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EQUIPMENT AND TECHNIQUES FOR MAKING PRESSURE MEASUREMENTS
IN SUPERSONIC WIND TUNNELS AT MACH NUMBERS UP TO 5

11 August 1952



U. S. NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

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NAVORD Report 2580

Aeroballistic Research Report 119

EQUIPMENT AND TECHNIQUES FOR MAKING PRESSURE MEASUREMENTS
IN SUPERSONIC WIND TUNNELS AT MACH NUMBERS UP TO 5

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ABSTRACT: The equipment and techniques described in detail in this report were developed especially for use in the Intermittent Supersonic Wind Tunnel for measuring pressures where the stabilization time is very important. The equipment consists principally of a manometer bank of 72 tubes with necessary valves, vacuum reference systems, special illumination which makes it possible to read meniscus positions with an accuracy of better than 0.004 inches, cameras for photographic registration, control equipment which makes semi-automatic operation possible, and a negative reader for taking data off the negatives. The techniques described give procedures for determining the dimensions of tubes running from the model to the pressure measuring equipment so that stabilization times will be equal to or shorter than the allowable blowing times. The theoretical basis for the procedure is given in the reference, NOLM 10677. An actual example of determining tube dimensions is worked out to illustrate the use of the procedure. This procedure, in effect, puts tubing system design on an engineering basis.

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The work described in this report makes it practicable to make pressure-measurements on a production basis in the Intermittent Supersonic Wind Tunnel at Mach numbers up to five. Theoretical work (Kendall, J. M., Time Lags Due to Compressible-Poiseuille Flow Resistance in Pressure Measuring Systems, Naval Ordnance Laboratory Memorandum 10677 (May 1950)), which preceded the building of the equipment described here, indicates what are the important factors in the stabilization time of a pressure measuring system and how the factors of the system may be controlled to give the minimum stabilization time. Minimizing the stabilization time is extremely important in the operation of supersonic wind tunnels, especially those of the intermittent type where the duration of a blow is strictly limited. The equipment was originally built especially for obtaining pressure distribution measurements over models at Mach numbers 5.18 and 4.28 but it has since been satisfactorily used at all Mach numbers between 5.18 and 1.56. A modification of the manometer banks currently being made makes it possible to extend the maximum pressure possible to measure up to full atmospheric pressure. A worthwhile modification of the negative reader yet to be made will incorporate photo-cell equipment to make the reading of the meniscus positions automatic with an IBM card punched to record the reading. This work was sponsored by the Navy Bureau of Ordnance under task number NOL-188-52.

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IN SUPERSONIC WIND TUNNELS AT MACH NUMBERS UP TO 5

INTRODUCTORY REMARKS

1. The equipment described in this report was developed for use with the Naval Ordnance Laboratory Supersonic Wind Tunnel at White Oak, Silver Spring, Maryland. The equipment makes it possible to determine pressure distributions over the surface of a model in the test section of the wind tunnel at all the currently usable Mach numbers 5.18 and down. Because of the built-in automatic control and photographic registration, it is easily possible to operate the equipment with no more than two persons. Also described in this report is a film reader which takes data directly from the photographic negatives, and by an analog mechanism directly gives the data in pressure, pressure ratio, or pressure coefficient form, depending on the way the reader is set up.

2. The manometer has a bank of 72 glass tubes of which 63 are available for simultaneous measurement of pressures. When the tunnel operator begins the blow, the automatic control is started. It performs all subsequent operations required, such as turning on the illumination for photographing the meniscus positions, opening the valves in the leads between the model and manometer, etc., and stopping the wind tunnel after the photographs are taken. In addition to reducing the number of persons required for operating the equipment, the automatic control provides a precisely timed sequence for the various parts of the operation. Furthermore, it practically eliminates the possibility of human error in the sequence of operations, where a mistake such as opening the valves at the wrong time would cause a costly wind-tunnel shutdown.

3. The successful performance of this equipment is dependent on the proper layout of the model design and dimensions of the tubes which run between the model and the manometer.

4. The optimum dimensions for the tubes, and other considerations are covered in NOLM 10677, which is theoretical analysis of the stabilization time of pressure measuring systems. An improper

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proportioning of the tubes can easily increase the stabilizing time so greatly that it becomes impossible to attain stabilization within the allowable blowing time. On the other hand, decreasing the stabilizing time even a small amount makes it possible to increase the number of blows per day by an appreciable amount. At Mach 5.18, where the test chamber pressure is about 1 mm Hg, it is easily possible, when the tubing is properly designed, to attain stabilization to 1% in less than 18 seconds when initially starting with atmospheric air pressure in the system. If the meniscus positions are held between blows instead of returning them to the zero positions, the blowing time can be cut even a little shorter.

GENERAL DESCRIPTION OF EQUIPMENT

5. Very approximately, the over-all dimensions of the equipment are 9 feet wide, by 8 feet long by 4 1/2 feet high. As can be seen in Figure 1, which gives an over-all view, the equipment consists essentially of three parts: (1) the manometer banks with the reflector and lamps, (each manometer bank is 26" wide); (2) the vacuum pumping equipment used to maintain the vacuum reference for the manometers; and (3) the photographic equipment and control equipment. All of this equipment together weighs about 800 pounds. The frame work is welded angle iron construction painted "NOL Wind-Tunnel Green." The equipment is mounted on casters so that it can be rolled aside when not in use.

6. At least one operator is required to operate the wind tunnel, which includes setting the angle of attack of the model, and starting the blow when everything is in readiness. A second operator is required on the manometer equipment to operate the photographic equipment. He is required to load the cameras, pull up the film holder cover slides for the film holders before the blow starts, put back the film holder cover slides after the blow, and remove the film holders. The three cameras may be seen in Figure 1 on the camera table in the foreground.

7. When model changes and nozzle changes are to be made, it is, of course, necessary to make use of a different operating personnel.

CONTROL EQUIPMENT

8. The entire equipment operates almost entirely automatically. A controller, or programmer is used to do this. It is

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located under the middle camera, as seen in Figure 1. When the operator decides everything is in readiness to make a blow, he presses the start button on the wind-tunnel control console. Unless he presses the emergency stop button, every action thereafter is done automatically with the exception of the handling of the photographic films. The films are manually loaded in the cameras, the film holder cover slides are manually removed before the exposure and then are manually replaced, and the film holder taken out of the camera. All other operations, however, are carried out automatically. The purpose of having the operation as nearly automatic as possible is to:

- (a) Give a precisely controlled and timed sequence of operations.
- (b) Eliminate the possibility of human errors, which might cause costly shutdowns of the wind tunnel.
- (c) Reduce the number of personnel required to operate the equipment. For the higher Mach numbers where it is necessary to wait two or three minutes or longer, between blows for the pumping equipment to reduce the sphere pressure to the required pressure, two persons can operate the wind tunnel and manometer equipment. One man operates the wind tunnel and the other handles the camera films.
- (d) Speed up operations. When low Mach numbers are used and stabilization times are very short, the blows may be as short as five seconds duration. The sequence of operations required there, is simply too fast for a person to control them manually.

The things controlled are:

- (a) Turn on manometer illumination
- (b) Open manometer valves
- (c) Advance each Veeder counter by one
- (d) Operate camera shutters at the right time
- (e) Close the manometer valves
- (f) Shut off the illumination
- (g) Shut off the wind tunnel
- (h) Shut off the automatic controller

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9. These operations are controlled to an accuracy of about one-tenth of a second. An example of the 18-second program used for a pressure distribution test at Mach numbers 4.28 and 5.18 is as follows:

<u>Time of Operation</u> <u>Seconds</u>	<u>Operation</u>
0	Start of wind tunnel blow
1	Turn on illumination
3	Open manometer valves
15	Advance each Veeder counter by one
16	Operate camera shutters
17	Close manometer valves
18	Shut off wind-tunnel blow
18	Shut off illumination
19	Shut off automatic controller

The schematic diagram of Figure 5 indicates how this program can be carried out.

10. An emergency shut off feature was built into the automatic controller. If it is discovered that, for some reason, after a blow has been started, the tunnel should be shut down as fast as possible, this can be done by pressing the emergency stop. This may be required, for example, because a tube running from the model to the manometer has been broken, or sprung a leak. As soon as this is discovered, the emergency stop button may be pressed which will shut down the tunnel in an orderly fashion. If the manometer valves have not yet opened, the valve opener is sterilized, and the tunnel shut-down simultaneously with the pressing of the emergency button. If, however, the manometer valves have already opened, they will be shut off simultaneously with the pressing of the emergency stop button, and the tunnel will then be shut down. This procedure prevents the forcing of any air at atmospheric pressure into the manometers, as would happen if the tunnel is shut down before the manometer valves are opened. The emergency shut off also sterilizes the camera shutters.

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11. The cycle time can be changed by changing gears in the controller. Changing of the cycle time by this means changes all times in a fixed proportion. The times of the individual events are controlled by the cams operating the microswitches in the controller. Relative changes amongst the various events can be changed by rotating the cams or by machining different cut-away sections of the cams. The cycle time may run from about 4 seconds when a low Mach number is used to about 60 seconds when a high Mach number is used or when the pressures to be measured are a fraction of a mm Hg or when small diameter lead tubes between model and manometer with great flow resistance are used. It is, of course, necessary that the cycle time be set so that the meniscuses position have ample time for stabilization, but no longer than this. A longer time, of course, represents a waste of wind-tunnel blowing time.

12. The controller is mounted on a metal chassis 24" x 12". There are ten cams, each operating a microswitch. The shaft on which the cams are rotated is driven through change gears from a 1/20 hp, 4 pole induction motor whose speed is quite constant at 1760 rpm. The electric circuit diagram for the controller and the valve opener are shown in Figure 5. The cams are made from 5" diameter 1/16" thick sheet 17ST aluminum. The microswitches have rollers on the ends of the actuating arms which bear on the cams. The microswitches are actuated by cut-away sections of the cams and the times may be controlled to within one-tenth second. The main shaft on which the cams are mounted makes one revolution for each cycle after which it stops automatically at the end of the revolution. Relays in conjunction with two cams and microswitches provide a latch-in in order to cause the motor to turn the cam-shaft exactly one revolution and then stop. The latch-in feature is operated by a signal of .02 seconds or longer. The change gears between the motor and the camshaft may be chosen so that one revolution (which produces one cycle) can be made in time anywhere from about 4 seconds to as long as 60 seconds.

13. A 1/6 hp induction motor operates the manometer valves. The circuit for this valve opener and closer is included in the circuit diagram, Figure 5. This motor is commanded by the controller, except when the emergency stop is operated. To prevent coasting of the motor armature after valves are exactly open or exactly closed, a direct current is passed through coils of the motor to provide a very effective breaking action. This direct current flows through the motor coils only during the cycling time except when the valves are actually operating. At this time, the d.c. is cut off and 115v. a.c. applied to the motor to drive the motor in the normal fashion until the operation of opening or closing of the valves is complete, and then the direct current again passed through the motor coils.

DESCRIPTION OF THE MANOMETER BANKS

14. Figure 6 shows the general arrangement of the multiple manometer with the vacuum reference system. There are three banks of manometers, each an independent unit having 24 tubes and its own vacuum reference system. Each tube in each bank has its own valve which connects the manometer tube with the vacuum reference system, the model in the wind tunnel, or locks the reading in the manometer by shutting off all air flow in or out of the tube. The valves are operated by crank arms attached to the long shaft extending the width of the three banks. The shaft is operated by a crank and connecting rod system driven by the motor and gear system of the valve opener and closer. Each manometer tank is connected to its own vacuum pump system through a piece of 1 1/8" diameter copper tube. The vacuum pump system for each bank consists of a cold trap having a 4 quart Dewar flask filled with alcohol and dry ice, a diffusion pump with an air blower for cooling, and a Welch vacuum pump. A McLeod gage as shown in Figure 7, is connected to each vacuum reference system through three refrigeration packless valves, so that the McLeod gage can be connected to any one of the three systems. The piping for the McLeod gage is 3/8" diameter copper tubing with flare nut fittings. The large copper pipe of 1 1/8" diameter used for connecting the manometer tanks with the vacuum reference systems is soft soldered into copper elbows. These fittings, which are of the type used for copper water pipe systems in ordinary buildings, have been found to be very satisfactory for this work. The large diameter 1 1/8" piping reduces the air flow resistance for the air from the tank to the vacuum reference systems to a low value, so that it is easy to maintain a good vacuum reference in the tanks. The pressure during operation is usually less than two microns Hg. The joints between the copper elbows and the tanks are flanged joints sealed with O rings about 1 1/2" diameter. These joints can be taken apart by removing four screws.

Valves

15. Figure 8 is a schematic diagram (end view) of the arrangement of the manometer. It shows the manometer valve (for one tube), the glass manometer U tube, the tank with the fluid level, the meniscus in the glass tube, the flanged connection on the tank for connecting to the vacuum channel and connecting pipes between the vacuum reference channel in the valve bank and the tank. The lamp box and reflectors are also shown here in order to show their relation to the rest of the equipment.

16. It is to be noted that the area of the fluid surface in the tank is about fifty times greater than the combined fluid surfaces

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in all twenty-four menisciuses. This has been so arranged purposely because of several advantages. First of all, the sensitivity of a manometer of this type is (effectively) almost twice as sensitive as the simple U tube manometer. Only one meniscus must be read. The tank level is usually determined by having the end tubes always connected to the vacuum reference and by using the meniscus positions as the starting points for measuring the positions of all other menisciuses which are indicating pressures to be measured. The reference tube menisciuses, which seldom change their positions by more than one quarter of an inch, do so only when most of the other 22 tubes have large deflections. Another advantage of having the large surface area for the fluid in the tank is that it practically eliminates the error due to fluid remaining on the inside surfaces of the glass tubes when a large pressure is applied to the tube, and the menisciuses move far down. It is true that considerable fluid remains sticking to the inside surfaces of the glass, and therefore just this much fluid is temporarily subtracted from the total fluid in the system. In a simple U tube manometer, this amount of fluid subtracted from the system would make it difficult to get an accurate reading of meniscus positions. But with the large surface area of fluid in the tank of the manometer described here, the subtraction of this fluid which sticks to inside surfaces causes only a negligible error. The large tank fluid surface is changed by an amount that is only about 2% of the error (under worst conditions) that would occur in judging pressure by measuring only one meniscus of a simple U tube manometer. Actually, in the manometer described here, even this error is practically non-existent since the reference tubes are simultaneously read each time, the other tubes are read and the true indication of pressure is the difference in elevations of the tank fluid surface and tube meniscus surface. Hence, no time need be wasted waiting for the fluid to run down the inside surfaces of the glass tubes before reading, (or photographing).

