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CHARACTERIZATION OF TYPICAL PRODUCTION HOLE QUALITY AND INSPECTION TECHNIQUES.

VOLUME I PROGRAM SUMMARY.

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RUSSELL L. MC CORD

MARTIN MARIETTA AEROSPACE
DENVER DIVISION
DENVER, COLORADO 80201

DECEMBER 1979

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This technical report has been reviewed and is approved for publication.

Edward Wheeler

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Project Engineer

FOR THE COMMANDER:

H. A. Johnson

H. A. JOHNSON
Chief, Metals Branch
Manufacturing Technology Division

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Hole Quality	Tapering	Rifling
Hole Shape	Barrelling	Burrs
Perpendicularity	Ovality	Tears
Bellmouthing	Surface Finish	Laps
		Scratches

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Survey and on-site evaluation of fastener hole production processes were conducted to assess the characteristics of fastener holes as they are now being produced in industry. Details of a general written survey and the response by Industry are presented. Design of the experimental work being performed on the program is described. Major emphasis of the program was on personnel tooling process and cost control methods as characterized by the size, shape, surface finish, surface texture and alignment. A unique, (over)

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automated hole measurement system based on air gaging and analysis by programmable machine processing was used to characterize dimensional and shape parameters. An example of data acquisition and analysis is included.

Results show that design engineering tolerances are generally met by current process applications. Inspection methods are inadequate in identifying individual discrepancies in hole characteristics, but aid in process control to assure conformance to design criteria. Tooling, stack clamp up and hole to hole spacing were identified as the most dominant variables in current industry production.

FOREWORD

This final Technical Report covers work performed under Contract F33615-76-C-5443 from 15 March 1977 to October 30, 1979. It is published for technical information only and does not necessarily represent recommendations, conclusions or approval of the United States Air Force.

This contract with Martin Marietta Aerospace was initiated under Project 825 6(I) and was administered under the direction of Mr. E. Wheeler of the Metals Branch, Manufacturing Technology Division, United States Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio.

The Program Manager for Martin Marietta Aerospace was Mr. Ward D. Rummel. The program was conducted by the Advanced Programs, Research and Technology Section of the Quality Department, Martin Marietta Aerospace. Technical Director for the Program is Mr. Russell L. McCord. Other members of the Martin Marietta Aerospace organization were consulted, as needed, throughout the program.

We are especially grateful for the support of Mr. Ed Wheeler, Project Monitor for the Air Force Materials Laboratory. Special thanks are also due to Mr. Richard Stewart, Mr. Robert Urzi, Mr. Larry Salinas, and Dr. John Potter at the Air Force Materials Laboratory, for continual technical help and guidance.

We are likewise indebted to our co-workers at Martin Marietta with special appreciation of Mr. Frank Ross, Mr. George McGee, Mrs. Ruth Ann Rogers, Miss Marge Losey, Mr. Jim Tutchton, Mr. Andrew Myers, Mr. Richard Daum, Mr. Jack Shaunessey, and Mr. Bill Post.

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I. INTRODUCTION AND SUMMARY

The majority of aircraft structural overload and fatigue failures originate at fastener holes. Fastener hole inspection and repair are major cost elements in aircraft structures maintenance. Preparation of fastener holes constitutes a major cost factor in the initial production of an aircraft structure. Fastener holes are major contributes to the life cycle cost of an aircraft.

Emphasis on performance and initial production cost in aircraft procurement have in the past supported development and implementation of production methods which resulted in low initial unit cost. On a unit basis, holes are comparatively inexpensive to produce and expensive to maintain. Hole maintenance costs are currently a major factor in aircraft "retirement for cause".

The importance of care and attention in producing highly stressed fastener holes has been recognized as the aircraft industry has evolved and progressed. Field failure data have been used to improve design, production, inspection and field maintenance practices. Improvements have been based primarily on engineering judgement and on performance reports from field hardware.

The development of linear elastic fracture mechanics and its incorporation as a design tool has enabled new focus on design and production practices. A key driving force in application of linear elastic fracture mechanics has been its capability to provide quantitative acceptance criteria. Quantitative criteria can be used to measure improvements in production and maintenance processes if the same analysis methods are used as a basis for measurements. Analysis methods have been developed to determine an "Equivalent Initial Quality Method" for quantifying the quality of fastener holes. Methods are based on the results of tear down/analysis of aircraft which have been in service and of tear down/analysis of structures which have been tested under simulated flight loading. Variability of initial hole quality is indicated by the size, shape, texture, and direction of cracks emanating from the hole.

Tear down/analysis has revealed that a major source of cracks is the occurrence of initial manufacturing defects such as sharp corners, tool marks, etc.

The task of assessing hole performance may be separated into elements of:

1. Hole/fastener design - Assessment of loading, spacing, clamp-up, lubrication, etc.

2. Hole acceptance criteria - Identification of characteristics which affect service life.

3. Hole production methods - Identification of characteristics of holes currently produced by industry.

4. Hole maintenance - Identification of the characteristics of holes returned to service after current inspection and repair in service.

5. Life Cycle Cost - Identification of cost elements of current technology application and management methods; and analysis of cost elements for system operation using "optimum application and management methods".

A thrust was initiated by the United States Air Force Materials Laboratory to characterize hole acceptance criteria and hole production methods. Separate, independent studies were initiated (1) to qualify acceptance criteria for tapered fasteners, (2) to qualify acceptance criteria for straight shank fasteners, (3) to characterize hole production methods for tapered fastener holes and (4) to characterize hole production methods for straight shank fastener holes.

Results of these studies will form a basis for future planning, aircraft systems acquisition and aircraft systems modification and maintenance. This report addresses the fourth task of characterization of hole production methods for straight shank fastener holes.

II. PROGRAM OBJECTIVE AND SCOPE

The objective of this study program was to characterize the variables in current production of drilled fastener holes in primary aircraft structures, and to evaluate the results of quality assurance methods applied to such production.

The program output goal is a quantitative comparison of the capabilities of production methods. Capabilities are intended to be independent of the facility producing the hole.

Data collected is intended to provide a baseline of the capabilities of production processes as a function of production methods.

Variations in hole production and acceptance are recognized for variations in fasteners, structures usage and structural materials. Variations between companies and production facilities have also been noted. Variations noted are based on differences in design practices, tooling practices and management. The intent of this study program was to minimize subjective variations in philosophy and to maximize objective characterization of finished holes as a function of the production process. The production process was used as the common denominator for comparison and evaluation of current practices and results obtained in the aircraft industry. Our approach was to sample a variety of aircraft production facilities by correspondence and by physical witness and measurement of hardware during the production process.

The magnitude and complexity of the task necessitated limiting the number of physical measurements. The nature of the measurements being made and proprietary nature of the applications necessitated objective measurement of hole characteristics as a function of the materials and processes sampled and data reporting independent of the end products. A confidential agreement was established with each participating facility and was maintained throughout the program. The source of specific data was identified only to Martin Marietta Aerospace project team members. Specific data was provided to participating facilities in the form of an audit report. Use of such data was limited to internal production assessment and was not approved for use in advertizing or other external reporting.

Survey of general industry methods and practices was conducted by written questionaire. Survey of hole production equipment suppliers was conducted by telephone and written correspondence. Survey of specific production methods and results was conducted by on-site visit, analysis and validation.

The goal of the program was to provide a systematic sampling and characterization of typical aircraft hole production processes.

III. STATE OF THE ART ASSESSMENT

Hole production processes cannot be characterized by any single dominant factor. Tooling, equipment grind, feed, speed, cooling in combination with craftsmanship in application are most frequently identified as controlling elements of the complex process of "quality" hole production. A balance of the controlling elements is necessary for success. Emphasis on one or more elements may offset the influence of a second element when performed by an experienced operator. Process controls and applications are known to vary among aircraft manufacturers. Variations are due in part to design, tooling, manufacturing, and inspection philosophies of various manufacturers. An obvious point of departure for industry process characterization was a written survey of current industry practices and philosophies:

A. Survey of Current Aircraft Industry Practices:

A written aircraft industry survey was completed to provide a baseline status of current production methods.

The objective of this survey was to provide one measure of the status of current production methods. The focus of our contract program was for straight fastener holes in the 3/16 to 5/8-inch* diameter range as produced in aluminum alloy aircraft structures. We recognized that methods used and improvements suggested could be independent of material, hole size and requirements. The survey was therefore, oriented to hole production methods and was intended to characterize production methods.

The invited participants included both prime aircraft manufacturers and subcontract suppliers of aircraft components. It was recognized that prime manufacturers specifications are imposed on subcontractors, thereby limiting the scope of methods variations. Individual response from both prime contractors and subcontractors was desired to assess variations in requirements interpretation and reduction to a common shop practice, and to provide independent recommendations for improvement.

One hundred survey requests were sent out to manufacturers selected from industry contacts and from supplier listings in the Thomas Register. Participants were urged to answer all questions with recognition that some may not be applicable (N.A.) or may be sensitive (s) to a particular operation or organization. Participants were requested to note such questions and to answer all others as full as possible.

* Dimensioning of fasteners and fastener holes in the aircraft industry are in english units only. Measurement equipment was capable of both english and metric units but was reported only in english units to reduce the quantity of data handling.

