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THREAD CERTIFICATION

PDO 6984763, Final Report

C. W. Berry, Jr., Project Leader

Project Team:
W. J. Courtney, IITRI

October 1975

MASTER

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Prepared by C. W. Berry, Jr., D/142, under PDO 6984763

Air gaging of blind and through-type miniature threaded holes has proven feasible. Efforts to determine the flow at minimum and maximum threaded hole geometries were not successful. Additional work to determine these limits has been recommended. As a result of this work, a technique for air gaging hole diameters in printed circuit boards has been developed. This technique is recommended to replace plug gaging of these holes which is now considered a destructive test.

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SUMMARY

Bendix placed a contract with the Illinois Institute of Technology Research Institute (IITRI) to determine the feasibility of air gaging internal 0.6, 0.8, and 1.0 Unified Miniature Screw Threads (UNM) in through-threaded holes. The air flow measurements were made with a cylindrical GO plug gage in the center of the threaded hole. In addition to increasing the sensitivity of the measurement so that the thread form can be detected, the plug gage can be used to check the minimum minor diameter of the threaded hole in a production inspection tool. The theoretical and experimental evaluation showed that air gaging these holes was feasible.

Additional investigations were aimed at determination of acceptance criteria for a through-threaded hole, the effect of eccentricity between the plug gage used to increqse the sensitivity and the threaded holes, and feasibility of air gaging blind miniature threaded holes. Determination of the maximum and minimum flow limits for a threaded hole using an anodization process proved unsuccessful. IITRI showed that eccentricity of the air gaging probe to the threaded hole did not adversely affect air flow measurements, and showed that, if end constraints are met, gaging of blind tapped holes is feasible.

While IITRI's investigations were underway, probes for measuring through and blind miniature threaded holes were developed at Bendix. A repeatability of ±87 microinches (2.2 μm) at two standard deviations was obtained.

After IITRI completed their study, Bendix investigated the use of drilled and tapped masters, screw gages, and thread plug gages for determining the acceptance limits of threaded holes. The drill and tap study resulted in a better understanding of plastic flow in tapped holes and the expected yield for tapped holes using various drill sizes; however, efforts at making masters failed because of excessive tap breakage and the large spread of tapped hole sizes obtained at the minimum limit. Preliminary studies were completed using screw and thread gages. Both these methods showed enough promise to warrant future work. However, this work was not continued because part configurations were changed to allow large changes in lengths of threaded holes. An error analysis predicted that the change will result in a ±20 percent variation in the flow at the upper and lower limits of the threaded holes. Additional investigations aimed at determining air flow limits have been recommended.

As a result of this project, air gaging of printed circuit board (PCB) holes was analyzed. Previously these holes could not be gaged through conventional air gaging techniques because hole lengths were too short. A probe has been developed that can be used to air gage PCB holes with an accuracy of ±0.001 inch (25 μm). This probe has been recommended to replace plug gaging of PCB holes, which is considered a destructive test.

DISCUSSION

SCOPE AND PURPOSE

This project was designed to develop a method for gaging Unified Miniature Internal Screw Threads. The need for this capability arose from a specification which called for 0.6, 0.8, and 1.0 UNM through-threaded holes. Another specification required through and blind 0.5 UNM holes. Later, these requirements were expanded to include 0.6 UNM threaded holes. Toward the end of this project, part configurations were changed to allow large variations in thread length. This change had a significant effect on the predicted accuracy of the air gaging system chosen for measuring the miniature threads.

At present, there is no recognized method for certification of Unified Miniature Internal Threads. Some thread producers are successfully using a GO and NOT GO cylindrical plug gage to check the minor diameter of the thread and a GO thread plug gage for thread function. The performance of the tap is relied upon for all other characteristics of the internal thread. Because the assurance that the thread function, if checked by the above method, depends upon the inspector's acute sense of feel and the capability of the tap, this project was begun to improve functional certification methods for miniature internal threads. The scope of this project was limited by the desire to contact the thread form as little as possible. Because of this, air gaging of miniature threads was the only inspection method investigated.

ACTIVITY

Literature Search

The literature search produced little information regarding any universally accepted method for inspecting miniature threads. However, a better understanding of what thread gages will check and what areas should be considered when calibrating and recalibrating thread gages was ascertained. Abstracts of some of the publications reviewed during the literature search are given in the Appendix.

Two basic methods are used for acceptance of threads: inspection by attributes and inspection by variables. Inspection by attributes is a functional check of the maximum and minimum limits of a thread. In this check, GO and NOT GO plain cylindrical plug gages are used to check the minor diameter of an internal thread, and GO and HI thread plug gages are used to assure the function of all of the other characteristics of the internal thread. When inspecting an external thread form by attributes, GO and NOT GO ring gages are used for the major diameter, and GO and LO thread ring gages are used for all other characteristics (thread snap gages may also be used). In inspection by variables, each individual characteristic of the thread form is checked. Some of these characteristics for internal and external threads are shown in Figure 1. These checks are made through use of various contact and non-contact gaging methods. Neither type of gaging checks all features of a thread, although inspection by variables comes closer. However, if the manufacturing processes are known, higher reliability of parts may be obtained by choosing inspection methods which readily pick up those characteristics likely to go out of tolerance.

If an inspection by attributes acceptance program is used for threads, the elements of the thread gages that require calibration can be classified into those elements which require initial verification only and those which require recalibration. Pitch

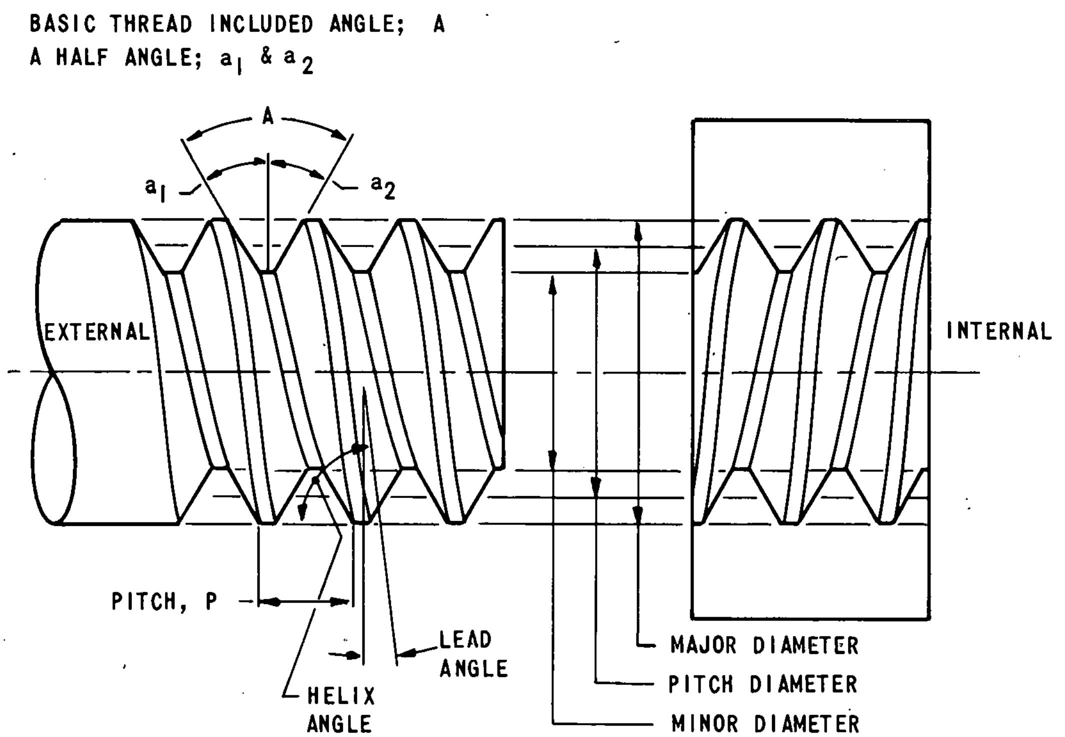

Figure 1. Thread Characteristics

diameter and flank angle are the characteristics of the thread which are subjected to wear. Therefore, they are the characteristics that must be recalibrated. All other characteristics should be checked when the gage is initially received.

The method being used by some manufacturers for gaging miniature threads is as follows.

- External threads: The major diameter of the external thread is inspected by either contact gaging or optical projection. All other dimensions are inspected by optical projections.

- Internal Threads: The minor diameter of the internal thread is checked with GO and NO GO plain cylindrical plug gages. All other elements are checked only for assembly limits by means of a GO thread plug gage. For the minimum material limits, the accuracy and performance of the tap is relied upon.

Bendix has had two problems using this inspection method for internal threads. First, great care has to be taken so that the GO thread plug gage is not broken off in the threaded hole. This is particularly true in the case of aluminum parts. In addition, small burrs are very difficult to remove from the 0.5 mm tapped holes. When the thread plug gage is screwed into the part, these burrs break off and tend to cause the gage to bind in the part. Second, on several occasions lots which contain parts with miniature threaded holes have reached the next assembly point only to have screws fall out of the holes because they are oversized. These events show that the performance of the tap cannot always be relied upon for minimum material in a threaded hole.

Theory and Experiments

The initial theoretical analysis and experimentation with air flow through miniature threaded holes was done by Illinois Institute of Technology Research Institute (IITRI).[1,2] In their studies, IITRI postulated that the air flow through a threaded hole could be approximated by treating the hole as an annular gap, compared experimental results with theoretical predictions, evaluated the effects of blind tapped holes, evaluated the effect of eccentricity, and investigated the use of anodization of thread forms to determine the air flow limits for threaded holes. After IITRI completed their studies, Bendix investigated the use of drilled and tapped masters, screw gages, and thread plug gages to determine the air flow limits of miniature threaded holes.

IITRI postulated that the air flow through a threaded hole which has a pin in the center could be approximated by laminar flow through an annular gap. Rayleigh's solution for this flow is

$$Q = \frac{\pi \cdot \Delta P \cdot \bar{P}}{8 \cdot \mu \cdot \ell} \left[b^4 - a^4 - \frac{(b^2 - a^2)^2}{\ln b/a} \right] \qquad (1)$$

where

Q = Total flow in N•m/sec;

ΔP = Pressure difference across the annular gap = $(P_1 - P_2)$ in N/m^2;

$\bar{P}$ = Average Pressure in annulus = $1/2(P_1 + P_2)$ in N/m^2;

μ = Dynamic Viscosity in $N \cdot s/m^2 = \frac{\beta T^{3/2}}{T+S}$

where

$\beta = 1.458 \times 10^{-6} \frac{kg}{sec \cdot m \cdot K^{1/2}}$,

T = Temperature in K, and

S = 110.4K;

ℓ = length of annulus in m;

b = outer radius of annulus in m (effective radius of tapped hole);

a = Inner radius of annulus in m (radius of pin in the threaded hole);

P_1 = Pressure up stream of annulus in N/m^2;

P_2 = Pressure down stream from annulus in N/m^2.

Figure 2 shows the annular flow concept. There is no derived equation for turbulent flow through an annular gap; empirical relationships must be used. The laminar flow equation (Equation 1) was developed for flow through a long annulus where end effects could be neglected. End effects must be considered for the threaded holes under consideration.

Figure 3 shows the experimental setup used to determine the importance of end effects for flow through an annular gap.

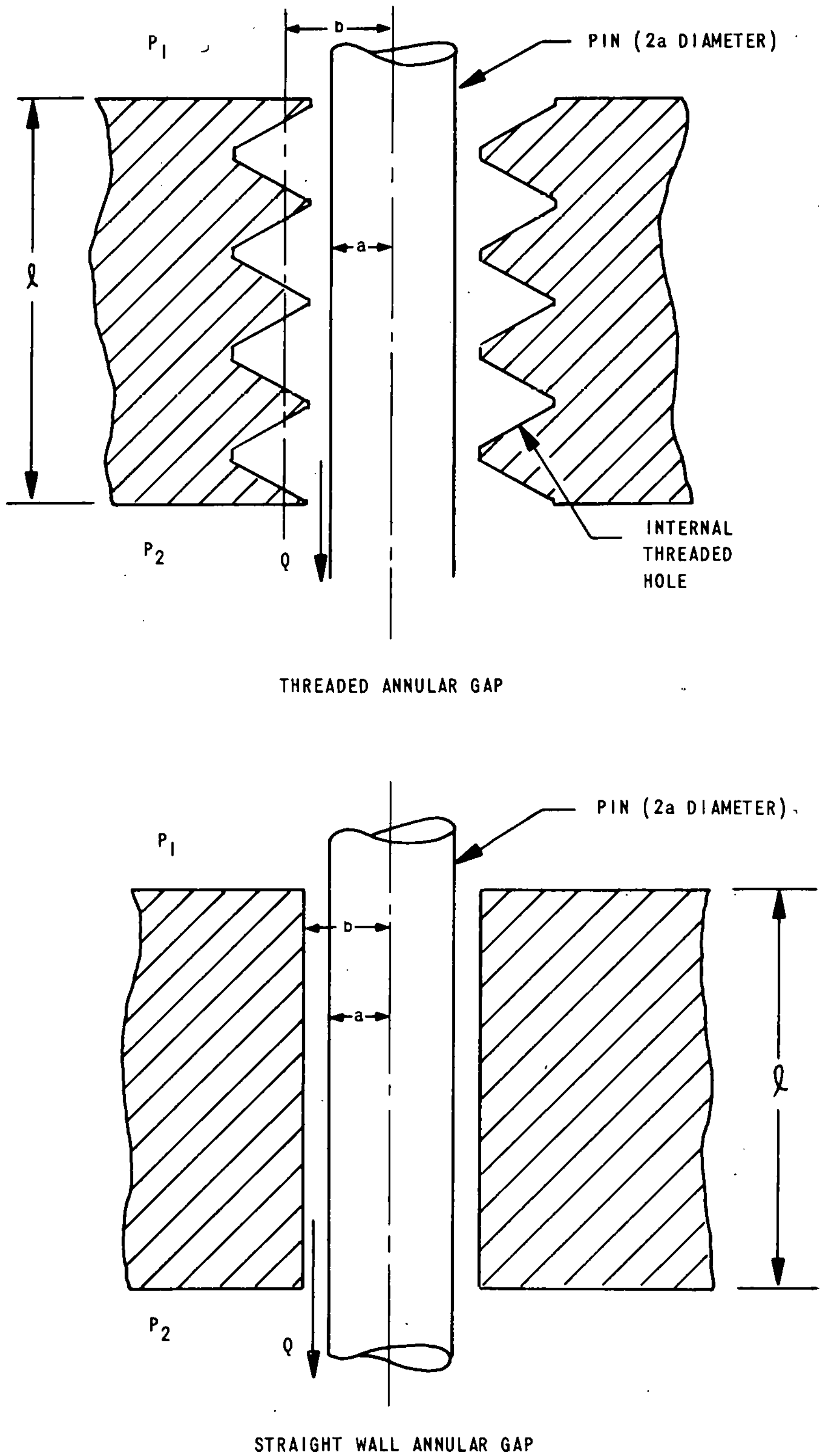

Figure 2. Flow-Through Annular Gap, Schematic

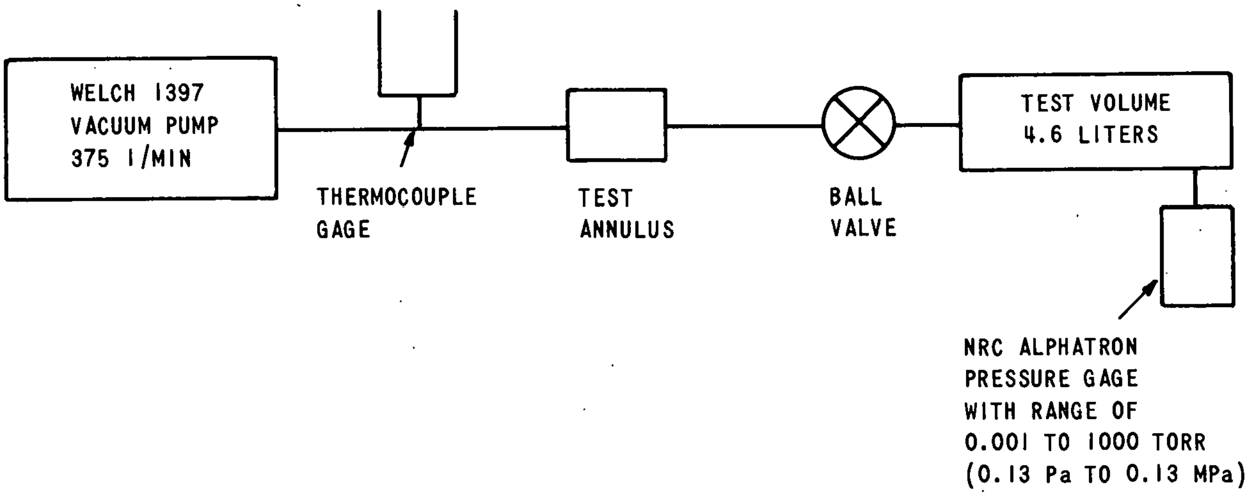

Figure 3. Experimental Set-Up

Before the test began, the 4.6-liter test volume was at atmospheric pressure. The capacity of the vacuum pump was sufficient to maintain the discharge pressure 0.001 times below the test volume pressure throughout the tests. Therefore, Equation 1 may be simplified as follows:

$$\Delta P = P_1 - P_2 \approx P_1$$

$$\bar{P} = (P_1+P_2)/2 \approx P_1/2$$

As the vacuum pump reduces the pressure of that test volume, the flow goes through a turbulent flow stage, a laminar flow stage, and a molecular flow stage. Turbulent flow is proportional to the square root of the pressure difference across the annulus, and the flow resistance or conductance is a function of the pressure difference dependent on the Reynolds number. Laminar flow is directly proportional to the pressure difference, and the conductance of the annulus is proportional to the average pressure in the annulus. Molecular flow is also directly proportional to the pressure difference, but the conductance of the annulus is independent of the average pressure in the annulus. If the flow is plotted against pressure on log-log paper, the graph will have three straight lines. At high pressure differences, the flow will be turbulent and there will be a straight line of slope 1/n, where n is greater than 2. At intermediate pressure differences, the flow will be laminar and the slope will be 2. At low pressures, the flow will be molecular and the slope will be equal to 1.