17. Each manometer tube is individually returned to the tank as is shown in Figure 8. This has the disadvantage, as pointed out in the discussion on the optical characteristics, of blocking some of the illumination from the reflector. But this disadvantage is more than offset by the advantage that the action of each tube in no way affects any other tube. This independence is not obtained when a common return conduit is provided for the joint use of all tubes. The difficulty with the common return conduit system is that when large pressures are suddenly and simultaneously applied to most of the tubes in a bank (a condition which is repeated with each blow of an intermittent supersonic wind tunnel), an excess pressure due to dynamic action in the common conduit temporarily forces the fluid to a higher level in the remaining tubes, including the reference tubes. This is quite

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undesirable because the fluid then might get into the valves where some of it will remain to produce a slug of fluid in the small openings there. Such a slug would cause an obstruction to the low pressure air flow to and from these manometer tubes.

18. When a manometer fluid is used which has a low kinematic viscosity, (e.g., alkazene or mercury) such fluid will oscillate in the manometer tube after a sudden change of pressure is applied to this manometer tube. It is then necessary to wait until the oscillation dies down before the meniscus position can be accurately recorded. This circumstance costs extra wind-tunnel blowing time, and this is especially undesirable for an intermittent supersonic wind tunnel. It is a relatively easy matter, however, to prevent this oscillation from occurring by putting in a restricting orifice in the manometer tube so as to provide damping to the oscillatory system. By experiment, it was found that satisfactory results were obtained by restricting the flow at the O ring seal where the glass tube returns to the tank. The sealing gland here has a hole only 0.093 inches in diameter and 0.250 inches long. This restriction provides approximately critical damping for both alkazene and mercury. For fluids like DC 200, 10 centistokes, or dibutylphthalate it provides a damping slightly greater than critical, but even so, the response time is still generally satisfactory. When mercury is used as the manometer fluid another kind of oscillatory trouble was at first experienced. Even when the damping from the restricting orifices is effective, oscillations persisted for a long time. After a search, the trouble was found to be due to surface waves which were set up in the mercury in the tank. The waves were initiated by the sudden return of a quantity of mercury to the tank by the tubes. Whenever the pressure applied to the tubes was changed, a series of baffles were put in the tank which effectively stopped the surface waves without harming the manometer performance in any way. The general arrangement of this anti-sloshing baffle used in the tank is shown in Figure 13. The surface of the mercury in the tank is broken up into eight smaller surfaces. There are connecting orifices joining the various portions with each other. It might be mentioned that the effect of the orifices with mercury flowing through them is not to provide viscous damping. This is practically impossible because the kinematic viscosity of mercury is practically zero. The damping comes about because turbulence is set up in the mercury around the orifices as the mercury flows through. This action is quite sufficient to stop the undesirable surface waves.

19. Figure 9 shows a schematic diagram of the valve bank which includes the valve plunger with O rings acting as piston rings for vacuum tight seals, the two port holes in the valve bank, the connection between the valve bank and tank to provide a vacuum reference in the

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vacuum reference channel, and the O ring packing seal between the glass manometer tubes and the metal of the valve bank.

20. The holes in the valve bank in which the valve plungers slide are very nearly $5/16$ inches inside diameter. The surface of each hole was lapped with a copper lap and fine emery powder. The surface finish is of 8 to 16 microinches of roughness. It is first necessary to remove the machine marks left by the reamer before the final polishing is done. These marks may be two or three thousand microinches deep unless the reaming is done properly. These marks should be avoided since it is quite a time consuming procedure to lap them out. After the holes in the valve bank were all lapped to the required degree of smoothness it was necessary to round the edges of the port holes very carefully in order to prevent the O rings from getting cut or abraided as they slide past the ports. A hole $3/32$ inches in diameter drilled in the $5/16$ inch diameter plunger hole naturally has very sharp burrs around the edge. The lapping process does not remove the burrs, and does no rounding of the sharp edges whatsoever. It is therefore necessary to round and polish these edges if satisfactory operation of the valves is expected. This rounding of the edges is a very difficult and unsatisfactory process unless it is done properly. After a great deal of thought and some experimenting was done, a process was finally worked out which proved to be entirely satisfactory from the viewpoints of both mechanical results and cost of labor. The tools and method are indicated in the schematic diagram of Figure 10. A punch was made with a projection on one side as shown in the details having the shape indicated by sections A-A and B-B. The rounded portion around the projection which gets forced in the metal of the valve bank around the port hole was very carefully polished.

21. The impression made in the valve bank by this polished surface was equally well polished. Using the tools shown in Figure 10, it was possible to round one hole in about one minute. The actual operation was done in a large drill press with the electric motor shut off, the drill press serving merely as an arbor press. A torque wrench was attached to the drill press handle so that a known and reproducible force of about 800 pounds could be applied to the swaging tool each time. The wedge plunger was made of brass, which is considerably softer than steel and so did not mark the inside polished surface of the valve plunger hole. It was usually necessary to use the extracting nut to remove the tools from the hole. The wedge angle used is about 20° . The swaging tool was used on both the vacuum reference channel ports and the nipple ports. It is advisable before using a swaging tool of this sort to try it out on a split block with $5/16$ inch holes drilled in and $3/32$ inch holes from the side in order to make sure that the swaging operation is satisfactory before trying it out on the expensive valve bank. An unsatisfactory swage could easily ruin the

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entire bank. The swaging punch was made of tool steel and hardened to Rockwell C55 around the projection. It is quite certain that the port holes must be rounded, or the O rings will not function properly.

22. The O ring plungers, as shown in Figure 9, were made from 5/16 inch diameter drill rod turned on a screw machine. The spacing of the O rings is such that the valve can connect the manometer tube either with the vacuum reference channel, or with the nipple for the tube running to the model in the wind tunnel. In addition, with the valve plunger half way between these two positions, the manometer is completely cut off and will hold approximately whatever reading the manometer has before cutting off. Double O rings are used at each place on the plunger to give added protection against leakage. If one O ring is damaged, the other O ring is still entirely capable of holding the vacuum. A life test of the O rings on this type of plunger showed that O rings life is considerably greater than 10,000 cycles, at which point the test was stopped.

23. A 3/32 inch diameter hole is drilled on the axis of the plunger to provide the communication between the ports and the manometer tube. Since this type of valve consists of a sort of piston in a cylinder, the manometer does not hold its reading accurately when the valve is in the off position. The plunger in moving up from the measuring position to the off position increases the volume of space in the manometer above the meniscus. Therefore, the reading to be held will be indicated by too low a pressure. Hence, with this type of valve, accurate readings can be taken only when the valve plunger connects the manometer to the nipple running to the model in the wind tunnel.

24. The valve plunger has a 0.065" wide slot milled in the top end, and a pin hole drilled through the plunger normal to the slot. A connecting link 1/16 inch thick is held in the slot by a cotter pin. The other end of the connecting link is fastened with another cotter pin into a slot in the crank arm mounted in the valve shaft. When it is desired to disconnect a manometer tube which is not needed in the bank, the crank arm cotter pin is removed and inserted in the hole in the plunger provided for this purpose. The location of this hole is shown in Figure 10. In this way, any number of the tubes in a bank can be taken out of service. When a tube is not in use, it is necessary to disconnect its plunger from the valve shaft as just described so that no air can get into the vacuum reference system when the valve shaft is rotated.

25. The vacuum reference channel also shown in Figure 10 is connected to the tank by means of a pipe at each end of the valve bank. These two pipes are sloping downward back to the tank, as are also the large holes through the ends of the valve bank. The purpose of these slopes is to make sure that any manometer fluid which finds its way

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into the vacuum reference channel is able to run back into the tank where it belongs.

26. Both ends of the glass tube are connected to the metal parts of the valve and tank by means of O ring packing gland seals. The seal consists of 2 or 3 O rings between the glass and metal with a metal O ring retainer which puts some compression on the O rings. The amount of compression in the O rings by the retainer is nowhere great enough to cause breakage of the glass tube ends. These seals, when properly greased with Dow Corning high vacuum grease have proved to be almost completely trouble free with no leaks whatever. Despite the fact that there are 48 of these seals in each manometer bank, plus all the O ring seals in the valve plungers, the over-all leakage is quite negligible as evidenced by the ease with which the reference vacuum may be brought down to two microns or less. As discussed elsewhere in this report, the greatest trouble from failure to reduce the vacuum reference to 2 microns is due to outgassing of the system, especially the manometer fluid. The tightness of the O ring seals is no doubt helped by the manometer fluid. The principle experience so far has been with alkazene as the manometer fluid. This fluid attacks O rings very rapidly causing almost instant swelling. The O rings in the packing gland seals are completely confined, so that they cannot swell to a greater volume that is permitted by the available volume. When this much swelling occurs, the seals become perfect for all practical purposes.

27. Referring once more to Figure 10, it is seen that if the valve plunger is removed from the valve bank by pulling it up, the inside surface of the hole vacated by the valve plunger is of the same diameter and in line with the glass manometer tube. The advantage of this arrangement is that the glass manometer tubes can easily be cleaned by running a little square piece of cloth (in firearms terminology, a "gun patch") on the end of a ramrod down into the glass. Before this is done, the vacuum pump is turned over two or three turns by hand which sucks the manometer fluid down and out of the way, so that the gun patch may be run into the glass the entire length of the glass tube without dipping into the manometer fluid. It is sometimes necessary to clean the tubes, especially when some Dow Corning high vacuum grease gets mixed into the alkazene. These two substances are not compatible so that the vacuum grease coats or fouls the inside surface of the glass tube, especially where the zero pressure position of the meniscus is. A similar trouble was found when mercury is the manometer fluid. Since it was discovered that this grease and alkazene or mercury are incompatible, a bare minimum quantity of the grease is applied to the valve plunger O rings. After this, no further trouble was experienced from this cause.

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Glass Tubing

28. The glass tubing used is so called 10 mm (outside diameter) pyrex tubing. As purchased in twenty-five pound lots this tubing comes in four foot lengths, and about 1 mm wall thickness. As received, the tolerance on outside diameter appears to be about plus or minus 1 mm, which tolerance is too great. Precision glass tubing could be bought, but this tubing is prohibitively expensive. What was done and found to be quite satisfactory, was to purchase about ten times as much standard tubing as was expected to be used, and then to select the pieces which had dimensions close enough to the required values to work satisfactory with the O ring seals. It was found that by using a tolerance of plus or minus one-tenth of a mm on the outside diameter, about 15% of the pieces of tube could be passed.

29. There is another reason why it is desirable to have the tubing of uniform diameter. The surface tension of the transparent fluids used in the manometer all have surface tension capillarity of about 25 dynes/cm. This surface tension is responsible for lifting up the bottom of the meniscus by an amount equal to about 1 mm. The amount of this capillary effect is greater the smaller the inside diameter of the tube, being approximately inversely proportional to the inside diameter. A ten percent change in diameter then would cause about 0.1 mm change. This is the maximum error which can be tolerated in the accuracy of the manometer. Therefore, the inside tube diameter tolerance should be held to approximately one tenth this amount. The one-tenth mm tolerance on the outside diameter of the tubing just about insures the required accuracy.

30. The selected four foot lengths of tube were bent into the required U shape by a professional glass blower. He used a special gas burner which heated a length of the tube equal to the amount which forms the bend and the tube was bent around a wooden form. The glass blower was able to bend the tubes at the rate of about four per minute, so that bending all of the glass tubes required about twenty minutes. The ends of the glass tubes were then sawed to length using a so-called rubber cut-off wheel cooled with two streams of water. A fixture made of wood made it easily possible to hold all lengths to the required dimensions with a tolerance of about plus or minus 0.003 inch. After cutting the ends to length, the ends of the tubes were fire polished just enough to begin to obliterate the saw cut marks. This fire polishing helps to remove strains which makes the tubes a little less likely to break while handling them. A greater amount of fire polishing would have reduced the diameter of the ends sufficiently to spoil the 0.1 mm tolerance.

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Manometer Fluids

31. The first requirement for a fluid for use in a manometer which must measure low pressures (i.e., down to 1 mm Hg and less) is that the fluid have a very low vapor pressure at room temperature. Otherwise, these fluids will vaporize when the pressure is sufficiently reduced. This requirement immediately throws out such fluids as water and alcohol, or mixtures of these fluids with other fluids such as glycerine to obtain a fluid with a different density. There are several fluids, however, which meet the requirement of low vapor pressure. These fluids are listed in the table below along with their density ρ in grams/cm³ and kinematic viscosity in centistokes.

Fluid	density g/cm ³	kinematic viscosity centistokes
Dow Corning 200	.93	10
Dibutylphthalate	1.05	10
Alkazene (dibromoethylbenzine)	1.739	3
Acetylene tetrabromide (C ₂ H ₂ Br ₄)	2.95	--
Mercury	13.6	very low

32. Of these fluids, dibutylphthalate, properly prepared, probably has the lowest vapor pressure, with mercury next, DC 200 next, alkazene next, and acetylene tetrabromide last. No experience has been had with acetylene tetrabromide but it is understood that its vapor pressure is low enough that it might be used in a manometer of the sort described here provided a cold trap is used to condense this fluid as it distills over from the manometer tank to the vacuum pumps. The main purpose of the cold trap is to prevent such fluids from getting into the vacuum pump and contaminating the pump oil there. Both acetylene tetrabromide and alkazene will probably go right through the diffusion pump since the diffusion pump is constantly cleansing its own oil and passing the contaminant on to the forepump. Alkazene distills over from the tank at a rate of about one tablespoon full every 24 hours. The cold traps properly charged with dry ice and alcohol catch the alkazene almost 100%. D.C. 200 is much better than alkazene, while dibutylphthalate and mercury apparently do not distill in sufficient quantity to require a cold trap.

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33. It is desirable to have the kinematic viscosity of manometer fluids which wet the glass surfaces to be as low as possible. The lower the kinematic viscosity, the faster the fluid runs down the inside wall surfaces of the glass tubes. As mentioned elsewhere, the fluid sticking to the inside surfaces of the glass tubes is just so much fluid temporarily removed from the system. The large surface area of the fluid in the tank practically eliminates the effect of the sticking. Clean mercury generally does not wet glass surfaces and hence, from this point of view, is an ideal manometer fluid. In this connection, however, the kinematic viscosity of mercury is of little significance.

34. Mercury and D.C. 200 have no noticeable effect on the rubber in the O ring, and again these two fluids are very good. Alkazine, dibutylphthalate, and acetylene tetrabromide cause very marked swelling of the rubber in O rings. Not only have the O rings increased their dimensions after absorbing any of these three fluids, but they also have decreased their tensile strength and abrasion resistance, both of which effects are very undesirable when the O rings are used as piston rings on the valve plungers. When swollen, the O rings are forced into port holes when the valve plunger is operated, and this is very apt to damage them. Certainly the life of the O rings is greatly reduced by swelling. Even the vapor from alkazine in the course of several weeks seems to cause O rings to swell. No investigation was made of the effect of alkazine or dibutylphthalate on other O ring materials than the usual O ring material which is understood to be synthetic rubber. Where O rings are used only for gaskets to seal joints, the swelling is not in the least harmful, and if anything, the swelling is beneficial in that it probably causes a better seal.

