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ABSTRACT

Certain types of special-purpose vacuum systems require a higher order of cleanliness than can be obtained with oil diffusion pumps. Ionization pumps of one form or other appear promising for small-volume or sealed-off systems. For large continuously pumped systems, mercury diffusion pumps provide the only presently practical means of achieving low pressures without contamination by migration of organic materials.

This paper deals with the vacuum design considerations of large systems involving the application of 8-inch through 32-inch mercury diffusion pumps. The selection, rating, and optimization of pumps are discussed along with the closely allied problem of baffling the pumps. The materials of construction and methods of fabrication to avoid subsequent system contamination are dealt with in detail. System interlocking and its associated instrumentation are illustrated by referral to the operation of a large particle-accelerator vacuum system.

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INTRODUCTION

Certain experimental procedures and special processes require a high vacuum in which any appreciable amount of hydrocarbon contamination is detrimental. It is widely recognized that the migration of pump fluids from oil diffusion pumps contributes significant amounts of contaminating organic material to the pumped volume. Several approaches are possible in avoiding such contamination. The present trend is toward ionization and sorption pumps of one form or another, and considerable promise is indicated.[1,2,3] However, presently available pumps of this type have serious shortcomings for general usage: (a) they are not of sufficient capacity to justify their application economically on large continuously pumped systems, (b) they are not well adapted for pressure-cycled or high-throughput systems, and (c) their term of useful performance without shutdown

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*Work done under the auspices of the U.S. Atomic Energy Commission

[1] Foster, Lawrence, and Lofgren, Rev. Sci. Instr. 24, 388 (1953)

[2] Schwarz, Rev. Sci. Instr. 24, 371 (1953)

[3] Divatia and Davis, Committee on Vacuum Techniques, Inc., 1954 Vacuum Symposium Transactions 40 (1954)

for overhaul is quite limited. The classical approach has been the use of mercury diffusion pumps. Prior to 1946 this had been restricted to small systems, since large, high-capacity mercury pumps had not yet been developed. In general these small systems represented the application of well-known laboratory techniques described in detail, for example, in Reference 4. This technique, in which the vacuum system was often constructed of glass, is still in considerable usage, and the published information is entirely adequate. Subject matter here is therefore rather arbitrarily restricted to pump sizes for which standard glass parts are not available. It is the purpose of this paper to describe the technology of a class of special-purpose vacuum systems that require the application of large, high-capacity mercury diffusion pumps of greater than 6-inch nominal diameter. The techniques described are, of course, also applicable to smaller systems where it is desired to avoid the fragility of glass construction.

The selection of mercury as a diffusion-pump fluid is not always a clear-cut decision, and it is not possible here to rigorously define the conditions under which it should be selected. Experience, however, has shown certain applications which indicate definite advantages in the use of mercury. These are categorized as follows:

1. Those vacuum systems in which high voltage gradients are

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[4] J. Strong, Procedures in Experimental Physics, Prentice-Hall, 1938.

present and in which oil vapor tends to instigate voltage breakdown in the residual gas as well as to form leakage paths on insulators. This category includes ion sources, resonant-cavity linear accelerators, and high-voltage test cavities.

2. Those vacuum systems which are a part of an apparatus in which collision processes with migrated oil vapor can seriously impair the functions of the machine. This includes electrostatic particle accelerators of both the Van de Graaff and Cockroft-Walton types. The application of mercury pumping to these systems has been discussed by Gale in Reference 5.

3. Those vacuum systems in which traces of hydrocarbons must be kept to an absolute minimum in order not to mask or distort measurements of the system processes. This category includes mass spectrometers and furnaces for precision vacuum evaporation of materials.

MERCURY DIFFUSION PUMPS

Large high-capacity mercury diffusion pumps are of quite recent vintage. The history of their development is of considerable assistance in explaining the somewhat prominent gaps in the knowledge of variables in their performance. The two decades from 1915 to 1935 represent a period of great progress in high-vacuum technique, much of which was due to the constant improvement

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[5] Gale, Committee on Vacuum Techniques, Inc., 1954 Vacuum Symposium Transactions, <u>100</u> (1954)

of mercury diffusion pumps. The high point of this development can be characterized by a pump capable of a speed of 60 liters per second and of attaining pressures down to 10^{-7} mm of Hg. However, the concurrent development between 1928 and 1935 by Burch, Hickman, and Sanford, and others, of organic fluids suitable for the replacement of mercury in diffusion pumps proved to be a more attractive approach in achieving higher-capacity pumps. The reasons for this are equally pertinent today: (a) for most applications no vapor trap was needed between the oil pump and the vacuum enclosure, and (b) considerably less restriction was placed on the materials of construction of the pumps and vacuum plumbing for oil systems. The further development of oil pumps is well known, but little further attention was given to mercury pumps until Alexander[6] in 1946 investigated some of the factors affecting mercury-pump performance and demonstrated a pump capable of 1400 liters per second between 10^{-2} and 10^{-4} mm of Hg. Beginning in 1946 a considerable number of nuclear particle accelerators were built, and it became increasingly obvious that for certain types of these machines the contamination of surfaces, due to the migration of oil from the diffusion pumps, gave rise to effects seriously limiting their performance. To overcome these difficulties it became necessary to develop large mercury diffusion pumps with capacities up to thousands of liters per second and capable of base pressures to 10^{-6} mm Hg or below.

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[6] Alexander, Journal Scientific Instruments, 23, 11 (1946)

The approaches adopted were the scaling up from small existing designs or, emulating the pioneers in oil pumps of 20 years earlier, using mercury in modifications of large oil pumps. The resulting product has proven to be operationally adequate and includes commercially available pumps up to 32 inches in diameter. Even larger experimental mercury pumps have been built with measured capacities (unbaffled) of up to 50,000 liters per second. Reference 7 describes a "slit" pump of unconventional geometry featuring a straight 6-foot-long rectangular-aperture nozzle assembly. This pump achieved speeds of 50,000 liters per second and a base pressure (trapped ion gage) of 10^{-7} mm of Hg.

There has been little impetus to develop a mercury pump on the basis of the unique thermodynamic characteristics of mercury as a fluid. For example, Fig. 1 is a plot of vapor pressure versus temperature for mercury and several typical high-vacuum diffusion-pump oils. It illustrates the orders of magnitude of difference in this characteristic of the fluids over the range of temperatures indicated. This temperature range, moreover, includes the typical operating conditions, such as boiler temperature and condensing-surface temperature, of both oil and mercury pumps. It is difficult to reconcile these opposing characteristics in the same pump design. The fact that present mercury-pump configurations are slower and more sensitive to operating conditions than their oil counterparts raises the question about the

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[7] Lind and Steinhaus, California Research and Development Company, Report MTA-14, 1953.