The survey questionaire was divided into four categories and the results analyzed and divided as follows:

1. Design Factors Related to Hole Quality.

2. Production Factors Related to Hole Quality.

3. Inspection Factors Related to Hole Quality.

4. Cost Factors Related to Hole Quality.

Twenty-five completed surveys were returned and thirteen letters of regret were received. Responses were segregated into the following groups for analysis:

Group A -- 9 responses - High performance aircraft design/manufacturers (Military Jet)

Group B -- 4 responses - Traditional aircraft design/manufacturers (Piston aircraft and light aircraft)

Group C -- 3 responses - Helicopter design/manufacturers

Group D -- 2 responses - Engine design/manufacturers

Group E -- 7 responses - Component Hardware Suppliers/Manufacturers

Survey results may be summarized as follows:

1. <u>Design Factors Related to Hole Quality</u>

   a. Fracture mechanics has been used as a primary basis for design of some high performance aircraft but is not the basis for most designs in current production.

   b. Zoning of critical areas is not used as a standard method for requesting special attention in production.

   c. Classification of characteristics and tolerances for acceptance criteria are not established by test analysis. Tolerances are established by past practices and production experience.

d. Hole production methods are not generally specified or recommended, by engineering drawings or processes.

2. Production Factors Related to Hole Quality

a. Drill characteristics are considered to be the most important factors for close tolerance holes.

b. Production methods are not initially selected on the basis of hole tolerance or other characteristics specifications.

c. Destacking and deburring are practices by most manufacturers.

d. Deburring methods and criteria are generally invoked by established workmanship standards.

e. Drill grind and regrind inspection are generally performed by the drill operator.

f. Operator training is variable and is primarily on-the-job.

3. Inspection Factors Related to Hole Quality

a. Inspection is generally by visual and "go" - "no-go" plug gages.

b. Inspection is generally increased for critical holes.

c. Frequency of gage calibration is variable among manufacturers and with the job to be performed.

d. Process and inspection reliability are generally monitored by supervision and periodic audit.

4. Cost Factors Related to Hole Quality

a. The cost of producing a single hole is not known at most facilities. Cost factors for multiple holes are used by most manufacturers but are variable among manufacturers.

b. The distribution of cost for various steps in hole production varies among manufacturers.

c. Manufacturing cost is not generally affected by relaxed hole tolerance. Inspection costs may be reduced.

d. Inspection costs vary with the criticality of the hole and acceptance criteria.

A detailed tabulation of survey questions and respective responses is included in Volume II of this report.

The wide variation in response concerning factors most critical to precision hole production prompted further survey of equipment/tool suppliers to ascertain "recommended practices".

B. Tooling Survey:

Tooling used to position and hold work pieces during drilling is known to be a major factor in producing precision holes. A rigid tool is an aid in producing high quality holes but is usually specified for interface and interchangeability of a structure rather than for hole quality. No common denomination could be identified for tooling produced by various manufacturers.

Drill equipment manufacturers generally recommend rigid tooling to react high bit point pressure and to provide precise location and stability. Precision bushings are required with a chip clearance of one to one and one-half bit diameters from the workpiece. Drill position is not limited but counterbalance is recommended for drilling vertical surfaces.

C. Drilling Equipment Manufacturers Survey:

During the course of the survey, standard and specialized drilling equipment from a half dozen or more manufacturers were seen in production operations. These equipments may have been essentially "off-the-shelf" models or special adaptations to suit the specific needs of the hardware or fixture design.

Most manufacturers of drilling equipment offer engineering assistance to modify their equipment to special situations and design to custom requirements when this approach is more cost effective than adaptation of off-the-shelf items. This assistance includes recommendations for "speed and feed" control to obtain optimum tool life and efficiency as well as acceptable workmanship. Optional equipment for the various systems is available to cover almost any conceivable fixturing arrangement necessary to accommodate production.

Standard systems usually list a spindle accuracy of .001 inch T.I.R. measured .500 inch from spindle locknut. This value is acceptable for holes where the total tolerance is .004 inch and depth does not exceed .625 inch. Precision equipment with spindle accuracy of .001 inch T.I.R., a taper of .0005 inch, and depth of up to 3.0 inches is available. Systems of this level of precision are adequate for the condition seen during the survey. Since these units are off-the-shelf" the ratings and accuracy are based on mildsteel, 2024 aluminum and 90 P.S.I.(pounds per square inch) air supply. The use of this equipment in more severe applications can result in an increase in maintenance time or loss of accuracy.

A written and telephone survey of drilling equipment manufacturers was conducted to establish a "recommended practice" for use of equipment. All manufacturers expressed caution in recommending specific actions.

Generally, the manufacturers of drilling equipment offer comments like:

1. Maintenance must be performed on time.

2. Use lowest drill speed possible for hard materials.

3. Operating gas pressure must be 90 PSI with unit operating.

4. With proper maintenance equipment can last 25 years.

5. Reaming speeds should be lower than drilling speeds.

6. Precision of .001 or better requires reaming.

7. Most do not offer a recommendation of drill bushing to work piece clearance, some say 1 to 1.5 x drill diameter.

8. Lubrication of the drill/work should be the drill manufacturers option.

9. Taper mount drill chucks are more accurate than thread on type.

10. Rigid tooling is a must for close tolerance holes (.001) and clamp-up pressure must exceed drill load.

11. Experimentation, at the start of production to adjust, drill penetration, feed speed, retraction technique (rotating or not), variation of reaming speed, lubrication, and drill change-out time is a must.

12. Precision location of holes is no better than drill plate bushing (drill wobble) tolerance.

13. Bushings for reaming should be a different size from drill bushings.

14. Gun Drilling (carbide tip) is considered to be the most accurate technique for deep holes. And, when used with a coolant the need for reaming is eliminated in many cases.

15. All manufacturers agreed that drill motor lubrication and cleanliness are established to precision hole production.

16. Specific maintenance procedures (except cleanliness) were not offered. "Maintenance is necessary when bad holes are produced."

Most manufacturers agree that, while they do not have specification for runout below .001 inch T.I.R., proper fixture design can insure better accuracy. Most welcome the opportunity to offer assistance in the planning stage to obtain the optimum from their equipment.

D. Drill Bit Manufacturers Survey:

A telephone survey of drill bit manufacturers was conducted to establish a "recommended practice" for use of the tools provided. Responses were varied. A summary of responses includes the following:

1. "Drills are only roughing tools. Reaming is the only way to get precision holes."

2. "Drill point geometry is the most important factor for precision holes. The point center must be within 0.0005 inch."

3. "Feed and speed are important to hole quality and tool life. The optimum feed and speed for drilling a stack containing dissimilar materials must be based on the toughest material in the stack. The drill will be less efficient in the softer material since slower speed and feed is generally recommended for harder materials."

4. "Depth of the hole should be a factor in selecting feed and speed. For holes less than three (3) diameters deep, a nominal handbook feed and speed can be used. For holes deeper than three (3) diameters, the speed should be progressively reduced to one-half the nominal speed for holes six (6) diameters deep."

5. "Heat build-up is critical to hole quality and tool life. Heat may cause lip distortion and tool loss. Heat can also cause chips to ball up and distort the hole."

6. "Double margin drills are the current state-of-the-art and may be expected to hold a tolerance within 0.002 inch. Double margin drills make rounder holes than a regular bit. The second margin, on the trailing edge, provides better support but also generates more heat. It acts similar to a piloted drill."

7. "A core drill provides additional support and is preferred by some manufacturers for medium precision and precision operations in tough materials."

8. "A double margin step drill should be used for medium precision operations. The pilot drill should be about 0.030 inch diameter less than the finish drill. This tool is particularly good in thinner materials of three (3) times the drill diameter deep (thick) or less."

9. "Precision holes require a finishing operation. A conventional bit and reamer provide the best precision in two generations. A piloted reamer may be used if sufficient chip clearance between the drill pilot and the reamer can be assured."

10. "A reamer provides additional stiffness for control of hole geometry. Chip clearance and cooling must be provided to gain benefit from a reaming operation."

IV. DESIGN OF THE EXPERIMENT

Survey results provided a basis for state-of-the-art assessment of current industry practices and tools. Design of an experiment for observation and measurement on aircraft production lines had to be accomplished in a minimum time period, had to provide minimum interference with the production process and had to be nondestructive. Our approach was to address characteristics of concern to manufacturers and to include observation of characteristics which had been identified on other programs.

A. <u>Industry Standards:</u>

Characteristics most frequently identified in hole quality acceptance criteria include:

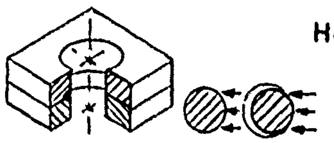
1. Hole Size and Geometry

Hole size and geometry tolerances are imposed to avoid load concentration on the shank of the fastener or along the axial length of the hole. Conditions commonly associated with variable hole size and geometry include:

a. Hole Diameter

Concern: Fastener engagement and load concentration.

Typical Criteria: $\pm$ 0.0005 to $\pm$ 0.005 inch.

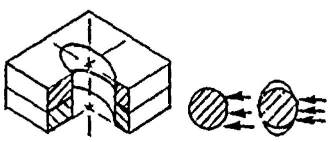


Hole Diameter

b. Ovality

Concern: Fastener engagement and load concentration.

Typical Criteria: $\pm$ 0.0005 to $\pm$ 0.005 inch.

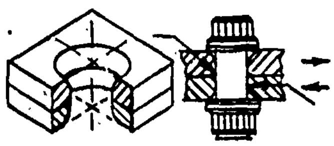


Ovality

c. Bellmouthing Coresting/Taper

Concern: Fastener engagement and load concentration.

Typical Criteria: $\pm$ 0.0005 to $\pm$ 0.005 inch.

