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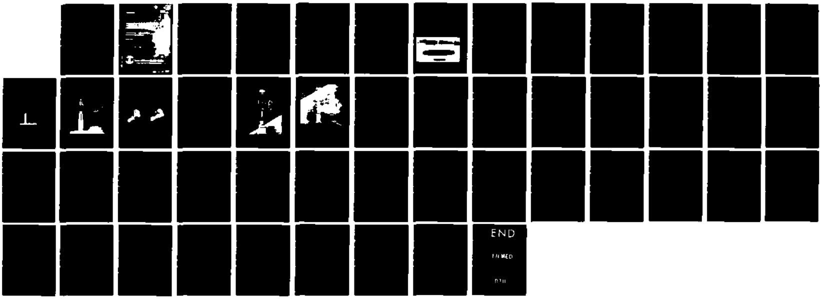

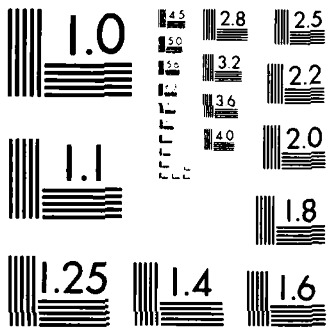

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A simple, nondestructive, noncontaminating technique for the inspection of assembled projectiles for minimum ullage, is presented. The technique is based on the use of ideal gas formulas and the change in the pressure of a system that results from a known change in the system volume. The laboratory demonstration apparatus based on the technique is described. Suggestions for application of the technique in a production facility are presented.

FOREWORD

This report describes a simple technique for the nondestructive inspection of assembled projectiles for minimum internal free volume (ullage) to allow for safe thermal expansion of the explosive charge. An apparatus for laboratory demonstration of the technique was conceived and assembled at the Naval Surface Weapons Center (NSWC), Dahlgren, Virginia. Although originally assembled only for feasibility demonstration, the apparatus was subsequently used at the Naval Ammunition Depot (NAD), Crane, Indiana, in the HIFRAG projectile pilot production program.

The authors would like to acknowledge the helpful discussions of W. Klaus, A. Wenborne, T. Swierk, W. Mock, Jr., and S. Burnley.

This report has been reviewed and approved by W. S. Burnley III, HIFRAG Program Manager, Ammunition Branch; D. L. Brunson, Head, Technology Branch; and C. A. Cooper, Head, Gun Systems and Munitions Division.

Released by:

R. J. ARTHUR, Deputy Head
Weapons Systems Department

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I. INTRODUCTION

In 1970, the Naval Surface Weapons Center (NSWC) was tasked to develop and field a new family of 5-in./54 gun ammunition. Projectile design improvements included provision for increased safety via the use of a separate, encapsulated billet of plastic-bonded explosive (PBX) and a two-piece projectile body. The explosive billet could be subjected to nondestructive testing and acceptance procedures prior to insertion into the metal projectile body. The emphasis on safety was motivated by dissatisfaction with the safety record of conventional 5-in./54 ammunition, having experienced a series of disastrous inbore premature explosions that commenced late in the 1960s.[1]

Figure 1 shows a disassembled two-piece 5-in./54 HIFRAG projectile along with a simulated explosive billet. The fore and aft parts of the metal projectile body are held together by a press-fit knurled joint. Figure 2 is a schematic of an assembled two-piece projectile.

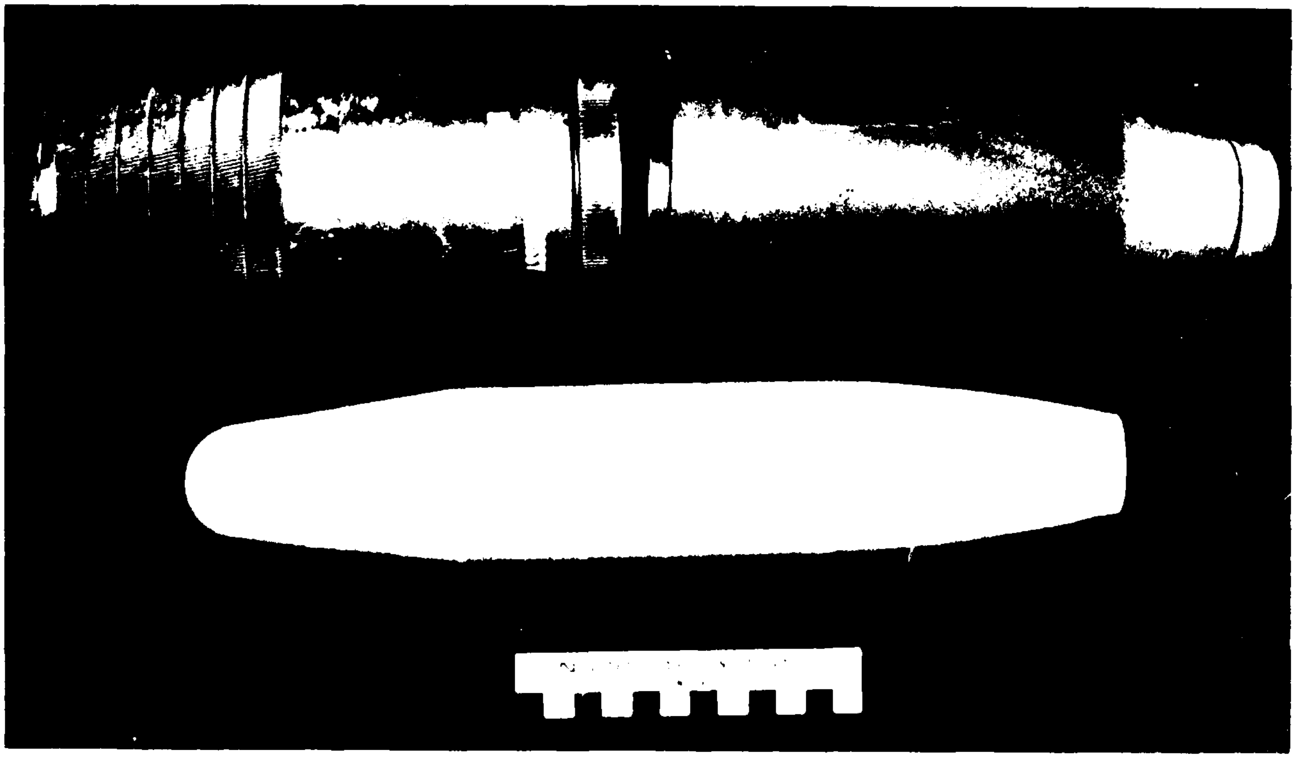


FIGURE 1. PHOTOGRAPH OF UNASSEMBLED TWO-PIECE 5-IN./54 (HIFRAG) PROJECTILE AND SIMULATED ENCAPSULATED EXPLOSIVE BILLET.

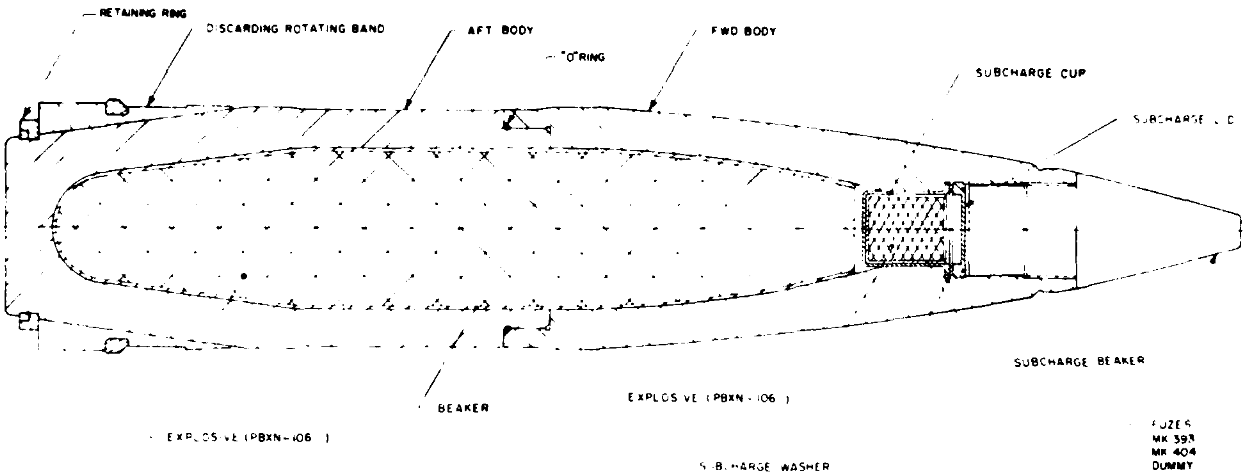


FIGURE 2. SCHEMATIC OF AN ASSEMBLED TWO-PIECE PROJECTILE. NOTE UNOCCUPIED INTERNAL VOLUME BETWEEN THE EXPLOSIVE BILLET AND THE SUBCHARGE CUP.

During the extensive development and test program, it was found necessary when dealing with the cold-cast PBX explosives to provide ample room (ullage) for thermal expansion of the encapsulated billet. This was to prevent a dangerous situation in which the explosive expanded against the base of the subcharge cup during thermal cycling over the specification range of -65°F (-53.9°C) to +160°F (+73.9°C). While the thermal coefficients of expansion for the PBX explosives are similar to those of conventional explosives (10 times that of the steel projectile)*, their densities are more than 99% of theoretical maximum density (TMD), as compared to 96% TMD for conventional bursting charges. Lacking "internal ullage" in the explosive itself, PBXN-106 billets require a minimum of 2.5 in.^{3} (~41 cm^3) of peripheral clearance within the projectile at an ambient temperature of 77°F (25°C). At this temperature, the billet is loose in its shell just like a peanut.[1]

Because of the safety implications of maintaining minimum ullage, a means of measuring the ullage of each assembled projectile is needed. Initial attempts at determining projectile ullage involved filling the fore and aft projectile parts with water, then pouring out and measuring the water. The billet volume was determined by a water displacement method. These measurements were plagued by uncertainties introduced by the temperature of the water and of the parts being measured, the wetting of the metal surfaces, and the consequent adherence of a film of water. Accurate bookkeeping was required on each fore and aft body part and billet so that they could be selectively assembled to provide the proper ullage. The presence of water on the metal parts also required subsequent drying to prevent rusting. This approach was time-consuming (and hence costly in labor) and was not suitable for production inspection of assembled projectiles. If water was poured

*The thermal coefficient of linear expansion for PBXN-106 is 6.722 x 10^{-5} in./in./°F, and for steel is 0.65 x 10^{-5} in./in./°F.

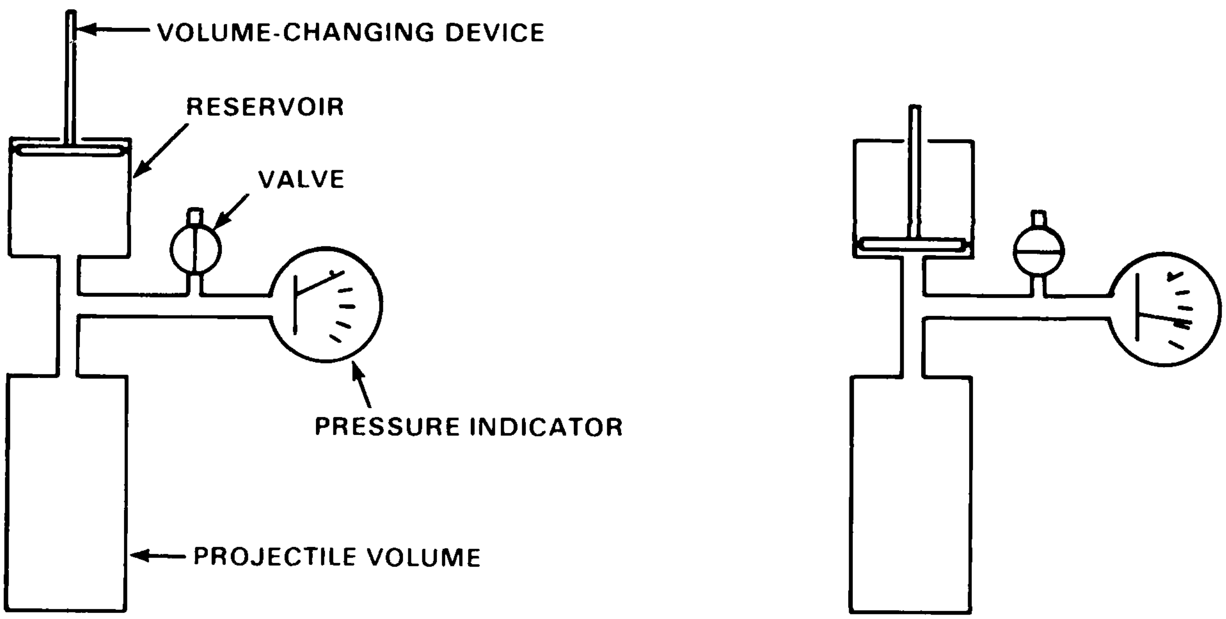
into an assembled projectile, there was no way to ensure that it all came back out, and, there was no satisfactory means of drying the projectile interior.