35. As mentioned elsewhere, Dow Corning vacuum grease is not compatible with alkazine, and probably is not compatible with any other fluid with the possible exception of D.C. 200.

36. All of the fluids listed in the table have a certain affinity for contaminants. Even mercury seems to take up a certain amount of moisture. The other fluids are far worse in that they will each absorb a large quantity of air, as well as water vapor, alcohol, benzine, gasoline, varsol, acetone, etc. After cleaning a manometer with any of these solvents, it is necessary to put the empty manometer on a vacuum pump until a good vacuum is obtained. Only then should the fluid be put in.

37. Before putting the fluid in the manometer, however, it is usually worthwhile to give it a treatment to remove as much contaminant as possible. One good treatment is vacuum distillation of the fluid immediately before filling the empty manometer which has been tested

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for vacuum tightness. A variation of the vacuum distillation is to use a "purifier" of the sort shown of Figure 17, which consists of a 5 liter flask, to which a vertical condensing tube has been connected by a glass blower. The condensing tube is water jacketed and cooled with flowing cold water. The fluid boils in the bottom of the flask, condenses on the walls of the condenser, and runs back in the flask to boil again. The volatile components are removed by the cold trap and vacuum pump.

38. The flask is heated by an electric hot plate with a thin sheet of asbestos between hot plate and flask. After the fluid begins to boil, there is a certain amount of so-called bumping, an action resembling miniature explosions in the fluid. A quantity of glass broken into small pieces with sharp edges is supposed to reduce bumping, but it is not entirely effective. The bumping, however, seems to cause no particular harm. The fluid should be boiled in the purifier for perhaps an hour. An examination of the cold trap cooled either with dry ice and alcohol, or with liquid nitrogen usually reveals 10 to 50 m.l. of fluid contaminant given off by the purifier. During the purifying process, a good vacuum of not more than five microns Hg should be maintained, though a considerably higher pressure will still decrease the contamination of the manometer fluid considerably over no purification at all. The purified fluid should be poured immediately and directly from the purifier into the manometer. This direct pouring avoids the possibility of contamination from using an intermediate vessel for pouring. The final conditioning of the fluid must be done in the manometer and should start immediately after it has been poured in from the purifier. The vacuum reference system of the manometer should be started up and kept running until a good vacuum in the vacuum reference system is obtained and all bubble formation in the manometer fluid has ceased. It is just about impossible to make an accurate reading with a manometer which is bubbling on account of the disturbance caused by the formation of the bubbles, their rising to the fluid surface, and then bursting. Sometimes it is necessary to keep the vacuum reference system pumps running several days to get the outgassing of the fluid complete.

39. A small amount of time has been spent searching for hysteresis effects in manometer fluids. In all of the clear fluids which wet glass, no effect which could rightly be called hysteresis has been found. With the large surface of fluid in the tank, the effects of wetting the glass are almost completely eliminated. With mercury the case is quite different. Mercury always seems to have a very rigid skin over its surface, which is probably due to oxidized metal which contaminates most mercury. This skin acts something like a thin skim of ice which forms on the surface of a pond in cold weather. If the skin is broken up, it forms again very quickly. The force required

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to break the skin is sufficient to show up in the pressure in the manometer as a hysteresis. A second cause of hysteresis in mercury comes about by the variable amount which mercury tends to stick to glass. The shape of rising meniscus in a mercury manometer is quite rounded while a falling meniscus is quite flat, and sometimes even concave upward if the mercury is not too pure. The hysteresis effects in mercury limit the accuracy of mercury manometers to about 0.05 mm Hg pressure. A large diameter of over 10 mm inside diameter or larger, and very pure mercury and clean glass would probably make it possible to decrease the 0.05 mm Hg error a little. By using such a fluid as dibutylphthalate, it appears to be possible to reduce the error to 0.001 mm Hg by careful procedure.

Results of Accidents and Mistakes

40. With a manometer equipment as complicated and delicate as the one described here, there are bound to be some mishaps in using it. However, none of the things most apt to happen cause especially serious trouble. Probably the worst mishap that is usually encountered is the coming loose of one of the tubes running between the model in the wind tunnel and the nipple on the manometer bank. If one of the tubes come off, or if one tube is accidentally cut in two, or unexpectedly develops a big leak, nothing happens until the manometer valves are opened after the wind tunnel is started.

41. When the valves are opened, atmospheric air rushes into the defective tube, blows the manometer fluid out of its glass manometer tube, and the air then continues flowing into the tank until the vacuum reference pressure builds to a higher pressure than the pressure on the surface of the model in the wind tunnel. When this happens, manometer fluid begins to flow out through the tubes to the model and flows out the pressure tap holes in the model, and then down the wind tunnel as a fine mist. About this time, it is usually discovered that something is wrong, and the emergency stop is operated. To repair the damage, it is necessary to find out what caused the unexpected leak, repair it, and then blow out each model tube with compressed air to remove all fluid from them. Also, the valves in the manometer should be blown out. The fluid lost should be replaced in the manometer. For the worst case when there are about 24 model tubes to blow out, the total lost time usually amounts to about an hour. Only the bank with the defect is affected. The other two banks, of course, are not affected since they are each on separate vacuum reference systems. In approximately one thousand blows, this mishap has happened twice.

42. Other mishaps are usually not as serious. If, for some reason, the manometer valves are opened at the wrong time so that

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atmospheric air rushes in all of the tubes, nothing much more happens than the loss of the vacuum in the vacuum reference systems. If the valves are turned off, the vacuum pumps usually have a sufficiently good vacuum to take data within four or five minutes.

OPTICAL CONSIDERATIONS

43. One of the most usual methods of illuminating manometer tubes in a bank for reading the meniscus positions is to place tracing paper immediately behind the tubes, and to place lamps behind the paper. This arrangement provides a very uniform illumination which is easy on the eyes and quite satisfactory for reading meniscus positions when a colored fluid is used in the tubes. If, however, a meniscus so illuminated is examined with a microscope, it is found to be very difficult to determine exactly where the meniscus is, or even to find some characteristic feature in the appearance of the meniscus which will serve as a marker to insure reproducible reading of the meniscus position.

44. After a brief investigation to improve the accuracy of reading, it was soon determined that if the meniscus is illuminated with specular light instead of the diffuse light provided by tracing paper with rear lighting, a meniscus position could be determined to an accuracy of better than 0.0001 inch. The lowest point on the meniscus which occurs on the axis of the glass tube then appears as a rounded surface. This may be seen in Figure 3, which is a slight enlargement over the original manometer tube. The illumination which would come through the fluid above the meniscus is abruptly blocked off by the meniscus, so that a dark portion representing the meniscus is clearly visible. The sudden change from full illumination just below the meniscus, to no illumination at the bottom surface of the meniscus serves as a very good marker for determining a meniscus' position, and this arrangement has been used in the manometer described here. It is not necessary, however, that the illumination for the tubes be specular in both directions. In the horizontal direction, the light can be diffused and will not harm the appearance of the meniscus, providing it is specular in the vertical direction. Such a light source is provided by a straight line source which is horizontal. If only one meniscus is to be illuminated, then a straight line filament electric light serves very well. Of course, such a light source must be moved up and down by an external means along with the meniscus. This may be done by attaching the light to the optical system which projects an image of the meniscus on the screen. Figure 11 shows the general arrangement of such an optical system for reading a meniscus position. Included in Figure 11, is a detailed sketch of the view of

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the ground glass screen when the meniscus has been set even with the fiducial mark on the screen. This was done by moving the entire optical system up or down to obtain this setting.

45. The above system is very satisfactory for reading a manometer with one tube. When it is necessary to read the positions of the meniscus of a large number of tubes simultaneously, an entirely different arrangement must be used. Photographic registration is about the simplest means of recording all meniscuses simultaneously. However, it is necessary to provide the proper illumination of the tubes for the camera.

46. For sharp registration of the meniscus, it is necessary, as already discussed, to have specular illumination in the vertical direction and diffuse in the horizontal direction. A straight line filament electric light bulb for each tube is not at all feasible for a manometer with many tubes. Instead, in the multiple manometer in use at the NOL Supersonic Wind Tunnel, a large polished metal elliptical shaped reflector in conjunction with a row of incandescent lights in a narrow box for the line source of illumination is used. Figure 12 shows this arrangement. The metal reflector was made by bending a flat sheet of polished stainless steel to the elliptical shape. It is held in this shape by a wooden frame, whose ribs were accurately cut on the band saw to the required ellipse. The metal is held to the ribs by many wood screws. The lamp source is made of a box whose length is equal to total width of the three manometer banks. The 60 watt light bulbs were spaced about four inches apart. Over the top of the box is a narrow strip of tracing paper which serves to give a uniformly illuminated surface which is long and narrow. This surface, of course, is not accurately a line source of illumination, but by experiment it was found that it approximated the line source sufficiently well to give good clear meniscuses. A blower has been provided at one end of the box to blow air through the length of the box. This is necessary because the lamps are dissipating over 1 k.w. of heat, which unless blown away by constant air circulation, would soon scorch the paper.

47. The three cameras visible in Figure 1, are home made, each consisting of a wooden box with the necessary accessories mounted in the box. The so-called "camera backs" of commercial manufacture, provide a ground glass viewing screen and also a means of receiving the cut film holders which are inserted in the cameras just before taking pictures. The shutters are home made and consist of an eight inch diameter disk of 1/32" thick sheet, 24 ST aluminum with a 2 1/2" diameter hole cut in the disk between the periphery and center of the disk. When the disk rotates one revolution, this hole passes in back of the lens and lets light through to the film for an exposure

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of about $1/5$ second. The three shutters are all geared together and operate simultaneously. They are driven by a $1/20$ hp induction motor which causes them to make one revolution only in response to a command from the controller. The lenses are Ilex Paragon Anastigmats F 4.5, focus 10", series S, which were obtained from the photographic supply department of the Naval Air Station.

48. The three particular lenses in use in these cameras were chosen from a group of about twenty-five lenses so that the focal lengths of the three were very nearly equal. In fact, the difference in focal lengths are less than 0.005" so that the sizes of images produced by the lenses, (when properly focused) are equal to within 0.05%. In using the lenses, the stops are usually set at about F 11 to give proper exposure to the film used which is Eastman Iso-Pan 8 x 10 cut film. This film appears to be entirely satisfactory, though probably other types of 8 x 10 cut film would also be satisfactory.

49. The axis of the lenses are mounted a little below the center of the camera box because the images of the meniscus are generally below the level of the cameras. This is shown in Figure 12. The lens boards are in a vertical plane which makes them parallel to the plane of the manometer tubes. The film is also in a vertical plane. With this arrangement, the images of the menisci are recorded on the films with their positions in exact proportion to the actual meniscus positions in the manometer. It is possible, therefore, to scale the negatives and have accurate results. The horizontal distance between the manometer tubes and the diaphragms of the lenses is exactly 48 inches. The distance for a good focus between the lens diaphragm and the film is very nearly 12 inches. Therefore, the size of the image produced by a lens is very nearly one-fourth of the size of the object. The cameras on the camera table are held at this fixed distance of 48 inches from the manometer banks by means of an angle iron frame work, which fastens the camera table to the manometer frame work. By this means, the size of the images photographed on the films is not permitted to vary because of relative motion between cameras and the manometer banks. The meniscus can move down from the zero pressure position to a distance of about 21 inches lower. Hence, the maximum meniscus deflection in the camera image is about 5 inches, which is about one-half of the 10-inch height of the film. The remaining height is used to record the blow number by photographing an electrically operated veeder counter, and also to photograph a fluorescent light with the respective tube numbers printed on it. Figure 2 shows a sample contact print of one of the camera pictures, which, in addition to the manometer tubes, includes the fluorescent light numbers and a veeder counter number in the extreme upper right-hand corner. The veeder counter number is quite small and sometimes difficult to see unless one is accustomed to reading it. A more legible veeder counter would be

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desirable. It was found to be necessary to add a resistance of approximately 1500 ohms in series with each of the fluorescent light tubes in order to prevent these lights from causing an overexposure in the film. Such overexposure would have decreased the legibility of manometer tube numbers printed on the fluorescent light tube.

Accuracy of Photographic Negatives

50. As mentioned above, when the manometer tube illumination is suitable, it is possible to pick the bottom of a meniscus with an accuracy of 0.0001" or better. This accuracy is considerably better than can generally be recorded on a photographic negative. In the original negative or even in the positive contact print of Figure 2, it is easily possible to pick the bottom of the meniscus with a reproducibility of 0.001". Since the reduction of the size of image in the photograph over the actual manometer is by a factor of 4, the accuracy of picking the meniscus in the negative referred to, the position in the actual manometer is about 0.004". If the manometer fluid is mercury, then the accuracy is 0.1 mm Hg, if measured in metric units, or 0.004" of Hg measured in English units. If the manometer fluid is D.C. 200 silicone, the accuracy is 0.00266" of Hg or 0.0067 mm Hg. The wires which are stretched before the manometer banks for calibration purposes are located about 1/2" out in front of the tube. The parallax which results from this arrangement has been calculated and allowed for in computing the over-all scale factors used in reading the negatives. An 8 x 10 negative to cover 24 manometer tubes may seem to be larger than necessary, but if any smaller size negative is used, the loss of accuracy would be in proportion to the reduction in negative dimensions. From experience thus far obtained, it is felt that these large size negatives are well justified, especially when working with high Mach numbers where pressures may be less than 1 mm Hg (0.040" Hg). With alkazene or D.C. 200 fluid in the manometers, this pressure can be read with an accuracy of about 1%.

51. As discussed in the section on the manometer, it is necessary to have the return tubes of the manometer return individually to the tank as shown in Figure 8. Since the tubes are of glass, they permit light to go through them, provided the manometer fluid is a transparent fluid. These tubes, nevertheless, cause a certain amount of interference with the illumination, which shows up in the photographs as several lines running up and down in each manometer tube, which may be seen in Figure 2 (enlarged). These lines are caused by the refractive effects of the return tubes on the front tubes and are not particularly objectionable, since the menisci can be picked without loss of accuracy in spite of them.

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52. Between each of the front tubes, there is a wooden slat to block off all light which comes between the tubes as can be seen in Figure 2. The purpose of slats is to make it easier for the person taking data off the negatives to see the tubes without having to disregard a lot of confusing detail which might be seen between the tubes. The slats between the fifth and sixth tubes, between the tenth and eleventh tubes, between the fifteenth and sixteenth tubes, and between the twentieth and twenty-first tubes, have respectively one, two, three, and four holes bored through the wood in order to make it possible to identify tubes independently of the fluorescent number lamp located above the tubes.