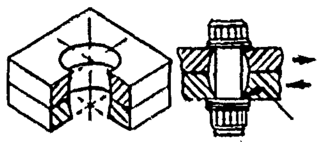


Bellmouthing

d. Barrelling

Concern: Fastener engagement and load concentration.

Typical Criteria: $\pm$ 0.0005 to $\pm$ 0.005 inch.

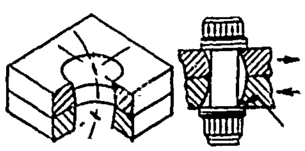


Barrelling

e. Straightness (Banana Hole)

Concern: Fastener engagement and load concentration.

Typical Criteria: $\pm$ 0.0005 to $\pm$ 0.005 inch.

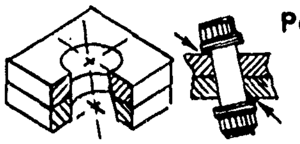


Straightness

2. Hole Alignment/Perpendicularity

Concern: Load concentration at the fastener head.
Clamp-up.

Typical Criteria: 0° to 2° from perpendicular.

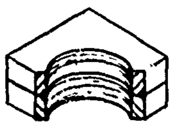


Perpendicularity

3. Surface Finish

Concern: Fastener engagement.
Flaw initiation.

Typical Criteria: 25 to 300 microinches.



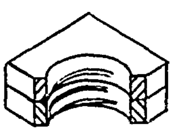
Surface Finish

4. Surface Texture

a. Rifling

Concern: Fastener engagement.
Flaw initiation.

Typical Criteria: No visual evidence.

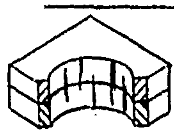


Rifling

b. Scratches

Concern: Fastener engagement.
Flaw initiation.

Typical Criteria: No visual evidence.

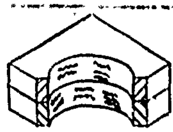


Scratches

c. Chatter Marks

Concern: Fastener engagement.
Flaw initiation.

Typical Criteria: No visual evidence.

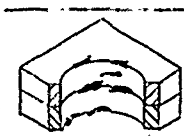


Chatter Marks

d. Burrs

Concern: Fastener engagement.
Flaw initiation.

Typical Criteria: No visual evidence.

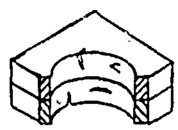


Burrs

e. Tears: Laps: Cracks

Concern: Flaw initiation.

Typical Criteria: No visual evidence.



Tears:Laps:Cracks

B. Test and Service Results:

1. Fatigue Test and Tear Down

Fatigue test coupons and built up airframe structure are subjected to extensive test and analysis to assess the capability of a structure to maintain its prime functional utility over the lifetime of the structure. Cracks emanating from fastener holes are the primary form of fatigue damage. In a recent study on mechanically fastened shear joints in aircraft, fifty variables, as shown in Table I, are listed as contributors to joint durability.[1] The number of variables involved and the lack of available analysis methods have traditionally relegated mechanically fastened joint acceptance criteria to engineering judgement and uniform shop practices.

In addition to full scale test of fatigue articles, recent work has included tear down and analysis of a "high time" structure in a fleet. Fatigue damage and damage tolerance analysis of fastener holes have included analysis of "equivalent hole quality" as characterized by an "equivalent initial flaw size." This method reduces crack initiation from all sources to a single parameter and assumes uniform hole loading for all load cycles.

For straight shank fastener holes, flaw origin is equally probable at the center, entrance and exit of the hole. The range of equivalent initial flaw sizes for a production aircraft fatigue test wing structure based on tear down analysis have been calculated to be from 0.00015 to 0.0022 inches in length. An accumulative probability of occurrence identifies an equivalent initial flaw length of less

TABLE I

Table I- Factors Believed to Influence the Fatigue Life of Mechanically Fastened Shear Joints

No.	Variable	Range
1	Amount of Load Transfer	0-100%
2	Stress Level in Material Fastened	0-100% Ultimate Strength
3	Stress Ratio "R"	-1.0 to 1.0
4	Physical Environment	Vacuum to Severely Corrosive
5	Countersink Depth/Sheet Thickness Ratio	0 to More Than 1.0
6	Head Sheet Material	Al, Ti, or Steel Alloys
7	Nut/Collar Sheet Material	Al, Ti, or Steel Alloys
8	Stack-up Thickness/Shank Diameter Ratio	0.1 to 10.0
9	Type of Loading	Constant Amplitude or Spectrum
10	Sheet Corrosion Protection	Bare, Clad, Primed, Anodized, Alodined
11	Degree of Cold Work of Sheet Material	None to Severe
12	Sealing	None to heavy
13	Fretting Protection	None, Shims, Lubricants, Adhesives
14	Shim Materials	Soft Al, Hard Al, CRES, Brass, Bronze, Plastics
15	Paint/Primer Thickness	0 to 0.010"
16	Gap Between Sheets	0 to 0.050"
17	Corrosion Protection at Installation	None, Dry, Wet Primer
18	Test Temperature	Any Desired
19	Temperature Cycling	Any Desired
20	Edge Distance/Diameter Ratio	0 to 4.0+
21	Fastener Spacing and Pattern	Any Desired
22	Hole Smoothness	25 to 300 Microinches
23	Hole-countersink Concentricity	0 to 1/4 diameter error
24	Hole Perpendicularity	0^{o} to 2.0^{o} Error
25	Countersink Perpendicularity	0^{o} to 2.0^{o} Error
26	Hole Circularity	Circular, Oval, Lobed
27	Countersink Circularity	Circular, Oval, Lobed
28	Hole Taper	0^{o} to 2.0^{o} Taper
29	Degree of Clamp-up (Fastener Preload)	0 to 100% Fastener Ultimate Strength
30	Interference Level	0 to 5% of Fastener Diameter
31	Degree of Hole Cold Work	0 to 8% of Hole Diameter
32	Amount of Fastener Shank Contract	0 to 100%
33	Hole Clean-up	None or Destack and Deburr
34	Radius Under the Head or Countersink	0 to 1.0 Fastener Diameter

Table I- (Concluded)

No.	Variable	Range
35	Fastener Finish Smoothness	25 to 300 Microinches
36	Fastener Driving Method	Pulled, Squeezed, Driven, Upset
37	Fastener Corrosion Protection	None, Plated, Sealed, Primed, Anodized
38	Type of Fastener Material	Steel, Ti, Al, Monel, MP35N, etc.
39	Nut/Collar Material	Steel, Ti, Al, Monel, MP35N, etc.
40	Nut/Collar Configuration	Coining or Non-coining
41	Type of Nut	Threaded or Upset
42	Type of Shank	Straight, Tapered, or Lobed
43	Countersink Angle	60°, 70°, 82°, 100°
44	Strength of Fastener Material	50 to 300 KSI
45	Type of Head	Countersunk or Protruding
46	Type of Recess	Hi-Torque, Torque-Set, Triwing, etc.
47	Hole Straightness	0 to 0.1 D Error
48	Number of Times the Fastener is Removed	Any Number
49	Fastener Head to Shank Perpendicularity	0 to 1.0° Error
50	Nut Angularity (Perpendicularity)	0 to 1.0° Error

than 0.01 inch (95% confidence). [2] [3] Such initial equivalent flaw sizes are not relatable to current hole quality acceptance criteria in current industry use.

The equivalent initial flaw size method does not account for load concentration and other geometry factors which are known to contribute to structures durability and which are included in current industry acceptance criteria. A criteria which identifies all characteristics and tolerances relating to hole durability is needed.

2. Coupon Tests of Fasteners Hole Quality

Fatigue test and analysis of coupons containing fastener hole anomalies have demonstrated that slight hole size and geometry variations do not appreciably affect the fatigue life in low-load transfer joints. [4]

An axial scratch produced by retraction of drilling equipment was shown to have a greater effect on fatigue life. Similar results were produced in analysis of "Taper-Lok" fasteners in test coupons. [5]

C. <u>On-Site Survey:</u>

Holes are currently characterized in production in terms of size, geometry, orientation, surface finish and surface texture. These factors are evaluated and controlled by various combination of operator and inspector observations. These factors together with the specific factors identified in prior fatigue test, tear down, and laboratory studies, were the basis for our physical examination, and for subsequent characterization of process variables.

The objective of an on-site survey was to:

1. Identify production processes and controls in current use;

2. Characterize holes produced in terms of current acceptance criteria and inherent qualities;

3. Characterize holes produced in terms of mechanical factors which may contribute to flaw initiation.

Our process evaluation plan consisted of:

1. Reviewing written process data (instructions to the operator).

2. Review of tools and tool control (tools provided to the operator).

3. Review of written inspection plans and acceptance criteria - (craftsmanship of the operator).

4. Review of cost analysis procedures (performance of the operator).

5. Witness of the process (validation of performance).

Holes produced were to be characterized by physical examination and assessment to engineering acceptance and inspection criteria.

Data analysis was to be performed by assessment of conformance to the manufacturer's criteria and by comparison of processes (and facilities) in terms of variables identified in Table I.

D. Output

The output of the on-site surveys and analyses was directed toward assessment of:

1. Hole quality as a function of production method.

2. Production method as a function of cost.

3. Inspection quality as a function of production method and

4. Inspection quality as a function of cost.

V. DIMENSIONAL MEASUREMENT - HOLE SIZE AND GEOMETRY

A. Industry Practices:

The primary method for dimensional control in industry is currently process control as assessed by "plug gage" inspection. Modified "plug gages," split ball gages, and air gages are used in special applications. Actual measurements are rarely recorded.