In order to meet the requirement for 100% inspection of assembled projectiles for minimum ullage in a production facility environment, a new technique was conceived at NSWC and a laboratory demonstration apparatus was developed. The technique is simple, nondestructive, noncontaminating, and can readily be used in a production facility environment. The ullage inspection technique is based on the change in pressure in a system that results from a known change in the system volume.

The principles of operation of the apparatus for projectile minimum ullage inspection are presented in Section II. The laboratory demonstration apparatus is described in Section III. Suggestions for production facility application of the ullage inspection technique are presented in Section IV. Section V is a brief summary. Appendix A contains the detailed instructions for initial setup and operation that were sent to NAD/Crane along with the laboratory demonstration apparatus for use in the HIFRAG pilot production program. Appendix B contains schematics of the projectile inspection fixture parts, the volume change reservoir, and calibration cylinder. Although the apparatus was intended for GO/NO-GO inspection of projectiles for minimum ullage, with minor modifications, it could be used to obtain the actual ullage value. Appendix C contains derivations of the equations needed when the actual ullage value is required. A calibration curve illustrating the functional dependence of ullage on apparatus pressure is provided in Appendix D.

II. ULLAGE INSPECTION TECHNIQUE

The ullage inspection technique is based on the change in the pressure in a system that results from a known change in the system volume. If part of the system is an unknown volume, this unknown volume can be related to the change in the system pressure. Figure 3 shows schematics of the inspection apparatus connected to an unknown projectile volume, V_x. The apparatus consists of a reservoir with a piston device for changing the reservoir volume, a valve, a pressure indicator, and connecting tubing. It is assumed that the volume of the pressure indicator is constant and is included in the volume of the connecting tubing.



(a) (b)

FIGURE 3(a). SCHEMATIC OF ULLAGE INSPECTION APPARATUS IN CONDITION A. THE VALVE IS OPEN AND THE SYSTEM IS AT AMBIENT (ATMOSPHERIC) PRESSURE. THE VOLUME-CHANGING DEVICE IS IN THE MAXIMUM RESERVOIR VOLUME POSITION.

FIGURE 3(b). SCHEMATIC OF ULLAGE INSPECTION APPARATUS IN CONDITION B. THE VALVE HAS BEEN CLOSED AND THE VOLUME-CHANGING DEVICE HAS THEN BEEN MOVED TO THE MINIMUM RESERVOIR VOLUME POSITION. THE SYSTEM PRESSURE IS HIGHER THAN THE ATMOSPHERIC PRESSURE OF CONDITION A.

In Figure 3(a) the apparatus is in Condition A, and the total system volume is

$$V^A = V_R^A + V_T^A + V_X \tag{1}$$

where V_R^A is the reservoir volume, V_T^A is the volume of the connecting tubing, and V_X is the unknown projectile volume.

The volume-changing device is positioned to maximize the reservoir volume. The apparatus pressure for Condition A is the ambient atmospheric pressure; this is achieved by opening the valve momentarily and then closing the valve.

In Figure 3(b) the apparatus is in Condition B, and the total system volume is

$$V^B = V_R^B + V_T^B + V_X \tag{2}$$

where V_R^B is the reservoir volume when the volume-changing device is positioned to minimize the reservoir volume. Note that $V_T^B = V_T^A \equiv V_T$, and V_X is unchanged. The apparatus pressure is now P^B. Note that $P^B = P^A + \Delta P$ where ΔP is the change in the apparatus pressure.

Then for constant temperature and atmospheric pressure, Boyle's Equation[2,3] for an ideal gas* gives

$$P^A V^A = P^B V^B \tag{3}$$

or

$$P^A\left(V_R^A + V_T + V_X\right) = P^B\left(V_R^B + V_T + V_X\right) \tag{4}$$

Now $V_R^A - V_R^B = \Delta V_R$, and, letting $V_R^B = 0$, $V_R^A = \Delta V_R \equiv \Delta V$

Then

$$P^A\left(\Delta V + V_T + V_X\right) = \left(P^A + \Delta P\right)\left(V_T + V_X\right) \tag{5}$$

or,

$$P^A \Delta V + P^A\left(V_T + V_X\right) = P^A\left(V_T + V_X\right) + \Delta P\left(V_T + V_X\right)$$

or,

$$P^A \Delta V = \Delta P V_T + \Delta P V_X$$

and

$$V_X = \frac{P^A \Delta V}{\Delta P} - V_T \tag{6}$$

*For temperatures and pressures of interest to this application, ideal gas formulas can be used with considerable accuracy. As an example, for air at 77°F and 1 atmosphere (at), the deviation from Equation (3) is on the order of 0.03%.[3,4]

Thus, in Equation (6) the projectile ullage V_X can be calculated from the apparatus parameters (constants) ΔV and V_T, the atmospheric pressure P^A, and the measured change in the apparatus pressure, ΔP.

Note, however, that the interest is in having an ullage volume that is at least as large as a specified minimum value. If the projectile is replaced with a calibration volume, V_C, and if the calibration volume is selected to be equal to the specified minimum ullage, then Equation (6) becomes

$$V_C = \frac{P^A \Delta V}{\Delta P_C} - V_T \qquad (7)$$

If Equation (7) is subtracted from Equation (6), then

$$V_X - V_C = \frac{P^A \Delta V}{\Delta P} - V_T - \left(\frac{P^A \Delta V}{\Delta P_C} - V_T \right) \qquad (8)$$

$$= P^A \Delta V \left(\frac{1}{\Delta P} - \frac{1}{\Delta P_C} \right)$$

or,

$$V_X = P^A \Delta V \left(\frac{1}{\Delta P} - \frac{1}{\Delta P_C} \right) + V_C \qquad (9)$$

Then as long as $\frac{1}{\Delta P} \geq \frac{1}{\Delta P_C}$, (or, $\Delta P_C \geq \Delta P$), V_X will be at least as large as V_C. For a GO/NO-GO type of ullage inspection, it then becomes unnecessary to know the values of ΔV, V_T, or P^A, as long as they do not change during the measurement of ΔP_C and ΔP. The task of inspecting a projectile for minimum ullage then becomes simply a comparison of the response of the apparatus when connected to a calibration volume with the response of the apparatus when connected to an unknown projectile ullage volume.

The procedure for inspecting a projectile for minimum ullage is then as follows:

1. Connect the ullage inspection apparatus to the calibration volume.

2. With the valve open, move the volume-changing device to the maximum reservoir volume position.

3. Close the valve.

4. Slowly move the volume-changing device to the minimum reservoir volume position.

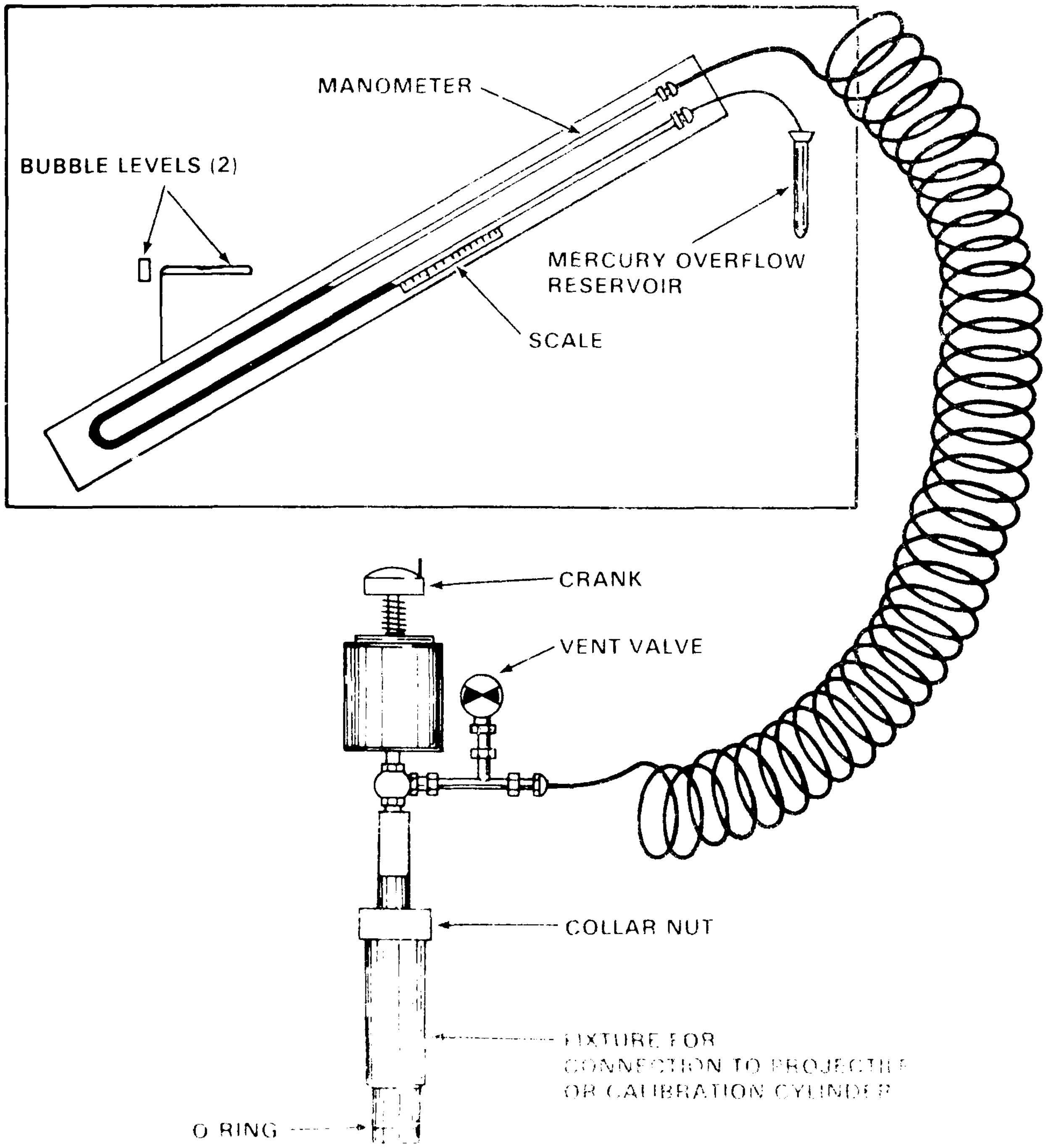
5. Note the indicated apparatus pressure.

6. Open the valve and disconnect the ullage inspection apparatus from the calibration volume.

7. Connect the ullage inspection apparatus to the projectile volume.

8. Repeat steps 2 through 5.

9. If the apparatus pressure is less than or equal to the pressure obtained with the calibration volume, then the projectile ullage is greater than or equal to the specified minimum ullage.