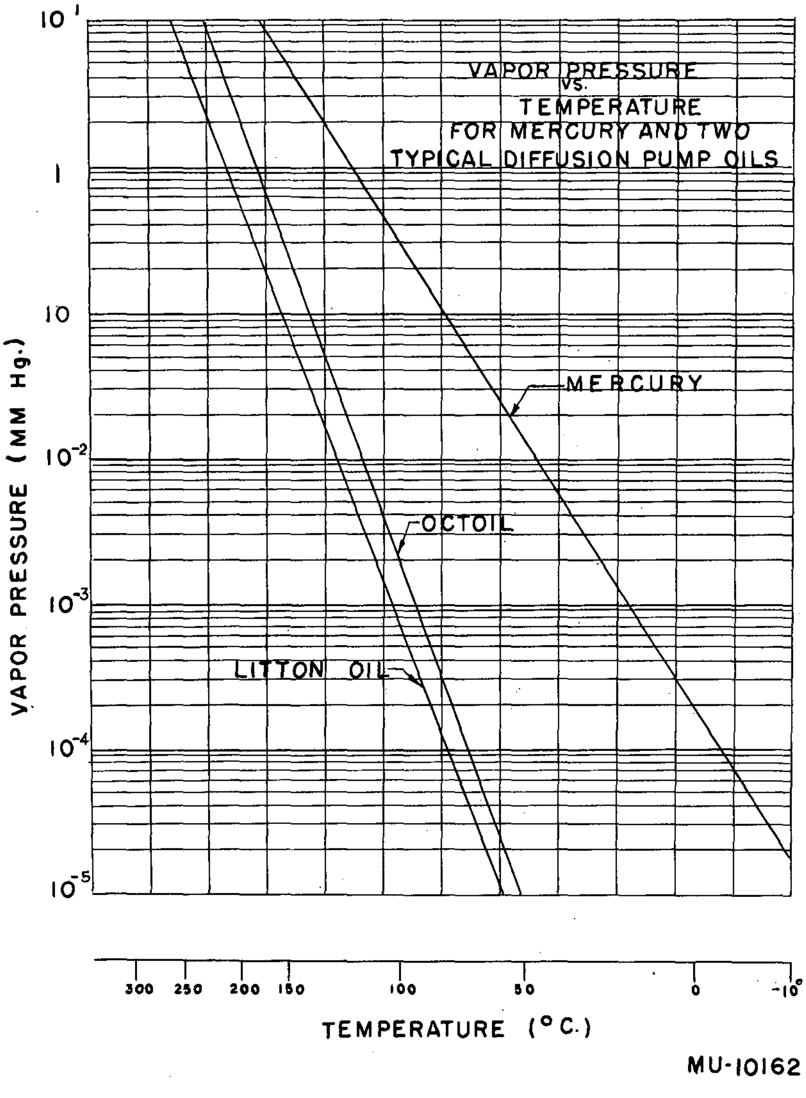
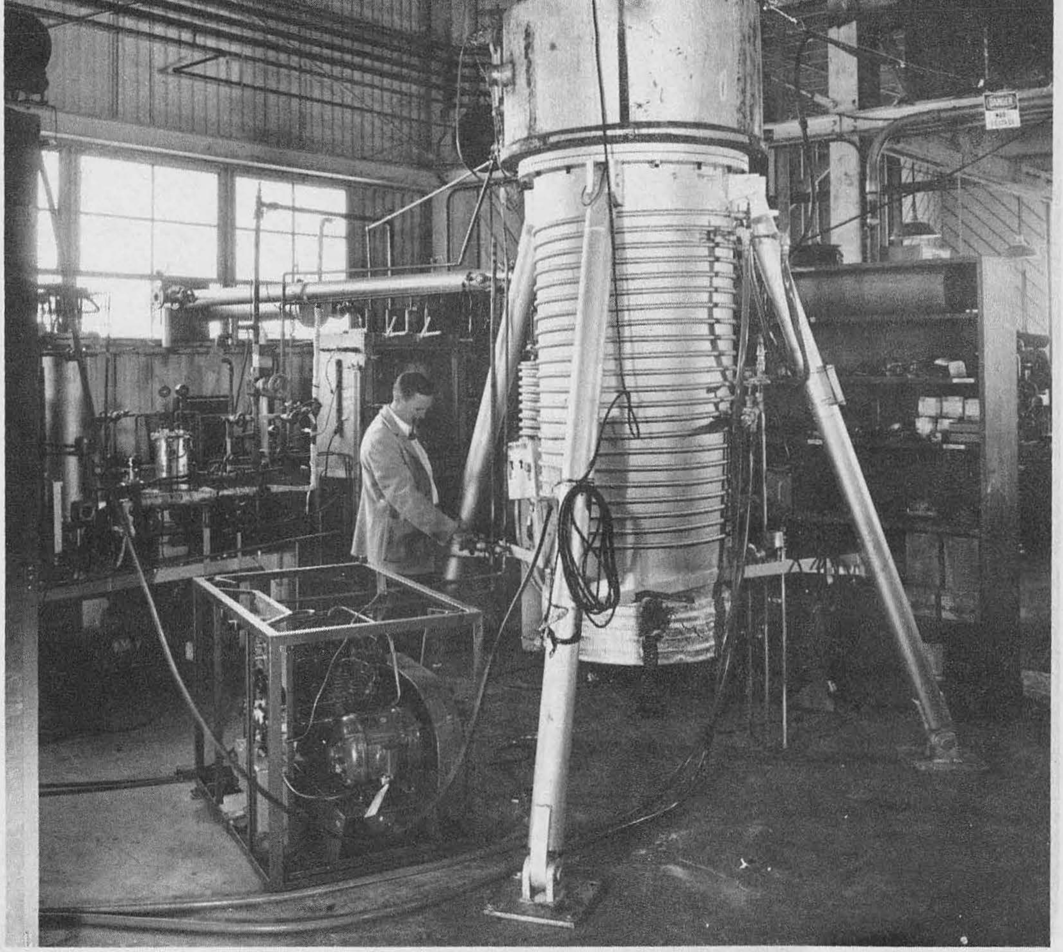

VAPOR PRESSURE
VS.
TEMPERATURE
FOR MERCURY AND TWO
TYPICAL DIFFUSION PUMP OILS
MERCURY
OCTOIL
LITTON OIL
VAPOR PRESSURE (MM Hg.)
10 1
1
10
10-2
10-3
10-4
10-5
300
250
200
150
100
50
0
-10°
TEMPERATURE (°C.)
MU-10162

Fig. 1

basic design of mercury pumps rather than indicating any inherent inferiority.

Figure 2 shows a complete 32-inch mercury pumping unit under test. Figure 3 is an assembly drawing of the unit in a cutaway view. The most prominent feature of this assembly is the elaborate precautions required to control the migration of mercury. This is typical for all mercury installations, and the unit will serve as a general example for illustrating the pertinent features.

Figure 4 is a speed-vs-pressure curve for the 32-inch unit shown above, plotted on the speed curve as furnished by the manufacturer for the unbaffled pump. This curve is a graphic illustration of the price that must be paid in capacity for the control of migration of mercury vapor. It further exemplifies the point that the speed of an unbaffled mercury pump is only of academic interest. The high vapor pressure of mercury at typical barrel temperatures (approximately 0.5 microns) and the extensive backstreaming characteristics of present mercury pumps make the inclusion of low-temperature baffles between the pump and the vacuum cavity absolutely essential if a high vacuum is to be attained. An effective baffling system is unfortunately an effective impedance also. As a rule of thumb, for baffle configurations that can be contained in a space generated by the circumference of the pump extended upward, the unbaffled speed is reduced by a factor of from 3 to 4. It is this net speed which is of practical importance in selecting pumps of suitable capacity for a system.



ZN-1404

Fig. 2

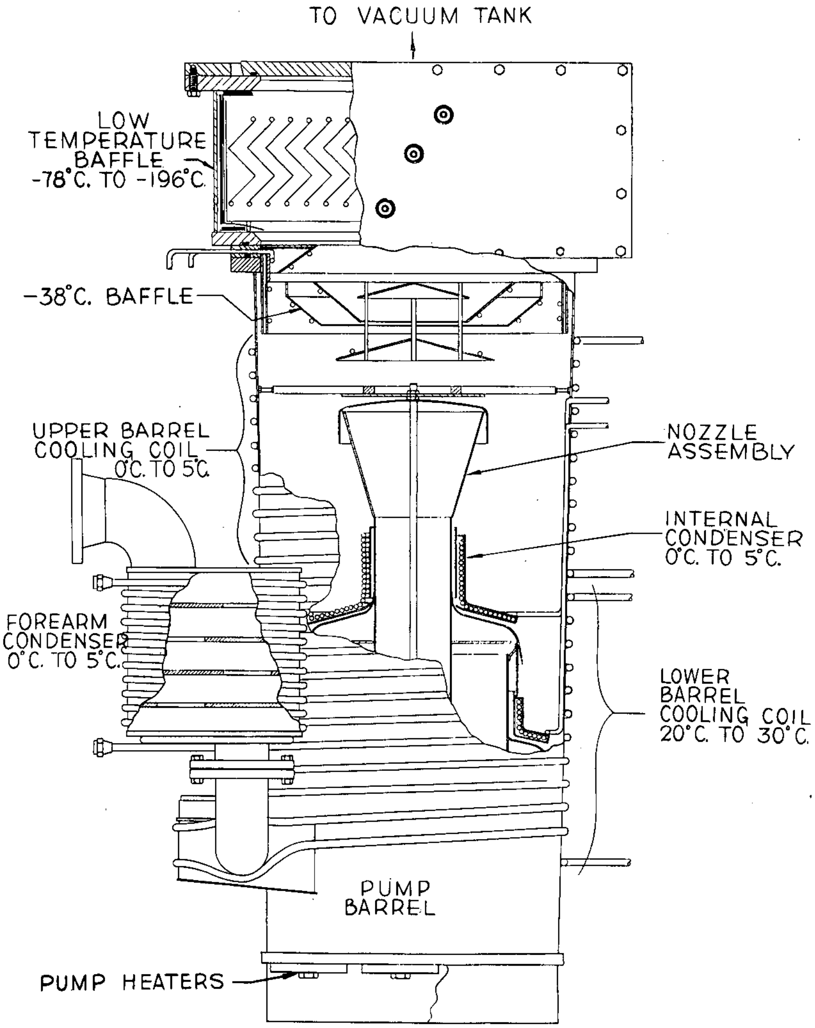

TO VACUUM TANK
LOW TEMPERATURE BAFFLE -78°C. TO -196°C.
-38°C. BAFFLE
UPPER BARREL COOLING COIL 0°C. TO 5°C.
NOZZLE ASSEMBLY
INTERNAL CONDENSER 0°C. TO 5°C.
FOREARM CONDENSER 0°C. TO 5°C.
LOWER BARREL COOLING COIL 20°C. TO 30°C.
PUMP BARREL
PUMP HEATERS
MU-10166