Figures 4, 5, 6, and 7 typify families of air flow curves for straight wall and threaded holes of various lengths. Air is able to pass through the hole which is threaded at a faster rate and, as the pin size in the hole is increased, this effect becomes more pronounced. The characteristic slope for the laminar flow regime may be found on each curve shown in Figures 4 through 7. Because these curves are pressure-time curves, the slope value is dp/dt. For the pump down of the test volume, the flow rate is

$$Q = V \frac{dp}{dt} \tag{2}$$

Figure 8 shows the flow obtained from Equation 2, using the experimental results plotted along with the experimental flow predicted by Equation 1. The solid curves (theoretical flow) showed different flow levels because end effects were not considered.

The effect of pin eccentricity was determined using the test setup from the previous studies. Figures 9 and 10 show that eccentricity of the pin did not affect the pump down time for the 4.6-liter test volume for a 0.5 UNM miniature female thread. Figures 11 and 12 are the concentric and eccentric pumpdown curves for a 0-80 thread, respectively. Threaded holes between these two sizes should act in a similar manner.

IITRI anodized 0.5 UNM holes in an attempt to correlate air flow to thread size. A sample of the results from these tests is shown in Figure 13. Although these tests show large changes in the flow rate with differing degrees of anodizing, the anodizing process resulted in unanticipated sizes of thread. Some thread forms were rounded off, whereas others were nearly perfect (Figure 14).

Figure 15 represents schematically 14 test runs. The bars show the range of experimental scatter, which has two sources: the usual uncertainty about any specific data point, and the difficulty of determining the exact size of the hole either with or without threads. The data shown was derived from flow where the pressure difference was 10 inches of Hg (34kPa).

By placing a seal on the back side of the test specimens and forcing air into the bottom of the hole through a tube, IITRI was able to show that blind holes could be gaged in a similar manner if two requirements were met (Figure 16). The first requirement is that a large enough flow area in the bottom of the hole exists so that air can turn around. In the case of a flat bottom hole, similar to that shown in Figure 16, a gap of 0.005 inch (0.13 mm) allowed more than necessary flow area. In an actual blind hole, the drill should provide most of the turn

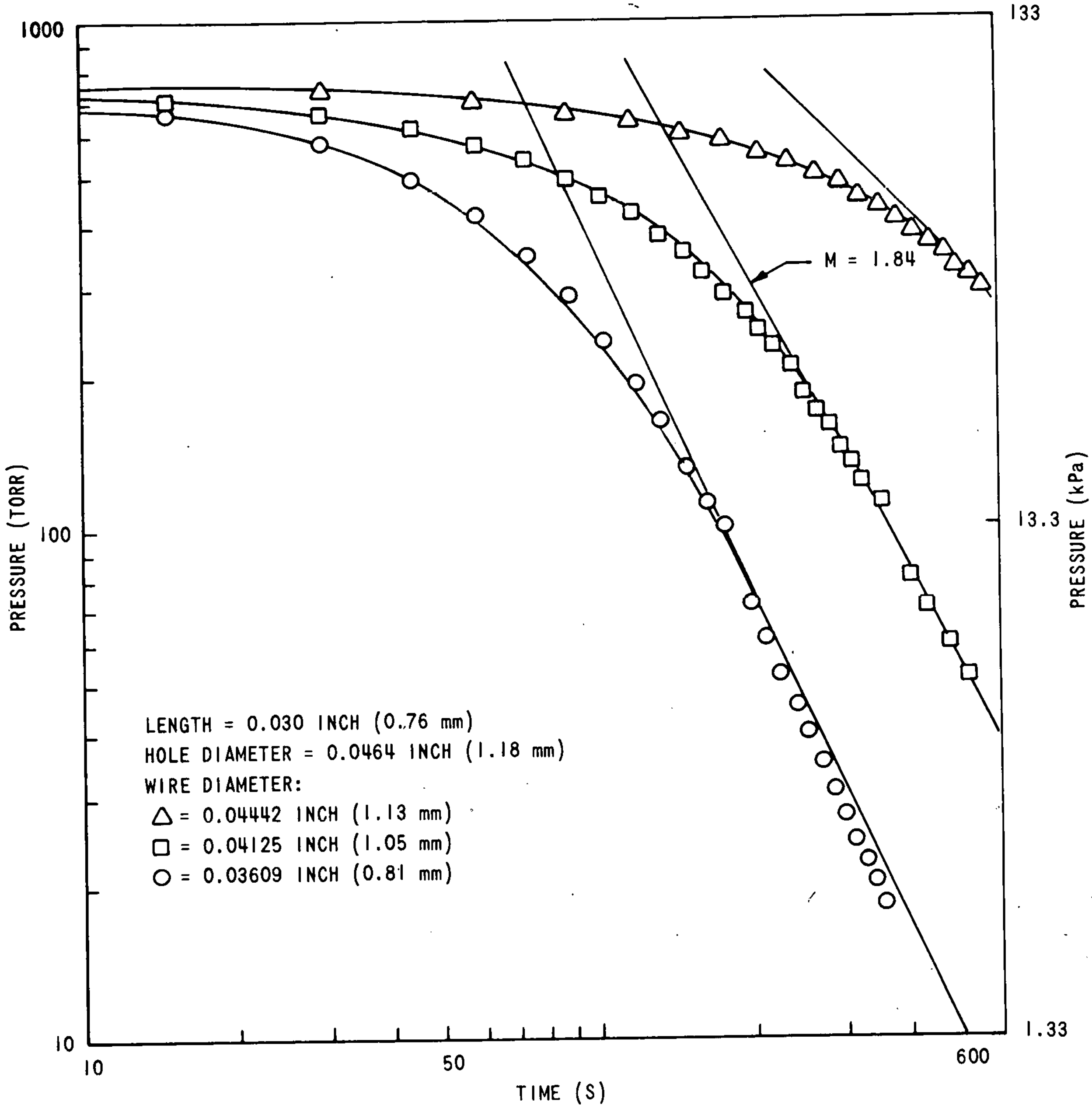

Figure 4. Pump Down Pressure Versus Time for Straight-Wall Hole, 0-80 Size

around flow area (see dotted lines in Figure 16) and the gap could be reduced. The second requirement is that the pressure at the bottom of the blind threaded hole must be the same as the pressure at the entrance of the through-threaded hole. If these requirements are considered, the acceptance criteria for through and blind threaded holes of the same lengths will be identical.

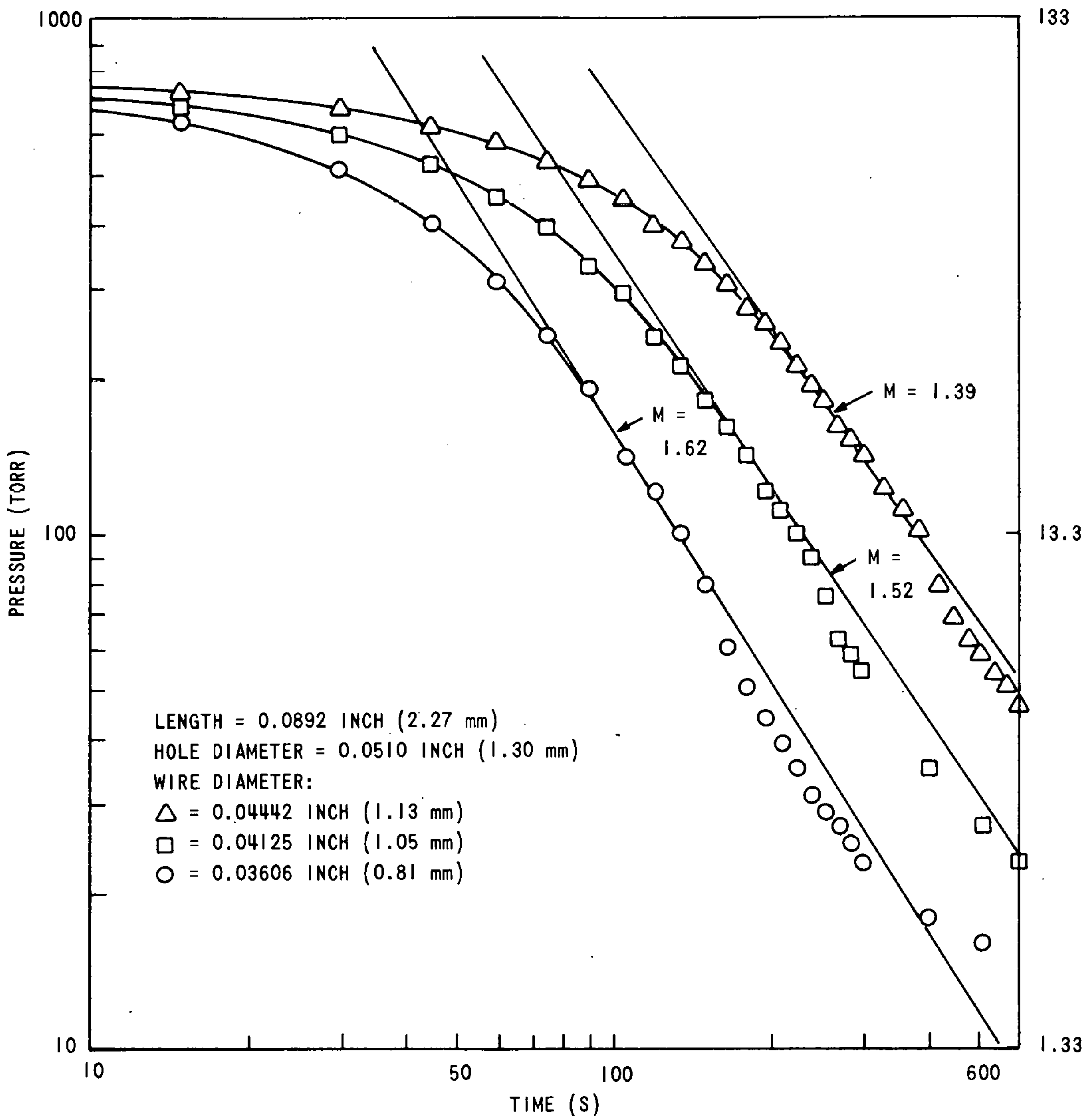

Figure 5. Pump Down Pressure Versus Time for 0-80 Tapped Hole

IITRI was not able to determine the air flow limits for acceptable miniature threaded holes using the anodization process; therefore, three parallel approaches aimed at determining air flow limits were undertaken at Bendix:

- Drills and taps were used to make tapped holes to the minimum and maximum allowable thread sizes;