MANOMETER
BUBBLE LEVELS (2)
MERCURY OVERFLOW
RESERVOIR
SCALE
CRANK
VENT VALVE
COLLAR NUT
FIXTURE FOR
CONNECTION TO PROJECTILE
OR CALIBRATION CYLINDER
O RING

4. Check the mercury column against the "calibration mark." If the column is above the mark, the projectile is rejected; if the column is below the mark, the projectile is accepted (Figure A-7).

5. Open the vent valve; turn the crank counterclockwise to the upper position until a slight resistance is felt. Loosen the collar nut (Figure A-8). Remove the inspection fixture from the projectile. Repeat the inspection procedure for the next projectile. Remember to recalibrate the inspection apparatus.

INITIAL SETUP AND CALIBRATION

1. Mount the 3- x 4-ft backboard so that the plane of the board is absolutely vertical according to the bubble level mounted on the backboard. Observe top and bottom designations on the board. Bottom should be level.

2. Loosen the wingnuts slightly; adjust the manometer to 30° from the horizontal according to the bubble level mounted on the manometer board. Retighten wingnuts and recheck the angle of the manometer.

3. Unless the equipment is moved to another location, steps 1 and 2 should not have to be repeated.

4. Connect the inspection unit, the tubing, and the manometer as shown in Figure A-1. Use care not to twist the pipe fitting sealed to the glass tube.

5. Prepare the inspection unit by turning the crank at the top of the unit counterclockwise to the upper position until a slight resistance is felt. Then open the vent valve (counterclockwise) and loosen the collar nut (counterclockwise). Insert the inspection fixture into the calibration cylinder as shown in Figure A-2.

6. Tighten the collar nut by hand until it stops. Close the vent valve and turn the crank clockwise to the lower position until a slight resistance is felt.

7. Using a clip or colored tape or other means, mark the position of the mercury column on the millimeter scale. This is the "calibration mark" (see Figure A-3).

8. Leave the mercury column at the "calibration mark" for one minute. If there is no perceptible moving back of the mercury column after one minute, the inspection apparatus is ready for projectile inspection. If the mercury column has moved back after one minute, there is a leak somewhere. Find and correct the leak. Repeat steps 5 through 8.

9. The calibration should be done about every quarter hour to account for changes in barometric pressure or temperature. When in doubt, recalibrate.

PROJECTILE INSPECTION PROCEDURE

1. Open the valve and loosen the collar nut. Turn the crank counterclockwise to the upper position until a slight resistance is felt. Insert the inspection fixture into the projectile as shown in Figure A-4.

2. Tighten the collar nut by hand until it stops, and close the vent valve (Figure A-5).

3. Turn the crank clockwise to the lower position until a slight resistance is felt (Figure A-6).

APPENDIX A

INSTRUCTIONS FOR INITIAL SETUP AND OPERATION OF ULLAGE INSPECTION APPARATUS

(These instructions are an edited form of the instructions that were sent to NAD/Crane along with the laboratory demonstration apparatus, for use in the HIFRAG projectile pilot production program.)

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2. G. Shortley and D. Williams, *Elements of Physics*, 5th Edition, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1971.

3. G. J. Van Wylen and R. E. Sonntag, *Fundamentals of Classical Thermodynamics*, 2nd Edition, John Wiley and Sons, Inc., New York, N.Y., 1973.

4. *Handbook of Tables for Applied Engineering Science*, 2nd Edition, R. E. Bolz and G. L. Tuve, Editors, CRC Press, Cleveland, Ohio, 1973.

5. Veeco Instruments, Inc., Terminal Drive, Plainview, New York.

6. Cajon Company, 32550 Old South Miles Road, Cleveland, Ohio.

7. Crawford Fitting Company, 29500 Solon Road, Cleveland, Ohio.

8. Nupro Company, 15635 Saranac Road, Cleveland, Ohio.

V. SUMMARY

A simple, nondestructive, noncontaminating technique for inspecting assembled projectiles for minimum ullage has been developed. The technique is based on the change in the pressure in a system that results from a known change in the system volume. If part of the system is an unknown volume, this unknown volume can be related to the change in the system pressure. A laboratory demonstration apparatus for this technique has been described. Suggestions for the production facility application of the inspection technique have been presented.

Several selected inert projectiles could be prepared as standards for ullage certification. They could be assembled with billets having slightly oversized sprues of simulant. The billet volume could then be adjusted by drilling into the sprue until the projectile ullage at 77°F was 2.5 in.^{3}. Having several standard projectiles would permit the use of multiple inspection stations at the loading facility. This would also permit interfacility standardization, if more than one facility were loading the same type of projectile.

IV. SUGGESTIONS FOR PRODUCTION FACILITY APPLICATION OF ULLAGE INSPECTION TECHNIQUE

The laboratory demonstration apparatus was conceived and assembled to show that a nondestructive technique for inspection of projectiles was feasible. The mercury manometer was used because it was the only gauge readily available in the laboratory that was suitable for the pressure range of interest. This type of gauge is fragile and has the disadvantage that as a pressure indicator its volume changes with pressure. It is suggested that the mercury manometer be replaced by a panel-mounted diaphragm or Bourdon tube gauge. The full-scale pressure range of the gauge that would be needed for the present apparatus is approximately 100 mm of mercury or approximately 2 psig. The gauge should be protected from pressure transients (such as when the vent valve is opened) by a suitable snubber.

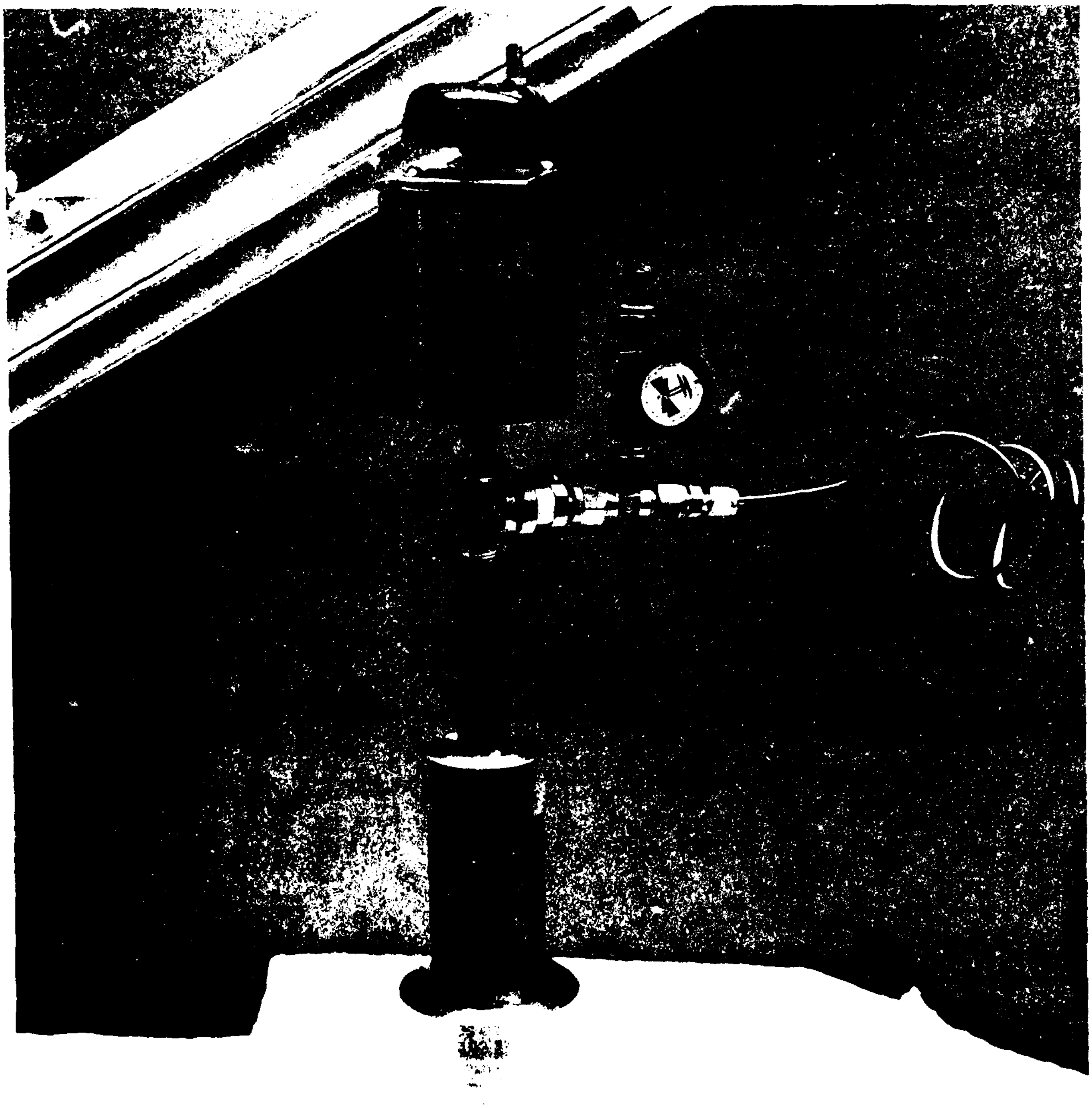
The aluminum calibration cylinder is adequate as long as the ullage inspection is performed in an area that is at or near the specified 77°F for which the minimum ullage is 2.5 in.^{3}, and as long as the projectiles are also at or near 77°F. However, for temperatures deviating from this specified temperature, the expansion or contraction of the explosive billet, the polyethylene beaker, and the steel projectile will change the minimum ullage accordingly.

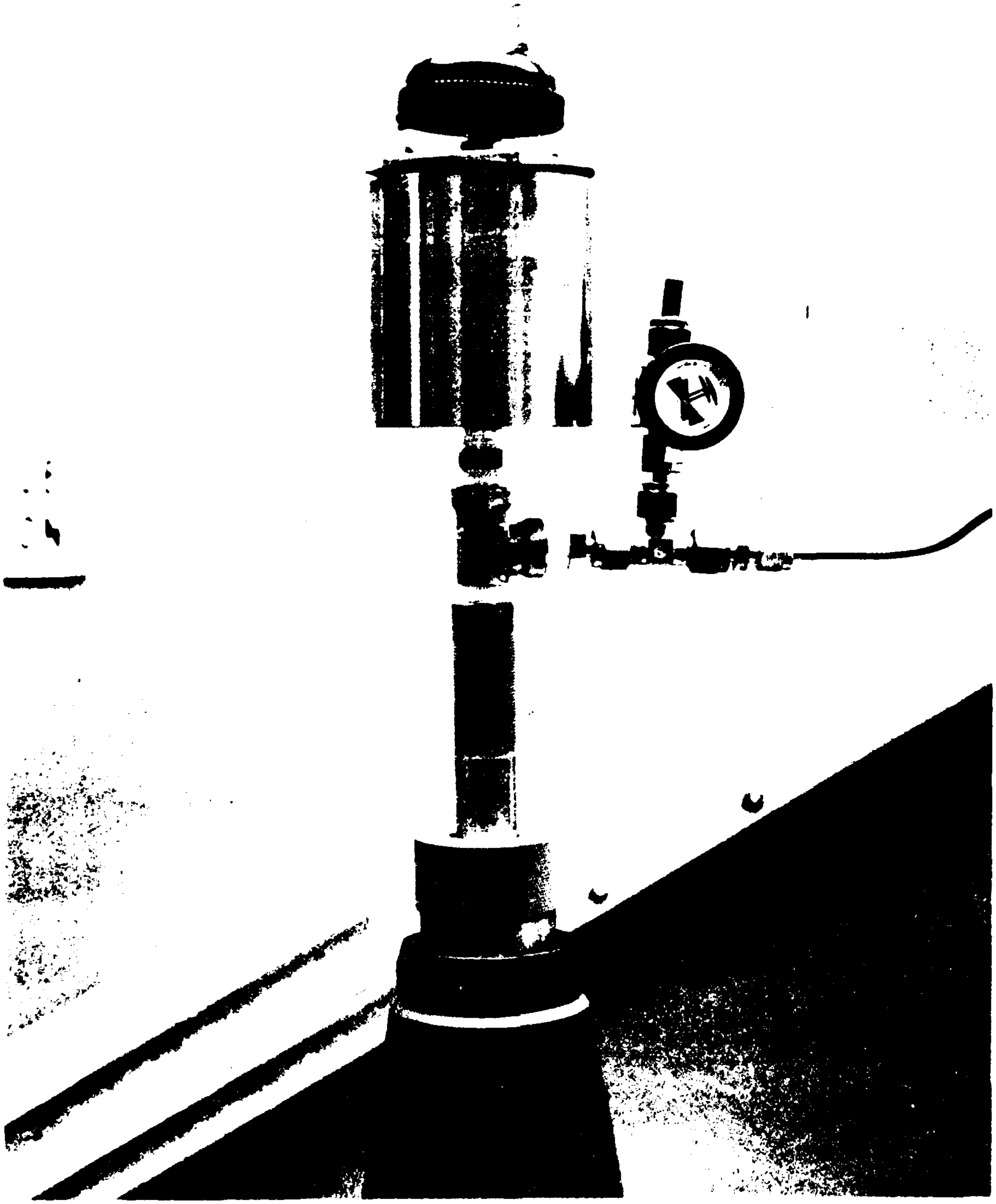
Recall that the change ΔV in a volume V of material due to a temperature change ΔT is

$$\Delta V = 3\alpha V \Delta T \tag{8}$$

where α is the thermal coefficient of linear expansion for the material.[2] Note the dependence of ΔV on the volume V. Then primarily because of the relatively large volume of PBXN-106 or inert simulant in a projectile, the variation in projectile ullage with temperature will not be the same as the variation in the ullage of the calibration cylinder.