Fig. 3

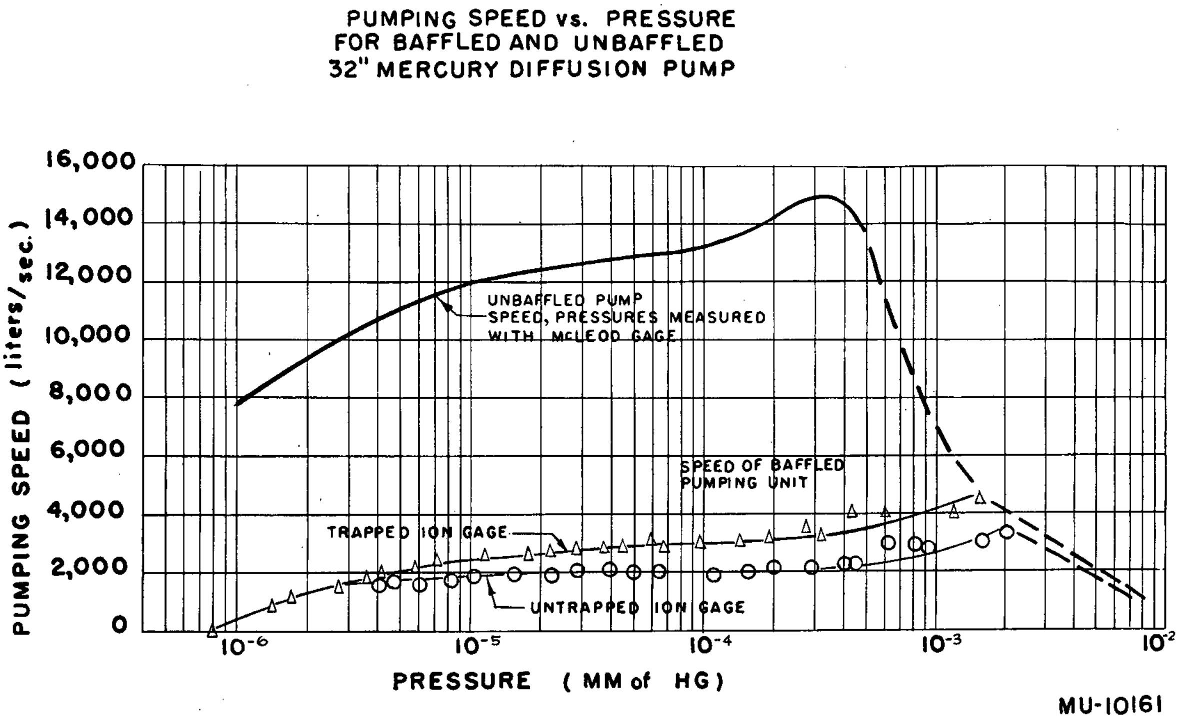

PUMPING SPEED vs. PRESSURE
FOR BAFFLED AND UNBAFFLED
32" MERCURY DIFFUSION PUMP
PUMPING SPEED (liters/sec.)
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
UNBAFFLED PUMP SPEED, PRESSURES MEASURED WITH McLEOD GAGE
SPEED OF BAFFLED PUMPING UNIT
TRAPPED ION GAGE
UNTRAPPED ION GAGE
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
PRESSURE (MM of HG)
MU-10161

Fig. 4

The effect of baffle conductance in reducing the pumping speed of a pump is predictable within limits and remains constant with time. This is not the case with the pump operating variables. Pumps are sensitive in varying extents to the condition and temperature of the condensing surfaces and the degree of cleanliness of the mercury in the boiler. Figure 3 shows the cooling circuits of the typical mercury pump and indicates a range of normal operating temperatures. It is desirable but not necessary to divide the barrel cooling into two circuits as shown. The lower barrel circuit has little effect on pump performance at any usual ambient water temperature other than the excessive heat it extracts from the boiler if it runs below about 20°C. The effect of variation of upper barrel and internal condenser cooling is typified by Figure 5 as reproduced from Reference 8. It is clear that for optimum pump performance the lower condensing-surface temperatures shown in Fig. 5 should be maintained. Temperatures down to -14°C have indicated still further improvement. However, the additional increase in pump speed has not been sufficient to offset the practical advantage of circulating water as a coolant. The lower limits of temperature for maximum pump performance have not been determined. A temperature of -38°C has been achieved on the condensing surfaces, but insufficient heater power was available on present cylindrical pump configurations to overcome the increased heat losses from the boiler and maintain steady

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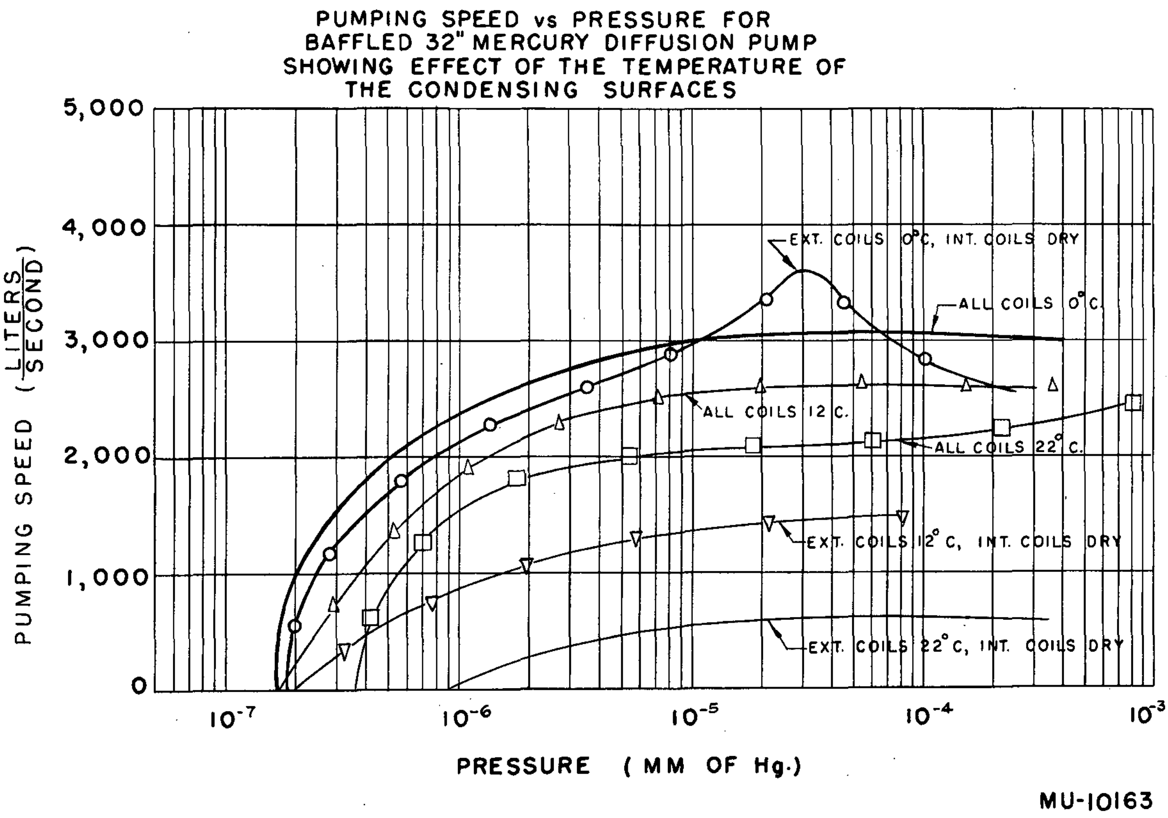
[8] Livdahl, California Research and Development Company, Report CRD-A15-32, 1953



PUMPING SPEED vs PRESSURE FOR
BAFFLED 32" MERCURY DIFFUSION PUMP
SHOWING EFFECT OF THE TEMPERATURE OF
THE CONDENSING SURFACES

Fig. 5

pump operation. Figure 5 also indicates the effect of using the internal condenser coil on pump performance. The improvement in speed from the use of the coil depends on the inlet temperature of the coolant. (This assumes that the same coolant temperature is used in both the upper barrel coil and the internal condenser coil.) The curves indicate that at 0°C coolant temperature little is to be gained by cooling the internal condenser. At the higher temperatures the speed is progressively improved by internal cooling, and at 22°C cooling-water temperature it is increased by 350%. Present pumps of less than 20-inch diameter do not have the internal condenser coil, and it is quite important from a performance standpoint that their upper-barrel cooling coil be maintained at a temperature as close to 0°C as possible.

Oxide films and foreign matter form as a scum on the surface of the mercury in the boiler over a few weeks' time. This appears to limit the rate of vaporization of the mercury, and the top jet will often stop pumping evenly. This results in a slow increase of base pressure of the pump, usually to about 10^{-4} mm of Hg, which can be quite difficult to diagnose. It can be corrected by increasing the heat input to the boiler or cleaning the mercury. It is usually desirable to forestall this occurrence by running the boiler at a heat input considerably above the minimum required for clean startup conditions. This has the further advantage of increasing the forepressure tolerance and does not especially affect the high-vacuum performance. After extended periods of operation, however, the mercury may have to be cleaned in any event. Mechanical cleaning in an "oxifier" type unit, followed by filtering through a gold-leaf filter, is adequate.

Any dirt, rust, or foreign matter on the barrel-wall condensing surface adversely affects pumping speed. Care should be taken to clean off any oil or preservative down to clean metal just prior to placing the pump in service. It has been the custom of some manufacturers to furnish the barrels flashed with a copper plating to assist the mercury in wetting the condensing surface. This helps the initial startup, but the copper washes off very rapidly and forms a lumpy amalgam with the mercury which must eventually be cleaned out. On a clean unplated barrel the mercury may take as long as 24 hours to "condition" the surface, but once it has done so the pump operates normally even after coming up to air.