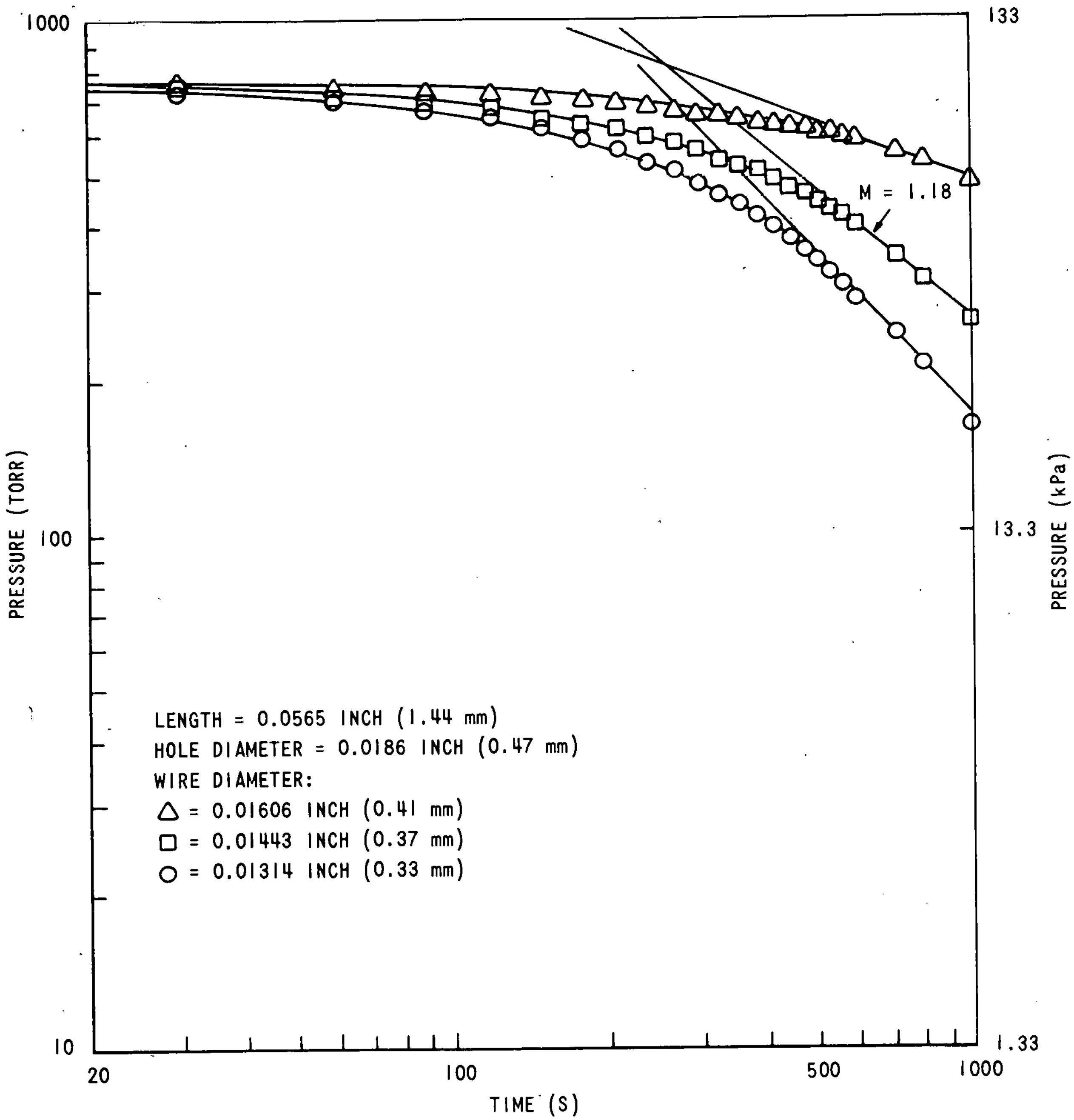

Figure 6. Pump Down Pressure Versus Time for Straight-Wall Hole, 0.6 UNM Size

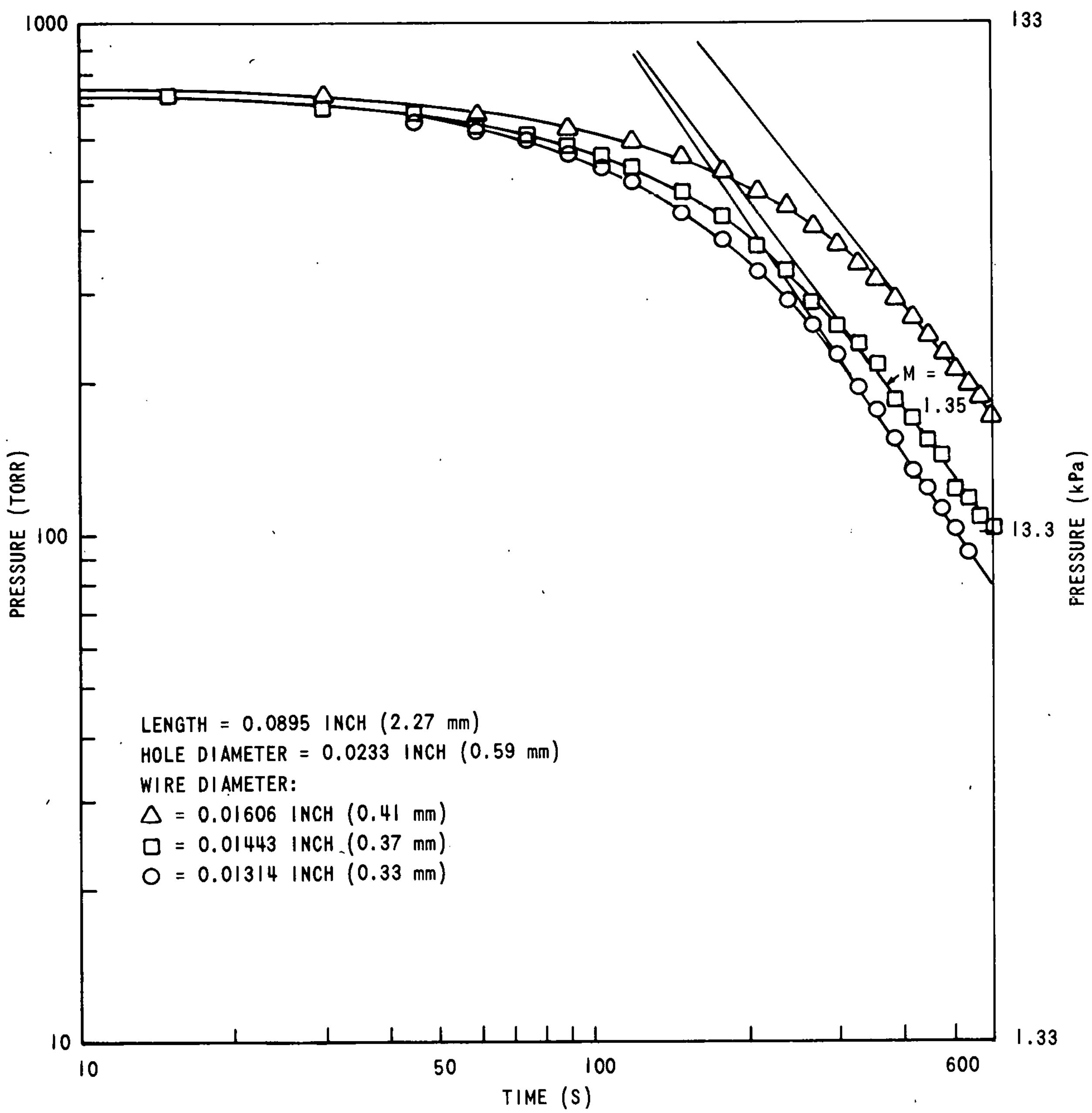

Figure 7. Pump Down Pressure Versus Time for 0.6 UNM Tapped Hole

- The flow through screw gages with a pin in the center was measured; and
- Flow through a cylindrical hole with a thread plug gage in the center was measured.

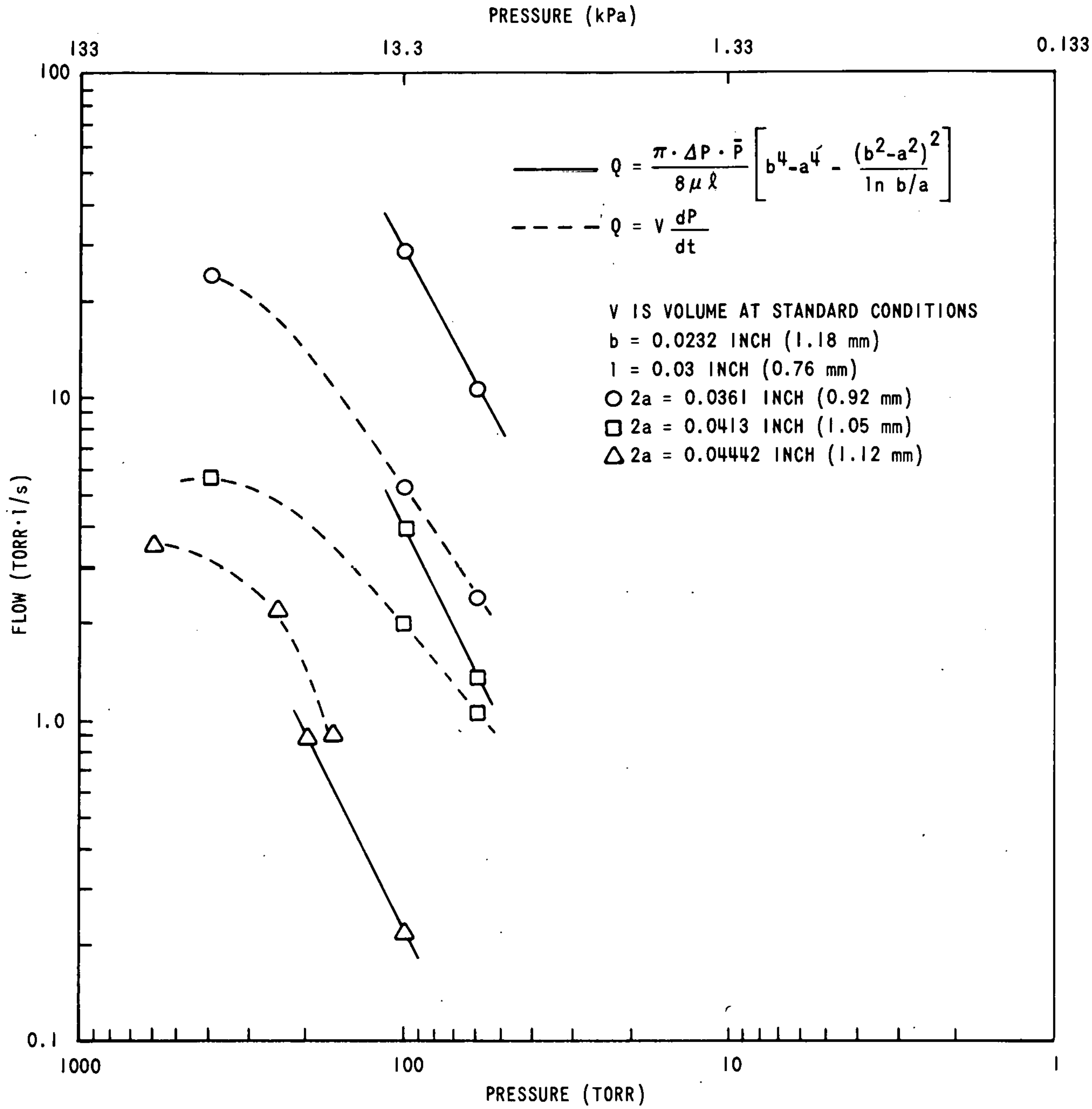

Figure 8. Flow Versus Chamber Pressure

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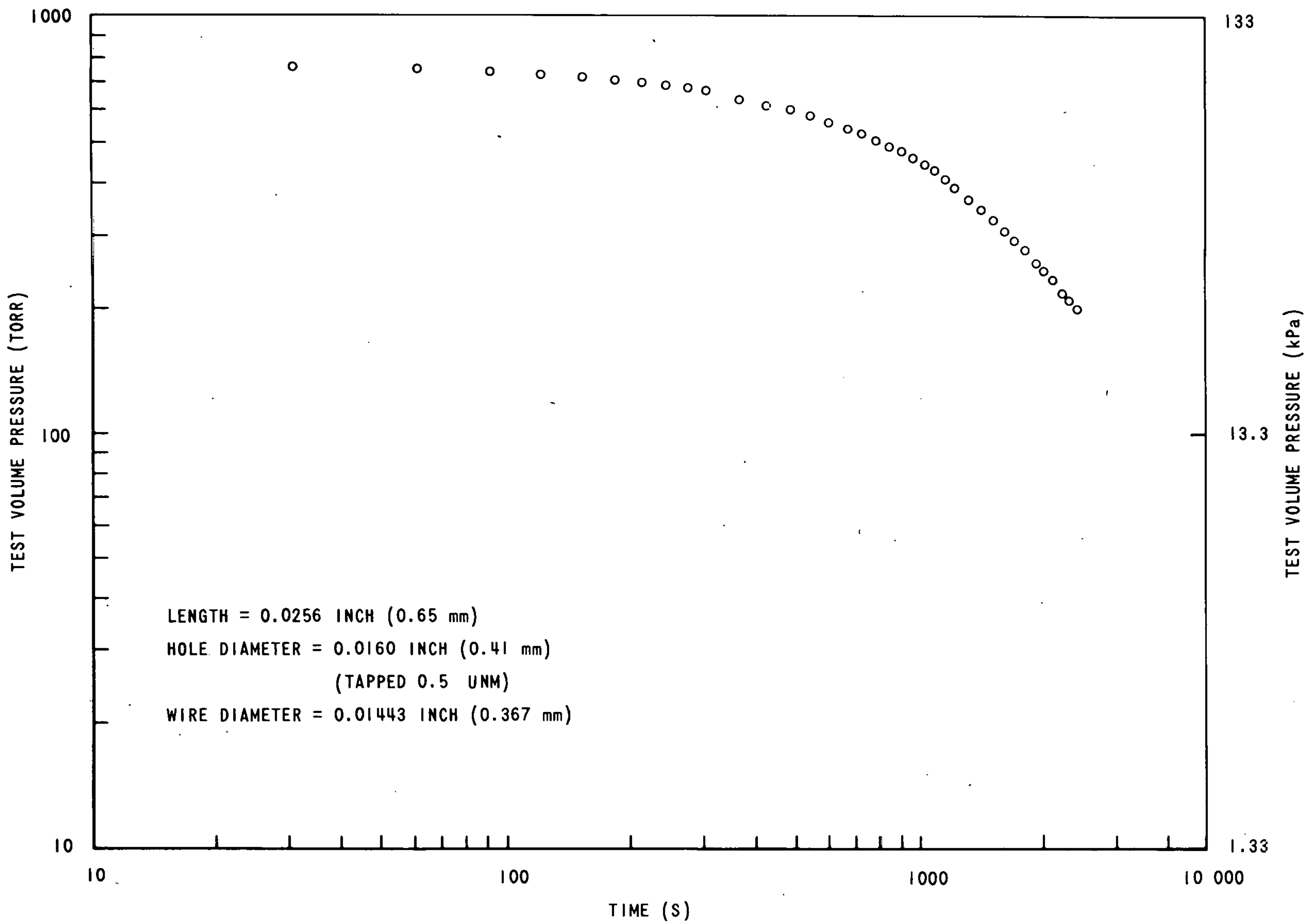