It is therefore suggested that a standardized inert projectile be used as the minimum ullage calibration volume. The standard projectile would contain an encapsulated billet of explosive simulant and the volume of the simulant would be adjusted so that the projectile ullage at 77°F would be 2.5 in.^{3}. This projectile would be kept with the explosive-filled projectiles so that they all would be equilibrated to approximately the same temperature prior to ullage inspection. Then if the temperature of the projectiles changed, the ullage of the standard projectile would change accordingly.





[illegible] TION UNIT
[illegible]

Cajon Hex Nipple,[6] Part No. SS-4-HN	(1)
Cajon Street Tee, Part No. SS-4-ST	(1)
Swagelok Male Adapter,[7] Tube to Pipe, Part No. B-401-A-4	(1)
Swagelok Union Tee, Part No. B-400-3	(1)
Swagelok Port Connector, Part No. B-401-PC	(2)
Swagelok Reducer, Part No. B-200-R-4	(2)
Swagelok Male Connector, Part No. B-400-1-4	(1)
Nupro Bellows Valve,[8] Part No. B-4H	(1)

A coil of 0.125-in. (3.175 mm) O.D. copper tubing was used to connect the inspection unit to the manometer. The tubing was coiled for increased flexibility. It was later replaced by a shorter length of 0.125-in. O.D. nylon high-pressure tubing, with a sleeve of copper braid to prevent static charge buildup on the nylon. High-pressure tubing was used because of its small bore and its resistance to stretching; its volume change at the pressures of interest would be negligible.

Figure 8 shows the unit inserted into an aluminum calibration cylinder. The length of the cavity in the cylinder was machined to be oversized and then carefully adjusted to be the specified minimum ullage volume by adding a small amount of epoxy to the base of the cavity.

Recall that in the derivation of Equations (6) and (9) for the projectile ullage in terms of measured parameters, it was assumed that the volume of the pressure indicator did not change during the inspection procedure. When the mercury manometer is used, the volume of the pressure indicator changes linearly with pressure (it is assumed that the manometer tube dimensions are uniform, so that the tube cross-section area is constant). This will not affect the GO/NO-GO inspection of a projectile for minimum ullage since the displacement of the mercury column is referenced to that obtained with the calibration volume. Modifications of Equations (6) and (9) to include the effects of a pressure-dependent change in the volume of the pressure indicator are discussed in Appendix C.

The cylindrical reservoir at the top of the unit contains a volume-changing device that is the stem and bellows assembly out of a high vacuum valve (Veeco[5] Part No. 2856-006). This assembly fits into the top of the reservoir and is sealed to the reservoir by a silicone rubber gasket and two screws. It provides a means of changing the apparatus volume by exactly the same amount each time the change is effected. Figure 6 shows the retracted and extended conditions of the bellows. A crank handle was added to the valve knob to facilitate turning of the shaft to retract or extend the bellows between stops. The stops were the square portion of the bellows assembly (for retraction) and the bottom of the reservoir (for extension). The threaded shaft and crank combination provides smooth, controlled movement of the bellows, avoiding "stick-slip" motion that would cause pressure oscillations inside the apparatus. Such oscillations could cause the mercury to overflow from the tilted manometer. The handcrank feature also limits the rate of change of volume so that isothermal conditions are maintained.

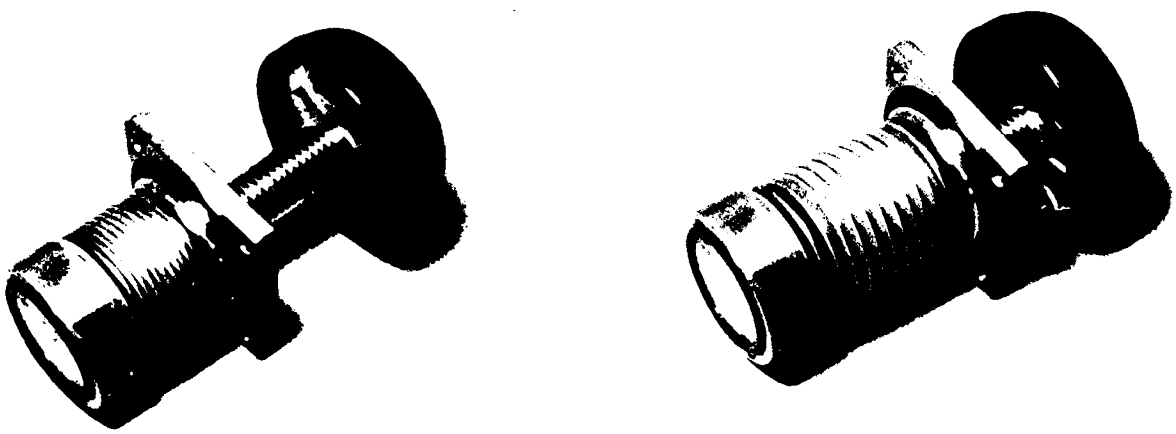


FIGURE 6. STEM AND BELLOWS ASSEMBLY FROM A VACUUM VALVE. THIS ASSEMBLY FUNCTIONS AS THE VOLUME-CHANGING DEVICE IN THE RESERVOIR OF THE ULLAGE INSPECTION UNIT. (a) RETRACTED CONDITION. (b) EXTENDED CONDITION.

Figure 7 is a close-up view of the inspection unit inserted in a projectile. The following additional commercial parts (and quantities) were used in the unit and in the connection to the manometer:

The fixture for connection to a projectile is designed to insert into the nose fuze opening as shown in Figure 5. A knurled collar-nut on the fixture is hand tightened to cause compression of an O-ring that forms a gas-tight seal between the fixture and the projectile. The lower end of the fixture is designed to occupy the same space inside the projectile as would be occupied by the subcharge cup (see Figure 2). The measured ullage is then the same as would be present after insertion of the subcharge cup.

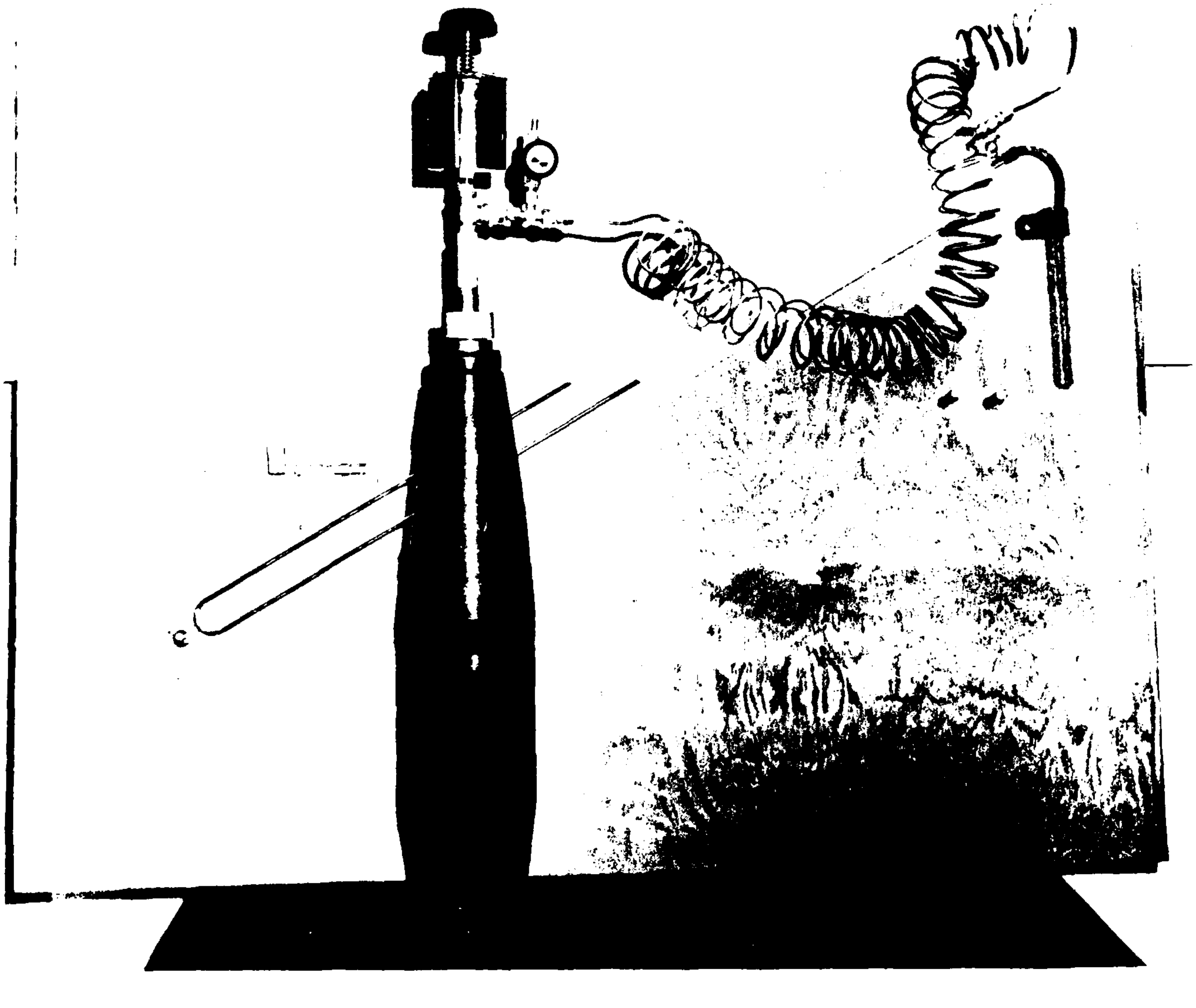


FIGURE 5. LABORATORY DEMONSTRATION APPARATUS; THE INSPECTION FIXTURE IS INSERTED INTO THE NOSE FUZE OPENING OF AN INERT HIFRAG PROJECTILE.

III. LABORATORY DEMONSTRATION APPARATUS

Figure 4 shows the laboratory demonstration apparatus and an inert HIFRAG projectile. A brass fixture for connection to a projectile, a steel cylindrical reservoir with volume-changing device, and a vent valve form a unit that is connected to a tilted mercury manometer via a coil of copper tubing. The manometer is tilted 60° from vertical to double the displacement of the edge of the mercury column for a given pressure difference. A millimeter scale is attached to the manometer to provide fiducial marks for mercury displacement comparisons.