Table I presents the specifications of presently available large mercury diffusion pumps known to the author. Certain qualifying remarks are in order. The baffled-pump "plateau" speed refers to the flat portion of the pump-speed curve between 10^{-5} and 10^{-3} mm of Hg. The speeds indicated are average values obtained in various installations at the Radiation Laboratory. The importance of baffle geometry and condensing-surface cooling have been noted. It has not been possible to optimize pump installations with respect to these factors in all cases. The average values tabulated reflect this fact as well as variations in performance between individual pumps. Certain installations exceed these values by as much as 25%. The "ultimate vacuum

LARGE MERCURY DIFFUSION PUMPS

Pump Designation	Pump Manufacturer	Nominal Pump Opening	Boiler Heater Power (watts)	Amount of Mercury Required	Limiting Forepressure (mm of Hg)	Baffled Pump "Plateau" Speed (liters/sec)	Ultimate Vacuum Untrapped (mm of Hg)	Ultimate Vacuum Trapped (mm of Hg)
6M3	Edwards High Vacuum Ltd.	10"	1300	200cc	0.5mm	250	2×10^{-6}	10^{-7}
500 liter per sec. Pumping System	High Voltage Engineering Corporation	8"	2500	1000cc	0.2mm	425	5×10^{-6}	5×10^{-7}
MHG-900	Consolidated Vacuum Corp.	10"	2500	40lbs	0.4mm	500	5×10^{-6}	5×10^{-7}
MHG-4000	Consolidated Vacuum Corp.	20"	4000	150lbs	0.2mm	1200	2×10^{-6}	10^{-7}
MHG-10000	Consolidated Vacuum Corp.	32"	12000	300lbs	0.25mm	3500	2×10^{-6}	10^{-7}

MU-10178

Table I

untrapped" column represents pressures as measured with untrapped ionization gages and without liquid nitrogen thimble traps in the vacuum cavity. The ultimate vacuum measured in this manner reflects the temperature of the pump baffle, and in many cases, depending on the baffle coolant, is considerably higher than that indicated in Table I. The "ultimate vacuum trapped" column represents pressures as measured by a liquid-nitrogen-trapped ionization gage. It will be noted that both ultimate vacuum columns indicate pressures somewhat higher than those usually considered readily attainable with mercury diffusion pumps. The point to be made is that these pressures were measured in large untrapped vacuum systems and represent what may be expected in applying mercury pumps in actual practice.

BAFFLES

Controlling the migration of the mercury from the pump is so closely allied with the over-all pump performance that it might well be included in the discussion of pumps. The complications of baffle design, however, justify its treatment as a separate subject. A considerable body of knowledge exists concerning the condensation of molecular mercury on solid surfaces in a vacuum (for example, References 9 and 10). The results of the

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[9] Volmer, "Kinetik der Phasenbildung", J. W. Edwards, 1945

[10] Schrage, "A Theoretical Study of Interphase Mass Transfer", Columbia University Press, 1953

early investigators who measured the condensation of mercury on surfaces were widely diverse. Recapitulation of these experiments indicated quite definitely that slight deviations from ideal conditions of cleanliness, both with respect to the vaporizing liquid and the condensing surface, were responsible for the lack of agreement. Large metal fabrications, such as baffles, even if cleaned thoroughly by any presently known procedures and handled with utmost care, are far from molecularly clean. This undoubtedly has considerable bearing on the observed fact that the baffles are far less efficient condensing surfaces than ideal theory would predict. There is also some doubt as to what temperature is required for the low-temperature baffle, as it relates to the question of the temperature dependence of mercury condensation.

A general scheme of baffling has been developed at the Radiation Laboratory which has proven to be operationally satisfactory. As shown in Fig. 3, the high-temperature baffle (-38°C) is mounted directly above the pump so that it is optically opaque and every molecule traversing the baffle in high vacuum must hit the cold surface at least once. Figure 6 is a photograph of such a baffle for a 32-inch pump. This condenses out the major portion of the backstreaming mercury, which builds up in large globules and drains back into the pump. Figure 7 was photographed through a small window built into the side of a 32-inch pump at the level of the lower baffle bottom plate. The photograph was taken during normal pump operation and shows the considerable holdup of mercury on the baffle. If the baffle temperature is allowed to

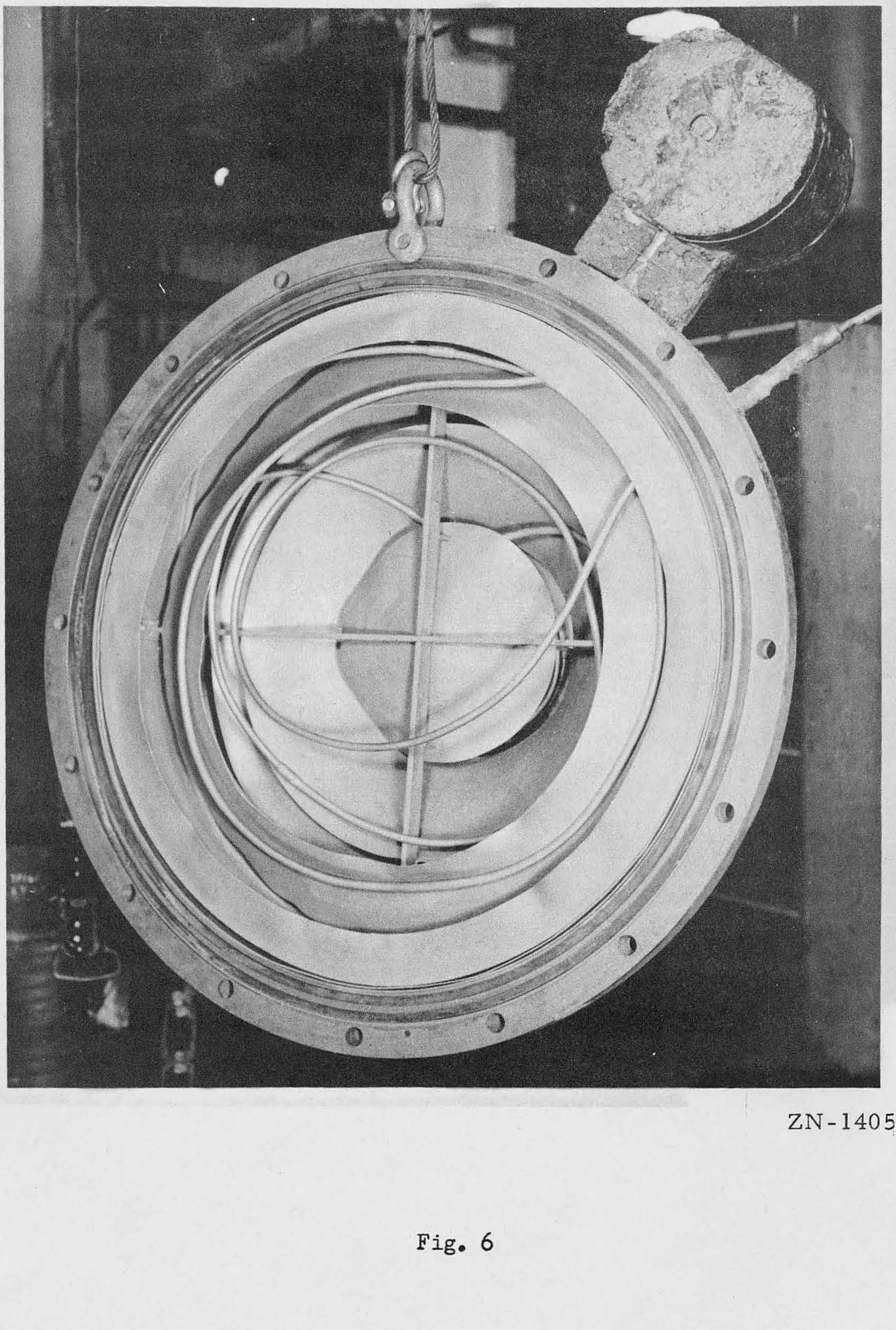

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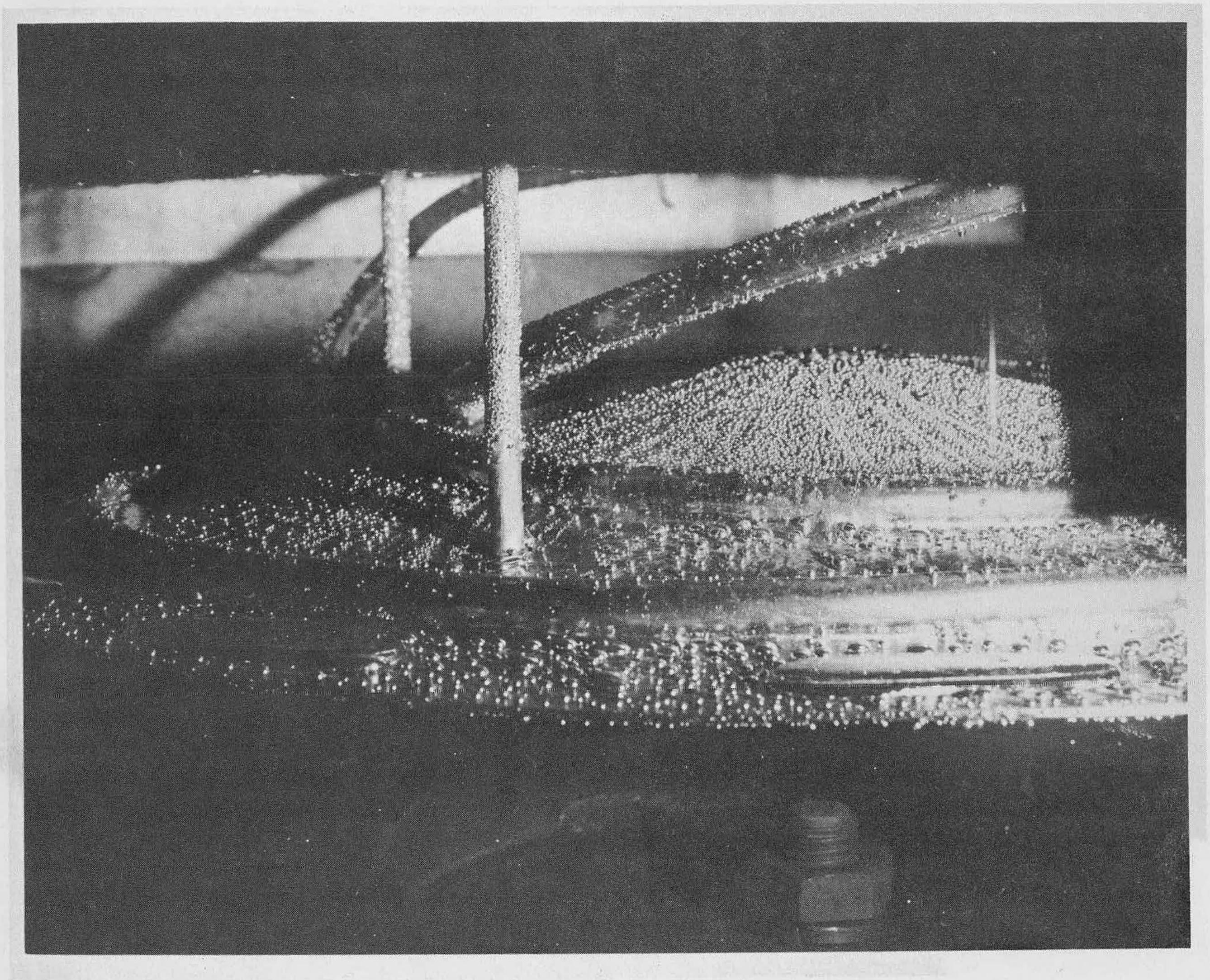
Fig. 6