Figure 9. Pump Down Time for 0.5 Tapped Hole by IITRI: Wire on Center

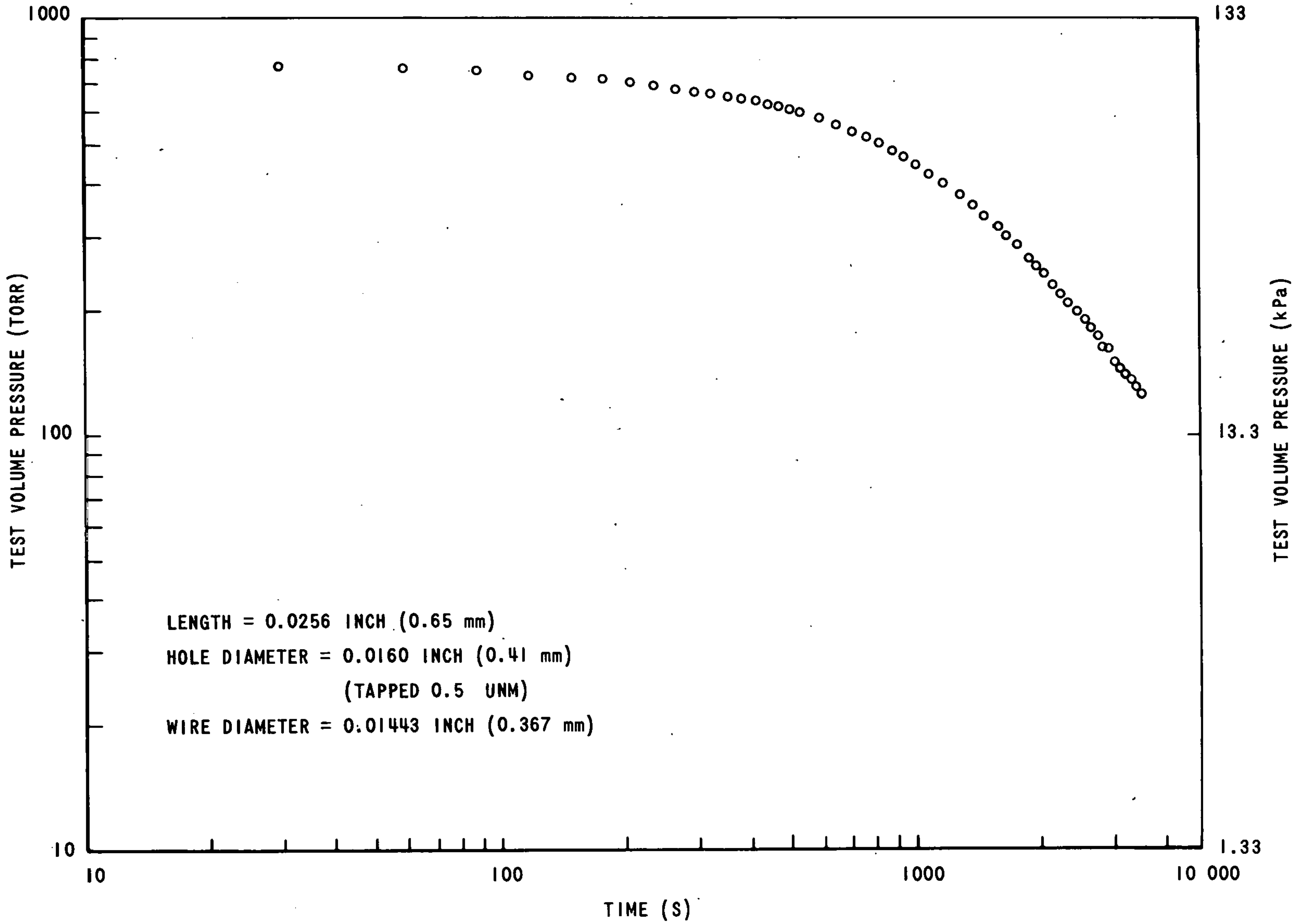

Figure 10. Pump Down Time for 0.5 Tapped Hole by IITRI: Wire off Center

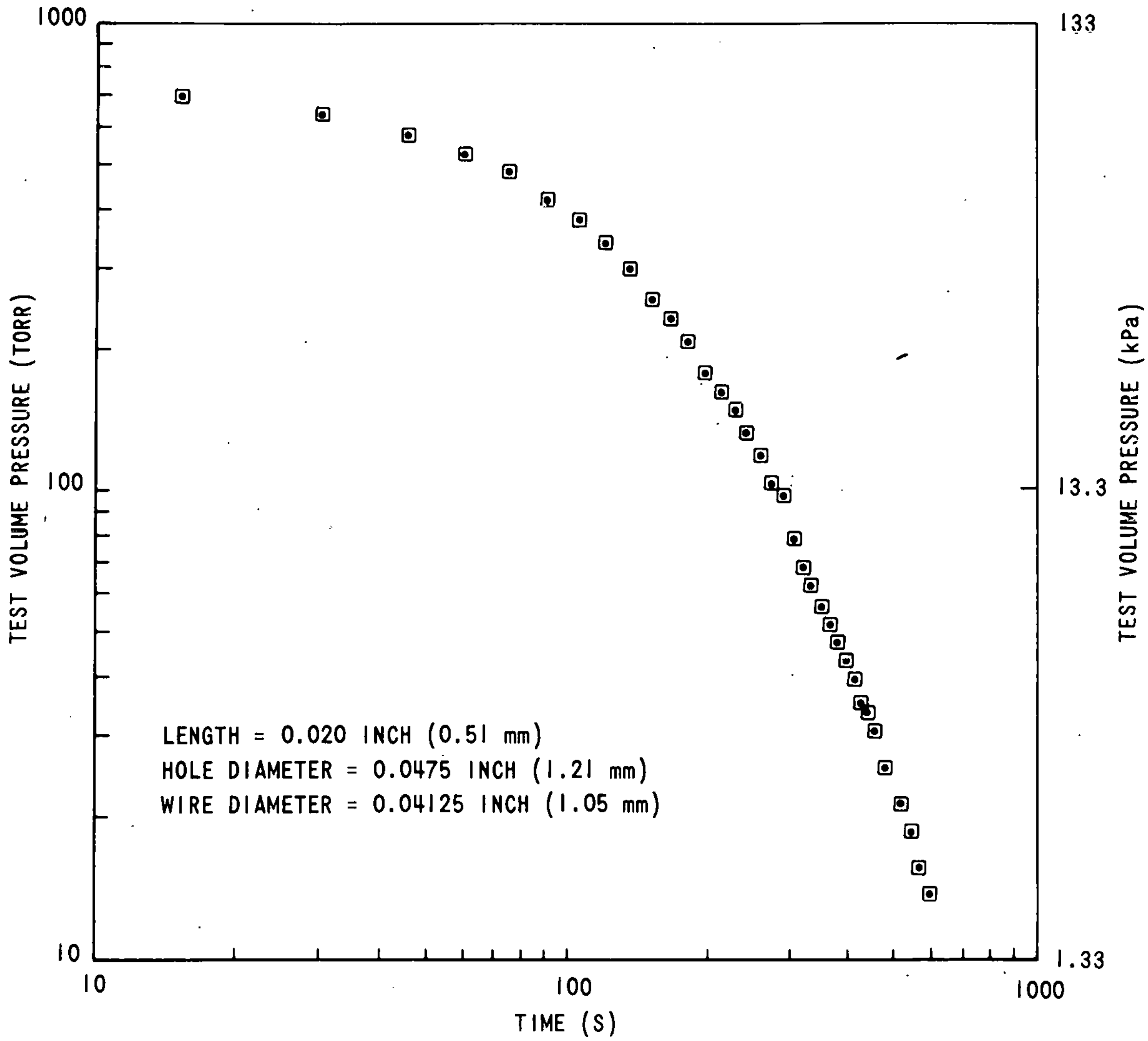

Figure 11. Pump Down Time Versus Test Volume Pressure: Wire on Center

Construction of masters using selected (by size) drills and taps was undertaken to determine the maximum and minimum allowable air flow through threaded holes. A secondary goal of this study was to obtain an understanding of the yield of acceptable threaded holes that could be anticipated using different drill sizes before tapping. This data was required to select the size of tools to make the high- and low-limit masters.

A Bendix part was chosen as the exemplar of parts with miniature threaded holes for the drill and tap master study. This part was made from 7075 aluminum and had three 0.6 UNM

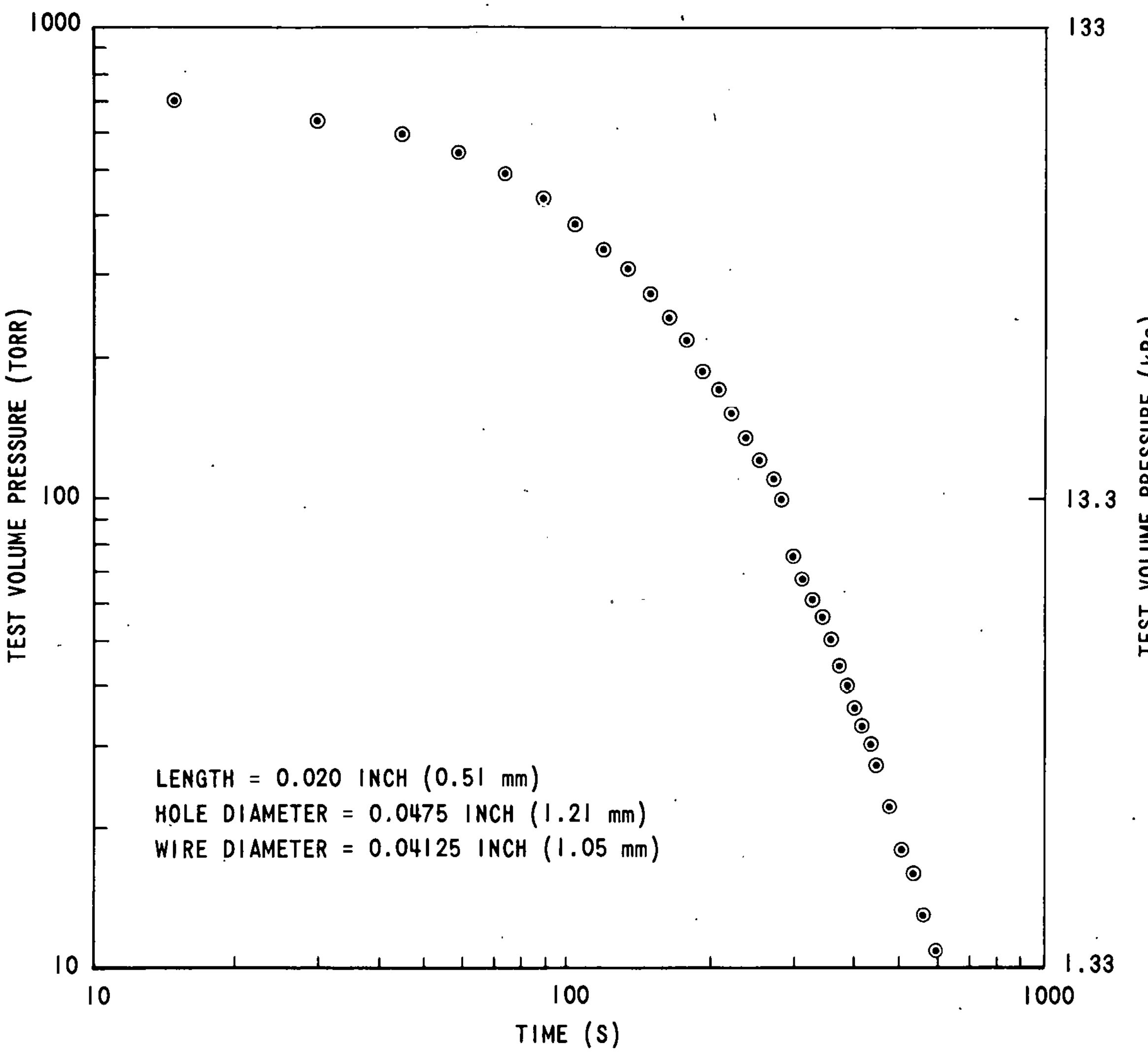

Figure 12. Pump Down Time Versus Test Volume Pressure: Wire off Center

threaded holes which could be 0.08-inch (2 mm) deep. Test plates were made to the desired thickness and 12 tapped holes were made in each plate with a particular size of drill and tap. Figure 17 and Table 1 show the results of this study. Of note in Figure 17 is the plastic flow of the aluminum as the holes are being tapped and the decrease in the standard deviation of the tapped hole's minor diameter as the drill size increases. Figure 17 and Table 1 show that a 0.0200 $\pm$0.0001 inch (0.51 $\pm$0.0025 mm) drill will give the highest yield for 0.6 UNM tapped holes in 0.08 inch (2 mm) 7075 aluminum parts. Table 1 shows that the minor diameter of the tapped holes is altered by

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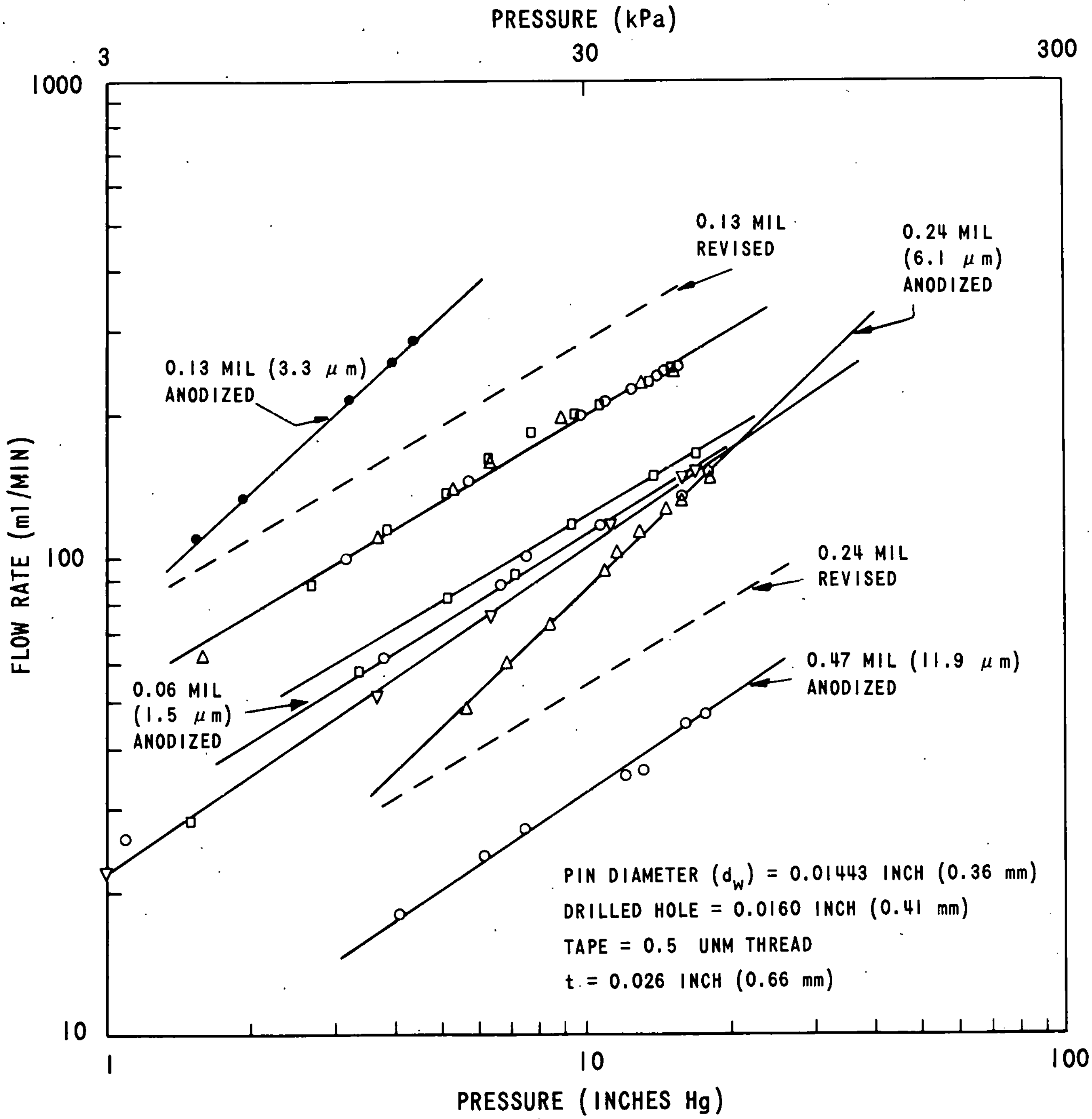
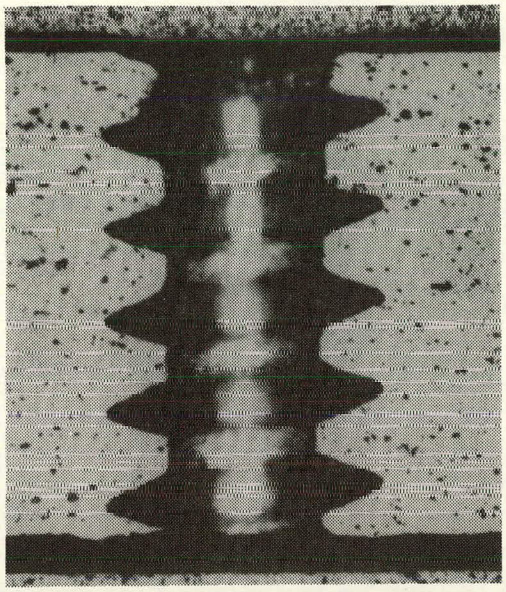
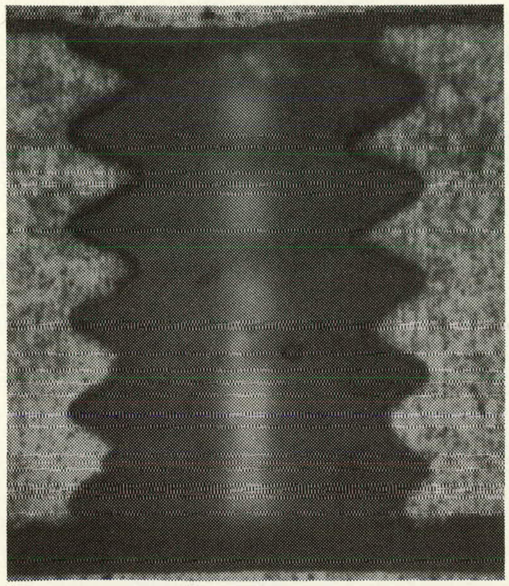


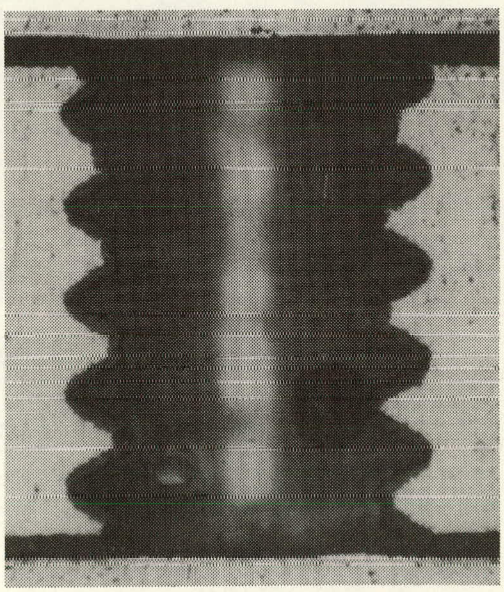
Figure 13. Flow Rate as a Function of Pressure