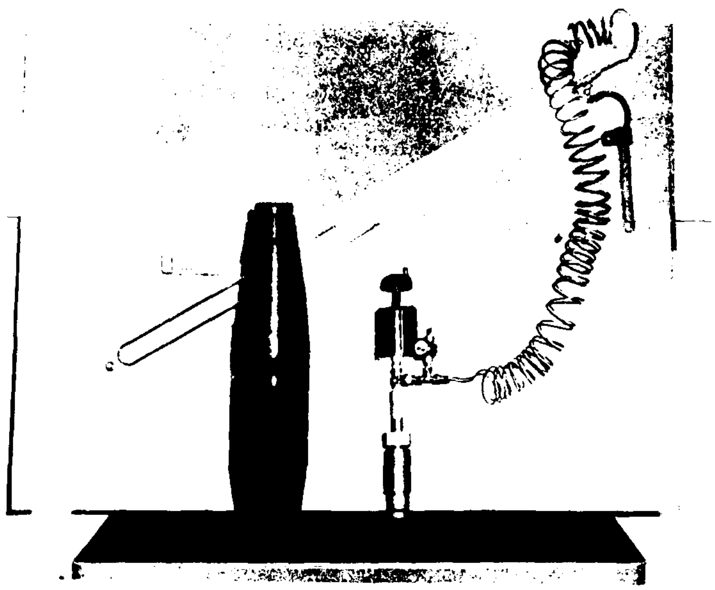


FIGURE 4. LABORATORY DEMONSTRATION APPARATUS AND AN INERT HIFRAG PROJECTILE. THE BRASS FIXTURE FOR CONNECTION TO A PROJECTILE, THE STEEL RESERVOIR WITH VOLUME-CHANGING DEVICE, AND THE VENT VALVE FORM A UNIT THAT IS CONNECTED TO A MERCURY MANOMETER BY A FLEXIBLE COIL OF COPPER TUBING. THE COPPER TUBING WAS LATER REPLACED BY A SHORTER NYLON TUBE COVERED WITH A COPPER BRAID. THE MANOMETER IS TILTED TO INCREASE THE DISPLACEMENT OF THE MERCURY COLUMN FOR A GIVEN PRESSURE DIFFERENCE. AN OVERFLOW TUBE AND TEST-TUBE RESERVOIR ARE ATTACHED TO THE MANOMETER. TWO BOLTS NEAR THE OVERFLOW RESERVOIR FORM A SUPPORT ON WHICH TO HANG THE INSPECTION UNIT WHEN IT IS NOT INSERTED IN A PROJECTILE OR A CALIBRATION VOLUME.

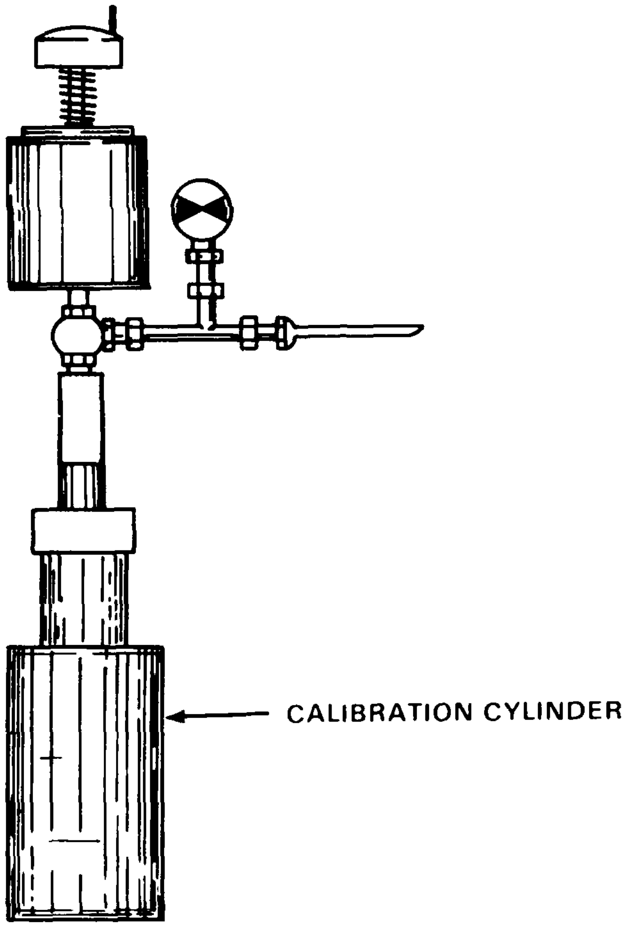


FIGURE A-2. ULLAGE INSPECTION FIXTURE INSERTED IN THE CALIBRATION CYLINDER.

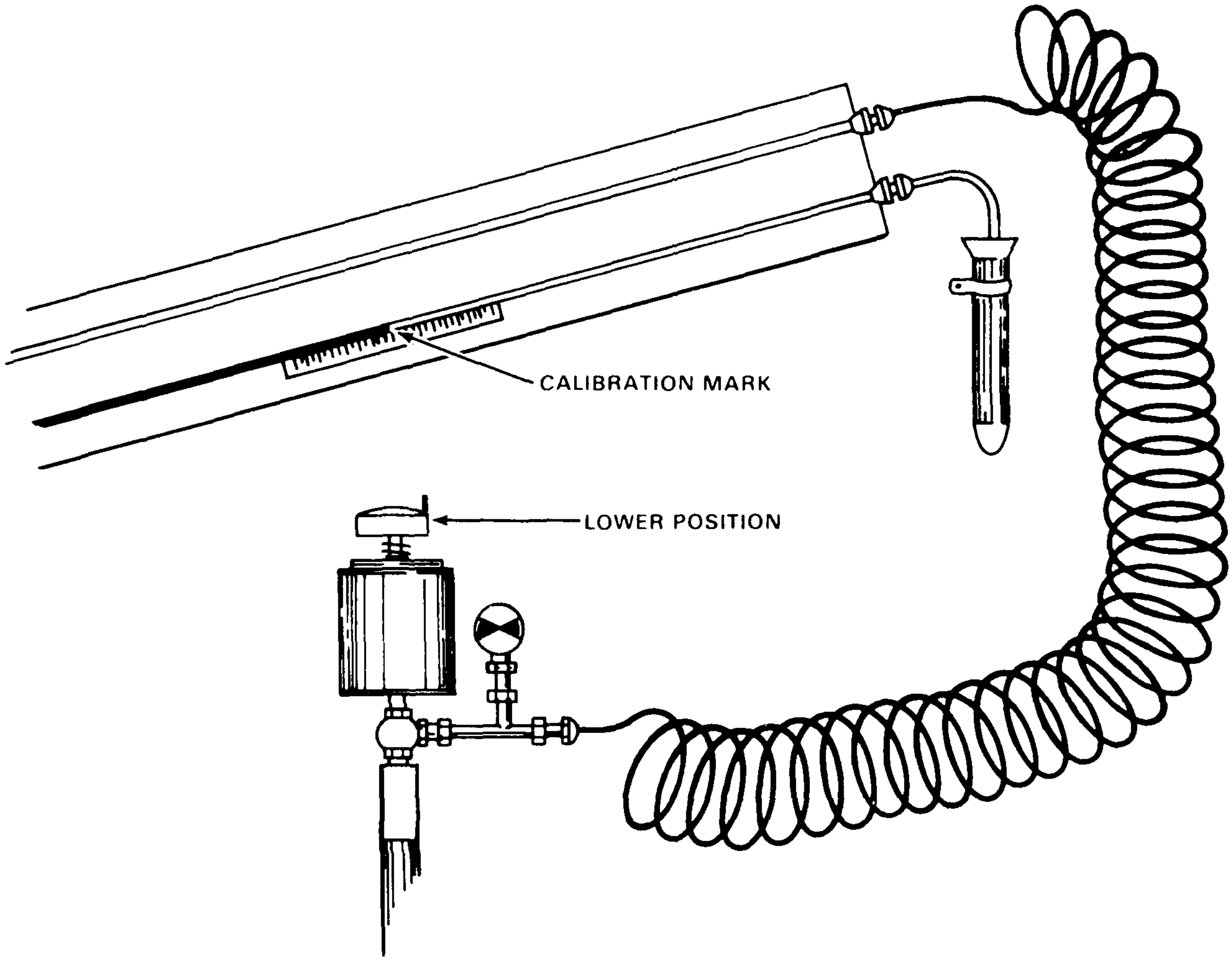


FIGURE A-3. CALIBRATION OF INSPECTION APPARATUS FOR MINIMUM ULLAGE.

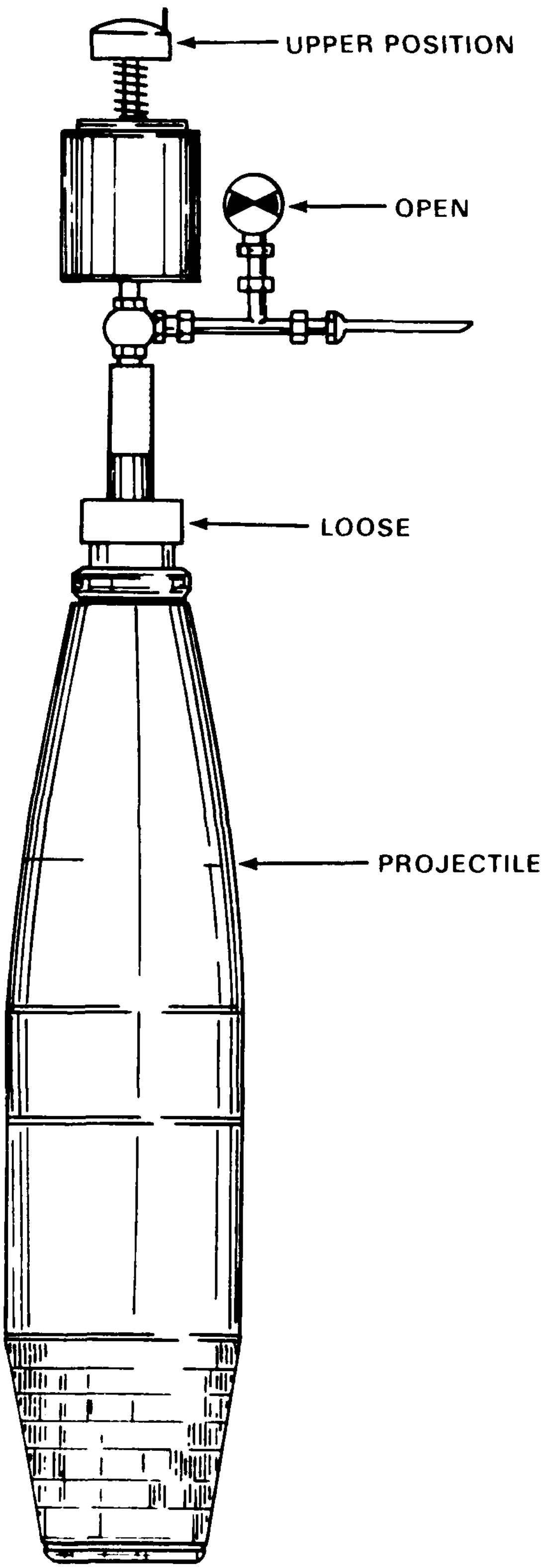


FIGURE A-4. PROJECTILE ULLAGE INSPECTION (STEP 1).