TUBES FROM MODEL TO MANOMETER

53. It seems to be the custom in constructing models for obtaining pressure distributions to use metal tubes in the model which run from the pressure tap holes on the model surface, and are usually of sufficient length to extend out past the downstream end of the sting so that other tubes may be attached to them which lead to the manometer bank outside the wind tunnel. These tubes are usually of a somewhat larger diameter than those which are inside the model, and may be either metal, plastic, or rubber. It has been the experience of the writer that as far as the tube material goes, it makes little difference which is used as long as the tubing has satisfactory mechanical characteristics, provided that the pressures to be measured are about 20 mm Hg or higher. However, organic materials such as most rubbers and plastics permit enough air to diffuse through the walls of the tubes to produce measurable disturbances to the pressure measurements made at 20 mm Hg and lower. On this account, as well as on the account of saving space, the writer recommends that thin walled metal tubing be used for the higher Mach numbers where the pressures to be measured may be as low as a fraction of a mm of Hg. Since thin walled metal tubes are rather delicate, it is necessary to handle them accordingly. The tubes should be taped up in a bundle, which may be of round cross section, or if necessary, may be of an elliptical cross section, which, when oriented properly, can provide some stream lining. The metal tubes can be obtained either in the hard drawn state or in the soft annealed state. The hard drawn tubing is stronger than the annealed tubing, but it has the disadvantage that it is much more difficult to bend into sharp turns without collapsing or even breaking in two. It has been the writer's experience that annealed tubing is generally more satisfactory than hard drawn tubing for the purpose considered here. The metals generally used are copper, stainless steel, and brass. The writer has also had some experience with silver tubing which, strangely enough, is not a great deal more

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expensive than any of the other materials. Annealed copper and annealed fine silver tubes are extremely soft and can easily be flattened by pressing them between the fingers. On the other hand, tubes of these materials are apparently more flexible than tubes of the same dimensions made of other metals. Coin silver tubes and monel tubes, because of the properties of the metal, cannot be made nearly as soft as annealed copper or fine silver, and accordingly, are more difficult to use where sharp bends are required. By thin walled tubing, is meant tubing with a wall thickness of 10 per cent of the diameter or even less. As discussed elsewhere in this report, it is very important to have the largest inside diameter tubing possible in order to reduce flow resistance, and the smallest outside diameter possible in order to get the largest number of tubes possible into a given hollow sting. The joining of two metal tubes to each other can be done by soldering when there may be any tension in the tubes, or if not, the tubes may be joined by using a short sleeve of closely fitting plastic tubing, as shown in Figure 15. This joint is very easily made or unmade, and is perfectly vacuum tight, and therefore is very convenient when it can be used, but it will not stand any tension since about one pound pull is enough to pull it apart. It is generally unsatisfactory to join two plastic tubes in a similar way, since the joint is very apt to leak. The inside surfaces of plastic tubes are usually smooth and round, but the outside surfaces of strip-a-tube tubing always has ridges where the tubes were joined to each other and these ridges make passage ways for air to leak into the joint. Vacuum grease or wax, properly applied, can prevent such leaking, but it is very difficult to do, and is usually unsuccessful.

54. After the tubes are all mounted in the model, and the extensions added to run the tubing out of the wind tunnel to the manometer, it is necessary to know whether any tube is either stopped up, partially stopped up, or is leaking. A certain percentage of the pieces of metal tube, as received from the supplier, are found to have cracks or pin holes in their walls. If such a leaking tube inadvertently is included in the bundle of tubes running from the model, the results range from bad to serious, as discussed under the section on manometer operation. It is very necessary therefore, that absolutely no leaking tubes be included. In order to test tubes for leaks and obstructions, the tube tester shown in Figure 14, which is the fluid dynamic version of the electronic ohmmeter, was constructed. With this device, it is possible to check tubes for leaks and also to measure the flow resistance through the tube. The device consists of a reservoir of compressed air, 0 - 100 psi, (sufficient to run the device for 45 minutes) a gage to read reservoir pressure, a pressure regulator to reduce the pressure to about 20 mm Hg, an on-off cock, a flowrator for measuring rate of flow of air in cm^3 per sec. through the model-manometer tube under test, and a manometer to measure the

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amount of pressure in dyn/cm² required to force the air through the tube under test. The tube running to the model which is to be tested, is connected to the tester as shown in the sketch. The stop-cock is adjusted so that the flowrator ball floats at a point near the top of the scale. Then the flowrator and manometer readings are noted. The flow resistance through the tube under test is obtained by dividing the pressure in dyn/cm² measured by the manometer by the rate of flow in cm³/sec. from the flowrator. The quotient is the flow resistance in terms of units, which in acoustics, are called acoustic ohms, but in fluid dynamics, have no name. The expected flow resistance for a tube may easily be calculated as explained under the section on theoretical considerations, using Poiseuille's law:

$$R = \frac{8 \mu l}{\pi r^4}$$

If the measured value of flow resistance is markedly different from the calculated value, then the explanation must be found. If the flow resistance is too high, then the tube is probably partially stopped up. If the flow resistance is too low, then the tube is probably leaking. A special leaking test should then be made. This test consists of stopping up the hole on the model surface with the finger tip, letting the pressure build up in the manometer until it is at the top of the scale, then shutting off the stop-cock, and noting whether the manometer meniscus holds exactly stationary, or whether it falls slowly or rapidly. If it falls any at all, as determined by a 15 second observation, then the tube should be carefully examined to find the leak. As mentioned above, a surprising number of pieces of tube have cracks and pin holes. It is usually much better procedure to check the tubing for obstructions and leaks before it is assembled into the model. Even if this is done, the tubes should again be tested for obstructions and leaks after assembling.

Bringing Tubes Out Through Wind-Tunnel Wall

55. There are many ways that tubes may be brought out of the tunnel from the model to the manometer bank. For high Mach numbers where it is necessary to have the tubes as short as possible, and also where there must be a certain amount of flexibility in the bundle of tubes to permit the angle of attack of the model to be changed without difficulties from the tubes, it is necessary to give careful consideration to this feature of the set up. A method of bringing out the tubes which have been used in the NOL Supersonic Wind Tunnel with satisfactory results, is shown in Figure 16. A hole about 4" diameter is cut in the side wall of the wind tunnel,

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and a clamping ring as shown is held in place with several bolts. Between the clamping ring and the wall is a piece of 1/8" thick rubber having the same diameter as the clamping ring. As many holes are bored through this piece of rubber as there are tubes to be brought out. Each hole is slightly smaller in diameter than the diameter of the tube to go through the hole. The tubes are greased with vacuum grease to make the tubes slide easily through the holes, and the rubber worked from the end of the tubes to the place along the tubes where it is to be used as a packing gland. In back of the rubber are three 1/8" diameter steel bars which are held in place by six cut-outs in the wind tunnel walls as shown in the sketch. The chief advantage of this type of packing gland is that the tubes are free to change their direction through the wall as the angle of attack of the model is changed. The tubing inside the tunnel is then not required to take up the entire charge when the angle of attack is changed since some of the change can be taken up outside the tunnel. Another advantage of this packing gland is, that there is no chance of a leak due to any joints, since of course, there are no joints in the tubing at the gland.

Determination of Tube Diameters

56. From the point of view of space limitations, it is desirable to use the smallest diameter tube possible as pressure leads coming out of the model. It is nearly always a struggle to get the required number of tubes in the model, and through the hollow sting, and so there is always the temptation to use too small a diameter of tubing. What would appear to be the proper approach to this problem is first of all, to decide how long a time one can afford to blow the wind tunnel before pressure stabilization is reached, and then design the tubing system so that this time is not exceeded. The designing of the tubing system to meet specified requirements is a relatively simple procedure. In addition to length of time decided for stabilization of pressures, the length of tubing from model to manometer must be determined, and the volume of the space in the manometer must be known for the pressure expected.

57. The model and sting dimensions are fixed by aerodynamic requirements, and the size of hole through the sting is fixed by the strength of sting required for the aerodynamic forces encountered. The designing of tubes from here on must proceed on a cut and try basis, the procedure being to start with the largest diameter tubes for the number of tubes required that will go through the hole size in the sting or model. The length of these tubes should be as short as possible, since once outside the sting, these tubes can be joined to larger diameter tubes which run the remaining distance to the manometer. We now guess the diameter of the large tube to be such

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as to have an inside diameter of about one and one-half or two times that of the small tube. The next step is to compute the stabilization time of this tubing system to see if it is at least as short as was decided to be necessary.

58. The procedure for making this computation is given below. If the stabilization time is too long with these tube dimensions now, then a larger size tube may be considered for use outside the model and sting. If the time cannot be shortened sufficiently by using the optimum size tube outside the model, then tubing of larger inside diameter must be used in the model and sting. Of course, if a manometer with a smaller volume can be used, this also will shorten the time. If the thinnest wall tubing, giving the greatest inside diameter feasible, still does not shorten the time sufficiently, then it is probably necessary to eliminate some tubes to make it possible to use a larger size for those remaining. If it is necessary to eliminate too many tubes to meet the aerodynamic pressure distribution measurements over the surface of the model, then it is possible to build two or more models and divide the required tubes up among them. In this way, it is always possible to have a stabilization time which will be as short as required. How far one must go in making compromises of this sort depends on the pressures to be measured, the higher the pressures, and the longer the permitted stabilization time, the less compromising to be done. Accordingly, low Mach number tests generally require much less compromise than do high Mach number tests.

59. The computation is very simple, usually taking only a few minutes to make each cut and try. The method of computation will now be explained by means of numerical example and reference to NOLM 10677. Let it be assumed that the pressure to be read is 10 mm Hg which corresponds to an ambient pressure obtained at Mach 3.5 when the tunnel has supply air at 1 atm. pressure. Let the small diameter tube be 1.00 mm inside diameter, of 60 cm length, and the large tube 2 mm inside diameter of 200 cm length. The manometer volume should be 10 cm³. This system is shown in Figure 18.

60. We shall find the flow resistance of the big diameter tube as an effective length of small diameter length and add the two together. The flow resistance of a tube, according to Poiseuille's law (see equation 18 of NOLM 10677) varies inversely as the fourth power of the radius, or the relative flow resistance per unit length is

$$R \left(\frac{r_1}{r_2} \right)^4,$$

where R is the flow resistance per unit length of the small tube r_2 the radius (or equally well, the diameter) of the large tube r_1 the

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corresponding quantity of the small tube. In the numerical example $2r_1 = r_2$ or $r_1/r_2 = 0.5$. The relative flow resistance of the large tube is $(0.5)^4 = 0.0625$. The length of the large tube is 200 cms. and the flow resistance in terms of the small tube is $0.0625 \times 200 = 12.5$ cms. The total flow resistance of both tubes is equivalent to $60 + 12.5 = 72.5$ cms. of the small tube.

61. The volume of the big tube must be added to the manometer volume. The volume of the big tube is $200 \times \pi \times (0.1)^2 = 6.28 \text{ cm}^3$. The total volume of the big tube and the manometer is $10 + 6.28 = 16.3 \text{ cm}^3$. The volume of the small tube can be neglected. Referring to Figure 12 of NOLM 10677 on the horizontal axis, we pick the point where the diameter is 1 mm corresponding to that of the small tube. We run up the ordinate from this point until it intersects the 10 mm Hg line. The ordinate at this point is .03, which is the value of t/lv to be used. The equivalent value of l was found to be 72.5 cms and the equivalent value of v was found to be 16.3 cm^3 which makes $lv = 1160$. The time then for pressure stabilization to 1% is given by $t = .03 lv = .03 \times 1160 = 35$ seconds.

62. If the pressure was 100 mm Hg, which corresponds to a test chamber ambient pressure for Mach 1.98, the time would be cut by a factor of 10, or stabilization would be reached in 3.5 seconds. It is to be noted, however, that the factor which is most important in determining the times is the tube diameter. The time is inversely proportional to the fourth power of this quantity, so that for apparently small increases of the inside diameter of the tube, the stabilization time decreases appreciably.

READER FOR NEGATIVES

63. The reader enables a person to read manometer meniscus positions in a photographic negative in terms of either (1) pressure in mm Hg, (2) pressure ratio (ratio of local pressure at tap hole on model surface to ambient pressure in the wind-tunnel test chamber), or (3) in terms of pressure coefficients. By setting up the machine so that it yields results in the form of either (2) or (3) above, it is frequently possible to avoid any further computation of the data, and the results can then be written down immediately in final form to become part of the report of the wind-tunnel test of the missile.

64. Figure 2 is a positive photographic 8 x 10 contact print made from a sample negative which shows the positions of the menisci of the 24 tubes in one bank of the multiple manometer. The positions of the menisci of the end tubes are used as zero

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references, since these tubes always have zero pressure applied to them. In front of the tubes in the manometer bank there are three 0.005" diameter wires, each stretched horizontally across in front of the tubes. One of these wires is just below the levels of the menisci in the reference tubes. The second wire is 15.00 cms below the first wire, and the third wire is 40.00 cms below the first wire. These wires can be seen in the negatives (also in the positive contact print) and serve to provide a 15 cm and a 40 cm interval respectively, which intervals are useful in checking the over-all factor for the camera and negative reader. The sharpness of the menisci in the photographic print is achieved by means of a special elliptical shaped reflector and line source illumination behind the manometer tubes.

65. Figure 4 is a photograph of the reading machine. The machine consists essentially of a movable table with a glass top on which is mounted the photographic negative. Under the table is a light condensing system to illuminate the portion of the negative under observation. Above the table is a projection lens mounted in a box. The box has two mirrors inside for reflecting the light beam the length of the box and back again, and has a ground glass screen on the end of the box on which the image of the meniscus under observation is projected. On the ground glass screen is a fiducial mark to which the menisci are brought by moving the movable table. To the right of the movable table is located the large dial which has a fine pointer and a special scale. The pointer rotates as the movable table is adjusted to bring each meniscus to the fiducial mark, at which time the type of result for which the machine is set up can be read directly on the dial. The mechanism connecting the pointer with the movable table is of the arc-tangent type, so that the scale on the dial is spread out at the low end, and compressed at the high end. This arrangement gives a reading accuracy which remains almost constant over about 90 per cent of the top part of the scale, and is of the order of one quarter of a per cent. The menisci may be set on the fiducial mark with an accuracy of about 0.001 inch in the negative. Since the negative is one quarter of the actual size of the manometer tubes, the actual meniscus positions in the manometer tubes can therefore be read to an accuracy of about 0.004 inches. To set up a negative on the table and make 22 meniscus position readings requires about seven minutes or about twenty-one seconds per meniscus position reading. About 20,000 readings have been made with this machine so far. NOL hopes in the near future, to develop a similar machine using photoelectric equipment, which is expected to increase the reading speed by a factor of about five.



