (paper coveralls and booties with rubber gloves) and disposable mercury vapor respirators should be worn when entering PE-3 under these conditions of a suspected mercury spill.
During this access, the Operators should not issue PE-3 keys to any other persons than those equipped with the mercury vapor survey meter.

Places to check mercury vapor concentrations (in order):

a. Ventillator for PE-3 access stairway at PS-4

b. PE-3 access door

c. PE-3 area, cautiously proceeding to the target shields

d. Inside the vapor shields enshrouding the targets (cautiously pulling the ends off of them, they are just taped)

If the Ø.1 mg/m^3 level is not exceeded, and no other problems with the targets are noted, verify that the beam intensity is < 1.3E11 and proceed with operations of the PB beam.

D. If vapor levels exceeding Ø.1 mg/m^3 are detected or if a survey meter is not available, call Roger Tokarek (293-5689) and the Fire Department who should send two people to enter the area with self-contained breathing apparatus (SCBA'S) to check for spills. The beam should remain turned off until these people arrive. To minimize the risks, a one hour cooldown time (for the mercury and the radioactivity) must be observed. No person is to enter this enclosure for any reason except for the personnel equipped with the SCBA's for this specific purpose. All personnel who enter in this manner must observe the normal precautions for radiation safety and ODH (except the need for escape packs is obviously waived due to the SCBA'S). A full set of anticontamination clothing (paper booties and coveralls with rubber gloves) must be worn during this exploratory access. If a spill has actually occurred, liquid mercury should be visible in the spill tray under the targets. If a spill has not occurred, R. Tokarek will carefully examine the targets and decide whether or not to resume operations. If a spill has occurred, the experiment is considered temporarily terminated and the cleanup should proceed as in part E. The targets will then be removed from the beam pending further evaluation of the situation by the Research Division Head. In this event, they should remain in the PE-3 enclosure (see below).

E. Proceed to clean up a spill as follows:

a. Personnel in SCBA'S and paper coveralls, booties, and rubber gloves will use "Hg Absorb" (special mercury absorbing material) stored in R. Tokarek's office on WH12W to absorb the the cooled mercury. The used absorbent material should then be dumped into plastic bags and separately stored in PE-3 in a dry place. This material will be kept separate from other radioactive waste because of the fact that its disposal will require special procedures. The general condition of the area will require detailed evaluation by radiation safety and industrial hygiene staff. The vicinity should be posted as a mercury contamination area by R. Tokarek.

b. The protective clothing worn should be disposed of as radioactive waste. The SCBA'S will, after their use, be considered to be contaminated with mercury and, if they cannot be successfully decontaminated, will have to be replaced by the experimenters. In the interim, the SCBA's should be stored in plastic bags.

c. After this cleanup procedure, all accesses to this enclosure will require full protective clothing in additional to the usual requirements for radiation safety and ODH. The mercury area should not be entered until the RD Safety Group and the Safety Section Industrial Hygiene staff have concluded that it may be safely done. Additional cleanup procedures may be specified by these people. Operation of the beams in this area may resume, subject to the above restrictions.

3. TRAINING SPECIFICATIONS

It will be required for R. Tokarek to receive SCBA training. A briefing of the Operations crew chiefs, Fire Department, and Security personnel will be coordinated by R. Tokarek and D. Cossairt. This will include, for the Operations crew chiefs, a demonstration of the proper usage of the mercury vapor survey meter.

Written By D. Cossairt DC

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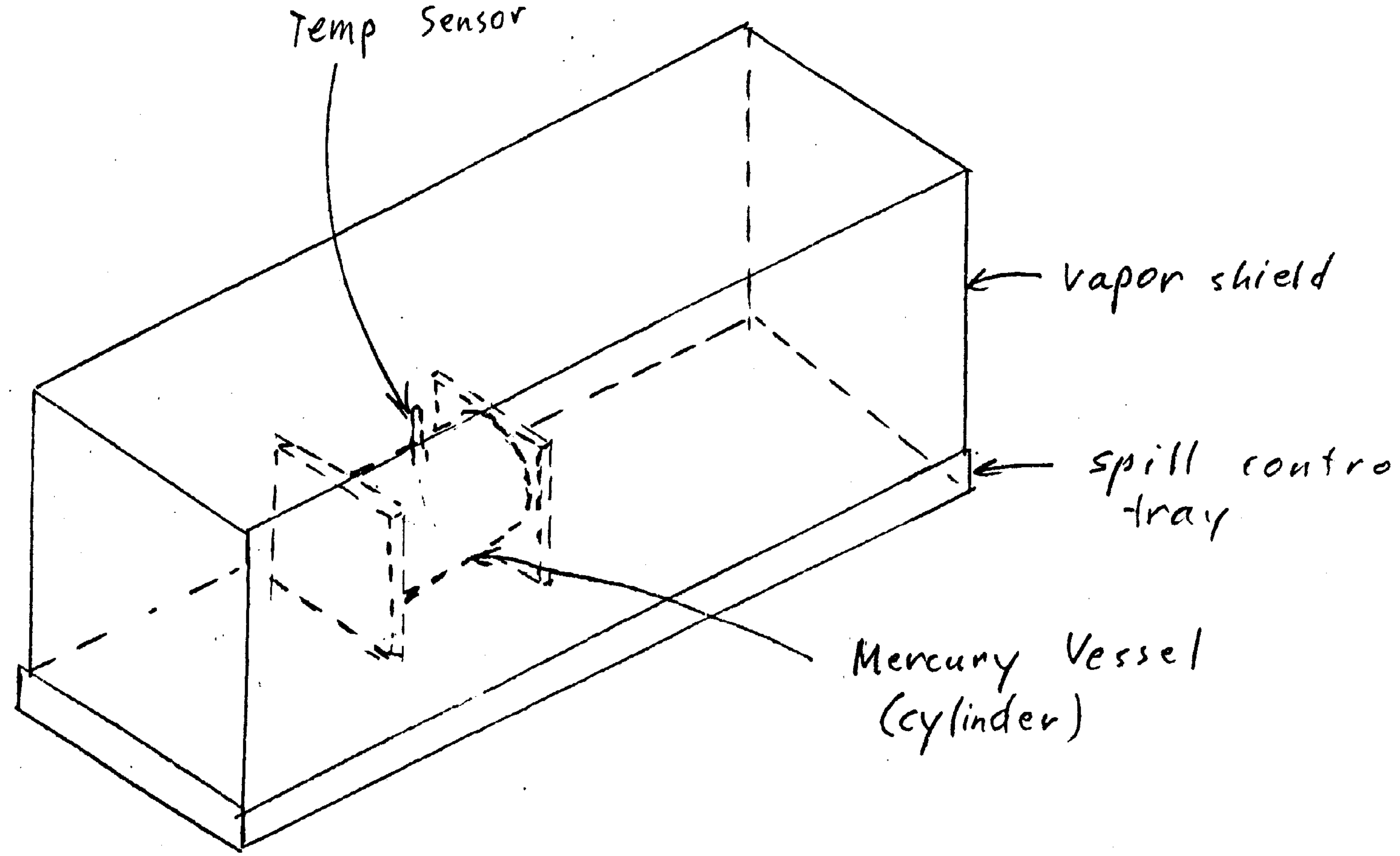
Experimental Areas Operations Logbook



Note, one tray contains 3 targets while the other contains 1

Figure 1