B. Selection of a Gaging Method

The gaging method selected for this program had to equal or exceed the precision of the most precise method used in industry. Special dimensional inspection methods were considered such as the capacitance gage which is under development by the Lockheed-Georgia Company (6) and the automated scanning systems which is under development by The Boeing Company (7) but were not ready for field application.

A system based on air gaging was selected as the primary method for our evaluations based on the attainable precision and the non-contact measurement capability. Split ball gages were selected to provide a referee method and to provide an additional measurement range capability.

C. Selection of the Air Gaging System

1. Operation - Air gaging systems may be based on principles of back pressure or on flow.

   A gaging system based on pressure is a comparator which measures the work piece size by sensing the flow of air through a gaging member such as an air-probe. The principle of operation is as follows:

   a. Supply air is passed through a particulate matter fitter;

   b. Through a dryer;

   c. Through a second particulate filter;

   d. Through a pressure regulator;

   e. Through a metering valve which reduces the pressure in proportion to the air flow required by the gaging member; and

   f. Through an air probe gaging head (See Figure 1).

   When the air probe is positioned in a hole, the rate of air flow is reduced in proportion to the clearance between the probe and the walls of the hole. A pressure sensor is installed in the line to measure the change in line pressure as a result of the change in flow. When "calibrated" against known (hole size) standards (termed ring gages) the system becomes a precision comparator. For small clearances between the air probe and hole wall (approximately 0.005 to 0.008 inch) the change in flow (and pressure) is directly proportional to the amount of clearance.

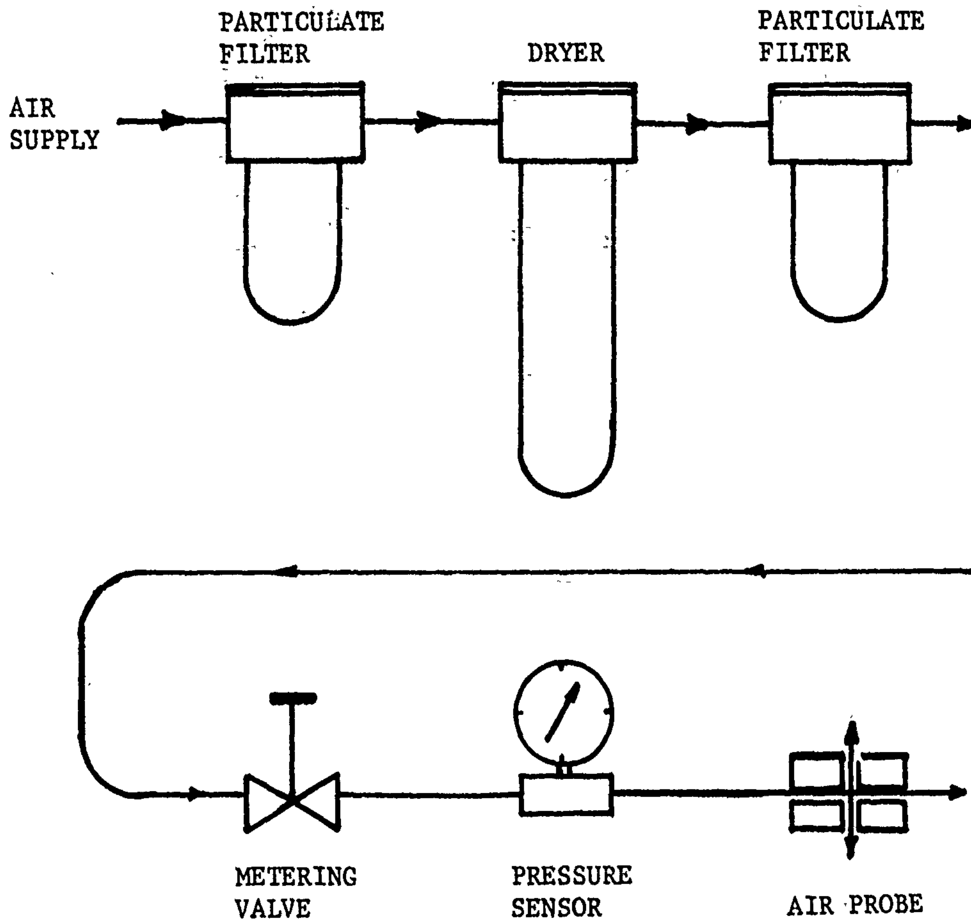


FIGURE -1 Air Gaging System

2. Air Probe - Gaging Member

The air probe which is shown in Figure Two (2) is used to gage the size of a hole. It consists of a cylindrical member in which air passages have been drilled to diametrically opposed nozzles. The clearance between the surface of the work piece and the nozzle determines the amount of air flow.

3. Differential Measurement

Since diametrically opposed nozzles are used, the flow of air through the gaging member is not affected by radial motion of the workpiece relative to the gaging member; only changes in the work piece size are detected by the air probe. This "differential type of measurement" is one of the most important features of air gaging. It eliminates the problem of "centering" which is critical in other gaging systems.

4. System Manufacturer

We selected gages manufactured by Western Gage Corporation [8] for use on this program. Through-hole probes were selected for all applications. A complete listing of the gage types and sizes is included in Volume II of this report.

D. <u>Selection of the Split Ball Gaging System</u>

1. State-of-the-Art

Several types of variable mechanical gages are available for hole measurement. A split ball gage is commonly used for hole measurement in the aircraft industry. Both direct and indirect units are available.

The indirect units are inserted into a hole and a ground needle is mechanically adjusted to expand the gaging ball to the diameter of the hole. The unit is then withdrawn and the diameter measured with a conventional micrometer.

Direct reading units are fitted with a dial indicator to sense the expansion of the gaging ball. The direct reading unit is faster and more precise, but is more expensive and more easily damaged than the indirect type. A direct reading unit was selected for use on this program.

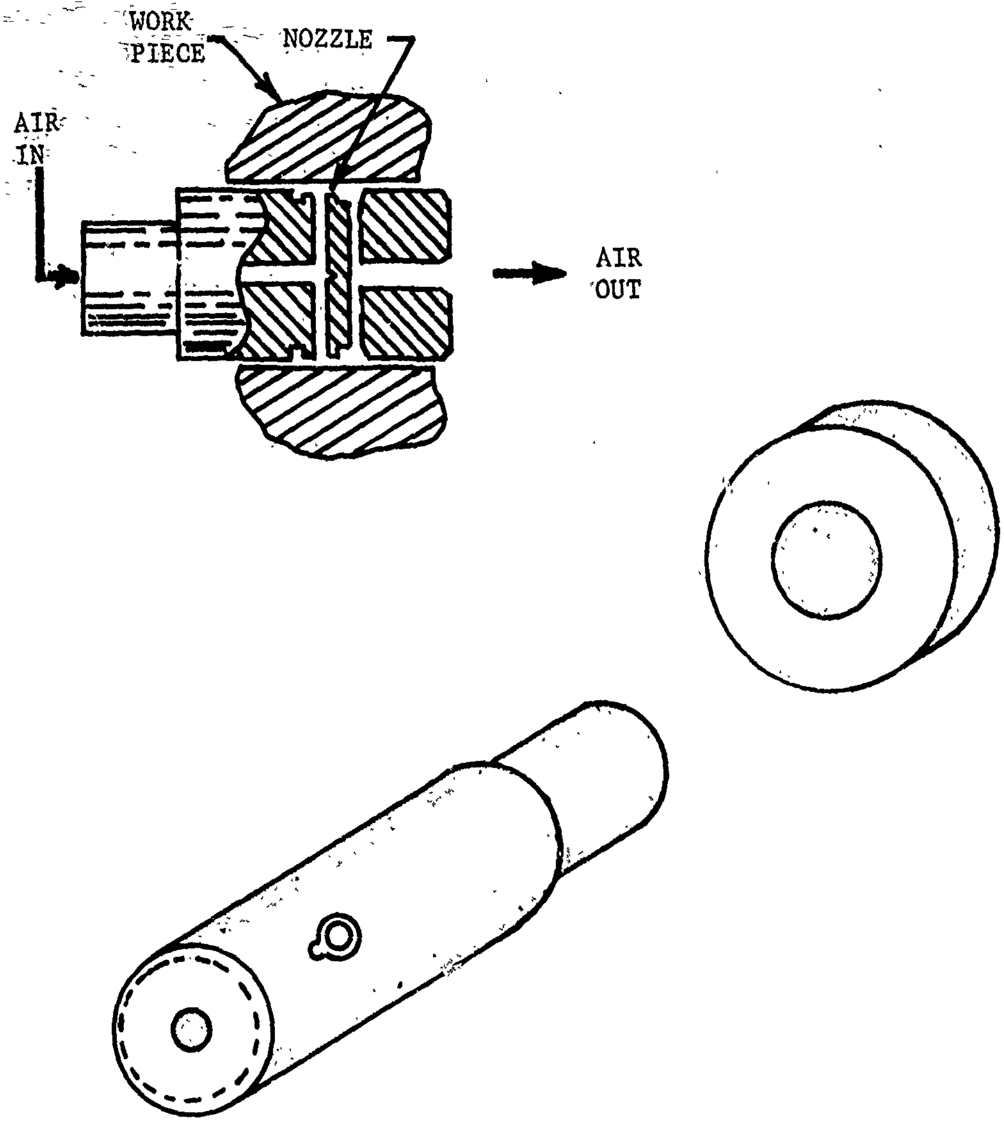


FIGURE -2 Air Probe (Through Hole Type)

2. "Dia Test" Bore Gages

"Dia Test" direct reading bore gages were selected for this program because of their "Slim-Line, T-Series" design, precision in readout and adaptability to electronic indicators. Units were supplied locally by "The Iver J. Esbenson Co.[9]. The Dia Test unit is illustrated in Figure 3 .