FIG. 1
GENERAL VIEW OF THE MULTIPLE MANOMETER AND ASSOCIATED EQUIPMENT. THERE ARE THREE BANKS OF MANOMETERS, EACH WITH 24 TUBES. EACH BANK HAS ITS OWN VACUUM PUMPING SYSTEM LOCATED AT THE EXTREME RIGHT. IN THE FOREGROUND IS THE CAMERA EQUIPMENT. UNDERNEATH THE MIDDLE CAMERA IS THE CONTROLLER WHICH SENDS COMMAND SIGNALS TO OPERATE THE VARIOUS PARTS OF THE EQUIPMENT AT THE PROPER TIMES. IN THE BACKGROUND IS THE NOL SUPERSONIC WIND TUNNEL.

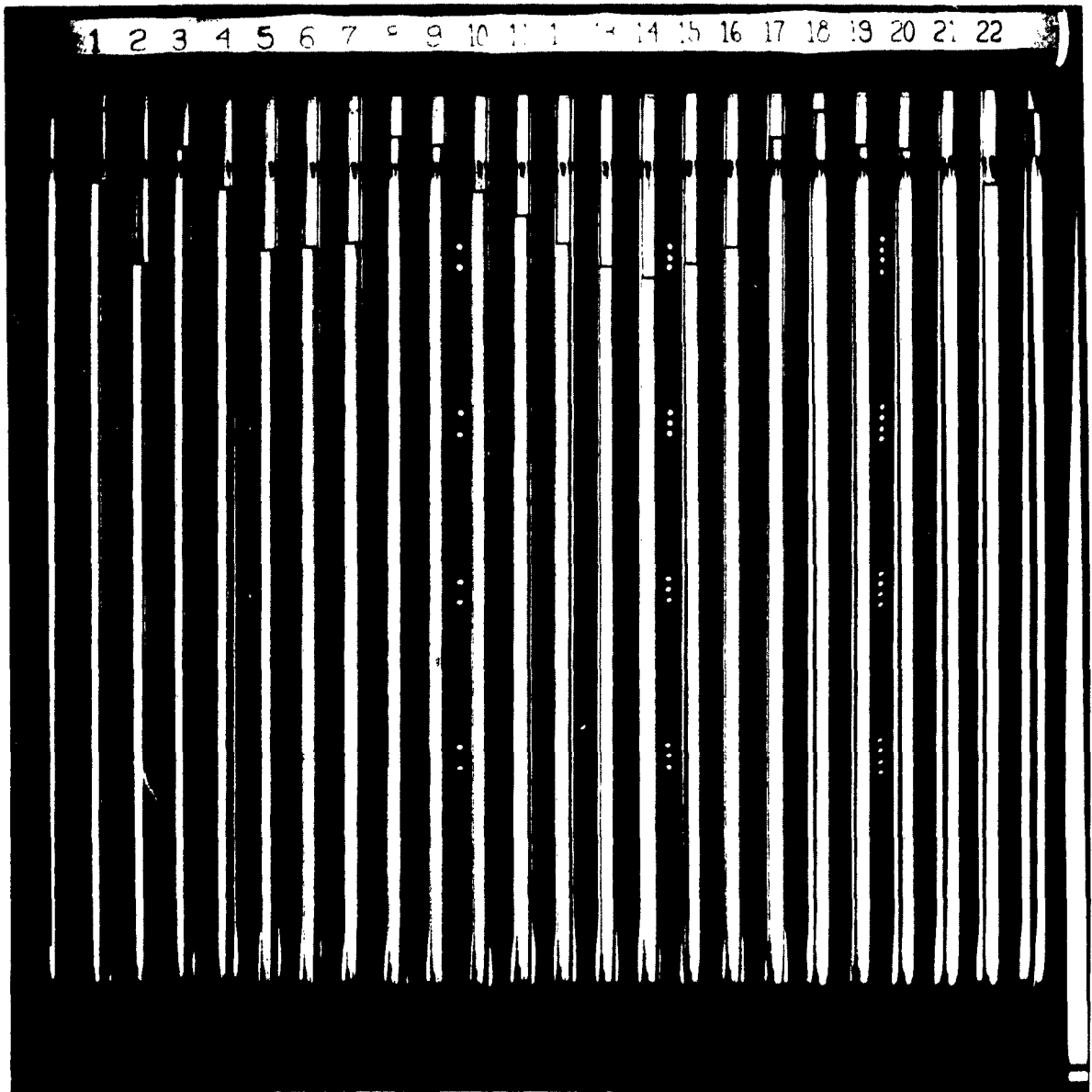


FIG. 2
A POSITIVE 8 X 10 CONTACT PRINT MADE FROM A SAMPLE NEGATIVE WHICH SHOWS THE POSITIONS OF THE MENISCUSES OF 22 MEASURING TUBES AND ONE REFERENCE TUBE AT EACH END. AN EXAMINATION OF THE MENISCUSES WITH A LUPE WILL SHOW THE EXTREME SHARPNESS OF BOTTOMS OF MENISCUSES.

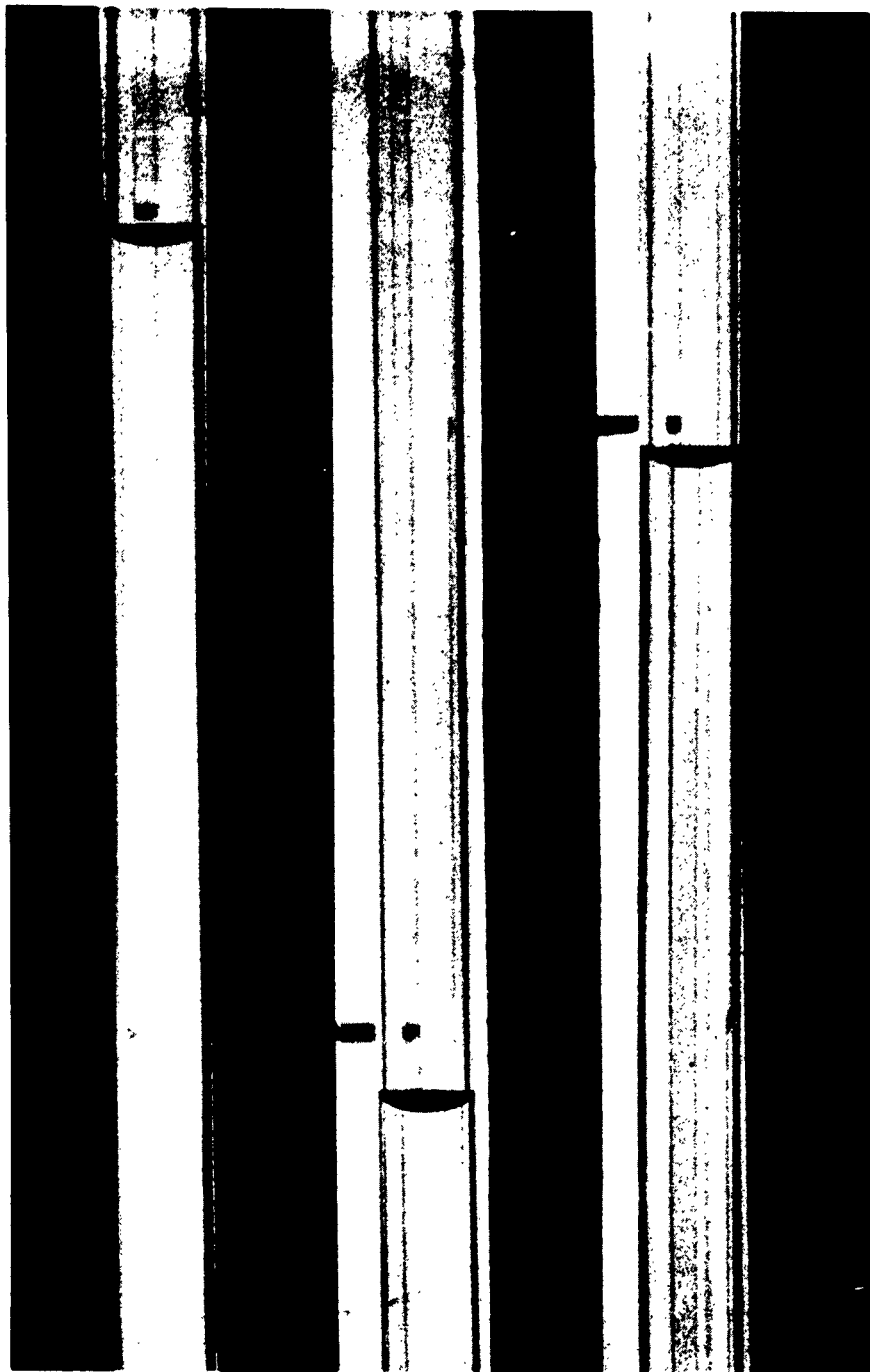


FIG. 3
APPEARANCE OF MANOMETER MENISCUSES WHEN ILLUMINATED WITH
AN ELLIPTICAL REFLECTOR WHICH GIVES SPECULAR LIGHT IN THE
VERTICAL DIRECTION AND DIFFUSE LIGHT IN THE HORIZONTAL
DIRECTION. NOTE THE SHARPNESS OF THE ROUNDED BOTTOMS OF
MENISCUSES. THIS PICTURE IS 1.3 TIMES AS LARGE AS THE
ACTUAL MANOMETER TUBES.



FIG. 4
NEGATIVE READER. THE NEGATIVE IS PLACED ON THE GLASS TOP MOVABLE TABLE. WHEN A MENISCUS IS SET TO THE FIDUCIAL MARK ON THE GROUND GLASS SCREEN, THE POINTER ON LARGE DIAL READS DIRECTLY IN PRESSURE, PRESSURE RATIO, OR PRESSURE COEFFICIENT DEPENDING ON THE SET UP OF THE MACHINE.