ZN-1406

Fig. 7

drop below the freezing point of mercury, huge crystals build up in a matter of several hours. Observation through the window has also revealed that discrete droplets of mercury are constantly being thrown back from the condensing surfaces. A baffle built to be opaque to individual molecules of mercury is hardly to be expected to operate efficiently in stopping bouncing droplets. A large amount of the baffle load-up of condensed mercury is probably from this source. The low-temperature baffle is designed so that no portion of it except the top surface sees anything warmer than the $-38^{\circ}C$ surfaces. Its geometry is such that the most direct molecular path through it at any possible angle of departure from a surface below it will include at least two bounces on the cold plates. If the baffle surfaces were ideal, i.e., molecularly clean, it would be expected that no mercury would get through. The departure from ideal conditions has been indicated, and over extended periods of time small amounts of mercury may get through. This seems to be somewhat dependent on the upper baffle temperature as well as the operation of the vacuum system. Roughing down the system to less than 100 microns before opening the diffusion pump gate valves keeps the high-pressure backstreaming to a minimum.

It has been observed that the base pressure of a mercury-pumped system is improved as baffle temperature is lowered. The degree of improvement that is due to better entrapment of mercury vapor rather than other system condensables has not been shown. The general problem is presently under investigation. Large vacuum systems are presently operating satisfactorily with low-temperature baffles running at -196°C, -108°C, -90°C and -78°C. The last case might be considered a maximum permissible temperature for high-vacuum operation in the light of present knowledge. A recently developed prototype mechanical refrigeration unit is operating at temperatures down to -130°C, and the attainment of -90°C[11] and -108°C[12] with mechanical refrigeration is entirely practical. Hence the means of reaching suitable baffle temperatures are readily at hand.

The forearm condenser requires a different approach in trapping out the mercury from that for the high-vacuum side baffles. Its function is to prevent any major migration of mercury from the boiler into the forevacuum line. Here the flow is in the viscous regime and the baffle configuration must be designed to produce changes of flow direction and turbulence so that the entrained mercury vapor will be brought into contact with the cold surfaces. Figure 8 shows a typical refrigerated (-38°C) forearm condenser used on a 20-inch mercury pump. Figure 3 showed a chilled-water-cooled (5°C) forearm condenser on a 32-inch pump. The operating temperature chosen for the forearm condenser usually is governed by the type of cooling available in adjacent equipment. As a matter of convenience it is often put in a parallel circuit with the diffusion pump upper-barrel cooling coil. When

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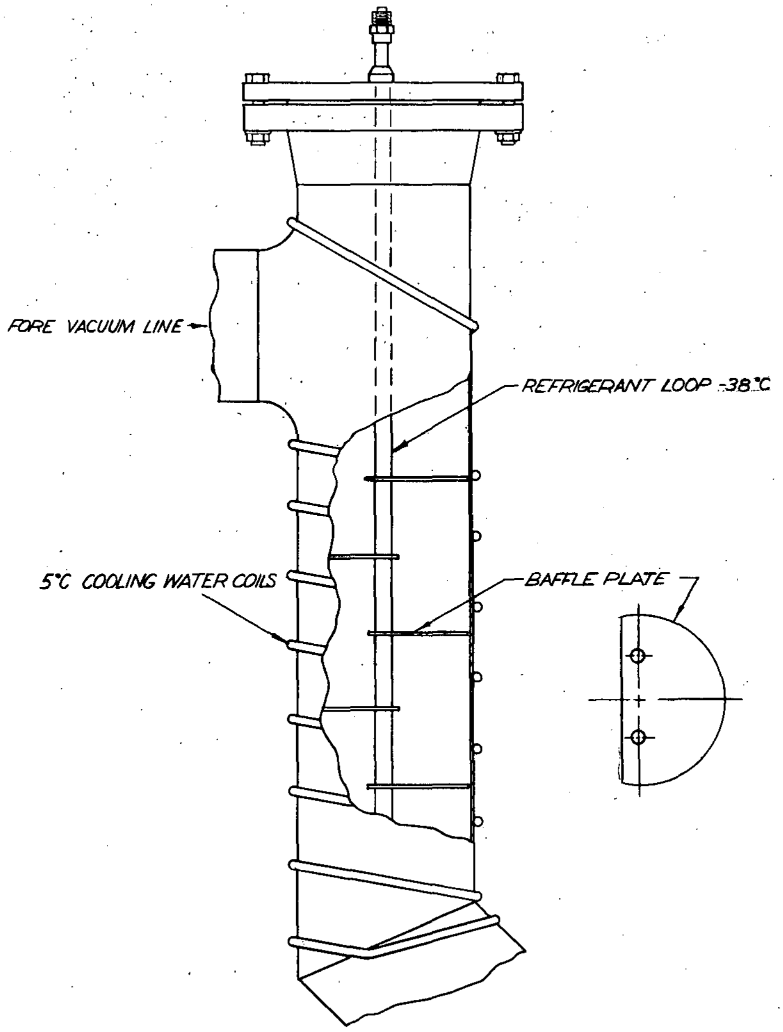
[11] Kennedy and Smith, Submitted for presentation and publication to Committee on Vacuum Techniques, Inc., 1955

[12] Kennedy and Smith, Unpublished Data



20" MERCURY DIFFUSION PUMP
FOREARM CONDENSER

MU-10180

Fig. 8

a water-cooled forearm condenser is used, it is usually desirable to have a low-temperature refrigerated clean-up trap in the line also. This serves the double function of catching any mercury vapor that gets past the forearm condenser and of preventing any mechanical pump oil from migrating toward the vacuum tank. The forearm condenser must always be kept cold until the pump boiler has reached ambient temperature. Otherwise substantial amounts of mercury can be lost up the forevacuum line. At best, a quantity of expensive mercury must be replaced and the forevacuum line will be thoroughly contaminated. At worst, actual physical damage can be done to the mechanical pump if sufficient mercury accumulates to "slug" it.

If the vacuum system incorporates a separate roughing line, a trap is often included in the line to be used only during the roughing operation. It is usually liquid-nitrogen-cooled, since it is not in use for extended periods, and it prevents oil migration from the roughing line into the tank. It should be taken out and cleaned while still cold after each roughing operation.

MATERIALS OF CONSTRUCTION AND METHODS OF FABRICATION

The materials of construction and methods of fabrication of the components of a mercury-pumped vacuum system are important in two respects: (a) the high reactivity of mercury with many metals and alloys is well known,[13] and care must be taken in the selection of the materials for the portions of the system that "see" mercury; (b) hydrocarbon contamination in the vacuum enclosure during the construction period as well as during subsequent system operation is determined by the suitability of materials and proper methods of fabrication.

The rate of reaction of mercury with materials is related directly to the temperature, and those parts that are exposed to hot mercury are of maximum concern. For this reason the pump casing and nozzle assemblies are all constructed of ferrous metals that are not attacked at significant rates. The baffles and forevacuum line are the only other components exposed to amounts of mercury of any consequence. The baffles are normally at a low temperature except during shutdown periods, when they warm up to ambient temperature for defrosting. The materials of their construction must be selected to tolerate this condition.