A complete listing of the gage sizes and accessories is included in Volume II of this report.

E. Gage Handling Tooling

Measurement of hole diameter at a single point by the air gage method may be accomplished with the aid of a simple, hand held, wand. Measurement of ovality in a plane within a hole requires depth control for either two jet or four jet gages. Assessment hole shape requires multiple measurements at various depths within a hole. Capability to reposition and duplicate measurements requires tooling. Our program required both precision and repeatability. A gage positioning tool was therefore designed and fabricated to provide the necessary control.

The "Western Air Gage" probes feature an impingement jet which is approximately 0.030 inch in diameter, a jet relief ring which is approximately 0.25 inch in diameter, and an end flow port. Based on these features, sampling of the holes at 0.0625 intervals through a hole and at 0^{o}, 45^{o}, 90^{o} and 135^{o} positions across the diameter in a selected plane was specified. The multiple measurements at known and controlled positions provides a basis for analysis of the hole shape profile and an assessment of geometric shape features as shown in Figure 1.

"Western Air Gage" probes covering the size range from 1/8 inch through 5/8 inch require two different adapter tubes. The tubes are respectively .250, .375 and inch in diameter. The tool was designed and built as illustrated in Figure 2 . The overall height of the tool was 6 inches and its overall diameter was 2 inches. The bushing sleeve, -1, was used with the smaller adapter tube for hole diameters under 0.437 inch. Two different alignment base units, -3 and -5, were used to accommodate the different size probes. Grooves in the -2, "Elevation Plane Adapter" were machined to interface the -4, "Latch" and to provide depth positioning in increments of 0.0625 inch.