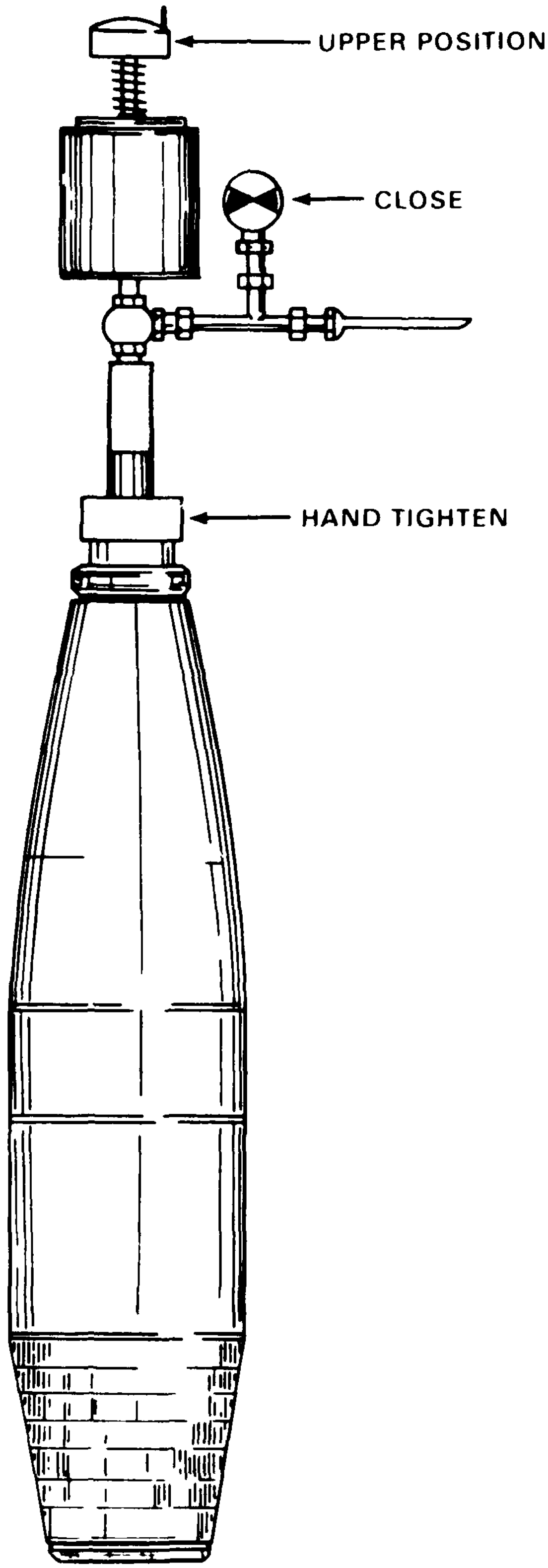


FIGURE A-5. PROJECTILE ULLAGE INSPECTION (STEP 2).

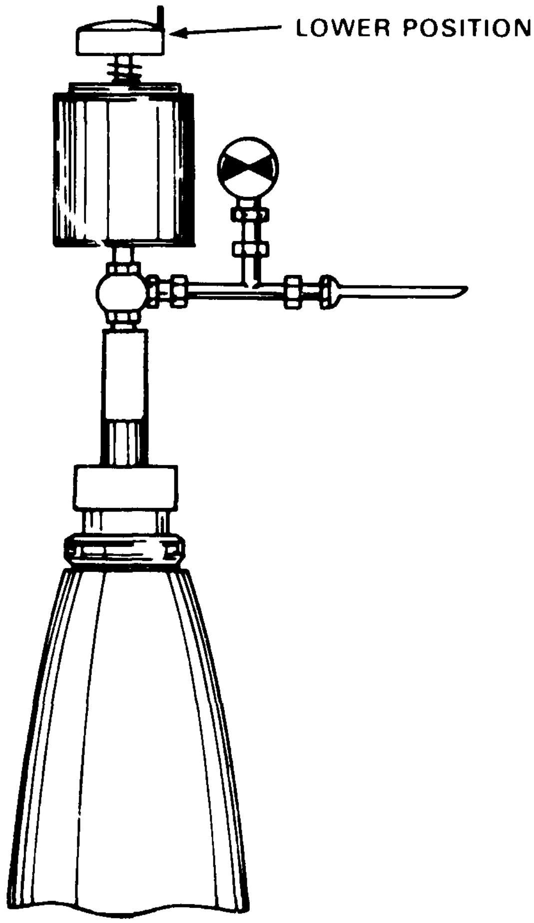


FIGURE A-6. PROJECTILE ULLAGE INSPECTION (STEP 3).

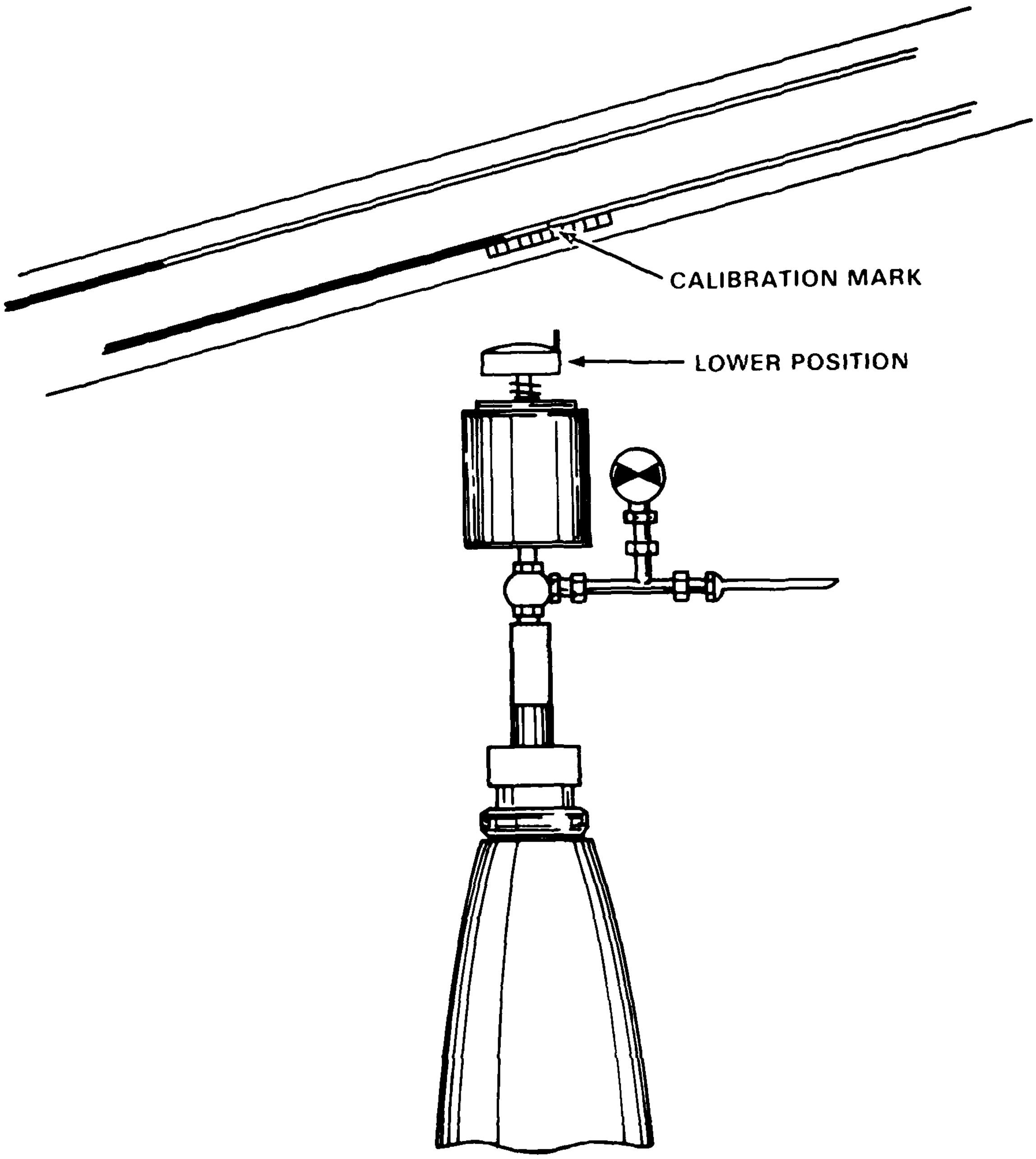


FIGURE A-7. PROJECTILE ULLAGE INSPECTION (STEP 4).

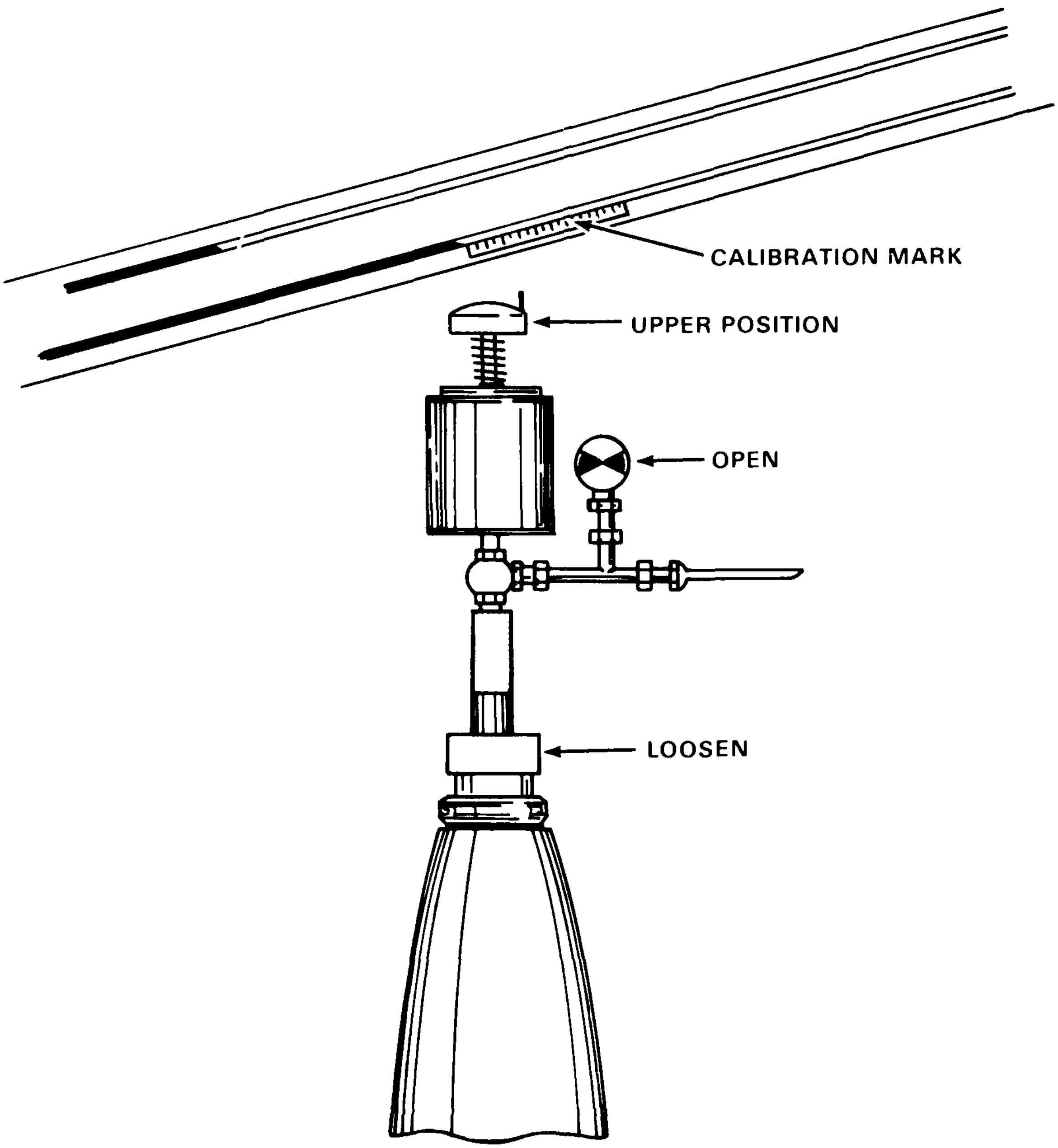


FIGURE A-8. PROJECTILE ULLAGE INSPECTION (STEP 5).