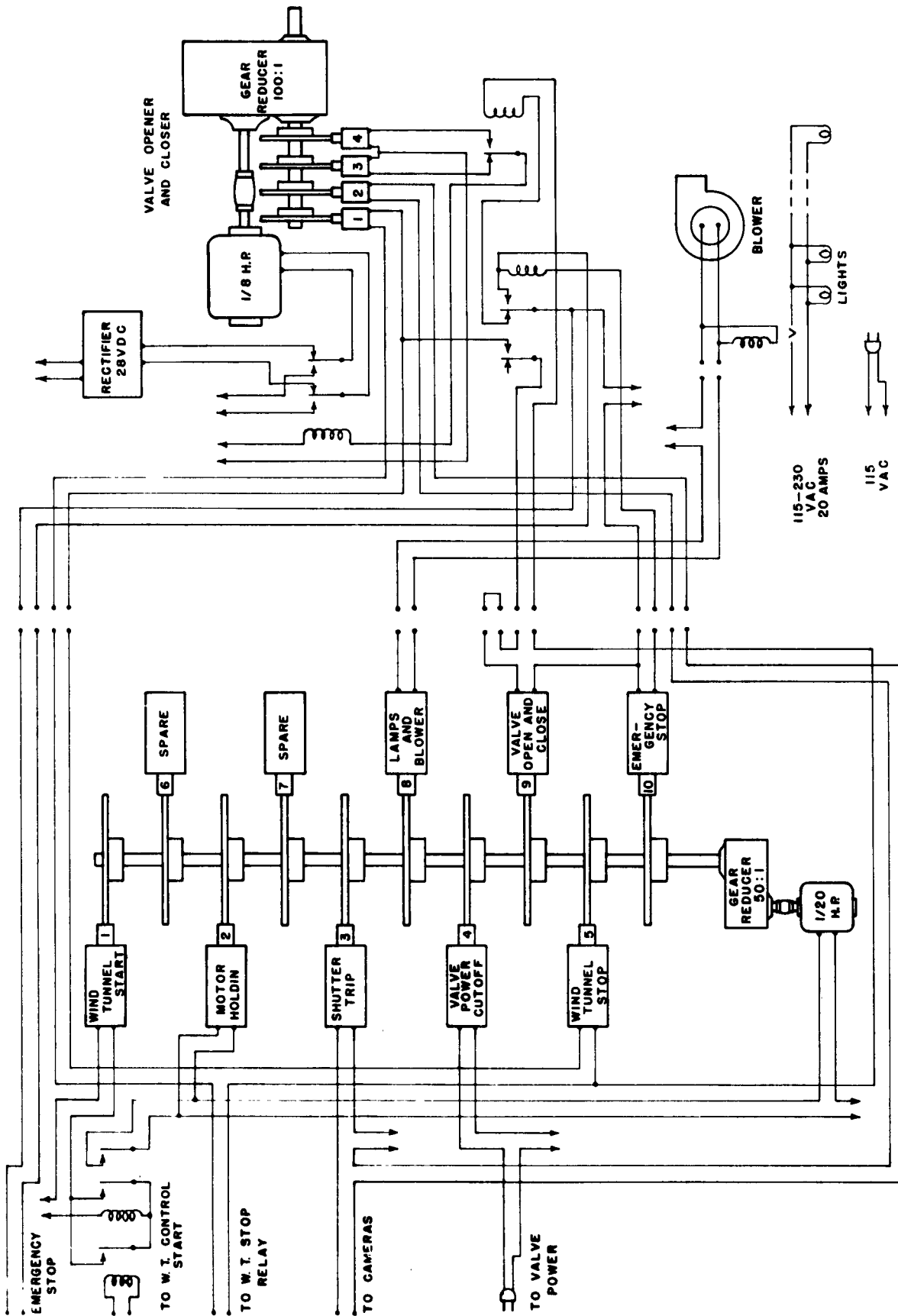


FIG. 5 SCHEMATIC DIAGRAM OF CONTROLLER

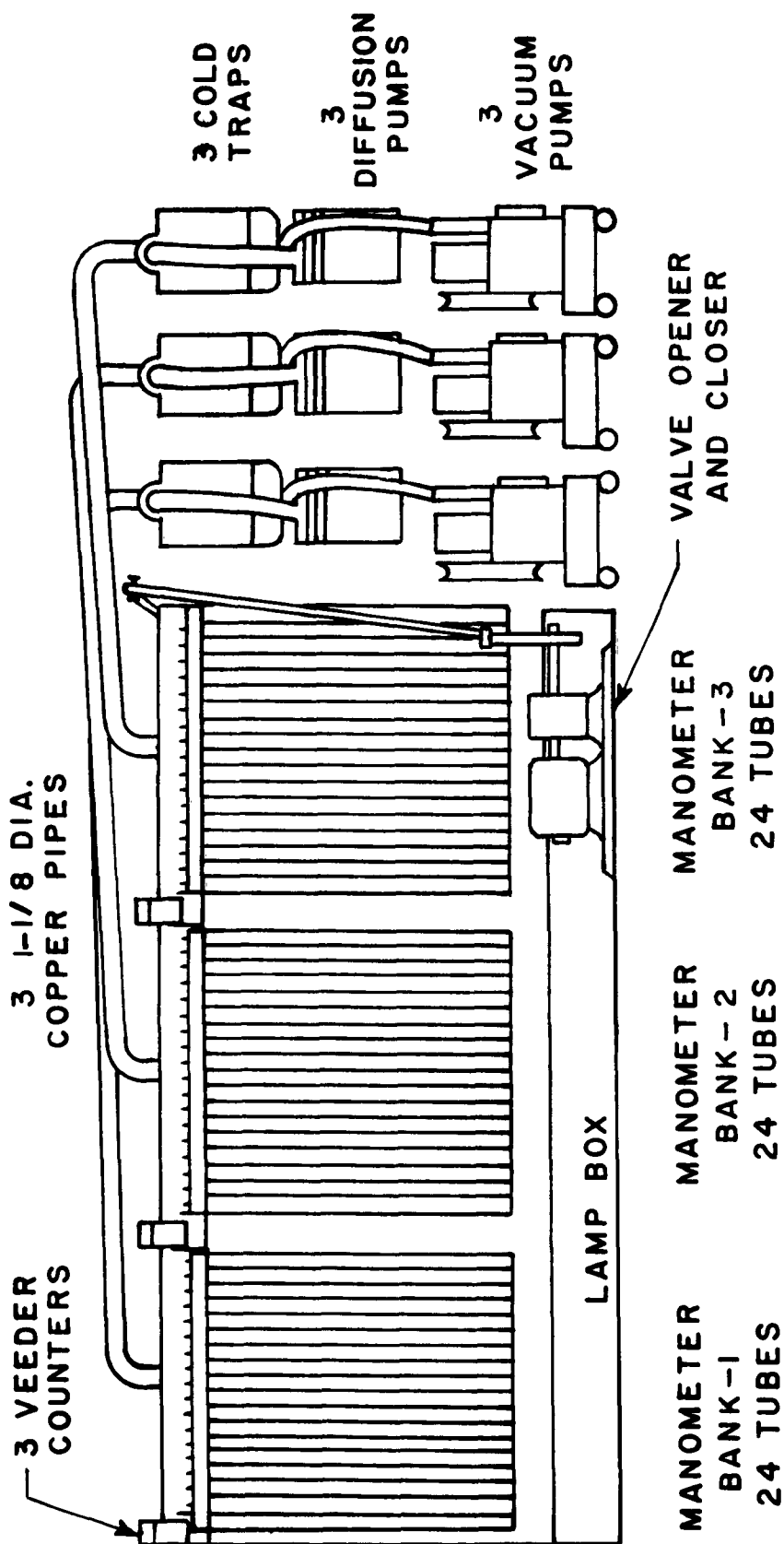


FIG. 6 GENERAL ARRANGEMENT OF
MANOMETER BANKS AND VACUUM
REFERENCE SYSTEM. MCLEOD
GAGE NOT SHOWN

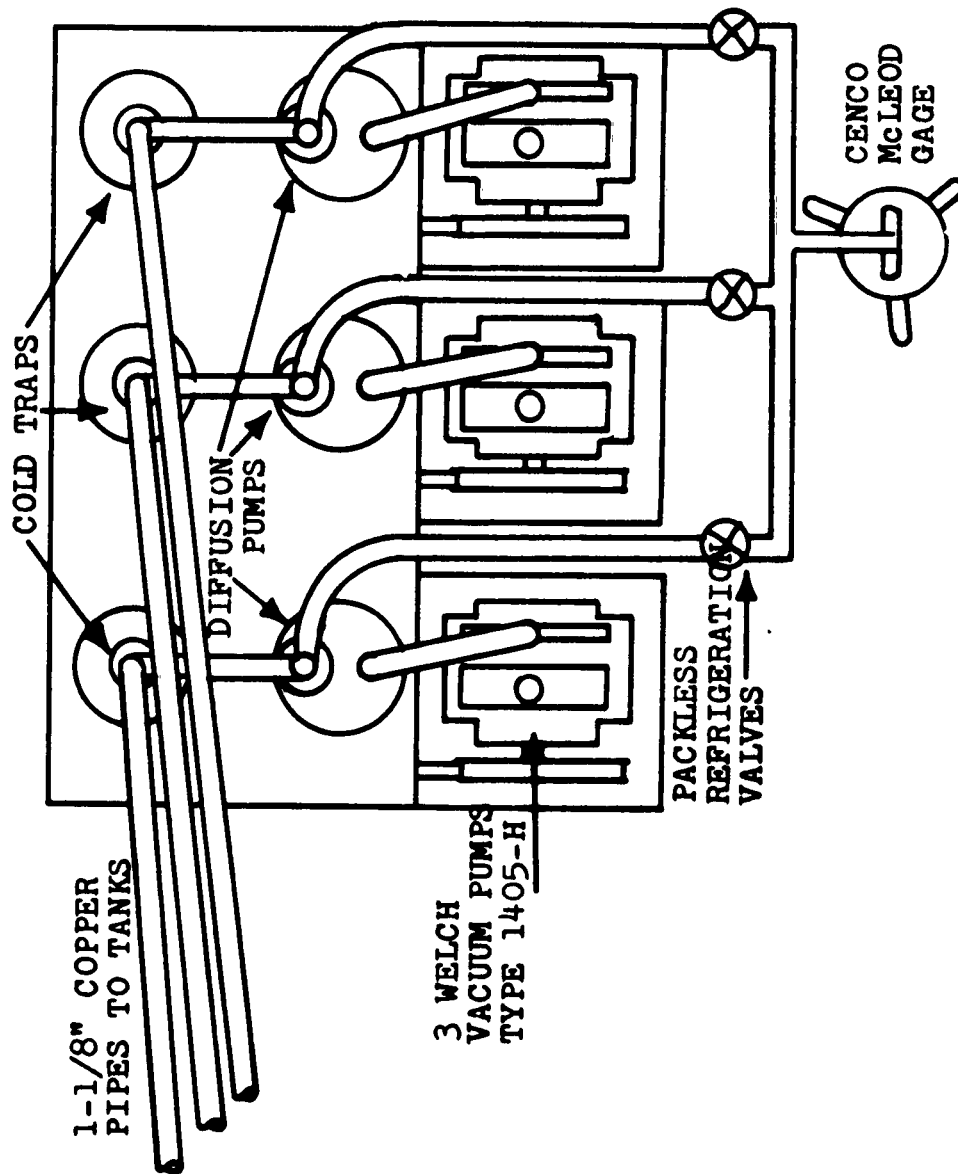


FIG. 7 TOP VIEW OF REFERENCE VACUUM SYSTEM INCLUDING McLEOD GAGE

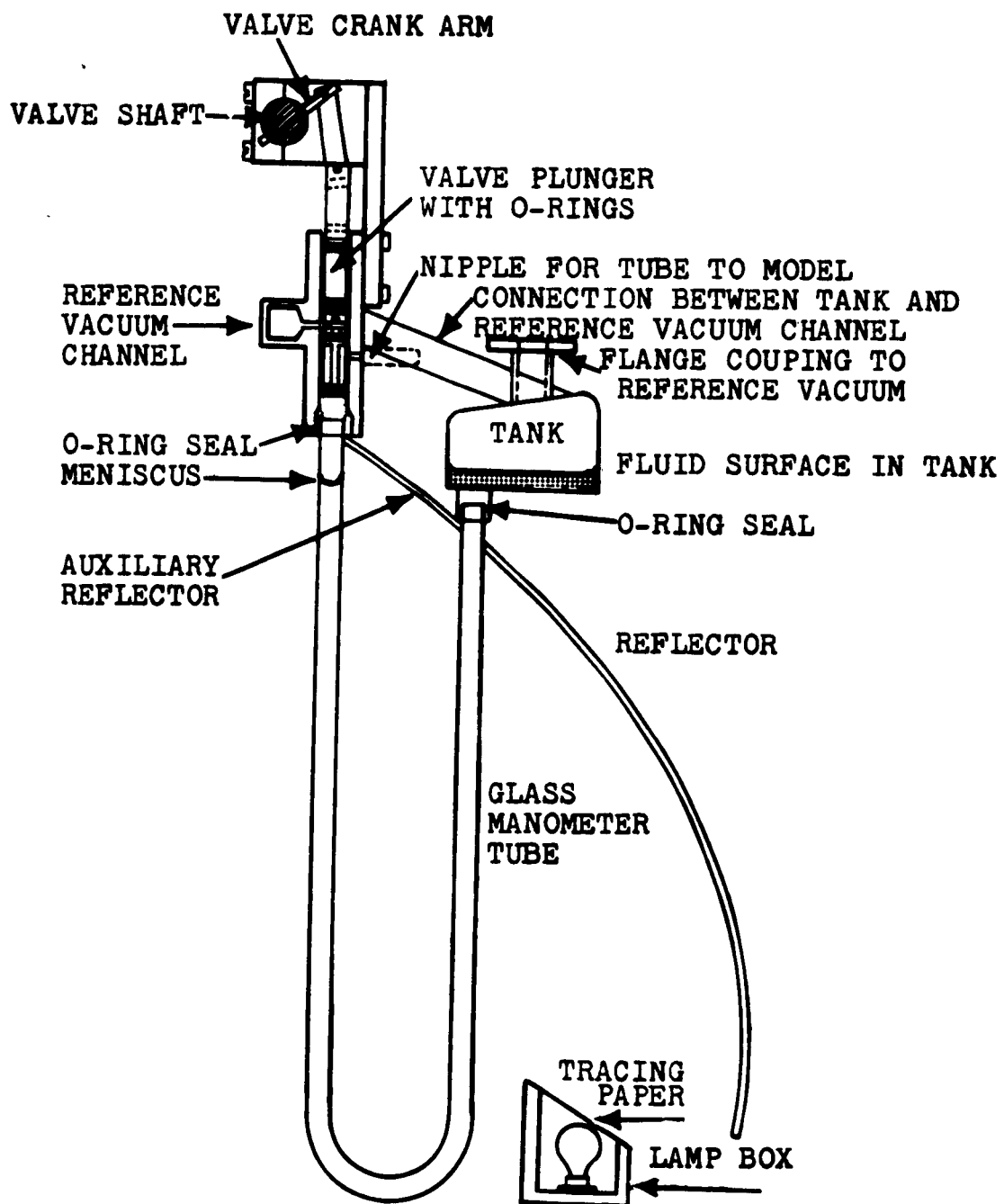


FIG. 8 SCHEMATIC DIAGRAM OF 24-TUBE MANOMETER
(END VIEW)