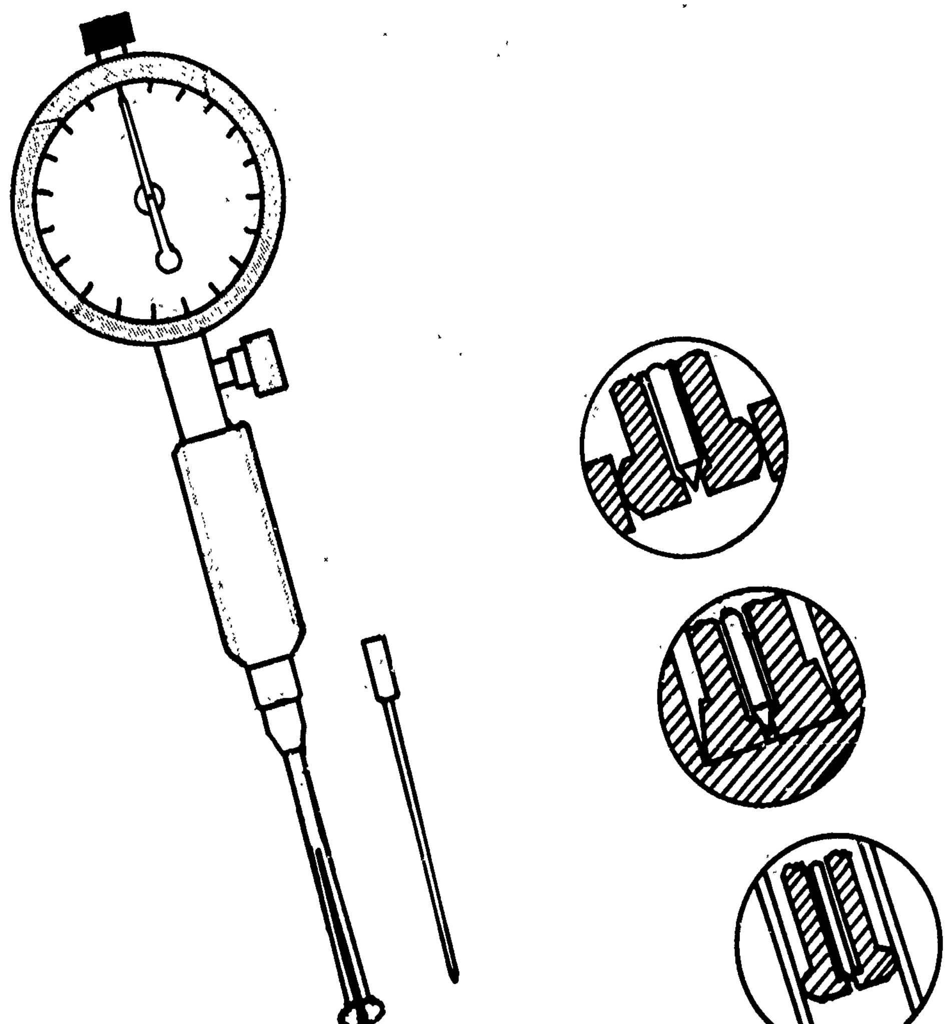


FIGURE - 3 The "Diatest" Split Ball Type Gage

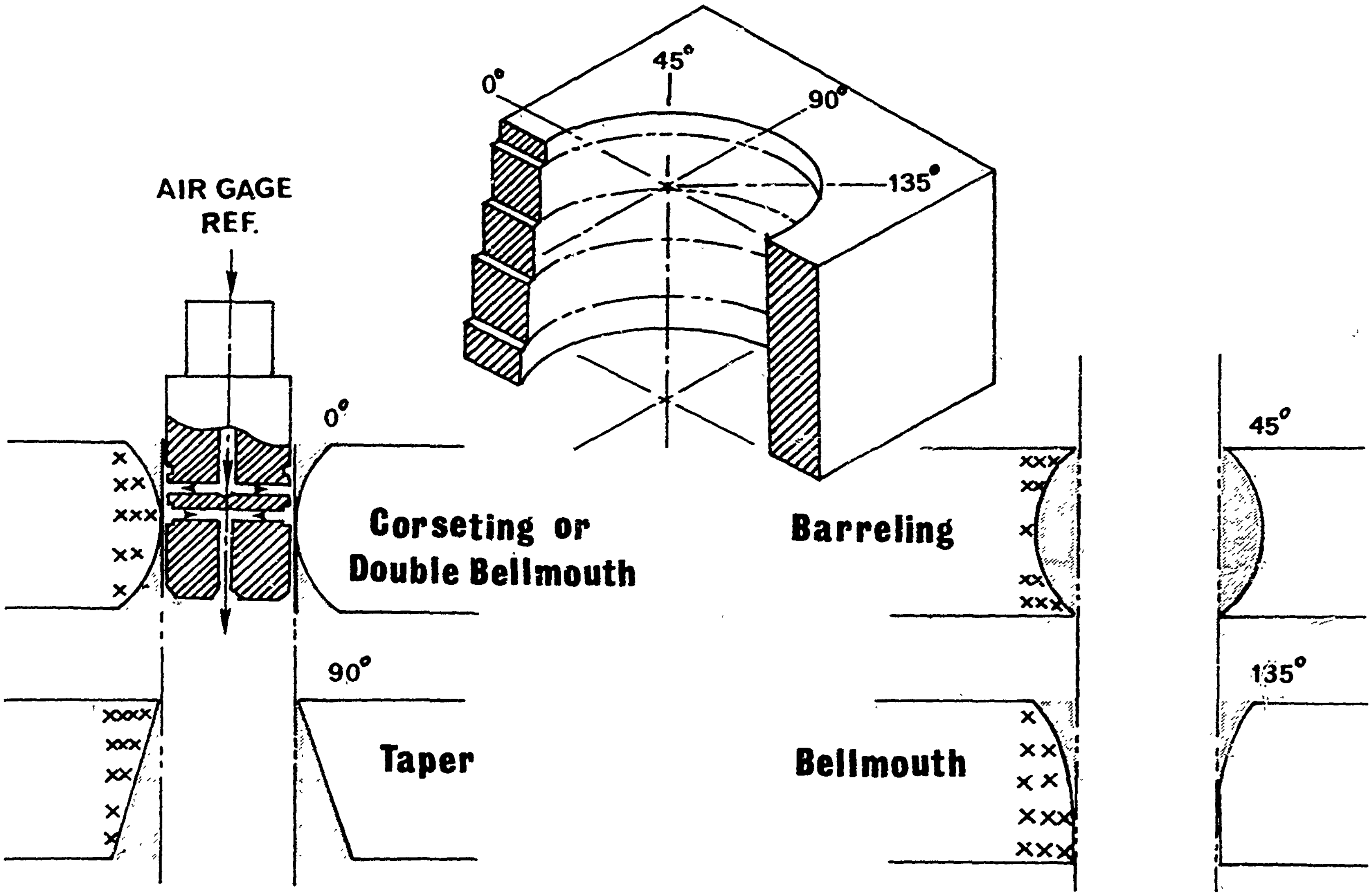


FIGURE 4 TYPICAL CONDITIONS REVEALED BY HOLE PROFILE ANALYSIS

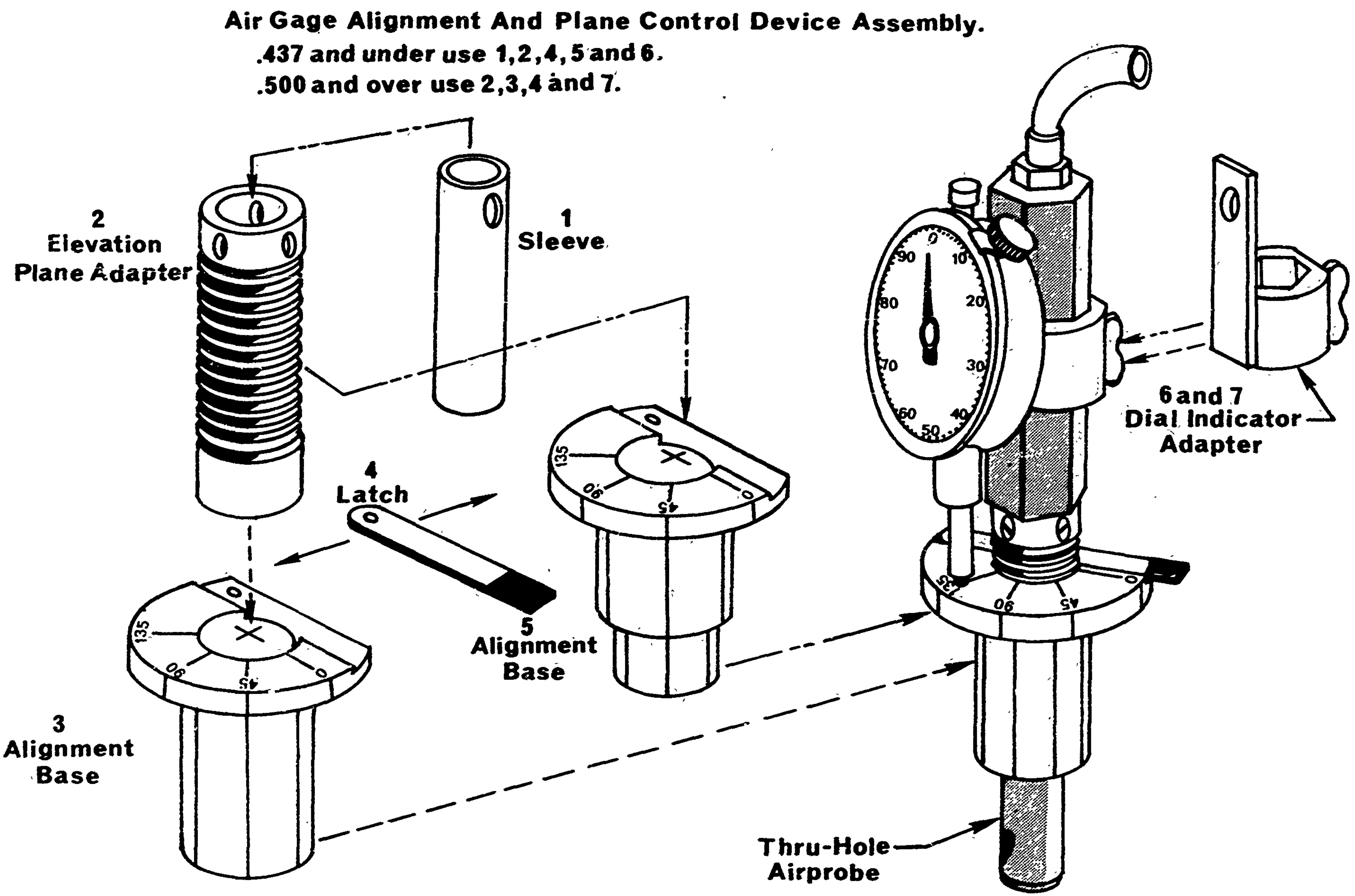


FIGURE 5 AIRGAGE ALIGNMENT AND PLANE CONTROL TOOL

A dial indicator was initially fit to the unit to provide a positive visual indication of probe depth. It proved too cumbersome to use in the field and was later discarded in favor of incremental "plane counting" to indicate depth.

Index marks at the 0^{o}, 45^{o}, 90^{o} and 135^{o} azimuth positions were inscribed on the alignment base to enable consistent and reproducible positioning of the two jet probes within the hole.

Use of the tool consisted of:

1. Inserting the air probe in the hole;

2. Positioning the jet orifice at a point approximately .0625 inch below the top of the hole (the relief ring ig used as a visual positioning reference);

3. Establishing a 0^{o} alignment with the jet in the direction of the gravity vector, for inclined surfaces or in a pre-determined position, for horizontal surfaces;

4. Measuring and recording the diameter at the 0^{o} position;

5. Rotating to the 45^{o} position; measuring and recording the diameter;

6. Rotating to the 90^{o} position; measuring and recording the diameter;

7. Rotating to the 135^{o} position; measuring and recording the diameter;

8. Incrementing down one plane (0.0625 inch) and repeating steps 3 through 7; and

9. Repeat of the process through the thickness of the material.

F. Programmable Data Collection and Analysis System:

The task of measuring and recording multiple measurements in a series of holes is tedious and time consuming. Automation of the measurement and recording process was desirable.

A commercially available, portable, air gage measurement system was located. The system was purchased from the Alina Corporation[10]. It features:

1. Hewlett-Packard Programmable Desk Calculator, Model HP #9815 . . . . 2008 memory steps.

2. A Hewlett-Packard Model 98133A Interface (9 digit binary coded decimal "BCD" input and 8 bit parallel output).

3. Alina - Pretec Analog - BCD converter unit.

4. Alina - Pretec Electronic differential amplifier.

5. Alina air-electronic converter. This unit contains a differential diaphragm as the pressure sensing element and an LVDT sensor to convert mechanical movement to an electronic signal.

6. Foot switch (Single Pole - normally open) for remote data entry.

The modular design and low cost of the Alina system make it attractive as a labor savings approach to repetitive, precision measurement while providing a permanent record of actual inspection characteristics.

G. Software Development:

1. Program Capabilities

A software program featuring basic dimensional measurement methods was purchased with the Alina System. The instrument calibration and instrument address routines were modified and incorporated into the software developed for this program. The data recording medium used by the Hewlett-Packard Model 9815A, Programmable Calculator is a high speed magnetic tape which can store 96,000 data bits. The magnetic tapes were used for storage of data collection programs, raw hole dimensional data and data analysis programs. Program and data files are program addressable for file management and sequential (chain) program analysis.

FIGURE 6 PROGRAMMABLE MEASURING SYSTEM

2. Program Structure

From sampling theory, it can be shown that a series of 29 observations is necessary to establish a 90% confidence that the observations (and dispersions) therein are representative of the population. A sample lot size of twenty-nine (29) holes was selected as the basis for characterizing a production process by measurement and analysis of resultant hole characteristics. This sample size could be accommodated and a single data tape with a storage capacity of 130 observations per hole. In addition, the necessary data acquisition programs could be accommodated on a single tape. 130 data entries could be accommodated along with 40 data descriptor entries within the 2008 step memory. Data acquisition tapes were formatted with 6 program files and 30 data files. The extra data file provided convenient storage for data from an "extra" hole without re-formatting in those cases where difficulty was encountered on a single hole and the data determined to be invalid. File structure was as follows:

a. File 0, was an automatic loading file when the calculator was turned on. All entry and branching was made through this file.

b. File 1, through 30 were data files.

c. File -0, provided for hand input of data.

d. File -1, provided for interface data entry and storage of calibration data.

e. File -2, provided printed header information and prompting for data.

f. File -3, input data and records data on tape.

g. File -4, provided quick print out of data in the data format.

A series of 29 holes on a single data tape was the "Lot Sample" for the process.

3. Program Functions Data Acquisition

Program logic was to print prompting messages for all required calibration and data entry such that no special operator knowledge or note keeping was necessary for performance. A space was provided between every four data entries to group data taken in a single depth plane. The next data entry to be input was displayed by the calculator display. Provisions were provided for back-up and correction of an accidental data entry. Additional housekeeping routines are provided for interrupted or split lot prompting and data acquisition.

A typical print-out of data as acquired during data acquisition is shown in Table II. All data entries were acquired and printed to six significant places. Data was later truncated to four significant places during analysis.

4. System Calibration - Validation of Hardware and Software

a. Calibration Standards

Calibration (set-up) rings purchased with the air gage system were certified to the nearest 5 millionths of an inch. Reference standards used by Western Gage Corporation are directly traceable to the National Bureau of Standards.

b. Air-Gage System Precision

A one quarter inch ring/probe combination was selected, the programmable data collection system set-up with the air-probe tool and calibrated. 29 repeative measurements were made using the 0.25000 inch ring as a gaging piece. A variation of thirty millionths for the twenty-nine measurements was realized. Similar results were obtained with other rings. The system was thus capable of providing better than a 3 to 1 precision for measurement to the nearest 0.0001 inch. The tightest tolerance to be addressed during the program was $\pm$ 0.0005 inches..

TABLE II

MARTIN MARIETTA AEROSPACE DENVER DIVISION PROJECT 1000	Printout of tape when calculator is turned on in the Auto/Start mode.
PRESS EITHER KEY A OR B. A= MANUAL DATA ENTRY. B= INTERFACE DATA ENTRY.	Choice of two ways to enter data, manually or automatically using software and air gage.
INTERFACE DATA ENTRY SELECTED	Air gage method selected.
DATE ? 103079	Date of inspection.
DATA SOURCE ? 115	Facility code number.
DATA LOT ? 1	Lot Number
HOLE NO. ? 1	Hole Number
ENTER RANGE AS SHOWN ON PRETEC AMPLIFIER	
INCHES CHOSEN. RANGE= 0.0100	Meter range used for taking measurements.
IF OK, PRESS RUN/STOP, ELSE PRESS 0	Double check to make sure the right range was selected.
DESIGN TOLERANCE L.L.=? 0.247000	Design lower limit of hole.
U.L.=? 0.250000	Design upper limit of hole.
GAGE SET-UP***** NOMINAL SIZE=? 0.250000	Nulling point on pretec meter.
LOWER LIMIT=? 0.247000	Lower limit for calibraton on pretec meter.
UPPER LIMIT=? 0.250000	Upper limit for calibration on pretec meter.