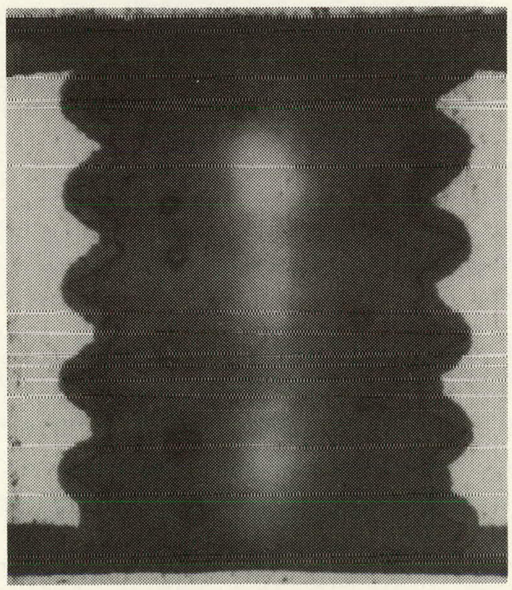
2024-T4 ALUMINUM
NO ANODIZING



1100-0 ALUMINUM
0.13-MIL (3.30 μm) ANODIZE



1100-0 ALUMINUM
0.24-MIL (6.09 μm) ANODIZE



1100-0 ALUMINUM
0.47-MIL (11.94 μm) ANODIZE

Figure 14. Thread Profile of 0.0160 Drill, 0.5 UNM Thread

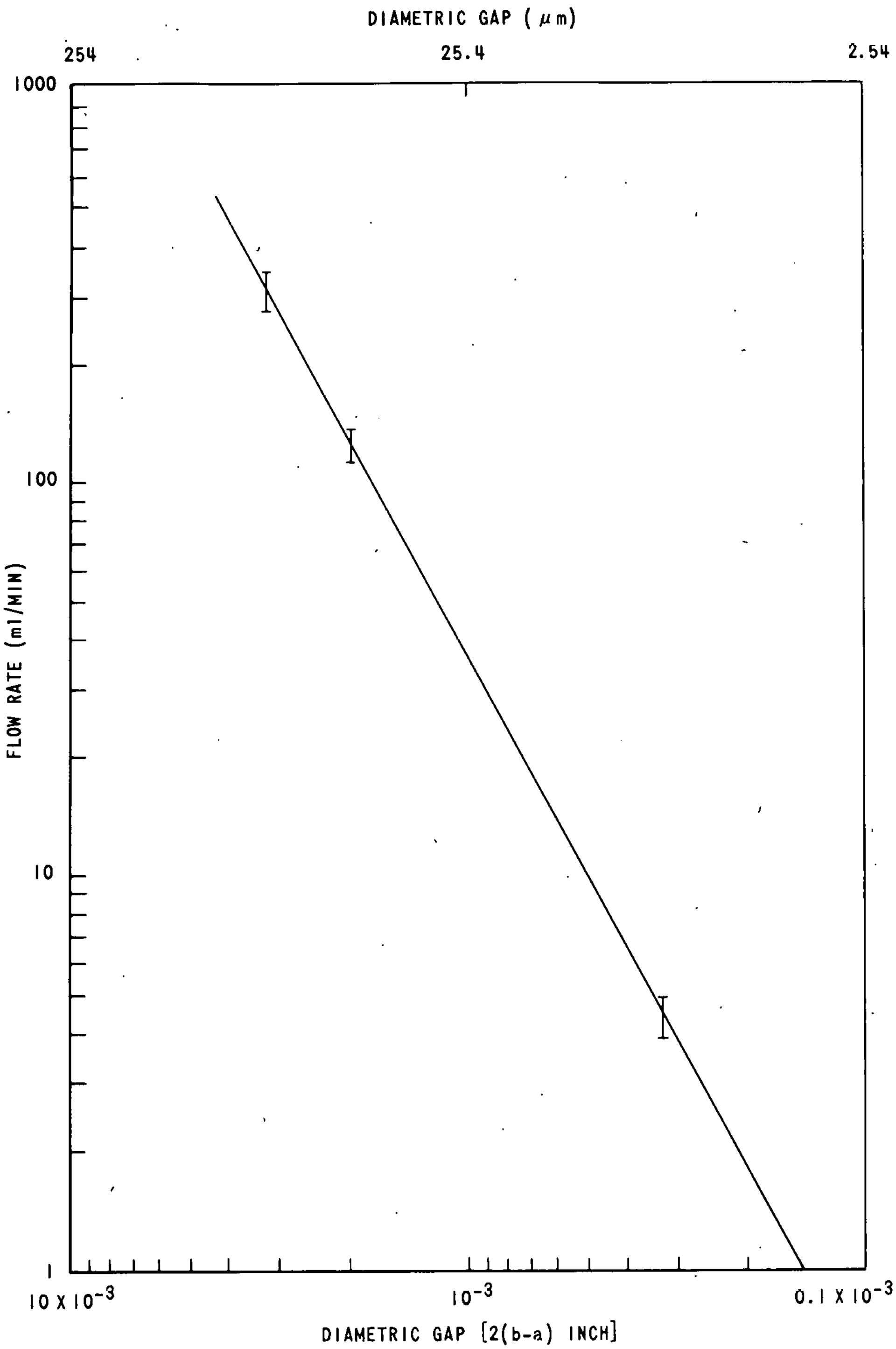


Figure 15. Effect of Annular Gap Size on Flow Rate

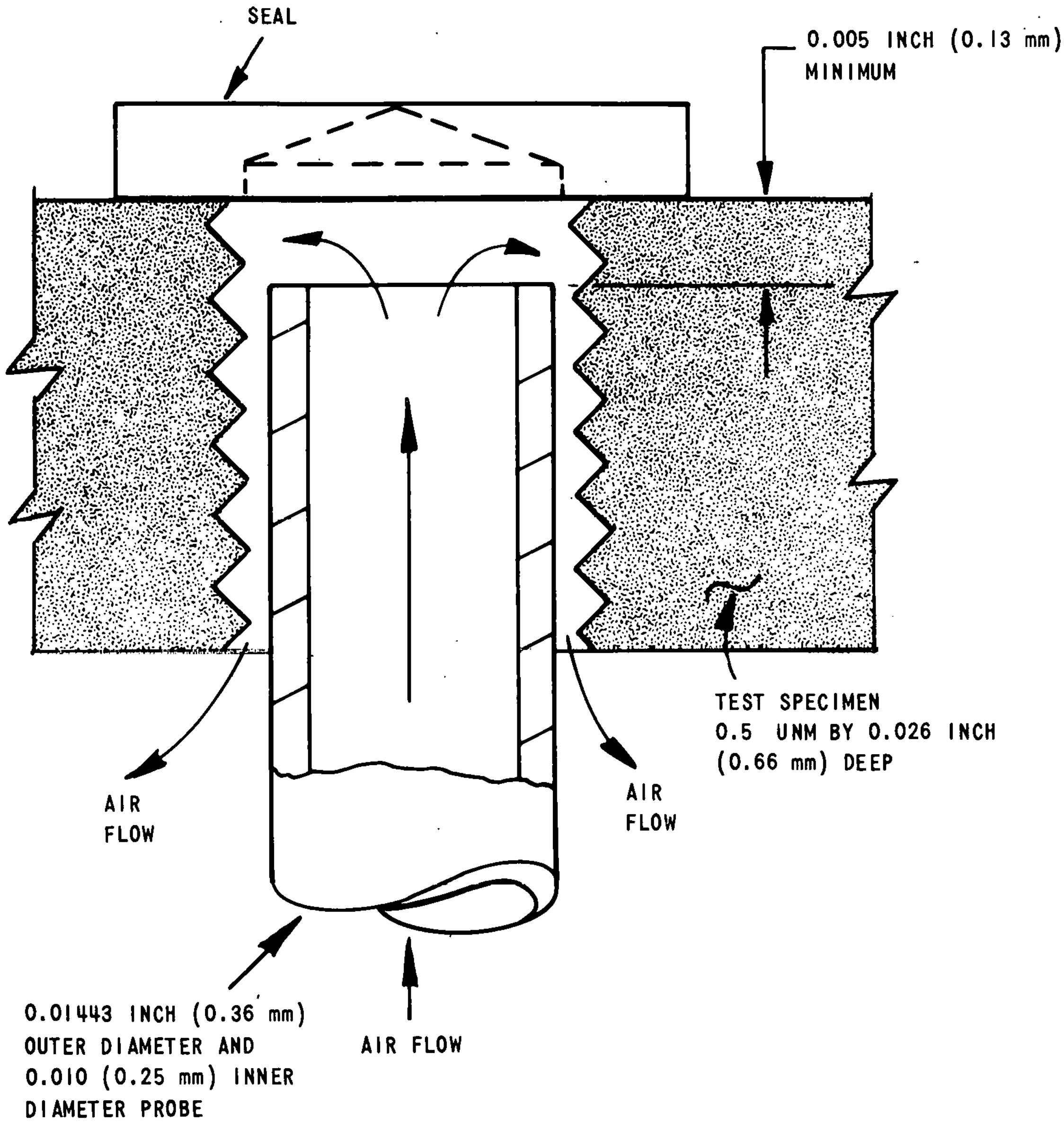


Figure 16. Air Gaging of Blind Holes

thread plug gaging. In addition to the six drill sizes shown in Table 1, 0.0190 and 0.0191 drills were used to make a threaded hole to the minimum allowable size. After several taps were broken with each size and part geometry was changed to allow changes in threaded hole depths that would cause flow changes greater than 20 percent of the total flow, no further attempts were undertaken and flow measurements were not made on available tapped holes.

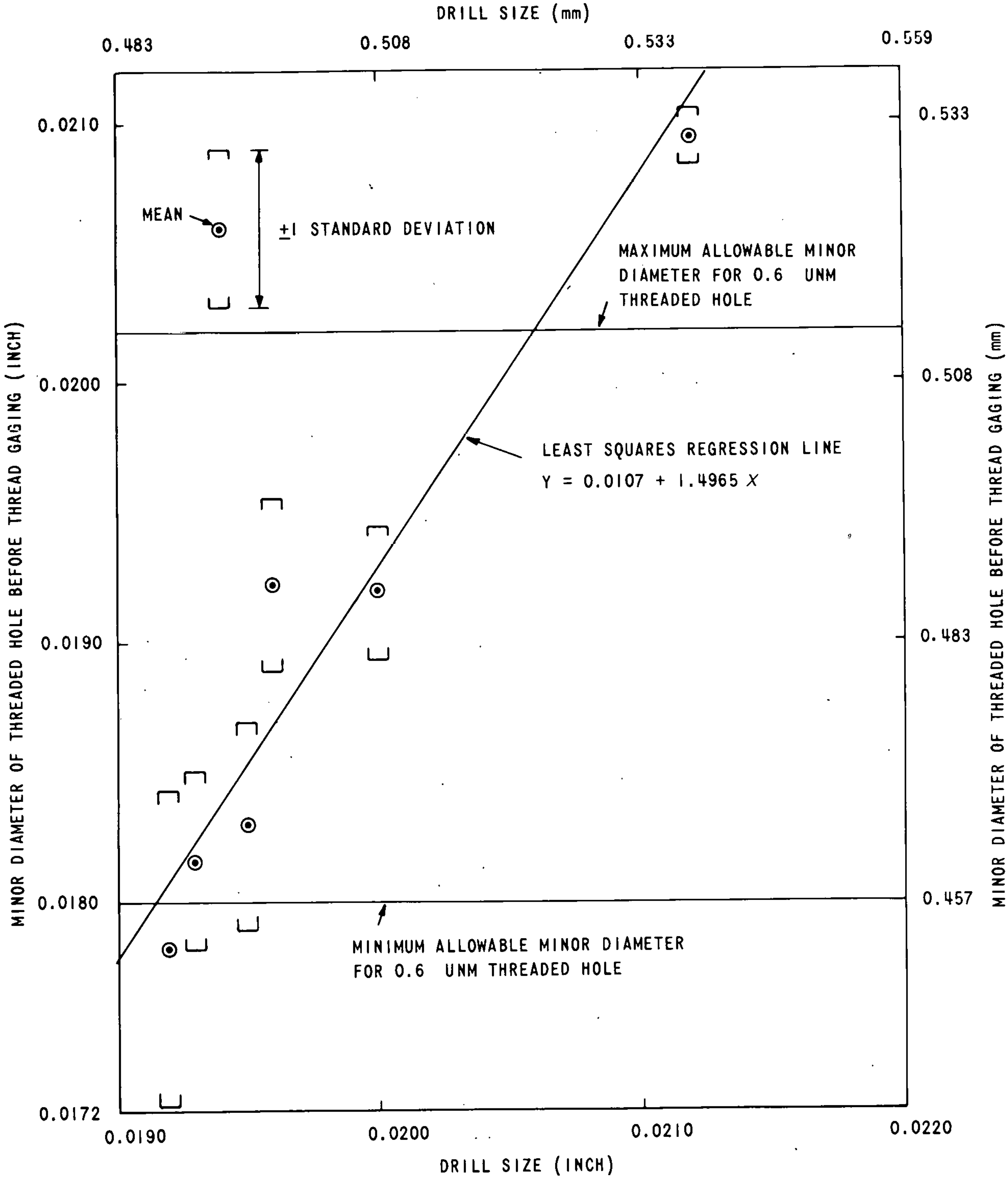


Figure 17. Plastic Flow After Tapping of 0.6 UNM Threaded Hole in 7075 Aluminum

Table 1. Yield of Tapped Holes From Various Drill and Tap Containers

	Drilled Hole		Minor Diameter After Tapping			Minor Diameter After Thread Gaging		
Drill Size (Inch)*	Mean Diameter (Inch)*	Standard Deviation (Inch)*	Mean Diameter (Inch)*	Standard Deviation (Inch)*	Tapped Holes That Accept Thread Plug Gage (Percent)	Mean Diameter (Inch)*	Standard Deviation (Inch)*	Notes
0.0195	0.01996	0.00025	0.01831	0.00040	83	0.01836	0.00046	
0.0192	0.01927	0.00010	0.01783	0.00060	42	0.01763	0.00049	Broke thread gage off in hole
0.0212	0.02150	0.00011	0.02095	0.0012	100	0.02098	0.00009	
0.0193	0.01943	0.00010	0.01816	0.00033	85			Tap broke in eighth hole
0.0196	0.01972	0.00006	0.01923	0.00033	100			
0.0200	0.01991	0.00003	0.01921	0.00025	100			

*1 inch = 25.4 mm

Air flow through GO and LO screw gages was measured so that cylindrical masters could be made that would have the same flow as the minimum and maximum size threaded hole. This approach was based on the concept that GO and LO screw gages were of known sizes and that an equation could be developed for the effective hydraulic radius of these thread forms in terms of the gage's geometric configuration. The geometric configuration of the minimum and maximum size tapped hole could then be used in conjunction with the equation for the hydraulic radius to make cylindrical holes that would have flow rates identical to the minimum and maximum size threaded holes. Figure 18 shows the flow through a LO and GO screw gage. Note the significant difference between the flow levels and the repeatability of the measurements. Recall that the tolerance on the minor diameter of a 0.5 UNM tapped hole is 52 μm and the difference in minor diameter of the two gages is 0.0305 mm, and that the major diameter tolerance is 27 μm for the tapped hole and difference in the two gages is 20 μm. These results substantiate IITRI's findings that air flow has sufficient sensitivity to measure miniature tapped holes. Figure 19 shows the flow through four GO screw gages. Note that the flow through pairs of gages with the same minor diameter is significantly different. This difference in flow could be attributed to different lengths of the gages or to different major diameters. Because determination of the effective hydraulic diameter depends on both these factors, further work with screw gages is required before an equation for the hydraulic radius of the thread form can be developed. The length factor can be eliminated by treating the screw gage like a blind hole and using a probe of known length as shown in Figure 16. The major diameter factor could be overcome by measuring the diameter by sectioning after flow measurements have been made.