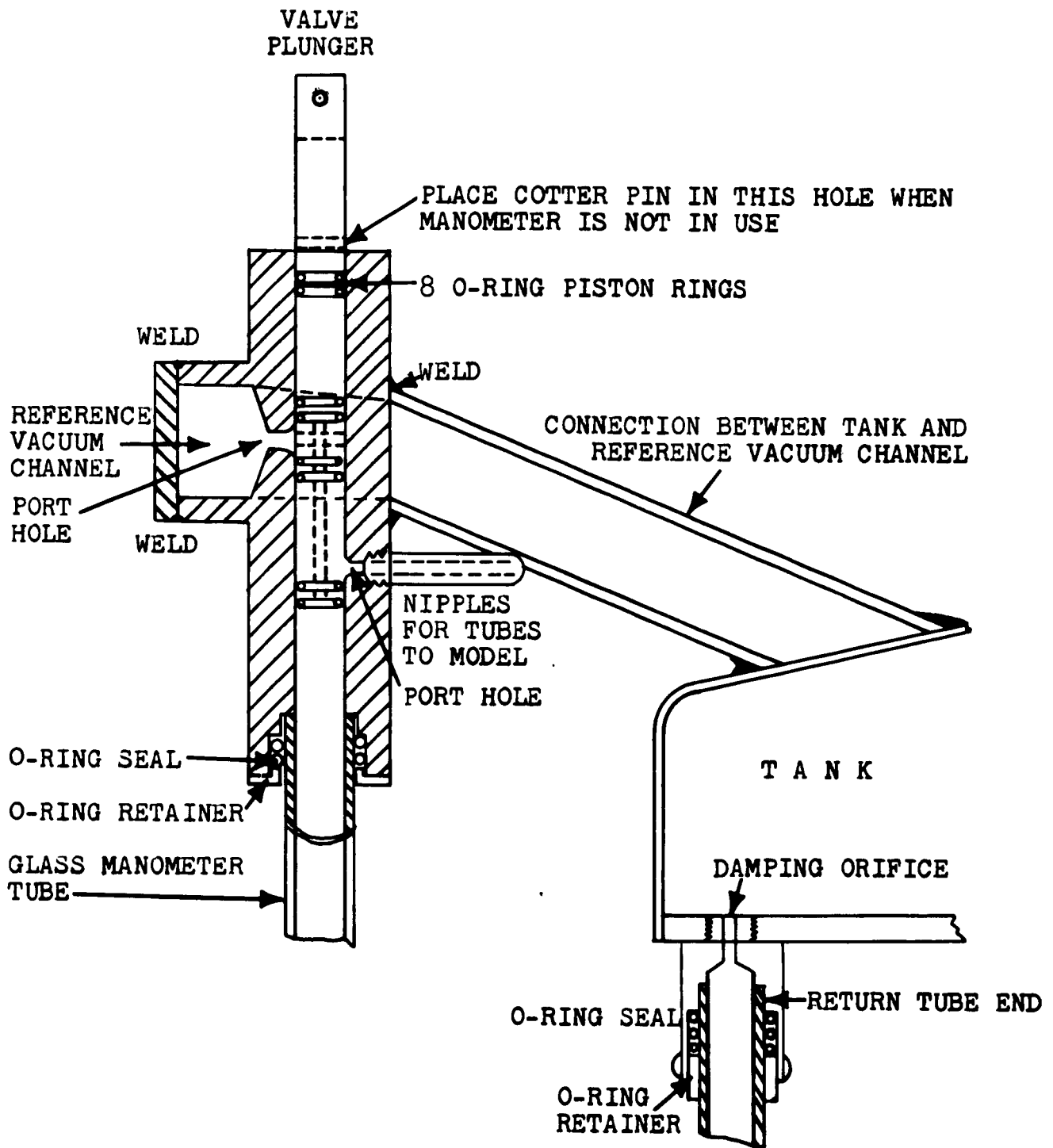


FIG. 9 SCHEMATIC DIAGRAM
OF VALVE BANK

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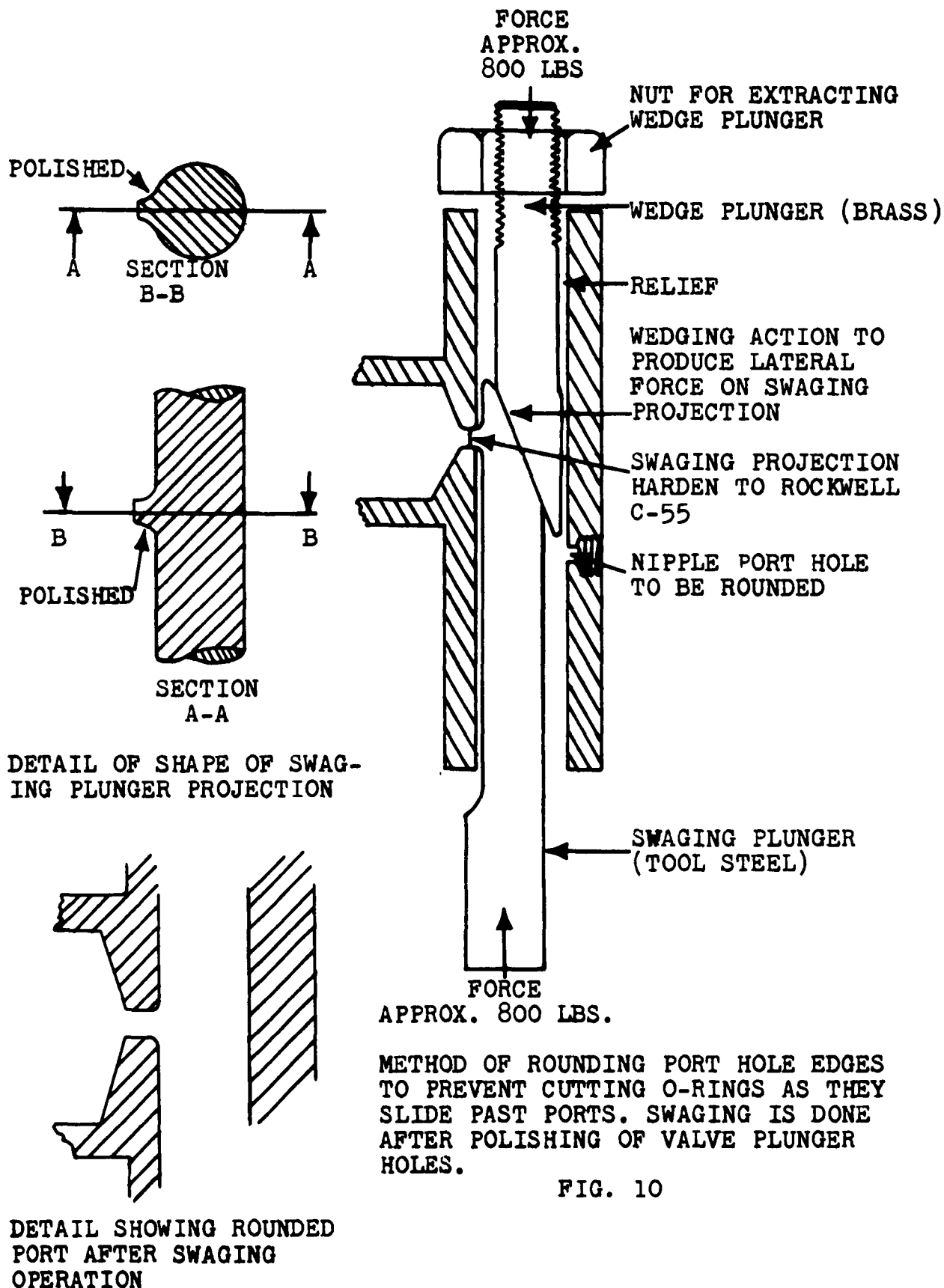
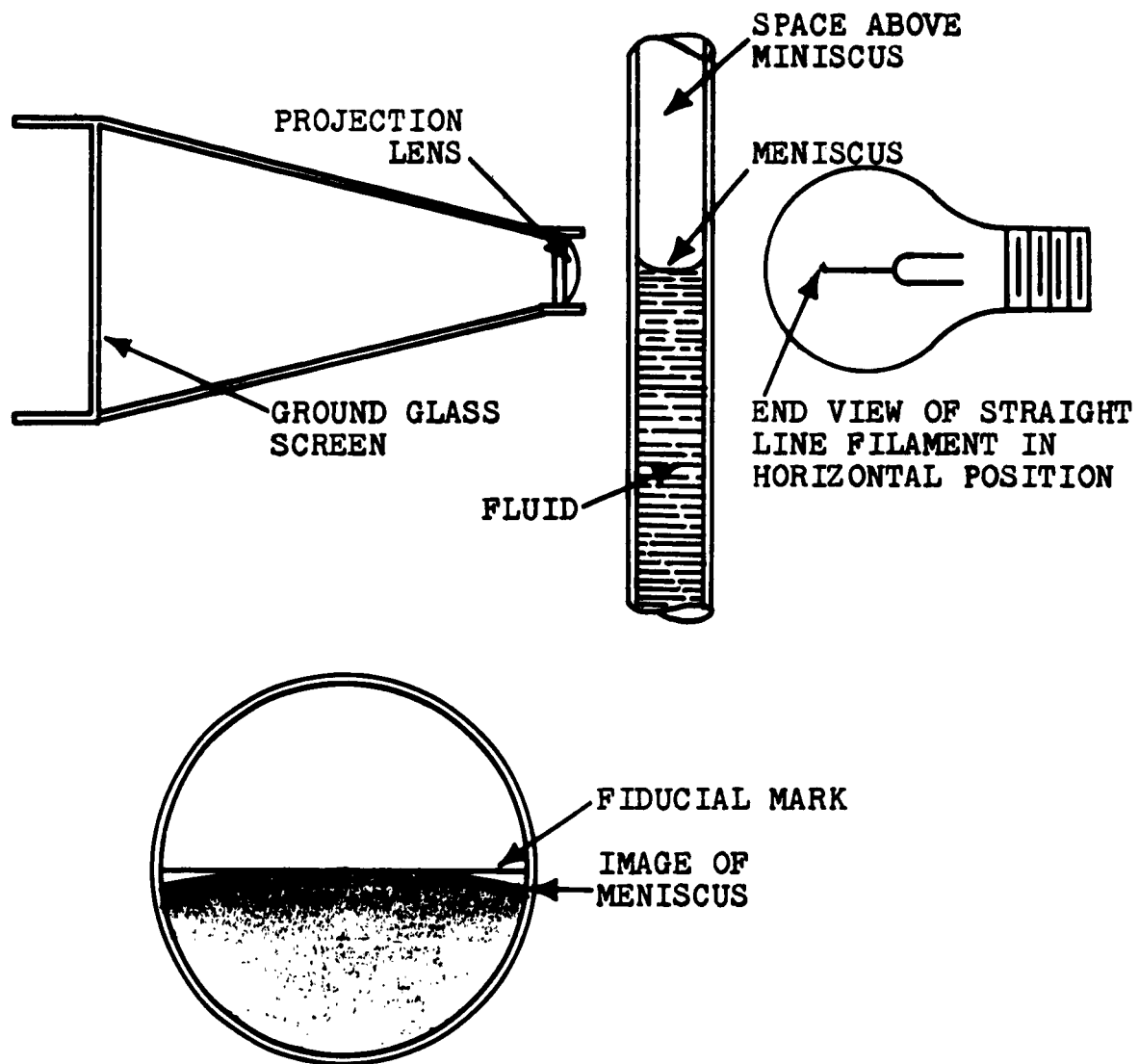


FIG. 10



APPEARANCE OF GROUND
GLASS SCREEN WITH BOTTOM
OF MENISCUS SET EVEN WITH
FIDUCIAL MARK. NOTE THAT
OPTICAL SYSTEM INVERTS
IMAGE OF MENISCUS. MAG-
NIFICATION ABOUT 10X.

FIG. 11

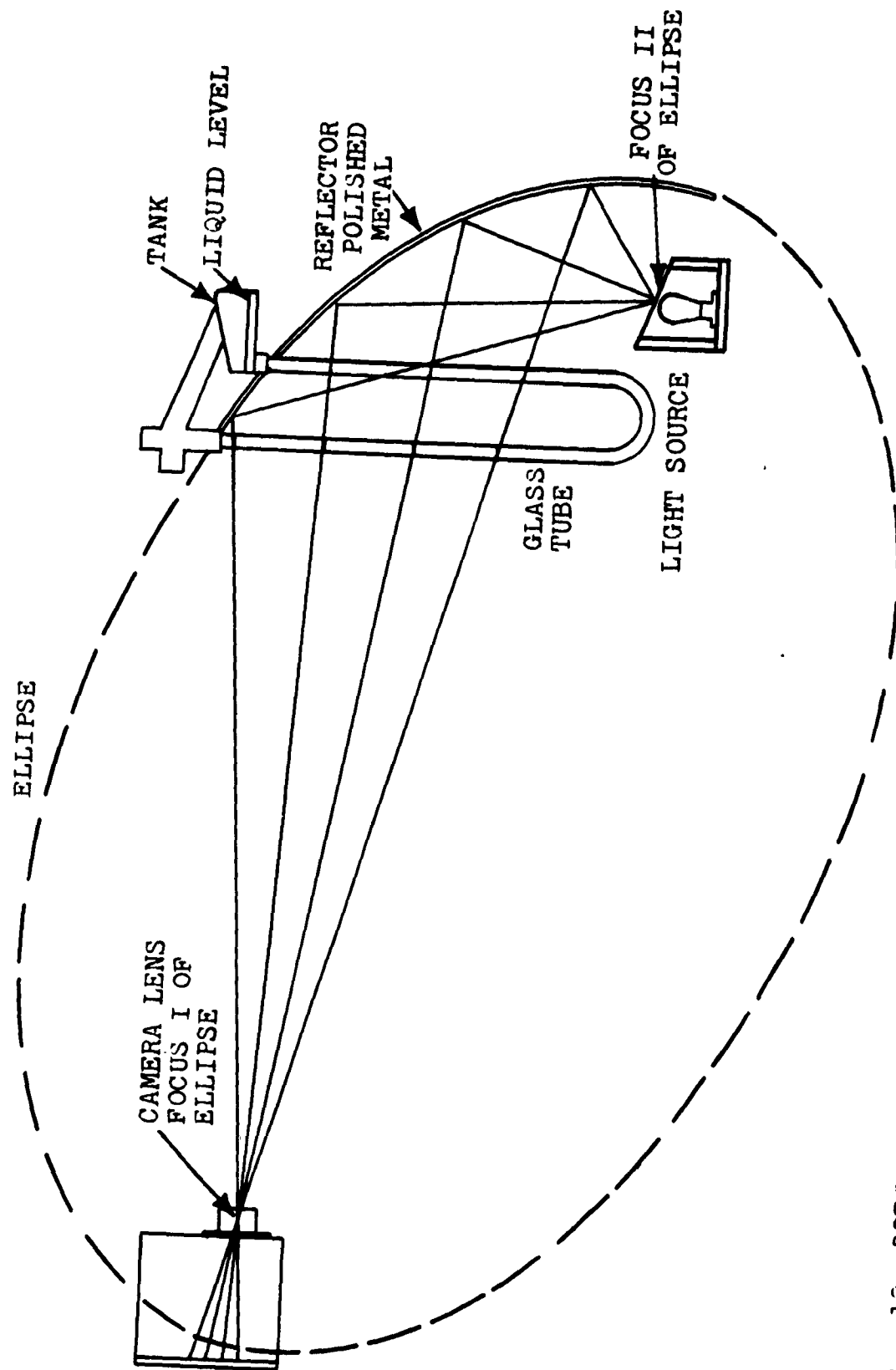


FIG. 12 OPTICAL SYSTEM OF MULTIPLE MANOMETER. MENISCUSES AT VARIOUS LEVELS ARE SHOWN, AND THE SPECULAR RAYS FROM THE REFLECTOR ILLUMINATING EACH MENISCUS.