TABLE II (Continued)

All keyboard entries are stocked in various memory registers.

TABLE III

PROJECT 1000
MEMORY REGISTERS

0	
1	Floating Temporary
2	Storage
3	
4	Executive Data File Number
5	Interface Amplifier Sealing Factor
6	Amplifier Range
7	
8	
9	
10	
11	Lower Limit Design Tolerance
12	Upper Limit Design Tolerance
13	Number of Entries
14	Highest Reading
15	Lot Number
16	Date
17	Data Source
18	Lowest Reading
19	Mean
20	Standard Deviation
21	Maximum Ovality 0^{o} - 90^{o} Axis
22	Level
23	C Coefficients for Mean
24	D And Standard Deviations
25	Hole Number
26	E Number of Entries Required For Mean and Standard Deviations
27	Maximum Ovality 45^{o} - 135^{o} Axis
28	Level
29	Lower Limit
30	Nominal Size Gage Values
31	Upper Limit

c. Split-Ball Gage System Precision

The system evaluation was repeated with the Dia Test split ball gages and the electronic LVDT (linear variable differential transformer) probe. Repeative measurement variation of less than 0.0001 inch was obtained in the laboratory but was not proposed for field operations in difficult attitudes. The basic problem of the system when used with the electronic probe is extreme difficulty in centering. The unit could be adjusted for a maximum value reading but the time and uncertainty in the output resulted in rejection of the system for field operations.

5. Program Functions

The programs for hole analysis were developed to provide maximum visibility of the drilling process in terms of resultant hole size, hole shape and distribution of measurements. Typical data output is shown in Table II. The sequence of operations was as follows:

a. Data was loaded into the calculator memory from the data tape.

b. Header information was printed to identify the source and type of data.

c. Actual data was printed in tabular form with oversize and undersize values identified by accompanying ++++++ or ------- labels.

d. Data was then separated and printed in tabular form through the hole as taken at each of the alignment (azimuth) positions within the hole. A quick-look at the data list provides identification of major shape features or discontinuities within the hole.

e. Basic statistical analysis of the data list was made and printed.

f. The maximum ovality between adjacent reading were calculated and the location (plane level within the hole) printed.

```
HOLE NO.         1
= = = = = = = = =
36  DATA ENTRIES
= = = = = = = = =

HOLE SIZE*
  UPPER LIMIT=
    0.252000
  LOWER LIMIT=
    0.249000
= = = = = = = = =

HIGHEST READING=
    0.252649
       ***
LOWEST READING=
    0.249422
       ***
MAX. OVERSIZE=
    ++++0.000649
       ***
MAX. UNDERSIZE=
    ----0.000000
= = = = = = = = =

RANGE OF THE LOT
    0.003227
= = = = = = = = =

ARITH. MEAN=
    0.250070
STD. DEV.=
    0.000785
STD. ERROR=
    0.000131
= = = = = = = = =

MAX. OVAL. 0-90=
    0.002063
  AT LEVEL      9
       ***
MAX.OVAL 45-135=
    0.001276
  AT LEVEL      9
* * * * * * * *
```

PROGRAM OPERATIONS -
This sequence performs basic statistical analyses on the data, calculates the maximum ovality, and prints out the results of analyses.

TABLE IV-1 - TYPICAL DATA OUTPUT FROM THE PROGRAMMABLE MEASURING SYSTEM

```
NOMINAL SIZE=
    0.250000
DESIGN TOLERANCE
 LOWER LIMIT=
    0.249000
 UPPER LIMIT=
    0.252000
* * * * * * * *
    0.249500
    0.249466
    0.249422
    0.249474
    0.249578
    0.249509
    0.249448
    0.249491
    0.249595
    0.249560
    0.249500
    0.249543
    0.249853
    0.249759
    0.249621
    0.249724
    0.249819
    0.249716
    0.249690
    0.249784
    0.250138
    0.249828
    0.249778
    0.250086
    0.250466
    0.249888
    0.250026
    0.250422
    0.251767
    0.250500
    0.250060
    0.251629
    0.252649++++
    0.250690
    0.250586
    0.251966
* * * * * * * *
  END OF DATA
      ***

= = = = = = = =
 36 DATA ENTRIES
= = = = = = = =
```

```
*.*.*.*.*.*.*.*.
PROJECT 1000
DATA ANALYSIS
FOR HOLE NO.    1

* * * * * * * *
DATE           99
DATA SOURCE   999
DATA LOT     9999
```

PROGRAM OPERATIONS -
This sequence prints identification information and actual data entries in the sequence acquired.

TABLE IV-2 - TYPICAL DATA OUTPUT FROM THE PROGRAMMABLE MEASURING SYSTEM

```
HOLE NO.        1
* * * * * * * *
0  DEG. ALIGNMT
     0.249500
     0.249578
     0.249595
     0.249853
     0.249819
     0.250138
     0.250466
     0.251767
     0.252649

45 DEG. ALIGNMT
     0.249466
     0.249509
     0.249560
     0.249759
     0.249716
     0.249828
     0.249888
     0.250500
     0.250690

90 DEG. ALIGNMT
     0.249422
     0.249448
     0.249500
     0.249621
     0.249690
     0.249778
     0.250026
     0.250060
     0.250586

135 DEG. ALIGNMT
     0.249474
     0.249491
     0.249543
     0.249724
     0.249784
     0.250086
     0.250422
     0.251629
     0.251966
* * * * * * * *
      ***
```

PROGRAM OPERATIONS - This sequence separates data into the respective azimuth orientation locations within the hole and prints data entries in the sequence acquired.

TABLE IV-3 - TYPICAL DATA OUTPUT FROM THE PROGRAMMABLE MEASURING SYSTEM

```
HOLE NO.        1
* * * * * * * *
--HOLE PROFILE--
0 DEG. ALIGNMT
*               0
*               1
*               1
*               4
*               3
*               6
*X              0
*XX             3
*XXX            1

45 DEG. ALIGNMT
*
*
*
*00
*00
*000
*0000
*0000000000
*000000000000

90 DEG. ALIGNMT
*
*
*
*0
*00
*000
*000000
*000000
*00000000000

135 DEG. ALIGNMT
*               0
*               0
*               1
*               2
*               3
*               6
*               9
*XX             2
*XX             5
* * * * * * * *
```

PROGRAM OPERATIONS -

This sequence separates data into respective azimuth orientations, subtracts the lowest value entry in the list from the remaining entries and plots a histogram of the difference in values.

The result is a cross section profile of the hole at the respective azimuth orientations. Differences in entry values are plotted in 0.0001 inch increments as "0" characters or in 0.001 inch increments as "X" characters with the additional 0.0001 inch variations printed in the right hand column.

The histogram shown is typical of a tapered hole configuration.

TABLE IV-4 - TYPICAL DATA OUTPUT FROM THE PROGRAMMABLE MEASURING SYSTEM

```
================
   HISTOGRAM
    OF DATA
  DISTRIBUTION
 FOR HOLE NO.  1

================


+
+
+
L.L.=VV=0.249000
+
+
+
+
+**
+********
+*****
+*****
+******
+*
O=VV=   0.250000
+*
+***
+
+
+*
+**
+*
+*
+
+
O=VV=   0.251000
+
+
+
+
+
+
+*
+
+*
+
+*
U.L.=**=0.252000
+
+*
+
  + = .0001 INCH
* * * * * * * *
```

PROGRAM OPERATIONS -

This sequence plots a histogram of data in 0.0001 inch increments. Each "*" symbol denotes a single data entry. An "O" symbol is used at the end of the line when the number of entries exceeds 15 at a single value.

TABLE IV-5 - TYPICAL DATA OUTPUT FROM THE PROGRAMMABLE MEASURING SYSTEM

g. Variation along a row of measurements within the hole was calculated and the variation from the minimum value printed as multiple "O" characters for variations of 0.0001 inch or more; or printed as multiple "X" characters for variations of 0.001 inch or more. When the "X" format was printed, the "X" indicates the variation to the nearest 0.001 inch and the variation in 0.0001 inch increments were printed as a digit in the extreme right hand column. The printing method provided an exaggerated representation of the shape of the hole in the thickness plane.

h. The data was truncated and a histogram of the distribution of measurements within the hole printed in increments of 0.0001 inch. This provided a measure of the process control attained during the drilling opration. A controlled process would be indicated by a normal or Gausian distribution of measurements centered between the upper and lower tolerance limits.

VI. HOLE ALIGNMENT - PERPENDICULARITY

Hole perpendicularity in production is controlled by fit up and tooling. Perpendicularity is not routinely measured in production and portable inspection tools could not be located. A test tool was designed and built to measure alignment characteristics on this program. The tool, shown in Figure 7 , consisted of a ground plug which was inserted into the hole and aligned to the surface of the part. The plug was threaded to a spherical ball joint which was attached to a 10 inch pointer. Alignment and azimuth were read-out directly by visual observation of pointer alignment with respect to a compass rose which was positioned in a plane perpendicular to the pointer tip.

Interface alignment was determined by rotating the plug to the limits in all directions and determining the average position and orientation.

A precision of less than 1/4 degree error was obtained by this method.