Flow through test plates with a GO thread plug gage in the center was measured so that an equation for the hydraulic radius could be developed. This approach was similar to that used with screw gages. Figure 20 shows preliminary results obtained using this method. Note that the repeatability is higher than that obtained for screw gages, and that with larger holes the rate of change of flow is lower. This indicates that the flow with the larger hole is in the turbulent flow range which would yield the higher repeatability and less sensitivity. This effort was terminated after learning of changes in part configuration which would not permit use of this inspection method for current production parts.

Error Analysis

To better understand how the variables in the flow equation (Equation 1) interacted and to obtain an understanding of the total variation in the flow, an error analysis was undertaken.

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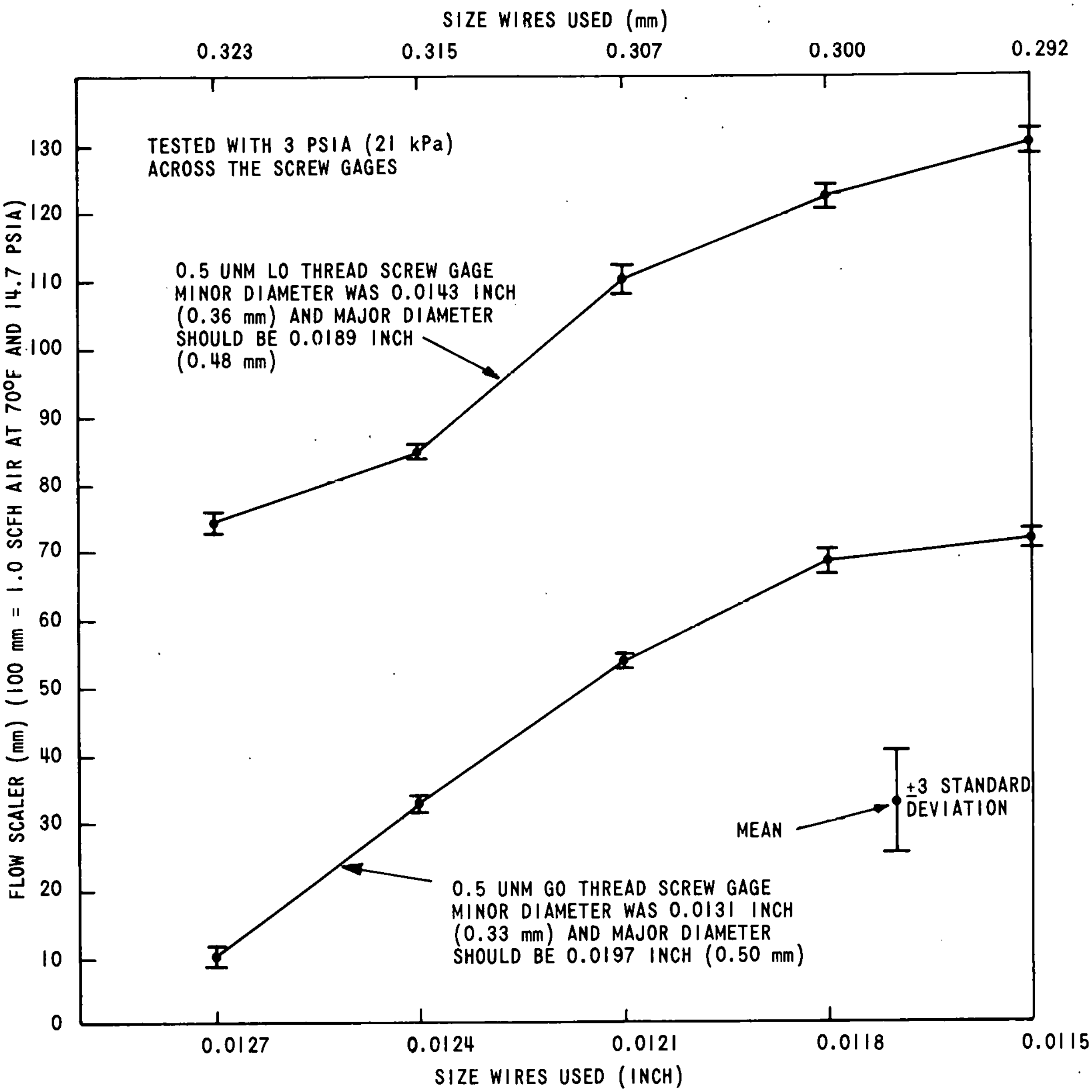

Figure 18. Flow-Through GO and LO Screw Gage with Size Wires in Center

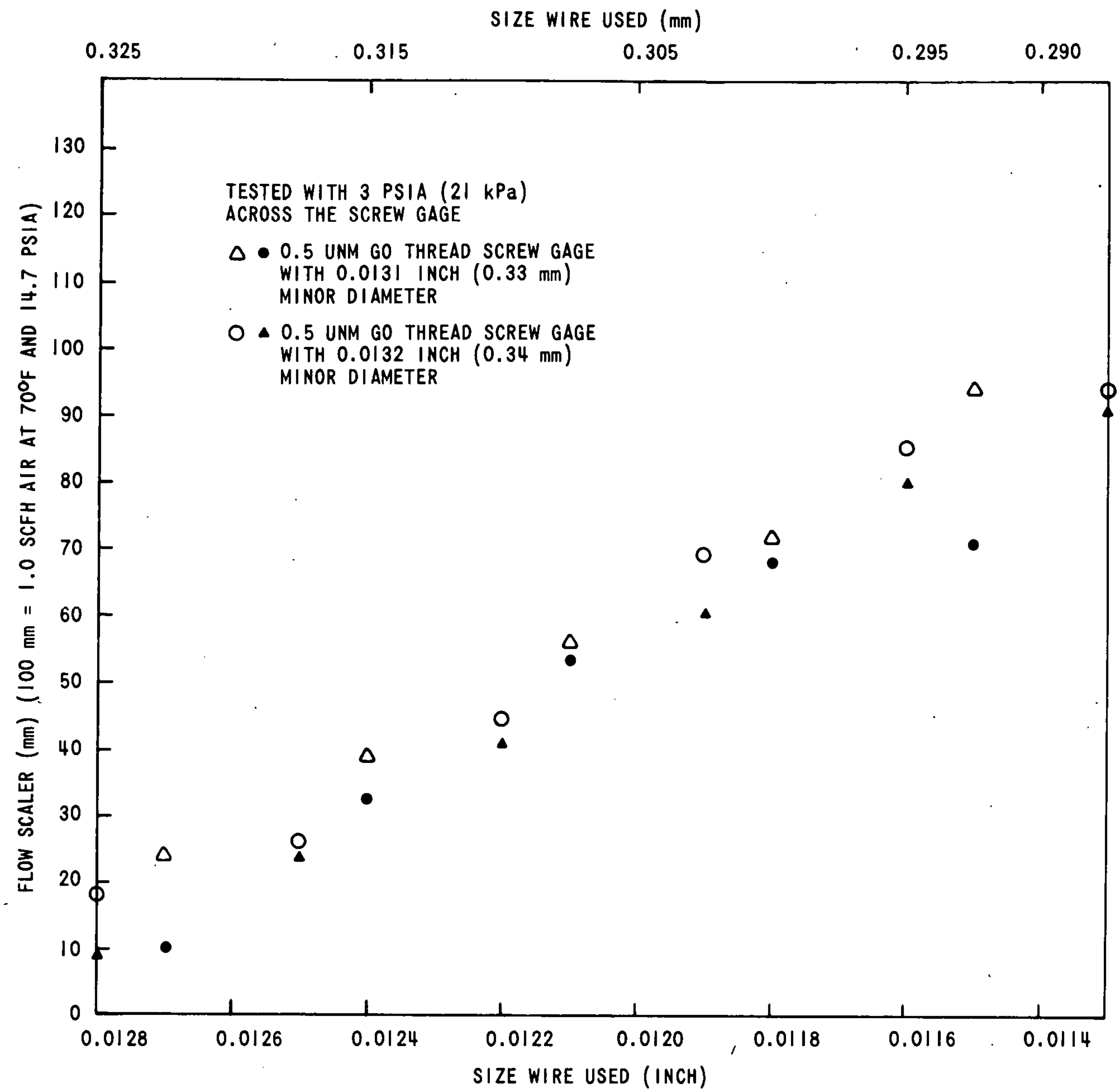

Figure 19. Flow-Through GO Screw Gage with Size Wires in Center

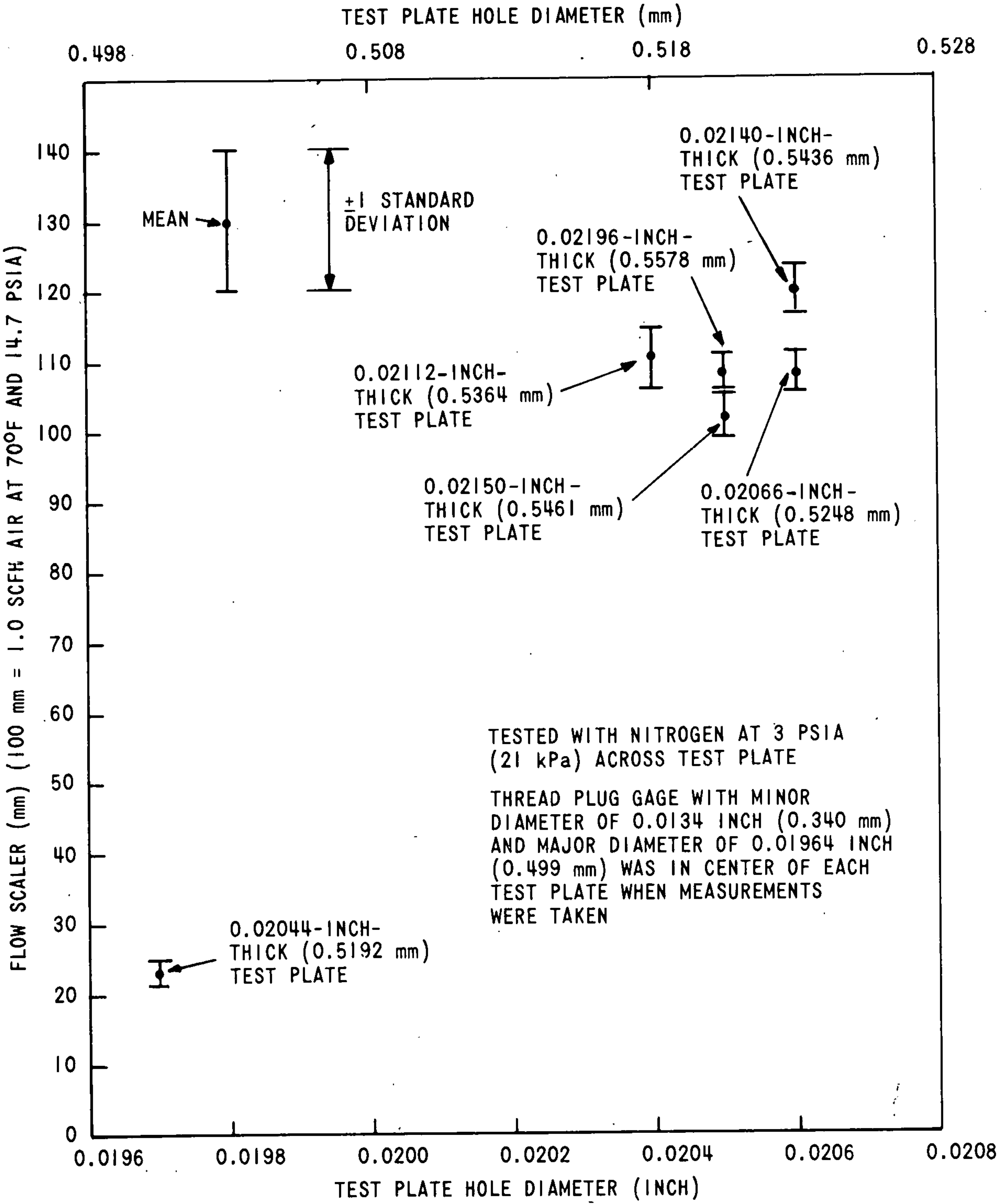

Figure 20. Flow-Through Test Plate with GO 0.5 UNM Thread Plug Gage in Center

The general equation for the variance of a function is obtained by use of the following equations[3]:

$$\sigma m^2 \ (f) = \left(\frac{\partial f}{\partial A} \ \sigma mA\right)^2 + \left(\frac{\partial f}{\partial B} \ \sigma mB\right)^2 + \ldots + \left(\frac{\partial f}{\partial N} \ \sigma mN\right)^2 \tag{3}$$

Where f is a function in terms of A, B, C, ..., N and each term has its own standard error σm.

For Equation 1, this relationship becomes

$$\sigma_Q{}^2 \ (f) = \left(\frac{\partial f}{\partial \mu} \ \sigma_\mu\right)^2 + \left(\frac{\partial f}{\partial \ell} \ \sigma_\ell\right)^2 + \left(\frac{\partial f}{\partial \bar{P}} \ \sigma_{\bar{P}}\right)^2 + \left(\frac{\partial f}{\partial b} \ \sigma_b\right)^2 + \left(\frac{\partial f}{\partial a} \ \sigma_a\right)^2 + \left(\frac{\partial f}{\partial \Delta P} \ \sigma_{\Delta P}\right)^2 \tag{4}$$

where

$$\frac{\partial f}{\partial \mu} = - \frac{\pi}{\mu^2 \cdot 8 \cdot \ell} \ \bar{P} \left[b^4 - a^4 - \frac{(b^2 - a^2)^2}{\ln b/a} \right] \Delta P \tag{5}$$

$$\frac{\partial f}{\partial \ell} = - \frac{\pi}{\mu \cdot 8 \cdot \ell^2} \ \bar{P} \left[b^4 - a^4 - \frac{(B^2 - a^2)^2}{\ln b/a} \right] \Delta P \tag{6}$$

$$\frac{\partial f}{\partial \bar{p}} = \frac{\pi}{\mu \cdot 8 \cdot \ell} \left[b^4 - a^4 - \frac{(b^2 - a^2)^2}{\ln b/a} \right] \Delta P \tag{7}$$

$$\frac{\partial f}{\partial b} = \frac{\pi \cdot \bar{P} \cdot \Delta P}{8 \cdot \mu \cdot \ell} \left[4b^3 - \frac{4b^3}{\ln b/a} + \frac{b^3}{(\ln b/a)^2} + \frac{4a^2 b}{\ln b/a} - \frac{2a^2 b}{(\ln b/a)^2} + \frac{a^4}{b \ (\ln b/a)^2} \right] \tag{8}$$

$$\frac{\partial f}{\partial a} = \frac{\pi \cdot \bar{P} \cdot \Delta P}{8 \cdot \mu \cdot \ell} \left[-4a^3 - \frac{b^4}{(\ln b/a)^2 \cdot a} + \frac{4ab^2}{\ln b/a} + \frac{2ab^2}{(\ln b/a)^2} - \frac{4a^3}{\ln b/a} - \frac{a^3}{(\ln b/a)^2} \right] \tag{9}$$

$$\frac{\partial f}{\partial \Delta \bar{p}} = \frac{\pi \cdot \bar{P}}{\mu \cdot 8 \cdot \ell} \left[b^4 - a^4 - \frac{(b^2 - a^2)^2}{\ln b/a} \right] \tag{10}$$

The following values for the individual variances (σm) of the variables in Flow Equation 1 were chosen to represent the expected variation during 1 week. This time period would be required to collect data necessary for development of an equation for the hydraulic radius of a thread form. Nominal values for the variables a, b, and ℓ are for the 0.6 UNM tapped holes used in the drill and tap study.