Copper is a favorite vacuum-system baffle material because of its high conductivity and easy workability. For mercury-pumped systems, however, it has certain disadvantages. Copper welded baffles are very difficult to fabricate and many common solders customarily used in assembling copper parts are rapidly attacked by mercury even at room temperature. This is especially true of ordinary 50-50 soft solder, which is not considered usable for this application. Some silver-copper-base hard solders,

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[13] Kelman, Wilkinson, and Yaggee, "Resistance of Materials to Attack by Liquid Metals", Argonne Report ANL-4417, 1950

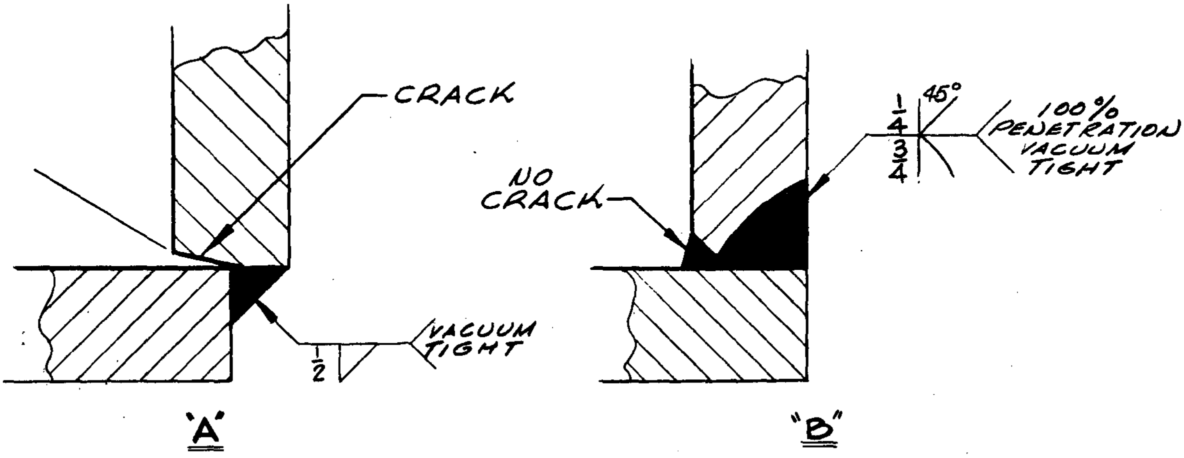
particularly those containing no lead or zinc, seem to be resistant to the attack of mercury at room temperature. With the limited data available, however, conservative design would dictate the nickel plating of assemblies using these materials. The typical baffle features a tortuous geometry and electroplating is generally not practicable. "Electroless" nickel plating has proven to be adequate protection, but can only be done over hard solders that do not contain any lead, zinc, antimony, cadmium, or tin. Suitable solders include Phoscopper and All-State 175. Nickel-plated hard-soldered (Phoscopper) assemblies have been in continuous service for 3 years with no sign of attack. Ferrous metal welded assemblies are entirely safe but are also difficult to fabricate. Cooling fins must be made of thick stock or cooling tubes be placed close together to avoid undesirable temperature variation over the baffle surface. The forevacuum line, including gages, valves, and fittings, particularly that section adjacent to the diffusion pump, should be constructed of mercury-resistant material. Enough mercury vapor carries over during extended periods of operation that it accumulates in puddles in low spots and could attack susceptible materials. Brass, aluminum, zinc, tin, and lead are all attacked at room temperature and their use should be avoided.

It has been observed that welding conforming to ordinary vacuum practice, as shown in Fig. 9 (a), leaves a small crack (drawn out of scale for clarity) between the plates of a typical corner joint. During subsequent machining operations such as facing flanged openings, etc., machining oil can easily run down into the crack. It has been found that this is virtually impossible to get out by cleaning, and oozes out into the tank for months afterwards. To avoid this it has been necessary to alter welding techniques, and full-penetration welds should be specified for joints as indicated, for example, in Fig. 9 (b). This, of course, increases the cost of fabrication, but allows cleaning after machining so that all major amounts of hydrocarbons can be removed.

The selection of vacuum-gasketing material for a large mercury-pumped system is usually a compromise between adequacy and convenience. Metal gaskets are desirable from the standpoint of vapor evolution, but their drawbacks from an installation point of view, especially in large systems, offset this advantage in most cases. The softer metals often used -- such as lead, 50-50 solder, fuse wire, indium, and gold -- are relatively easy to form into gasketing and join, but creep considerably under the heavy flange loadings required to make them seal. They must be tightened down several times after their initial installation. The harder metals such as copper and aluminum do not creep as much, but require even higher flange loadings. In either case, sealing surfaces on flanges or cover plates must be machined to very fine finishes, 32 micro-inches rms or better. The flanges and cover plates must necessarily be heavy, with closely spaced clamping bolts. On small openings these requirements are readily met, but for large apertures such as those associated with, say, a 20-inch mercury pump installation, considerable difficulty can be encountered. A 35-cubic-foot vacuum system with a 20-inch mercury pump and approximately 100 feet of lead gasketing has been built and made leaktight with considerable effort. Fluorocarbons such as Teflon and Kel-F are also good gasket materials from the vapor-evolution standpoint. However, for large installations they are even more difficult to use than metal gaskets. There is no reliable way of joining fluorocarbon gasketing material, and if the opening to be sealed requires a gasket larger than can be cut from a single sheet, it is almost impossible to make a satisfactory vacuumtight joint. These materials also require high sealing pressures, and cold flow considerably under the sealing load.

For many systems one of the synthetic rubber gasketing materials is suitable for gasketing, provided the amount of surface exposed to the high vacuum is minimized. This may be accomplished by designing metal-to-metal joints based on a suitable compression of the gasketing material. Figure 10 illustrates the type of gasket grooves used as standard design at the Radiation Laboratory for square or rectangular cross section gasket material. Such construction has been utilized on several large mercury-pumped accelerators with no obvious ill effects from the gasketing.

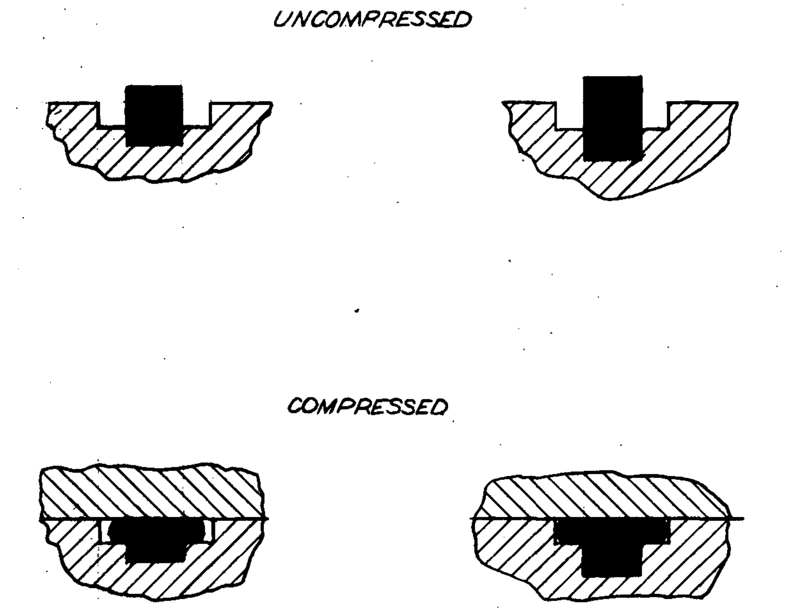
Moving shafts that transmit either rotational or longitudinal motion into the high-vacuum enclosure should communicate through seals that are not lubricated with contaminating materials. Bellows assemblies of various forms are ideal provided they can transmit the necessary amount of motion. For situations in which they are not adequate a "dry" seal has been developed which



TYPICAL VACUUM TANK WELDING DETAILS

MU-10160

Fig. 9



SQUARE CROSS-SECTION STOCK

RECTANGULAR CROSS-SECTION STOCK

TYPICAL METAL-TO-METAL GASKET GROOVES

MU-10179

Fig. 10

has proven leaktight in a number of applications. Figure 11 shows such a seal as applied to a 20-inch air-operated angle valve. The three inner sealing members are Teflon "O" rings, which provide the sliding surface for the shaft. The three outer rings are synthetic rubber "O" rings, which provide elasticity in the seal and make the static vacuum joint against the seal housing. Such a seal has considerably more frictional drag than standard lubricated "O" rings or Wilson or Chevron seals, and sufficient additional force must be provided for shaft actuation. It should be noted that great care is taken to protect the shaft and seal from dust and dirt. Further, no portion of the actuating shaft which comes from the oily air cylinder goes through the dry seal, and a drip collar and wiper rings are provided to prevent oil from flowing down to the clean part of the shaft.

VACUUM SYSTEM DESIGN AND OPERATION

Previous sections have dealt with the special features of the components of mercury-pumped systems. These have been presented in the frame of reference of standard vacuum technique. The application of the individual components to over-all system design is presented in the same manner; only those additional features pertinent to mercury systems are discussed.