APPENDIX B

SCHEMATICS OF ULLAGE INSPECTION FIXTURE PARTS, RESERVOIR CYLINDER, AND CALIBRATION CYLINDER

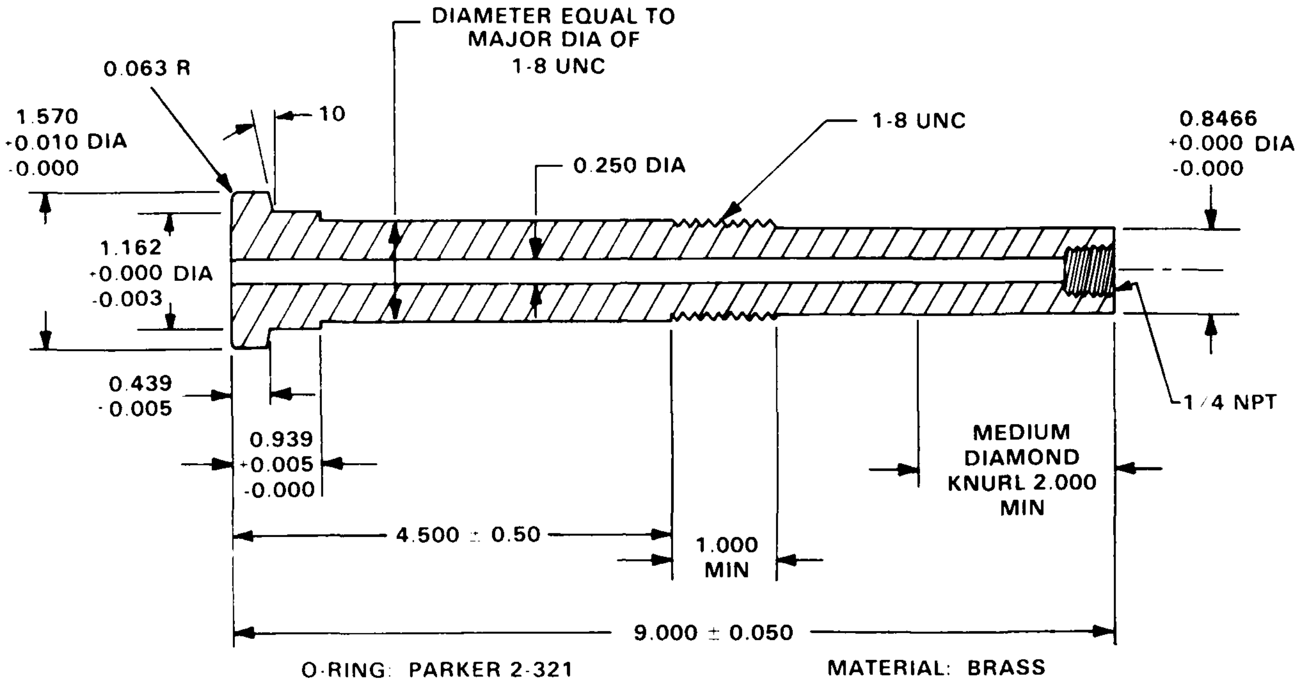


FIGURE B-1. SCHEMATIC OF INNER PART OF ULLAGE INSPECTION FIXTURE.

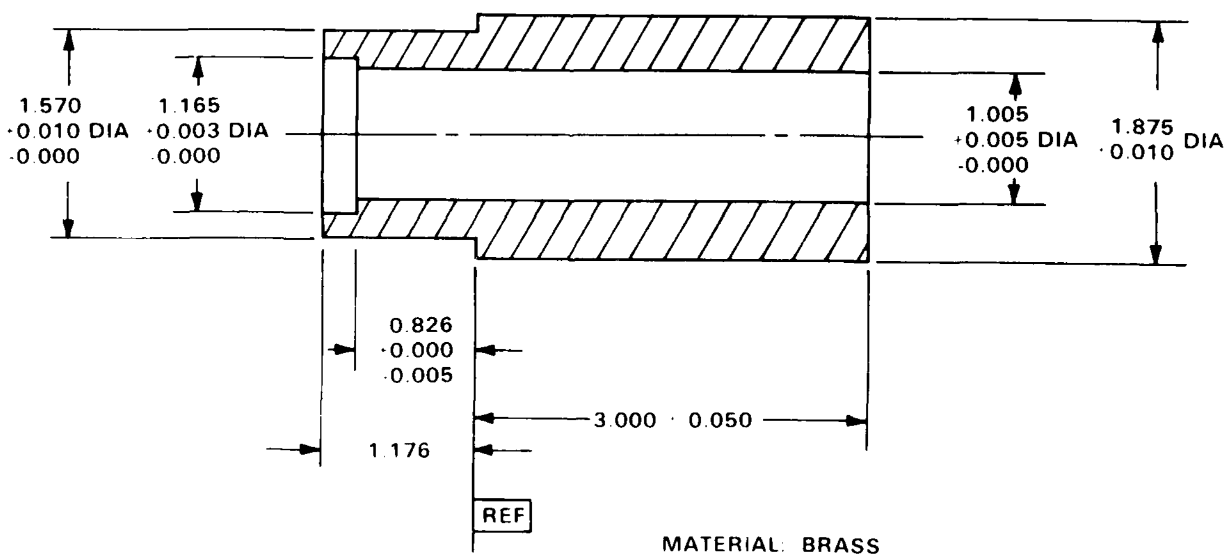


FIGURE B-2. SCHEMATIC OF OUTER PART OF ULLAGE INSPECTION FIXTURE.

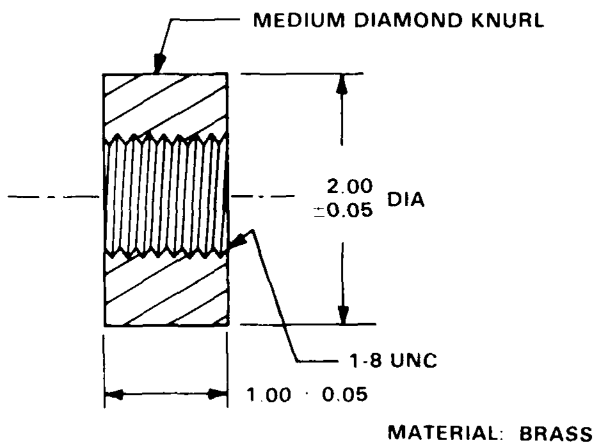


FIGURE B-3. SCHEMATIC OF KNURLED NUT FOR ULLAGE INSPECTION FIXTURE.

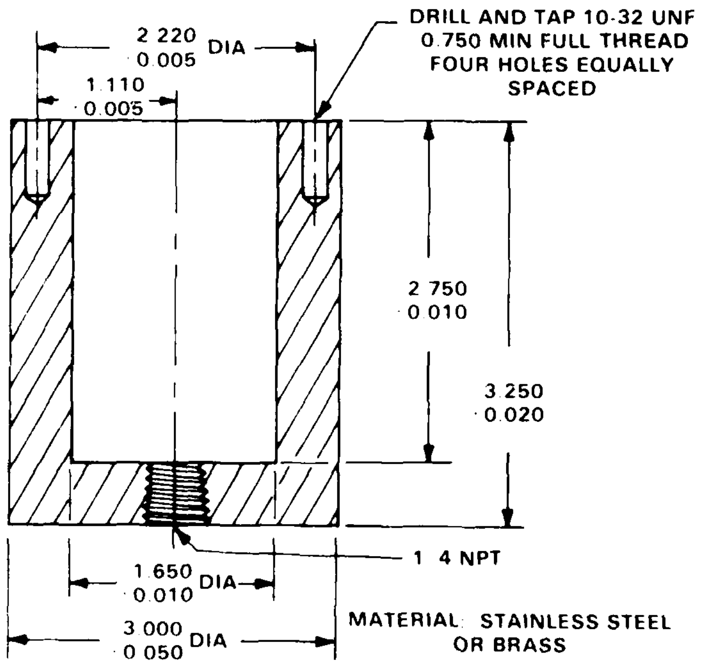


FIGURE B-4. SCHEMATIC OF VOLUME CHANGE RESERVOIR CYLINDER FOR ULLAGE INSPECTION APPARATUS.

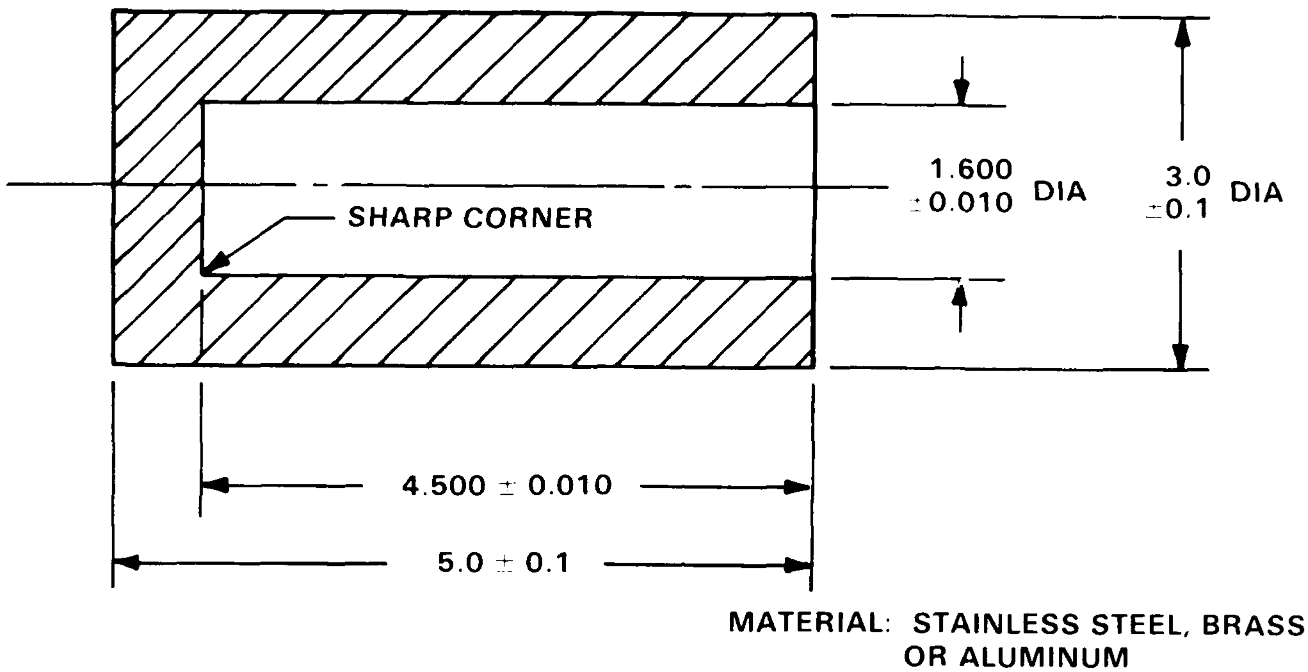


FIGURE B-5. SCHEMATIC OF CALIBRATION CYLINDER FOR ULLAGE INSPECTION APPARATUS.

APPENDIX C

DERIVATION OF EQUATIONS RELATING PROJECTILE ULLAGE TO APPARATUS PARAMETERS

DETERMINATION OF APPARATUS CONSTANTS ΔV AND V_T

If the actual ullage volume for a projectile is desired, then the atmospheric pressure, PA, the volume change ΔV, and the volume of the connecting tubing, V_T, will be needed in Equation (6). P^A can be measured directly with a barometer. A direct measurement of ΔV and/or V_T may not be practical; however, if two calibration volumes are available, these quantities may be determined indirectly.