μ = 1.829358×10^{-5} $N \cdot s/m^2$

Recall that for air, $\mu = \dfrac{\beta T^{3/2}}{T + S}$

where

$\beta = 1.458 \times 10^{-6} \dfrac{kg}{sec \cdot m \cdot K^{1/2}}$

$S = 110.4K$

$T = 74°F\ (296.493K)$

$\sigma_\mu = 0.5273 \times 10^{-7} \dfrac{N \cdot s}{m^2}$ (1/2 of $\pm$ 4°F temperature change in factory air liner)

$\ell = 2.020824 \times 10^{-3}$ m (0.07956 inch)

$\sigma_\ell = 1.40208 \times 10^{-5}$ m (Standard deviation of test plate thickness)

$\bar{P} = 1.156288 \times 10^{5}$ N/m^2 [(2 x 738 mm Hg + 5 psig)/2]

$\sigma_{\bar{P}} = 3.505429 \times 10^{3}$ N/m^2 (1/2 of $\pm$ 50 mm $\pm$ 0.05 psig)

$b_{min} = 2.577846 \times 10^{-4}$ m (0.010149 inch)

$b_{max} = 2.75971 \times 10^{-4}$ m (0.010865 inch)

Average annular gap for a 0.6 UNM thread.

$\sigma_b = 0.635 \times 10^{-6}$ m (25 microinches)

$a = 2.2606 \times 10^{-4}$ m (0.0089 inches)

$\sigma_a = 0.254 \times 10^{-6}$ m (10 microinches)

$\Delta P = 3.447379 \times 10^{4}$ N/m^2 (5 psig)

$\sigma_{\Delta p} = 3.447378 \times 10^{2}$ ($\pm$0.1 psia)

Substitution of the above values into Equations 1 and 3 yields the following theoretical values for the maximum and minimum flow, and the associated variation at a two sigma confidence level that could be observed during a week (after converting from N•m/s to torr-l/sec).

$$Q_{min} = 3.272 \pm 0.481 \text{ torr-l/sec}$$

$$Q_{max} = 13.225 \pm 1.412 \text{ torr-l/sec}$$

The variance in the flow shown above can be reduced by correcting for atmospheric pressure changes, by measuring b to a greater precision than the current $\pm$50 microinches (0.00127 mm), and by increasing the number of measurements of flow (Recall $\sigma_{pop} = \sigma/\sqrt{n}$, where n is the number of data points).

During actual use by production inspection, the variance in minimum and maximum flow readings for 0.6 UNM x 0.07956 inch (2 mm) tapped holes with a minimum depth requirement on thread length would be:

$$Q_{min} = 3.272 \pm 0.225 \text{ torr-l/sec}$$

$$Q_{max} = 13.225 \pm 0.600 \text{ torr-l/sec}$$

The 0.6 UNM tapped hole in Bendix part number AY292245 is typical for present production requirements. The thread length in this hole is 0.058 inch (1.47 mm) and this length can vary as much as $\pm$0.011 inch (0.28 mm). The maximum and minimum flow and variance that can be expected at two standard deviations for this part is as follows.

$$Q_{min} = 4.488 \pm 0.906 \text{ torr-l/sec}$$

$$Q_{max} = 18.130 \pm 3.538 \text{ torr-l/sec}$$

Note that the variation in flow for a tapped hole with a minimum depth requirement is $\pm$4.5 percent, whereas a typical tapped hole allows a $\pm$20 percent variation.

Probe Design

Probes for air gaging miniature threaded holes have been designed built and tested. Figure 21 shows the probe developed for through

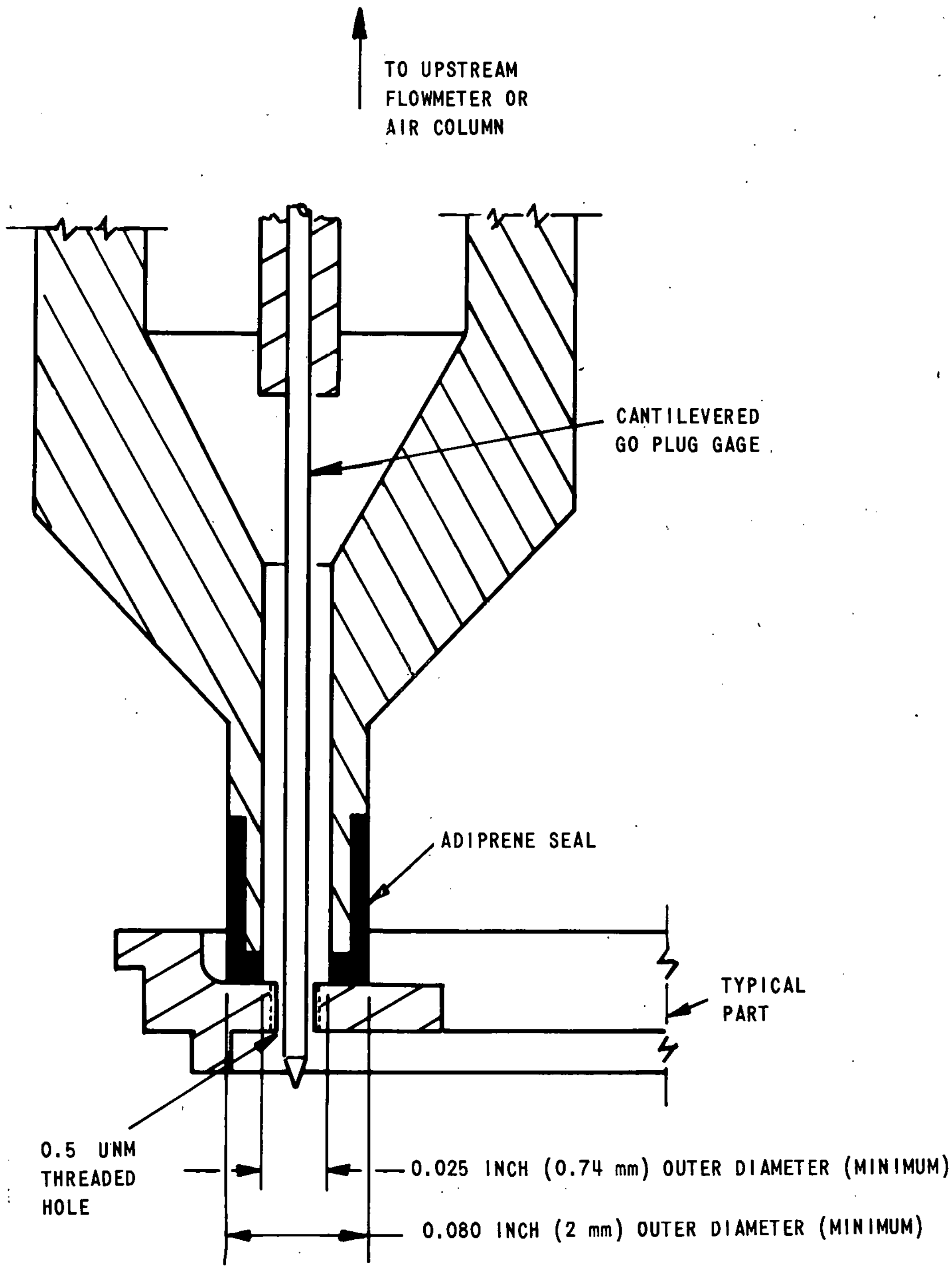

Figure 21. Air Probe for Through-Threaded Holes

miniature threaded holes. The probe uses an adiprene seal so that air is forced around the plug gage and through the tapped hole. The plug gage is cantilevered in the probe so that small side loads will easily move it to either side of the adeprene. This ease of movement along with the tapered tip of the probe allows the gage to engage the tapped hole even though it is not exactly centered. A repeatability study has shown that this probe repeats within ±80 microinches (2 μm) at two standard deviations.[4]

Figure 22 shows the probe design to gage blind holes. This probe will also work for through holes if one end is plugged and a gap large enough for air flow turn around is provided. Unlike the probe for through holes, this gage requires that the probe be positioned fairly precisely to engage the hole to prohibit damage to the hypodermic needle. Although this probe is harder to position, the length variable is eliminated by treating through holes as blind holes and greater accuracy can be obtained.

Air Gaging Printed Circuit Board Holes

During the literature search on this project, a method for air gaging miniature holes was uncovered.[5] IBM-Poughkeepsie devised a simplified air gaging technique for miniature holes based on a concept similar to the concept being used by Bendix to gage miniature threaded holes. In their technique, a solid pin is placed in the center of the hole and the hole's size is measured by the rate of flow through the hole. This technique is different from conventional air gages in that there are no orifices in the pin to provide an air inlet. In the past, the size of the hole and the depth of the hole that could be air gaged was limited by the size of orifice that could be constructed in the hole. To obtain sufficient sensitivity with conventional air gaging, the orifices area should be at least 1-1/2 times greater than the escape area, and the length of the hole should be at least 1-1/2 times greater than the orifice diameter.

IBM was contacted to determine the operating characteristics and limitations of the gaging system. They indicated that they had used this technique to gage holes with diameters between 0.009 inch (0.23 mm) and 0.058 inch (1.47 mm). They claimed a sensitivity of 5 microinches (0.13 μm), a repeatability of 10 microinches (0.25 μm), and an accuracy of 20 microinches (0.5 μm). They had large variations in the diameters of their holes as compared to the variation in length (recall the example in the error analysis section of this report where tolerance of the length of a tapped hole was increased).

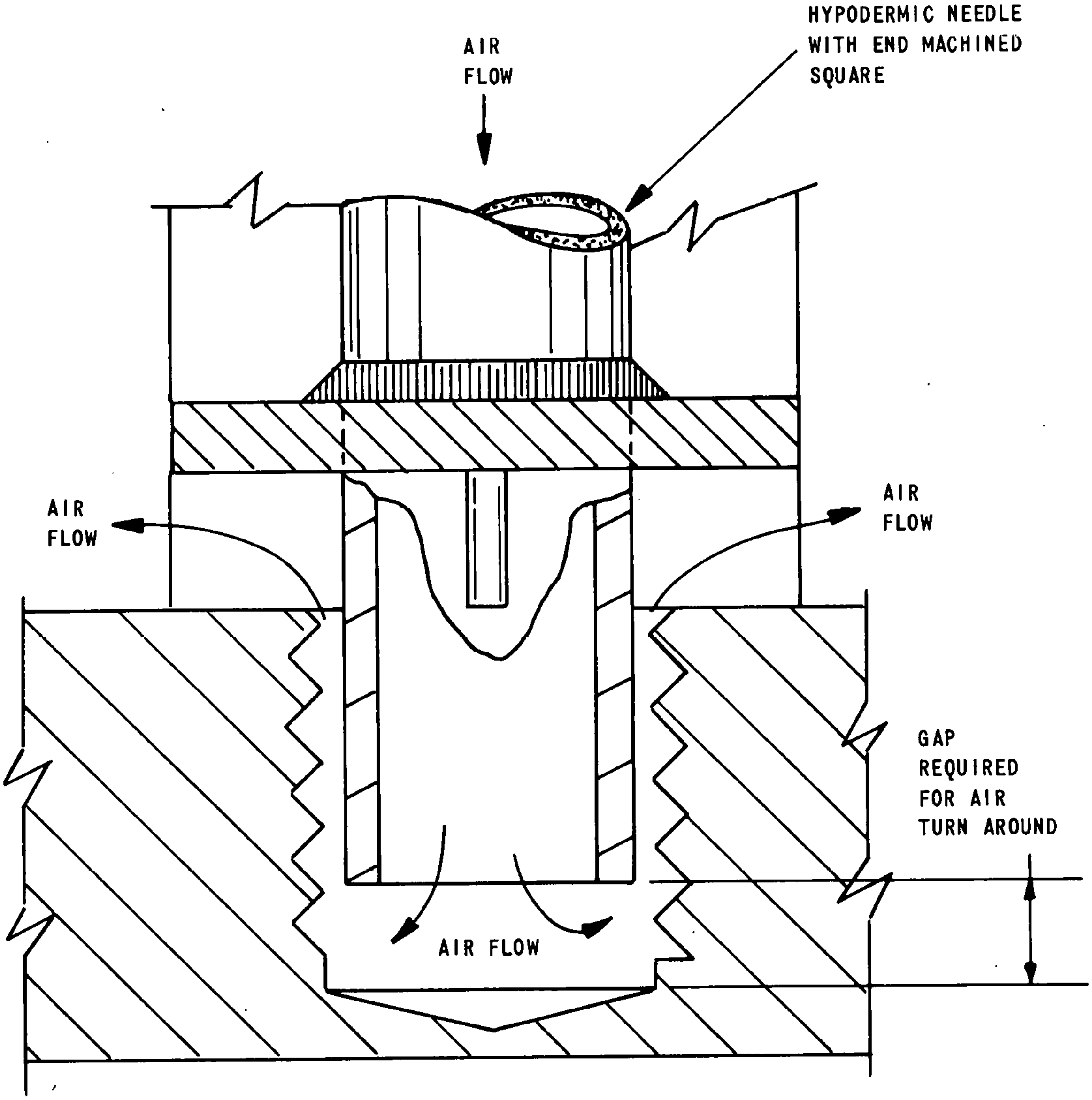

Figure 22. Air Probe for Blind Threaded Hole or Through Hole with One End Plugged

An analysis of the IBM technique for gaging holes showed that printed circuit boards (PCB) holes could be gaged in a similar manner. PCB holes are currently being gaged with GO and NOT GO cylindrical plug gages. This measurement is considered a destructive test, and parts gaged in this manner are scrapped. There are two reasons holes in PCB are now being gaged, and the need for variables data from these holes is anticipated in the future. The first requirement on PCB holes is that an electrical component fit in the hole. Second, the gap between the lead of the electrical component and the PCB hole must be within a range that allows a good solder connection. In addition to these two requirements, variables data will be required for PCB holes when plating thickness in these holes is measured by a four-point resistance method.

Figure 23 shows a fixture for a typical PCB which has 155 holes with diameter of 0.031 to 0.045 inch (0.79 to 1.14 mm). The four key features of the design include:

- A cantilevered size wire (Teflon pin may be used) in the center of the probe which deflects easily if contact is made with side of a hole and provides suitable sensitivity for the air measurement of hole being examined;

- A spring to permit retraction of the size wire in the event that an obstruction is encountered or the PCB is mislocated under the probe;

- A Teflon pad to prevent damage to the underside of the PCB; and

- An adiprene seal on the end of the probe which channels air into the gap between the size wire and the hole being measured.

This last aspect is the unique feature of the design. Conventional air gaging systems use a hollow cylinder which has one end plug and has orifices drilled perpendicular to the axis of the cylinder. These gaging systems are limited to 0.020-inch-diameter (0.508 mm) holes and larger by 0.040-inch (1.016 mm) minimum depth (the PCB previously mentioned is 0.032-inch (0.813 mm) thick).

Set-up of the gage involves several steps. The maximum limit on the air column is determined and set by using a master with a hole to the upper limit on the board and the thickness equal to the maximum board thickness. With the master in place in the fixture and the probe seated, gaging pressure is set between 2 and 4 psia. This position of the float represents the maximum hole size. The minimum limit is set in the same manner, using a second master made to the minimum allowable board thickness and with the hole to the minimum allowable diameter on the board.

Seven tests were made using the fixture shown in Figure 23 and PCB obtained from a lot of regular production parts. The particular part chosen for this study had 0.031 to 0.045-inch-diameter holes.