The proper operation of a mercury-pumped system requires the functions of the components to be interlocked by a control system

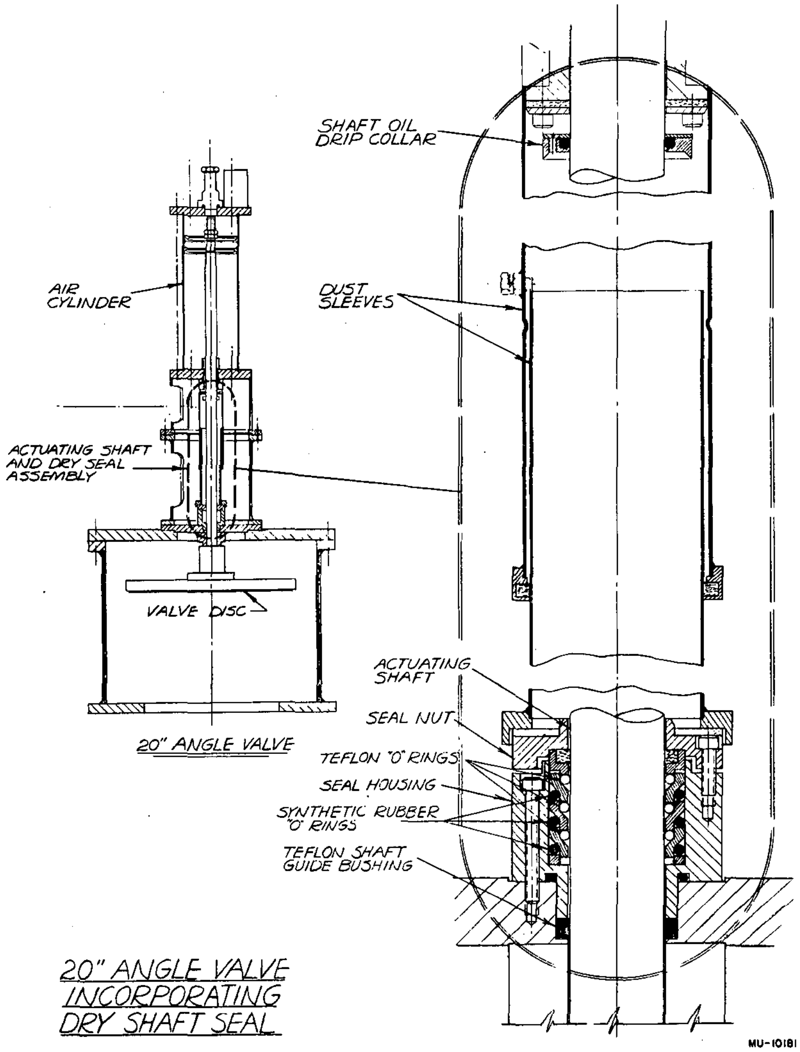

SHAFT OIL DRIP COLLAR
AIR CYLINDER
DUST SLEEVES
ACTUATING SHAFT AND DRY SEAL ASSEMBLY
VALVE DISC
20" ANGLE VALVE
ACTUATING SHAFT
SEAL NUT
TEFLON "O" RINGS
SEAL HOUSING
SYNTHETIC RUBBER "O" RINGS
TEFLON SHAFT GUIDE BUSHING
20" ANGLE VALVE INCORPORATING DRY SHAFT SEAL
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Fig. 11

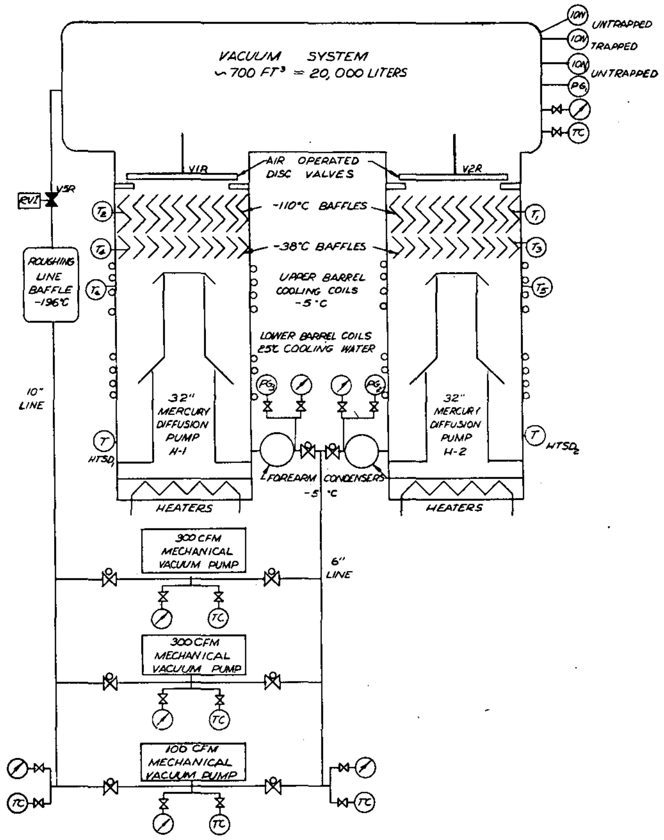
such that

(a) the vacuum cavity and individual vacuum components will be protected against serious damage upon failure of any of the supplied utilities, i.e., water, power, or compressed air;

(b) the individual vacuum components will be protected against failures of any other component;

(c) the apparatus of which the vacuum system is a part will be protected against damage due to impairment of vacuum or to operational errors.

The execution of these requirements can best be illustrated by referral to an actual vacuum system. Figure 12 is a schematic drawing of the vacuum system for a 90-inch cyclotron incorporating two 32-inch mercury diffusion pumps. Figure 13 is a photograph taken looking down on the pumps, gate valves, and valve manifold assembly. Figure 14 is a photograph of one of the 32-inch pumps as installed. In this case, the upper-barrel cooling coil and forearm condenser were cooled by direct expansion of refrigerant (Freon 12), which accounts for the lagging around these areas. The interlocking mechanisms are designated in the system schematic and their functions explained on the chart at the right. Since the pump fluid is not injured by exposure to the atmosphere when hot, as is oil, the general interlocking scheme is designed to prevent the migration of mercury. This is of particular importance here since the main vacuum tank is fabricated from aluminum.



VACUUM INTERLOCK EQUIPMENT		
NUMBER	DESCRIPTION	FUNCTION
PG 1	PIRANI GAGE INTERLOCK	PERMITS V1R & V2R TO OPEN WHEN TANK PRESSURE ≤ 100 MICRONS. CLOSES V1R & V2R IF TANK PRESSURE > 100 MICRONS
PG 2	PIRANI GAGE INTERLOCK	PERMITS V2R TO OPEN AND H-2 HEATERS TO COME ON WHEN PUMP FOREPRESSURE ≤ 250 MICRONS.
PG 3	PIRANI GAGE INTERLOCK	PERMITS V1R TO OPEN AND H-1 HEATERS TO COME ON WHEN PUMP FOREPRESSURE ≤ 250 MICRONS.
HTSD₁	TEMPERATURE SWITCH	SHUTS OFF H-1 HEATERS WHEN BARREL TEMPERATURE EXCEEDS 50°C.
HTSD₂	TEMPERATURE SWITCH	SHUTS OFF H-2 HEATERS WHEN BARREL TEMPERATURE EXCEEDS 50°C
ION₁	IONIZATION GAGE INTERLOCK	TURNS OFF HIGH VOLTAGE INSIDE TANK WHEN TANK PRESSURE ≥ 1 MICRON
T_1 & T_2	TEMPERATURE INTERLOCK	PERMITS V1R & V2R TO OPEN WHEN LOW TEMPERATURE BAFFLE ≤ -90°C. CLOSES V1R & V2R WHEN BAFFLE > -90°C.
T_3 & T_4	TEMPERATURE INTERLOCK	ADMITS REFRIGERANT TO -110°C BAFFLE WHEN -38°C BAFFLE ≤ -30°C
T_5 & T_6	TEMPERATURE INTERLOCK	ADMITS REFRIGERANT TO -38°C BAFFLE WHEN H-1 & H-2 UPPER BARREL TEMPERATURE ≤ 10°C.
RVI	ROUGHING VALVE INTERLOCK	PREVENTS V1R & V2R FROM OPENING WHEN V5R IS OPEN. PREVENTS V5R FROM OPENING WHEN V1R OR V2R ARE OPEN

	LEGEND
TC	THERMOCOUPLE GAGE
⊘	BOURDON VACUUM GAGE
⋈	DIAPHRAGM VALVE
⧓	AIR OPERATED GATE VALVE
PG	PIRANI GAGE
HTSD	MERCOID HIGH TEMPERATURE SHUT DOWN SWITCH
ION	ION GAGE
T	TEMPERATURE INTERLOCK
⊠	HAND OPERATED GATE VALVE