Let V_{C1} and V_{C2} be the two calibration volumes; then from Equation (6),

$$V_{C1} = \frac{P^A \Delta V}{\Delta P_{C1}} - V_T \tag{C-1}$$

$$V_{C2} = \frac{P^A \Delta V}{\Delta P_{C2}} - V_T \tag{C-2}$$

Subtracting Equation (C-2) from Equation (C-1) yields

$$V_{C1} - V_{C2} = \frac{P^A \Delta V}{\Delta P_{C1}} - V_T - \left(\frac{P^A \Delta V}{\Delta P_{C2}} - V_T \right) \tag{C-3}$$

$$= P^A \Delta V \left(\frac{1}{\Delta P_{C1}} - \frac{1}{\Delta P_{C2}} \right)$$

or,

$$\Delta V = \frac{V_{C1} - V_{C2}}{P^A \left(\frac{1}{\Delta P_{C1}} - \frac{1}{\Delta P_{C2}} \right)} \tag{C-4}$$

Note that V_T drops out in the subtraction. Now the expression for ΔV can be substituted back into either Equation (C-1) or (C-2) to calculate V_T:

$$V_{C1} = \frac{P^A}{\Delta P_{C1}} \left[\frac{V_{C1} - V_{C2}}{P^A \left(\frac{1}{\Delta P_{C1}} - \frac{1}{\Delta P_{C2}} \right)} \right] - V_T \tag{C-5}$$

or,

$$V_T = \frac{P^A}{\Delta P_{C1}} \left[\frac{V_{C1} - V_{C2}}{P^A \; \dfrac{1}{\Delta P_{C1}} - \dfrac{1}{\Delta P_{C2}}} \right] - V_{C1}$$

$$= \frac{V_{C1} - V_{C2}}{1 - \dfrac{\Delta P_{C1}}{\Delta P_{C2}}} - V_{C1}$$

or,

$$V_T = \frac{V_{C1} \dfrac{\Delta P_{C1}}{\Delta P_{C2}} - V_{C2}}{1 - \dfrac{\Delta P_{C1}}{\Delta P_{C2}}} \qquad \text{(C-6)}$$

Now consider the easily realized case where one of the calibration volumes is zero; i.e., the connection to the projectile is capped so that the only volume other than that of the volume change device is that of the connecting tubing (the pressure indicator volume is included in the tubing volume, and for a diaphragm or Bourdon gauge, or, an electronic capacitance gauge, the indicator volume is considered to be constant over the pressure range of interest). Let $V_{C2} = 0$; then

$$V_T = \frac{V_{C1} \dfrac{\Delta P_{C1}}{\Delta P_{C2}}}{1 - \dfrac{\Delta P_{C1}}{\Delta P_{C2}}}$$

and

$$[illegible] = \frac{V_{C1}}{P^A \left(\dfrac{1}{\Delta P_{C1}} - \dfrac{1}{\Delta P_{C2}} \right)}$$

Note that for a given inspection apparatus, it is necessary to determine V_T and [illegible] only once.

MODIFICATION OF APPARATUS EQUATIONS FOR USE WITH MERCURY MANOMETER

When a mercury manometer is used as the pressure indicator, the volume of the indicator changes linearly with pressure. If this change is considered to be a change in the volume of the connecting tubing (for simplicity, assume the manometer to be oriented vertically), then

$$V_T^B = V_T^A + \alpha\Delta h \qquad \text{(C-9)}$$

where α is the cross-section area of the manometer tube and Δh is the displacement of the mercury column on one side of the U-tube. Or, Equation (C-9) can be written as

$$V_T^B = V_T^A + \alpha \frac{\Delta P}{2} \qquad \text{(C-10)}$$

where ΔP is measured in millimeters of mercury.

Equation (2) then becomes

$$V^B = V_R^B + V_T^A + \alpha \frac{\Delta P}{2} + V_X \qquad \text{(C-11)}$$

and Equation (4) becomes

$$P^A \left(V_R^A + V_T^A + V_X \right) = P^B \left[V_R^B + \left(V_T^A + \alpha \frac{\Delta P}{2} \right) + V_X \right] \qquad \text{(C-12)}$$

Again we have $V_R^B = 0$, $V_R^A = \Delta V_R \equiv \Delta V$, and, $P^B = P^A + \Delta P$, so that Equation (C-12) becomes

$$P^A \left(V_T^A + V_T^A + V_X \right) = \left(P^A + \Delta P \right) \left(V_T^A + \alpha \frac{\Delta P}{2} + V_X \right) \qquad \text{(C-13)}$$

or

$$P^A \Delta V + P^A V_T^A + P^A V_X = P^A V_T^A + P^A \alpha \frac{\Delta P}{2} + P^A V_X + \Delta P V_T^A + \frac{\alpha}{2} \left(\Delta P \right)^2 + \Delta P V_X$$

or

$$P^A \Delta V = P^A \alpha \frac{\Delta P}{2} + \Delta P V_T^A + \frac{\alpha}{2} \left(\Delta P \right)^2 + \Delta P V_X \qquad \text{(C-14)}$$

Then

$$V_X = \frac{1}{\Delta P} \left[P^A \Delta V - P^A \alpha \frac{\Delta P}{2} - \Delta P V_T^A - \frac{\alpha}{2} \left(\Delta P \right)^2 \right]$$

or,

$$V_X = \frac{P^A \Delta V}{\Delta P} - V_T^A - \frac{\alpha}{2} \left(P^A + \Delta P \right) \qquad \text{(C-15)}$$

If the projectile ullage V_X is replaced by a calibration volume V_C, then Equation (C-15) becomes

$$V_C = \frac{P^A \Delta V}{\Delta P_C} - V_T^A - \frac{\alpha}{2} \left(P^A + \Delta P_C \right) \qquad \text{(C-16)}$$

If Equation (C-16) is subtracted from Equation (C-15), then

$$V_X - V_C = \frac{P^A \Delta V}{\Delta P} - V_T^A - \frac{\alpha}{2}\left(P^A + \Delta P\right) - \left[\frac{P^A \Delta V}{\Delta P_C} - V_T^A - \frac{\alpha}{2}\left(P^A + \Delta P_C\right)\right]$$

$$= P^A \Delta V \left(\frac{1}{\Delta P} - \frac{1}{\Delta P_C}\right) + \frac{\alpha}{2}\left(\Delta P_C - \Delta P\right)$$

or

$$V_X = P^A \Delta V \left(\frac{1}{\Delta P} - \frac{1}{\Delta P_C}\right) + \frac{\alpha}{2}\left(\Delta P_C - \Delta P\right) + V_C \qquad \text{(C-17)}$$

Note that as $\alpha \to 0$, Equation (C-15) reduces to Equation (6), and Equation (C-17) reduces to Equation (9).

For the case of the manometer that is tilted 60° from the vertical as in the laboratory demonstration apparatus, the displacement of the edge of the mercury colume is twice that for a vertical column for the same pressure difference (since cosine 60° = 1/2), so that the ΔP and ΔP_C values should be divided by two before using in Equations (C-15) or (C-17).

APPENDIX D

APPARATUS CALIBRATION CURVE

This calibration curve was obtained at NSWC prior to shipment of the apparatus to NAD/Crane (Figure D-1, Table D-1). The ambient conditions were 72°F and 779.5 mm Hg. This curve is presented only to show the functional dependence of ullage on apparatus pressure. Do not use this curve for minimum ullage determination, since the minimum ullage for HIFRAG projectiles is specified to be 2.5 in.^{3} at 77°F. The curve was obtained with the aluminum calibration cylinder (before epoxy was added to adjust the cylinder volume to be 2.5 in.^{3}). The cylinder ullage was changed by known amounts by adding water from a burette. A numerical curve fit to the data gives

$$y = \frac{936.5}{x} - 5.667$$

where y is the ullage in cubic inches and x is the displacement of the mercury column in millimeters on one side of the U-tube of the 60° tilted manometer.)

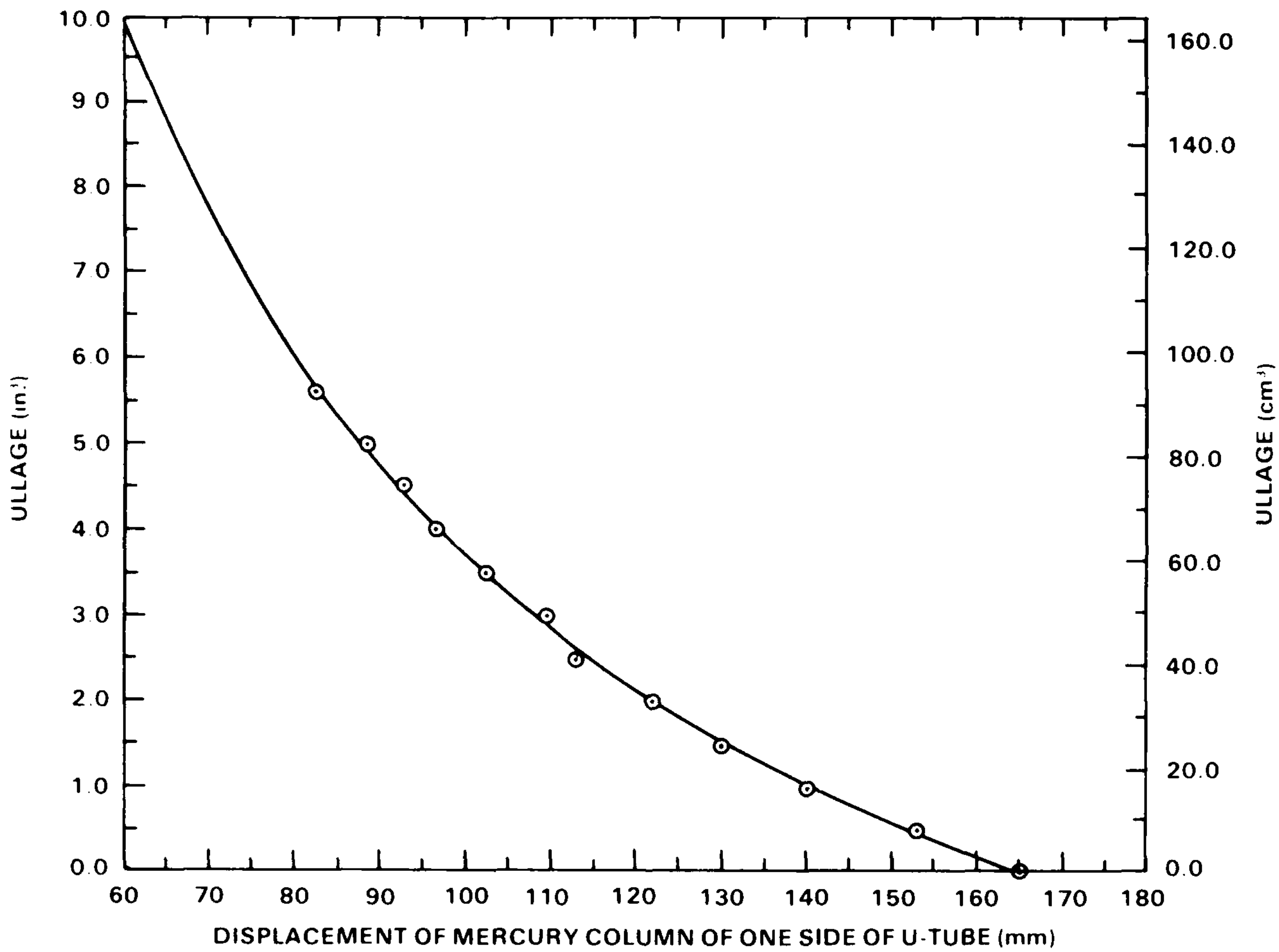


FIGURE D-1. APPARATUS CALIBRATION CURVE; THE AMBIENT CONDITIONS WERE 72°F AND 779.5 mm HG. THE SOLID LINE IS THE NUMERICAL CURVE FIT TO THE DATA. (DO NOT USE THIS CURVE FOR MINIMUM ULLAGE DETERMINATION, SINCE THE MINIMUM ULLAGE FOR HIFRAG PROJECTILES IS SPECIFIED TO BE 2.5 in.^{3} at 77°F.)

TABLE D-1. CALIBRATION DATA FOR ULLAGE INSPECTION APPARATUS: AMBIENT CONDITIONS WERE 72°F AND 779.5 mm HG

Ullage		Hg Displacement*
(in.^{3})	(cm^3)	(mm)
5.607	91.89	82.5
5.000	81.95	88.0
4.500	73.76	93.0
4.000	65.56	96.5
3.500	57.37	102.5
3.000	49.17	109.5
2.500	40.98	113.0
2.000	32.78	122.0
1.500	24.59	130.0
1.000	16.39	140.0
0.500	8.195	153.0
0.000	0.000	165.0

*Displacement of the mercury column on one side of the 60° tilted U-tube.

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