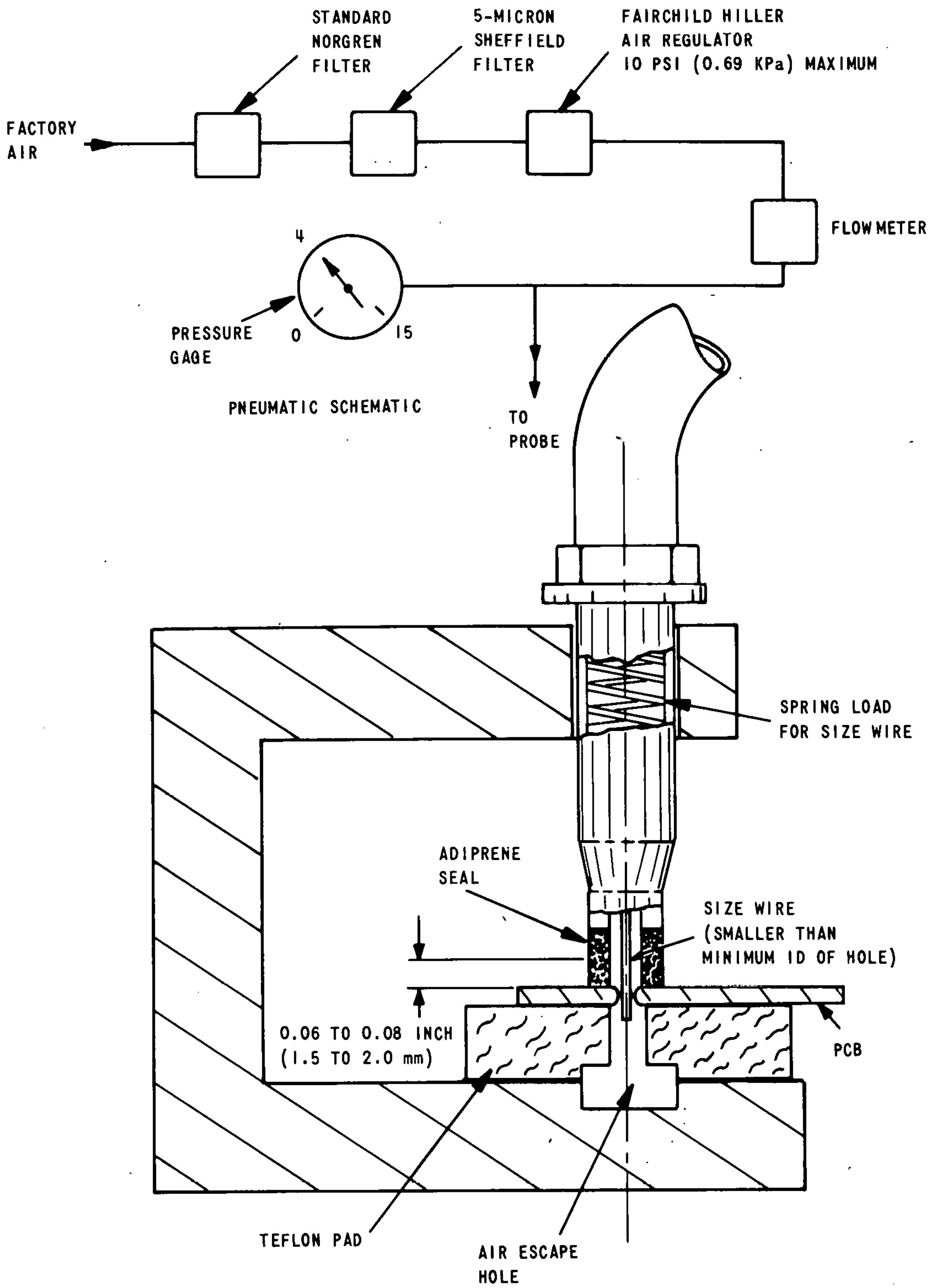

Figure 23. Fixture for Air Gaging Plated-Through Holes in PCB

Test 1

All holes (over 300) gaged were visually inspected for damage after gaging to determine if air gaging was truly a nondestructive test.

The annular ring of two of the holes was damaged by the point of the size wire used in the probe. There was no apparent damage to the walls of any of the holes.

Test 2

The probe was mastered using a standard air column and 0.045 inch (1.14 mm) and 0.031 inch (0.79 mm) diameter masters. Each hole was measured five times by two operators to determine the expected mastering errors.

Repeatability for the 0.045 inch hole was ±0.00102 inch (25.9 μm) at a 3σ (three sigma confidence level) and ±0.00015 inch (3.8 μm) at 3σ for the 0.031-inch-diameter hole. Note that there is a significant increase in standard deviation associated with the higher flow.

Test 3

The probe and air column as mastered in Test 2 were used to measure two holes on one PCB. In this test, the two operators measured each hole ten times so that the capability of the air gaging system could be determined.

Hole	Operator 1		Operator 2		Composite	
	Mean Dia. (Inch)(mm)	±3σ (Inch)(mm)	Mean Dia. (Inch)(mm)	±3σ (Inch)(mm)	Mean Dia. (Inch)(mm)	±3σ (Inch)(mm)
1	0.03536 (0.8981)	±0.00026 (0.0066)	0.03545 (0.9004)	±0.00014 (0.0036)	0.03540 (0.8992)	±0.00025 (0.0064)
2	0.03608 (0.9164)	±0.00029 (0.0074)	0.03619 (0.9192)	±0.00019 (0.0048)	0.03613 (0.9177)	±0.00030 (0.0076)

Note that high flow is associated with higher standard deviations.

Test 4

Using set-up for Tests 2 and 3, all 155 - 0.031/0.045 holes on one PCB were measured to determine the variation that could be expected within a part.

The mean hole diameter was 0.03513 inch (0.8923 mm). The hole sizes were distributed around this mean in a near normal distribution with $\pm 3\sigma$ equal to ± 0.00144 inch (36.6 μm). One of the 155 holes measured was outside the $\pm 3\sigma$ limit; its size was 0.03285 inch (0.8344 mm).

Test 5

The probe was mastered using a Matheson Co. No. 73 flowmeter with 4 psig (2.8×10^4 Pa) across PCB hole, and 0.045- and 0.031-inch-diameter masters. The purpose of the test was to compare performance of the flowmeter with a standard air column.

The repeatability for the 0.045 inch hole was ±0.00066 inch (17 μm) at 3σ and ±0.00024 inch (6.1 μm) at 3σ for the 0.032-inch-diameter master. Air column was better at smaller-hole diameter and worst at larger diameter (higher flow).

Test 6

The probe and flowmeter as mastered in Test 5 were used to measure two holes on five PCB from the same lot. In this test, both of the operators measured each hole five times. One of the holes was located in the center of the PCB and the other was located near the edge.

The repeatabilities of the two operators at a 3σ level were ± 0.00093 inch (24 μm) and ± 0.00114 inch (29 μm). A bias of 0.0006 inch (0.015 mm) was observed between the two operators. The difference between the repeatabilities for holes in the center of PCB and near the edge was less than 5 percent. The purpose of this test was to determine if the fixturing had any adverse effects of measurements. No fixturing effect was found.

Test 7

Each of the holes measured in Test 6 were measured with a microscope which was equipped with a digital micrometer, and the sizes of the holes obtained from air flow were corrected for the non-linearity of flowmeter and master thickness. The purpose of this test was to determine if air gaging misrepresented the hole size.

The mean values of the hole diameters obtained by both methods were within 0.00012 inch (3 μm). The repeatability of the microscope readings at 3σ was ± 0.0006 inch (15 μm).

ACCOMPLISHMENTS

- Theoretical and experimental evaluations have shown that air gaging miniature threads is feasible.

- Eccentricity of a pin in the center of a threaded hole does not significantly affect air-flow through the hole.

- Air gaging of blind holes has been shown to be feasible if sufficient clearance is allowed for air flow turn-around.

- Probes have been developed for air gaging through and blind miniature threaded holes.

- A 0.0200 inch (0.508 mm) $\pm$0.0001 inch (2.5 μm) diameter drill before tapping was found to give the highest yield for 0.6 UNM threaded holes in 0.08-inch-thick (2 mm) 7075 aluminum parts.

- A method for air gaging PCB holes with an accuracy of $\pm$0.001 inch (25 μm) has been developed.

- An air column with a spinning float was shown to have better repeatability than a tube-type flowmeter which uses a ball (the ball tends to stick when particles come through air lines at low flow rates).

FUTURE WORK

- If part geometry will allow threaded holes to be treated as blind holes, further work to determine air flow limits using screw gages and thread plug gages is recommended.

- A 0.0200 inch (0.508 mm) drill should be used for drilling 0.6 UNM holes in 7075 aluminum. Studies should be done with other thread sizes and materials so that the optimum yield of miniature tapped holes can be obtained.

- Air gaging of PCB holes should replace the destructive plug gaging test.

- Air gaging of holes which have diameter tolerance greater than length tolerances should be considered for holes which cannot be gaged using conventional air gaging methods.

REFERENCES

[1]W. J. Courtney, *Final Report IITRI Project J6262 - Feasibility Study of the Qualifcation of Miniature Internal Threads Using Fluid Flow.* Chicago: IITRI, November 4, 1971

[2]W. J. Courtney, *Final Report IITRI Project J6267 - Acceptance Criteria Definition for Fluid Flow Miniature Internal Thread Gaging.* Chicago: IITRI, April 24, 1972.

[3]K. C. Crandall and R. W. Seabloom, *Engineering Fundamentals in Measurements Probability Statistics and Dimensions.* New York: McGraw-Hill Book Company, 1970, p. 232.

[4]C. W. Berry, Jr., *Qualification of Miniature Internal Threads Using Air Flow* (Topical Report). Unclassified. Bendix Kansas City: BDX-613-716, September, 1972

[5]T. W. Townsend and J. L. Norton, "Thinking Small in Production," *American Machinist,* Volume 115, Number 18, September 6, 1971, pp 59-61.

Appendix

SELECTED ABSTRACTS

1. Scarr, A. J. T., *Metrology and Precision Engineering*, McGraw-Hill Publishing Company Limited, 1967, Chapter 10.

   The methods used by British for measurement of screw threads are discussed. Limit type gaging as well as measurement of individual elements of screw threads are discussed. Design of limit gages and what elements are checked by each type of limit gage are mentioned briefly. A detailed description of measurement methods and errors involved in measurement of major diameter, simple effective diameter, minor diameter, pitch, flank angle, form at the root, and form at the crest is given.

2. Greve, John W. ed., *Handbook of Industrial Metrology*, A.S.T.M.E., 1967, Chapter 14.

   General screw thread terminology, specifications for thread gages (plug, ring, snap, etc.), methods for certification of thread gages, and use of thread gages are discussed at length.

3. Strang, Arthur G., *The Role of the National Bureau of Standards in Screw Thread Metrology*, A.S.T.M.E. IQ-68-626.

   The development of thread standards from World War I to present is discussed. Methods for measurement of thread characteristics are discussed, along with errors associated with these measurements.

4. Davidson, M., *The Care and Use of Thread Gages - Their Surveillance and Control*, A.S.T.M.E. IG-69-599.

   The do's and don't's of thread gage use are discussed.

5. Shelby, Oscar J., *Procedures and Methods for Verifying Thread Gages*, A.S.T.M.E. IQ-69-598.

   Calibration and thread surveillance methods are discussed in depth. Measurement of individual characteristics of threads are discussed with pitch diameter, lead, and helix measurements given detailed coverage.

6. Bitlers, Philip F., *Concepts of U.S.A. Limit Gage Practices*, A.S.T.M.E. IQ-68-620.

This paper deals primarily with Limit Type gages. Thread Plug (Hi and Go), Thread Ring (Hi and Go), and Thread Snap Gages are discussed in depth. The merits of the limit type gage are discussed.

7. Heldmann, Ernest J., *Indicating Gages and Single Element Gaging*, A.S.T.M.E. IQ-68-621.

General discussion of indicating thread gages with special emphasis on gaging external threads. Although no one type of gage checks all the features of a thread, their use is shown to be economically feasible in most cases when the manufacturing method is known.

8. Twining, John B., *Specific Procedures and Methods of Checking Thread Gages*, A.S.T.M.E. IQ-68-624.

The basic procedures for the calibration of thread gages, measurement of thread wires, setting plugs (lead, thread angle, major diameter, pitch diameter, and root clearance), thread plug gages, thread ring gages, and indicating gages for internal and external gages are discussed. "When recalibrating setting plugs, it is only necessary to measure pitch diameter. Measurements should be taken at no less than three places along length of the plug. The pitch diameter should be recorded after each calibration. On thread plug gages, an additional check is required on first and second threads since they will show the most wear."

9. Heldmann, Ernest J., *Unified and American Screw Threads*, A.S.T.M.E. IQ-69-597.

General thread terminology is reviewed. Standard thread system requirements, thread profile, standard thread series, classes of threads, rounded root forms of threads, and general differences between thread systems are discussed.

10. *Calibration Procedure Ring Gages, Threaded*, Grumman Aircraft Engineering Corporation No. 1024201, November 15, 1965.

Detail calibration procedure for thread ring gages is presented. The element of feel is still incorporated. Pitch diameter and minor diameter are checked with S.I.P. measuring machine for sizes over 5/16 inch (8 mm) ID.

11. *Calibration Procedure Greenfield Thread Plug Class X or Class W,* North American Aviation, Inc. No. 1167-6, January 27, 1967.

This procedure covers the procurement and/or calibration of working thread plug gages. Such gages normally consist of a Go and Hi member mounted on opposite ends of a handle. The various elements of a thread gage that require calibration can be logically classified into two categories, those elements which require initial verification only and those which require recalibration. Major diameter, lead, and helical path deviation generally require no recalibration. Pitch diameter and flank angle do change with wear and must be recalibrated.

12. *Handbook H28* (1969), National Bureau of Standards, "Screw-Thread Standards for Federal Services," Part I, II, and III.

General specification of screw threads which includes dimensional requirements and tolerances for most thread forms.

13. *MIL-S-7742B* (2/2/68), Military Specification, "Screw Threads, Standard, Optimum Selected Series: General Specification For."

Gives the thread sizes that are recommended for use by agencies of the Department of Defense, and the gaging practice to be used by these agencies.

14. *MIL-S-8879A* (12/8/65), Military Specification, "Screw Threads, Controlled Radius Root With Increased Minor Diameter; General Specification For."

Defines the requirements for unified screw threads, classes 3A and 3B, altered to include a mandatory continuous radius of from 0.18042p to 0.15011p at the root of the external threads and with the minor diameter of both external and internal threads increased (over unified thread values) to accommodate the root radius.

15. *ISO Recommendation R1502* (June, 1970) (International Organization for Standardization), ISO General Purpose Metric Screw Threads - Gauging.

Specific tolerances for all types of internal and external thread gages. Gives function, control, and use of each gage that is recommended.

16. *MIL-STD-120* (9/9/63), Military Standard, "Gage Inspection."

Provides correlated technical information applicable to the inspection of gages, special tools, and measuring devices. The principal subjects covered are nomenclature, tolerances and fits, measuring tools and equipment, gages, and methods of measurement and inspection. All types of thread gages are discussed in detail (general description of gages and their function, use of gages, and gage inspection is covered).

17. *ASA B1.10 - 1958*, American Society of Mechanical Engineers, "Unified Miniature Screw Threads."

This standard covers necessary terminology, and dimensional information for manufacturing miniature threads 0.30 through 1.40 UNM. Internal threads are to be inspected as follows: Minor diameter is gaged with "GO" and "NOT GO" plain cylindrical plug gage; all other elements are checked only for assembleability limits with a "GO" thread plug gage. For the minimum material limit, the performance of the tap is relied upon.

18. *ASA B1.1 - 1960*, American Society of Mechanical Engineers, "Unified Screw Threads."

General Specification for Unified Screw Threads.

19. *USA Standard B1.2 - 1966*, American Society of Mechanical Engineers, "Gages and Gaging for Unified Screw Threads."

Gages for inspection of internal and external Unified Screw Threads by attributes are specified (gage construction tolerances are given). The use of these gages is discussed in detail.

20. *Machinery's Screw Thread Book*, 20th Edition, Machinery Publishing Co., LTD., London, 1969.

This handbook contains basic dimensional information necessary for manufacturing British Threads, Unified; American, American Translational, American Pipe, API, Casing and Standard Tubing, Continental and Horological Threads.

21. *ASME Screw Thread Manual*, "A Shop and Drafting Room Abridgement of the American - Unified Standards for Screw Threads and Their Gages," edited by Henry R. Cobleigh, 1953.

Gives tolerances for standard screw threads as well as gages for these threads.

22. MacKenzie, Robert V., *Screw Threads - Design, Selection, and Specification, 1961.*

Gives history of development of screw threads. Points out the breadth of screw threads: 0.30 UNM (0.0118 inch - 318 threads/inch) by 0.85 mm long on one end of the spectrum and 46.625 - 1.00 Pitch Buttress Thread by 34 m long on the other end. Gives nomenclature, definitions, symbols, and dimensioning systems for screw threads. The basic methods of screw thread production-chasing, die cutting and tapping, milling and hobbing, grinding, and rolling. Contains chapter on thread inspection and Quality Control.

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