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Fig. 12

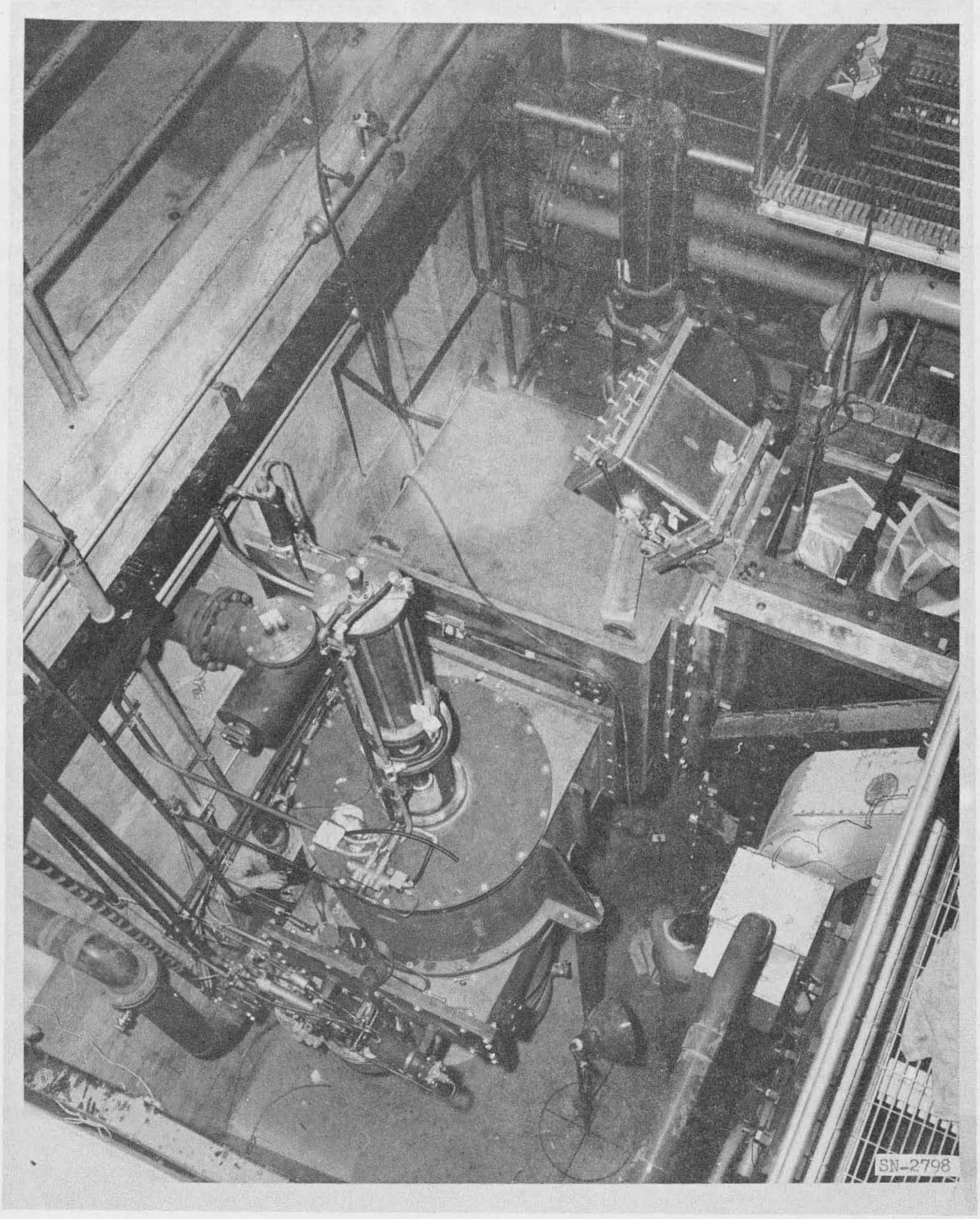

Fig. 13

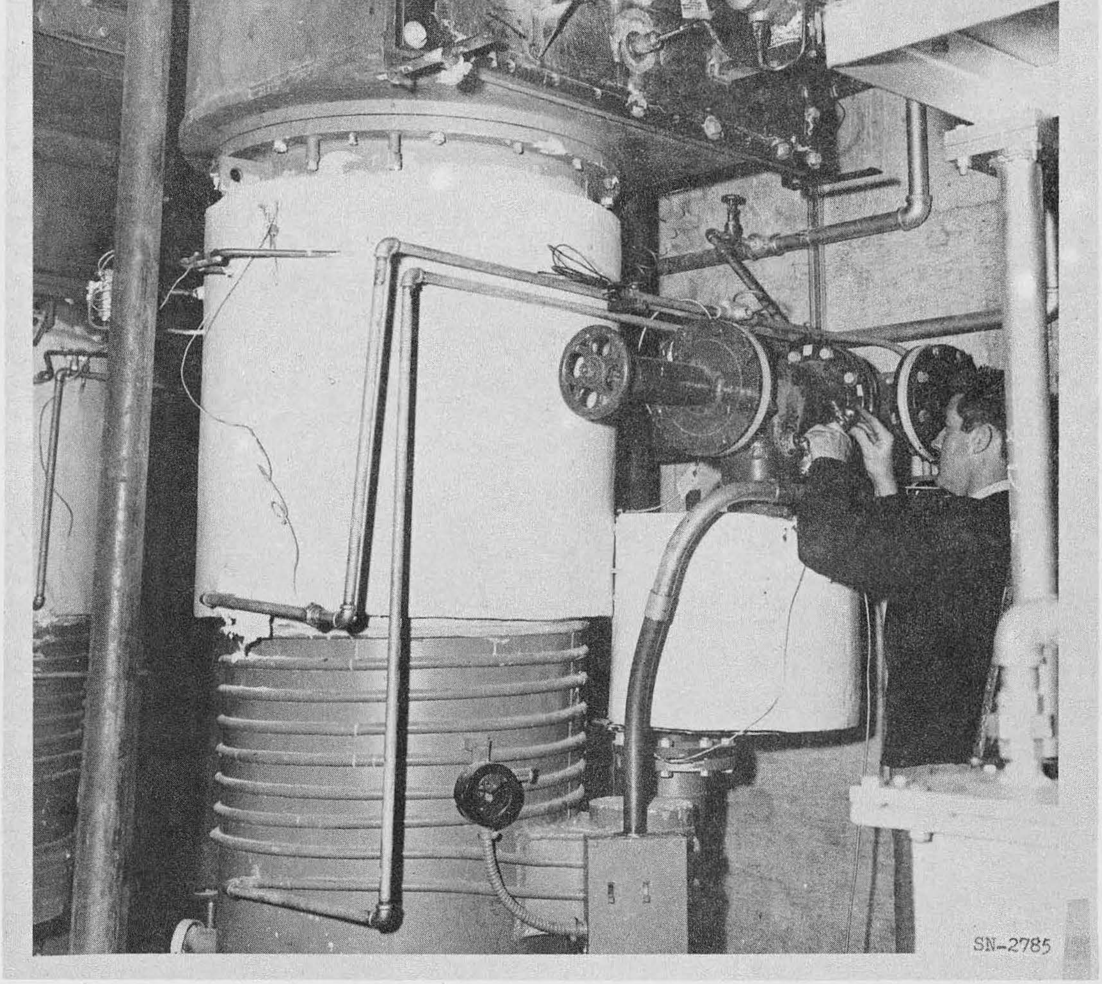

Fig. 14

The particular instrumentation that provides this protection is summarized as follows:

1. PG1 does not permit opening the diffusion pump gate valves until the tank pressure is less than or equal to 100 microns. This minimizes the high-pressure backstreaming. PG1 also closes the diffusion pump gate valves in case of a pressure burst to above 100 microns in the tank.

2. PG2 and PG3 do not permit the diffusion pump gate valves to open nor the pump heaters to come on when the forepressure exceeds 250 microns, the limiting forepressure of the pumps. This prevents the pumps from backstreaming into the tank during this period of unstable operation. PG2 and PG3 also close the gate valves and turn off the heaters in the event of forepump failure or any other cause that permits the forepressure to exceed its limiting value for stable pump operation.

3. T1 and T2 do not permit the diffusion pump gate valves to open until the low-temperature baffle is sufficiently cold to trap out backstreaming mercury. T1 and T2 also close the main gate valves in case of refrigeration-system failure, or for any other event causing the low-temperature baffle to exceed -90°C.

Any discussion of mercury-pumping systems should include mention of the toxicity of mercury vapor. A considerable body of literature exists concerning the health hazards of mercury (References 13 and 14 for example). Much of the information is

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[13] N. I. Sax, "Handbook of Dangerous Materials," Reinhold, 1951

[14] Beauchamp and Tebbins, Am. Ind. Hygiene Assoc. Quart. 12, 171 (1951)

inapplicable to the operation of mercury vacuum systems, but certain of the precautions should be adopted to minimize the possibilities of mercury poisoning.

(a) The exhaust of any mechanical pump that is backing a mercury diffusion pump should be vented outside into the open air.

(b) A mercury diffusion pump should never be disassembled or opened to air when it is still warm -- the high vapor pressure of mercury under these conditions makes this procedure especially dangerous.

(c) Welding or machining of parts that have been contaminated with mercury should be done in well-ventilated areas, preferably in the open air, by personnel protected with respirators and nonporous gloves.

(d) Disassembly of mercury pumps, cleaning of traps, etc., should be done in well-ventilated areas. Splash pans should be provided to catch spills, and free mercury so caught should be picked up and kept in closed containers. In the event of a large spill in an unconstrained area the mercury should be covered as soon as possible with water or a proprietary powder, Hg-X.

(e) It is advisable not to smoke while working with mercury-contaminated parts. It is very easy to contaminate the object being smoked with mercury from the hands and thence ingest it.

(f) Thorough washing of the person as well as of exposed articles of clothing is recommended after working with mercury-contaminated parts.

(g) As is usual in such matters, the standards set up for toxic levels of mercury are extremely conservative and in some cases unrealistic. For example, a toxic dose discovered by probing the floor in a well-ventilated room is not detectable at nose height. Commercial mercury-vapor detectors are available from General Electric and Harold Kruger Instruments.

In closing, it may be of interest that many of the techniques described in this paper were evolved during the construction of a vacuum system of some 220,000 cubic feet in volume. Forty-eight 32-inch mercury diffusion pumps were used to bring the tank down to a base pressure (untrapped) of 2×10^{-6} mm of Hg. A leak rate of 50 micron liters per second was attained by a leak-hunting procedure in which it was necessary to establish radio communication between the leak probers and the personnel on the leak detectors. The successful operation of this immense vacuum system indicates the possible performance attainable by the application of the technology described.

The Technology of Large Mercury-Pumped Vacuum Systems

List of Figures