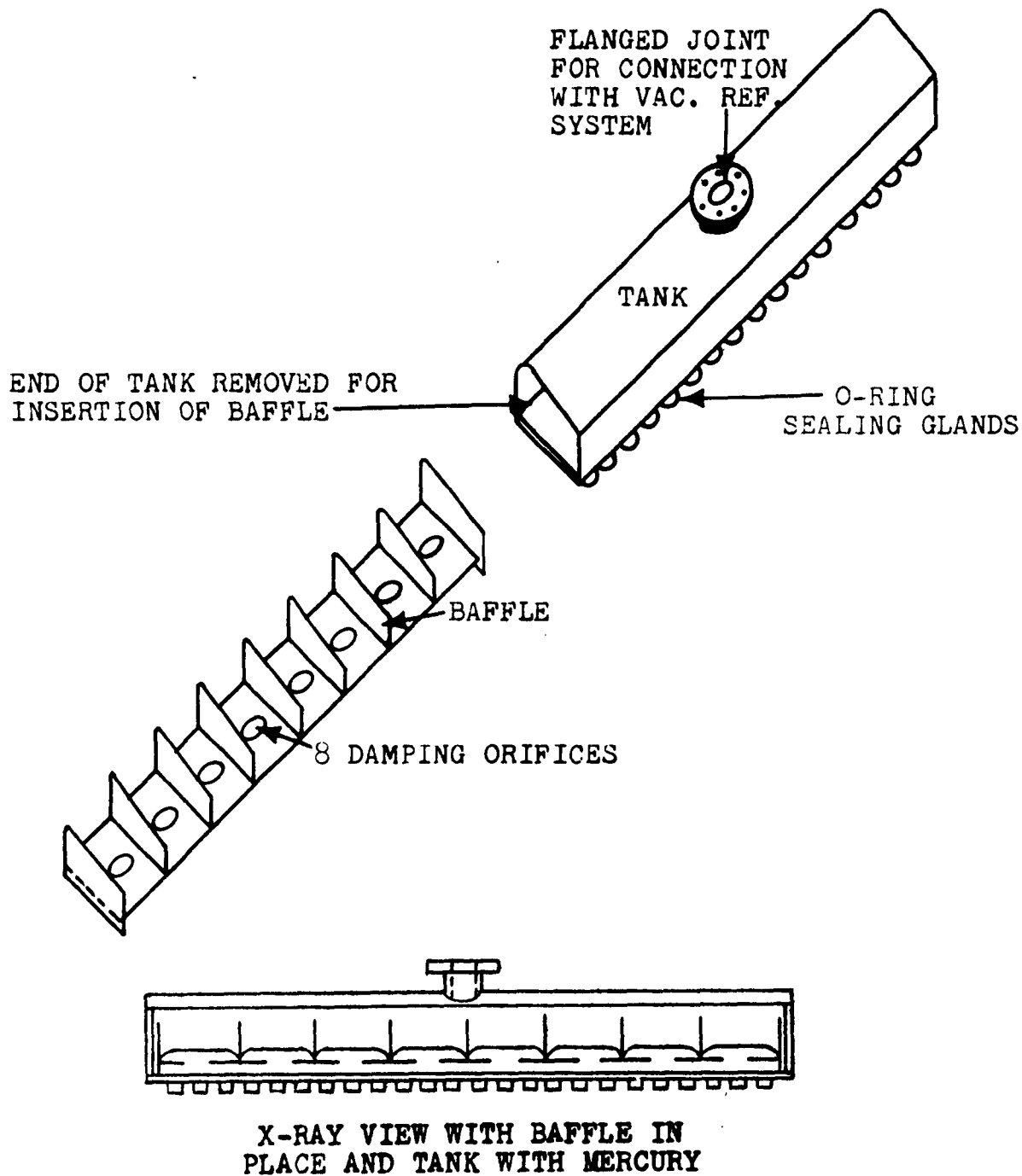


FIG. 13 ANTI-SLOSHING BAFFLE IN TANK TO INHIBIT SURFACE WAVES OF THE MERCURY

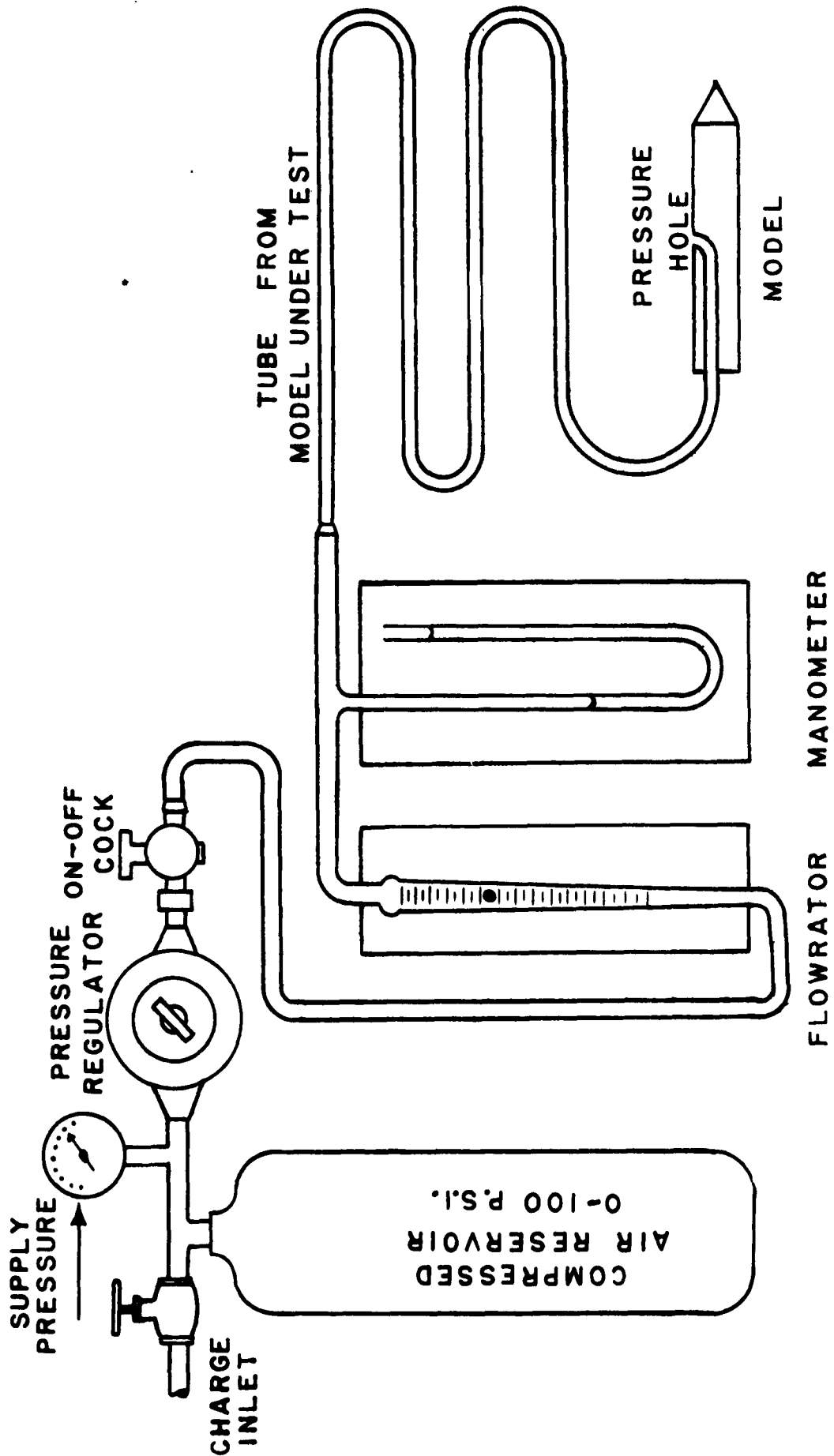


FIG. 14 WIND TUNNEL MODEL TUBE TESTER

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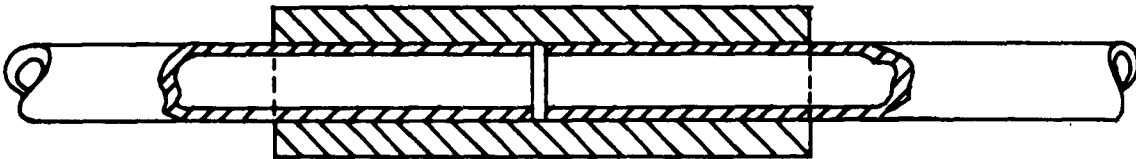


FIG. 15 CUTAWAY SECTION SHOWING THE JOINING OF TWO METAL TUBES WITH A SLEEVE OF PLASTIC TUBING. THE SURFACES OF THE METAL TUBES ARE THINLY COATED WITH DOW-CORNING VACUUM GREASE

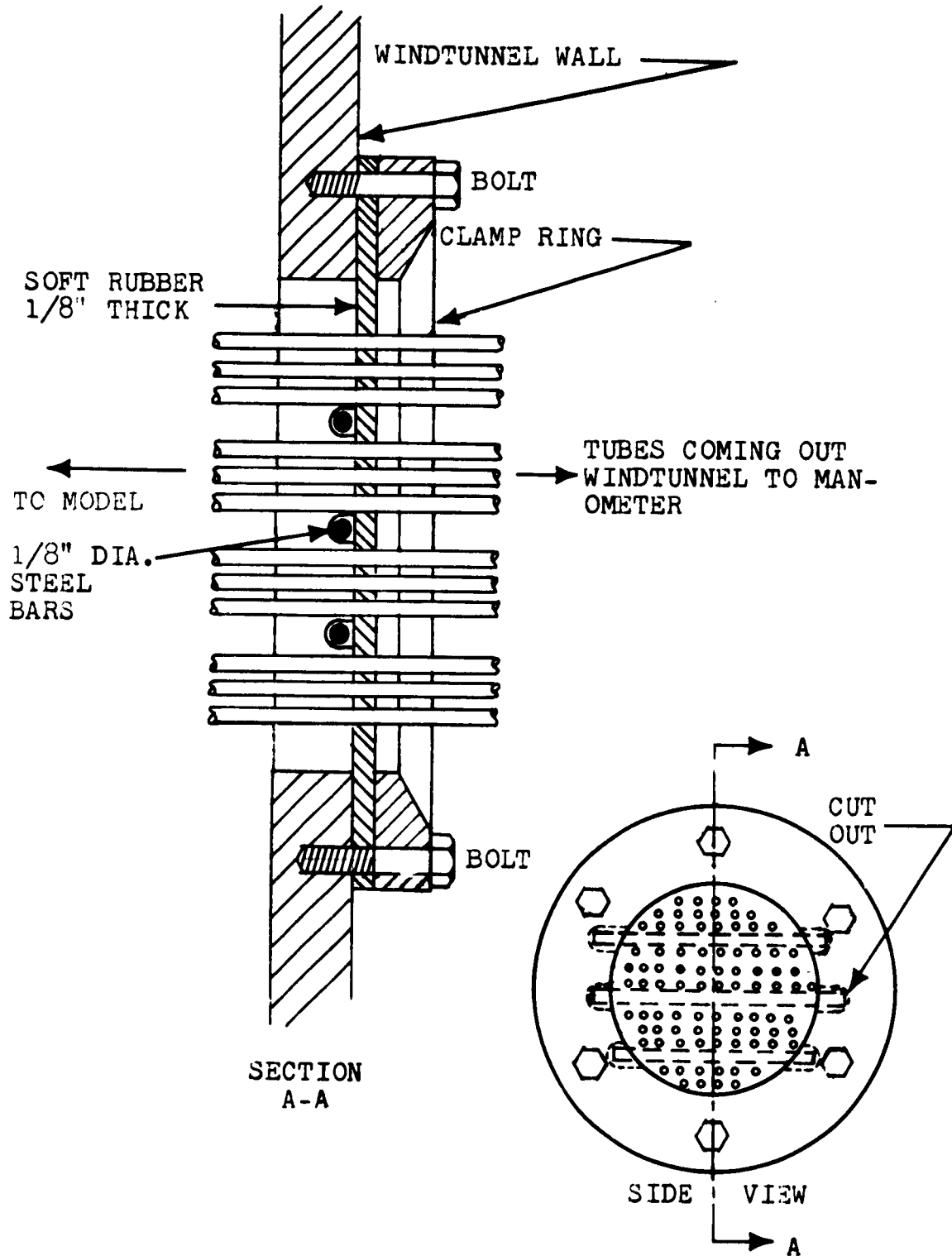


FIG. 15 PACKING GLAND FOR BRINGING TUBES OUT OF THE WINDTUNNEL

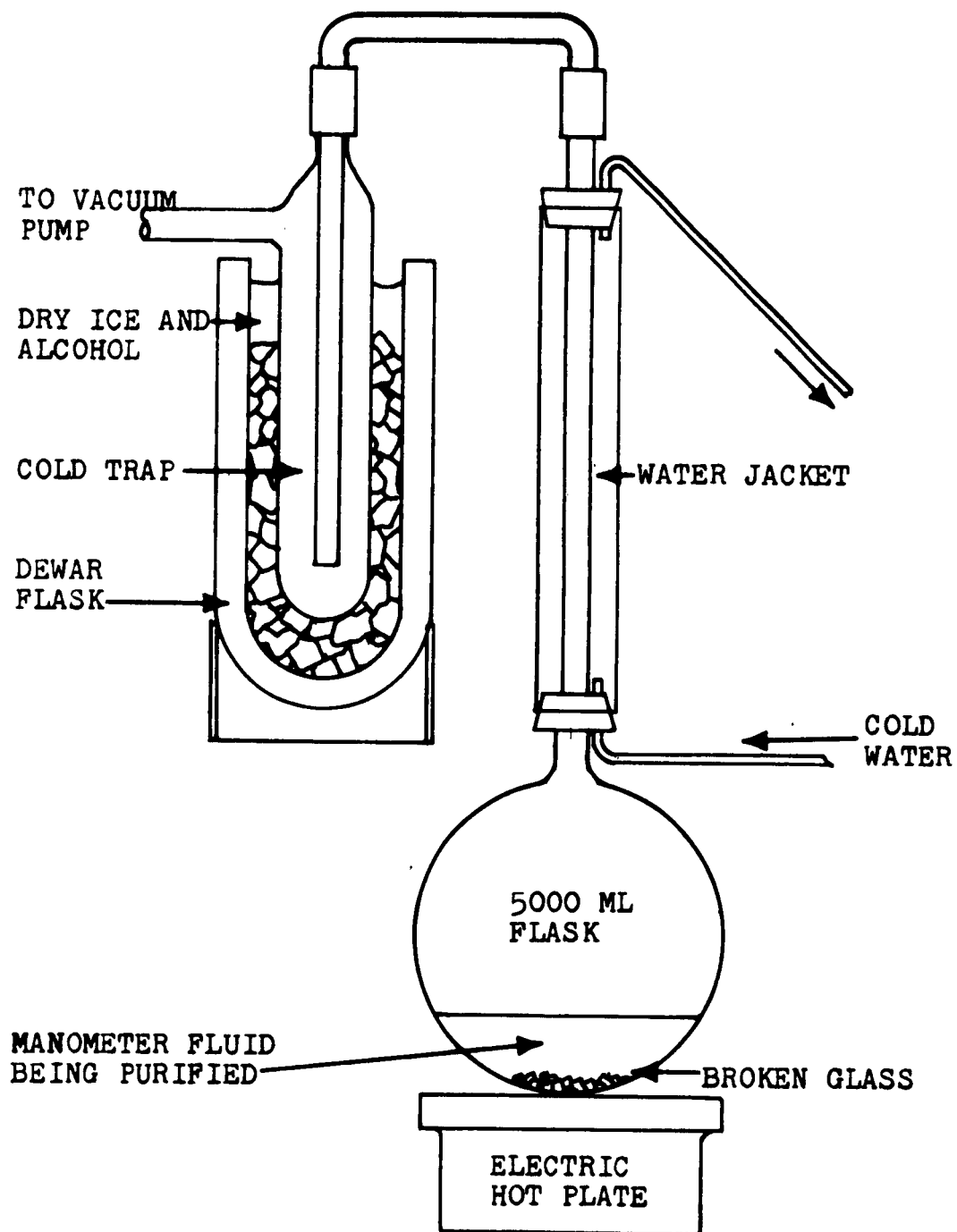
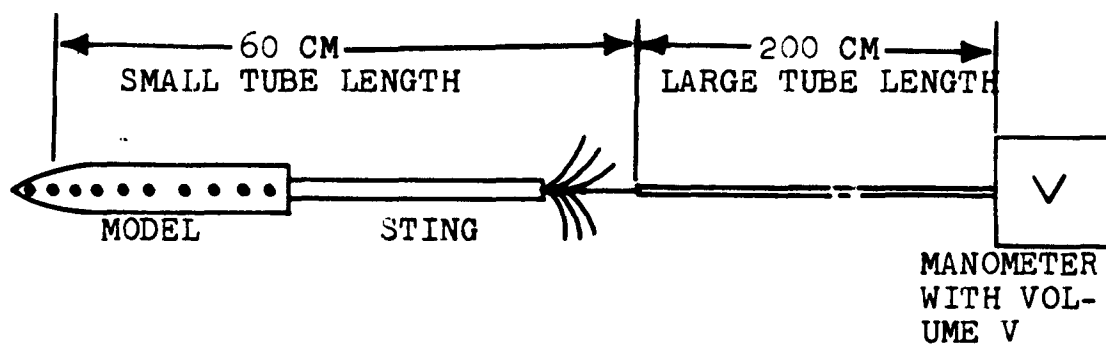


FIG. 17 MANOMETER FLUID PURIFIER

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SMALL TUBE INSIDE DIAMETER: 1 MM
LARGE TUBE INSIDE DIAMETER: 2 MM
LOWEST EXPECTED PRESSURE : 10 MM Hg
MACH NUMBER : 3.5

FIG. 18 EXAMPLE OF PRESSURE
DISTRIBUTION MODEL WITH TUB-
ING AND MANOMETER. ONE TUBE
SHOWN COMPLETE

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FIG. 19
APPEARANCE OF MAGNIFIED MENISCUS PROJECTED ON
NEGATIVE READER SCREEN.

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