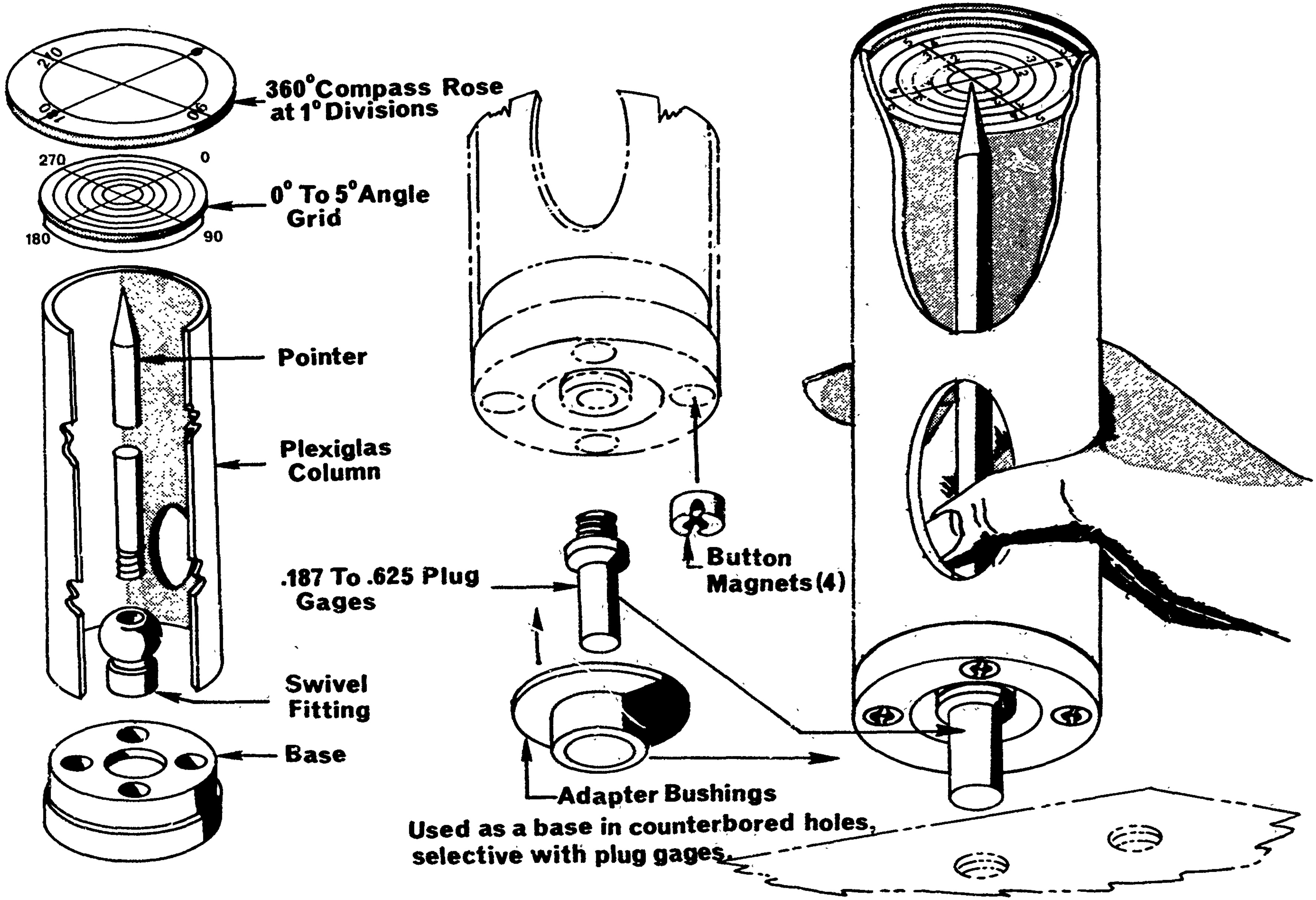


FIGURE 7 AZIMUTH AND ANGLE GAGING TOOL

VII. SURFACE FINISH

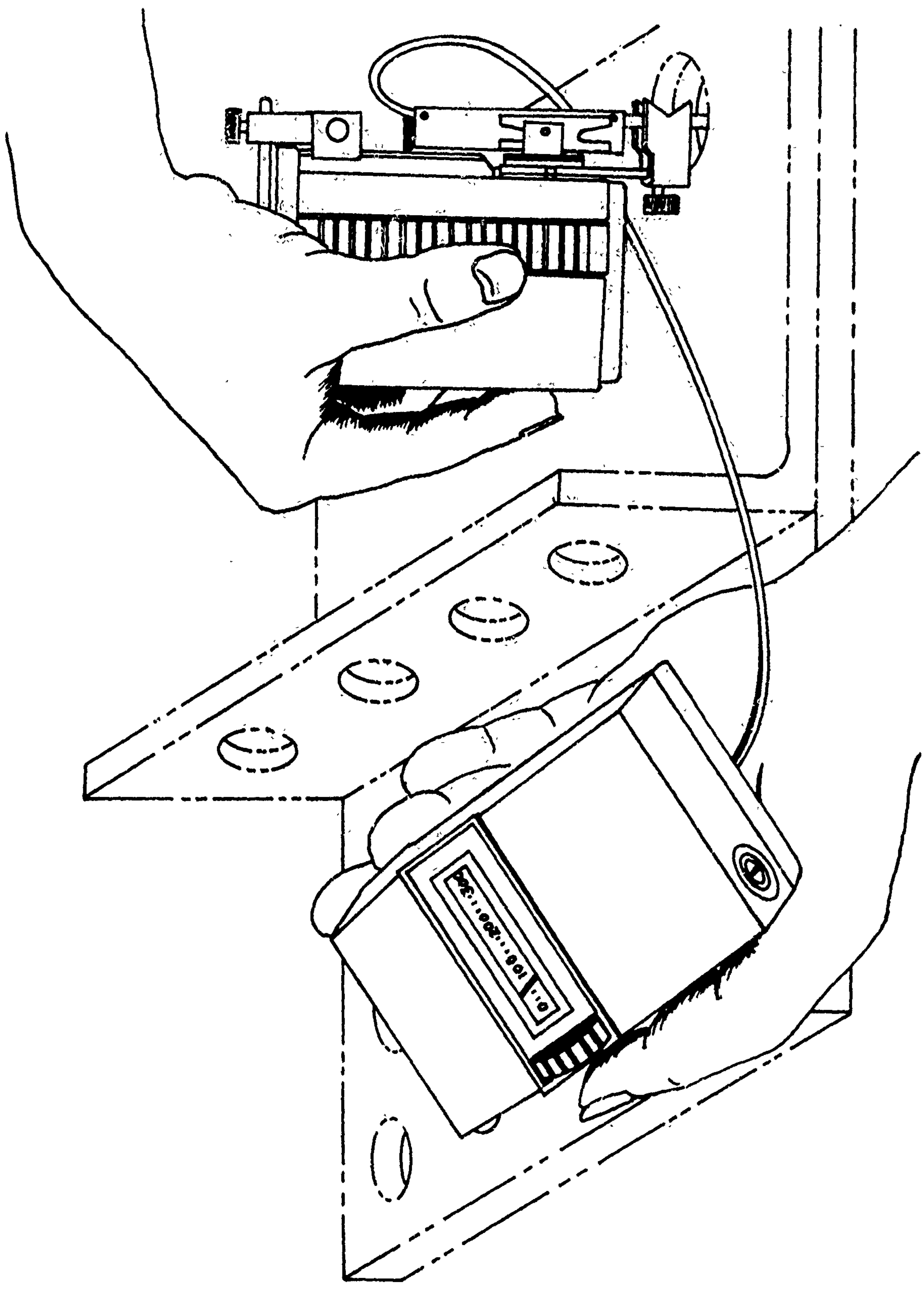
A. Measurement

Surface finish for holes is frequently specified in hole acceptance criteria but is rarely measured in production. Commercially available portable equipment for measuring surface finish is limited. Capability for direct measurement of surface finish in a hole was provided by a "Gould Model 71C0 Surf Indicator." (11)

This unit features a small bore probe with a diamond stylus, a hole positioning adapter and a hand held, battery powered drive motor. Operation of the unit is similar to conventional units used in gage laboratories. The unit is positioned in the hole with the stylus along the axis of the hole. The drive unit moves the stylus back and forth along the bore axis of the hole. Vertical movement of the stylus is sensed and converted to an electronic signal for processing and display as an "average" value of roughness along the path sampled. The unit leaves an axial scratch in the hole approximately 0.125 inch long and 0.0005 inches deep. This factor, together with recent tests which indicate that an axial scratch is one of the most detrimental factors in reducing structures fatigue, limited application of this unit. If a facility did not use such a unit in production, this unit was not used. No facility surveyed used this method.

B. Comparison

Surface finish has traditionally been identified with good workmanship in hole production. Most specifications of surface finish are interrupted as such and conformance is judged by visual inspection. As a comparator aid to visual inspection, a "Cylindrical Roughness Scale" was purchased from GAR Electroforming, Division of Mite Corporation." (12) This scale is an electroformed replica of half cylindrical surfaces of 0.50 inch radius and of varying surface finish values from 16 to 250 microinches. The unit may be used in direct visual comparison or in comparison with the aid of optical devices. The comparator method is detailed by the American Standards Association Specification B46.1 - 1962.



HOLE SURFACE FINISH (PROFILOMETER) MEASUREMENT SYSTEM

FIGURE 15 - HOLE SURFACE FINISH (PROFILOMETER)

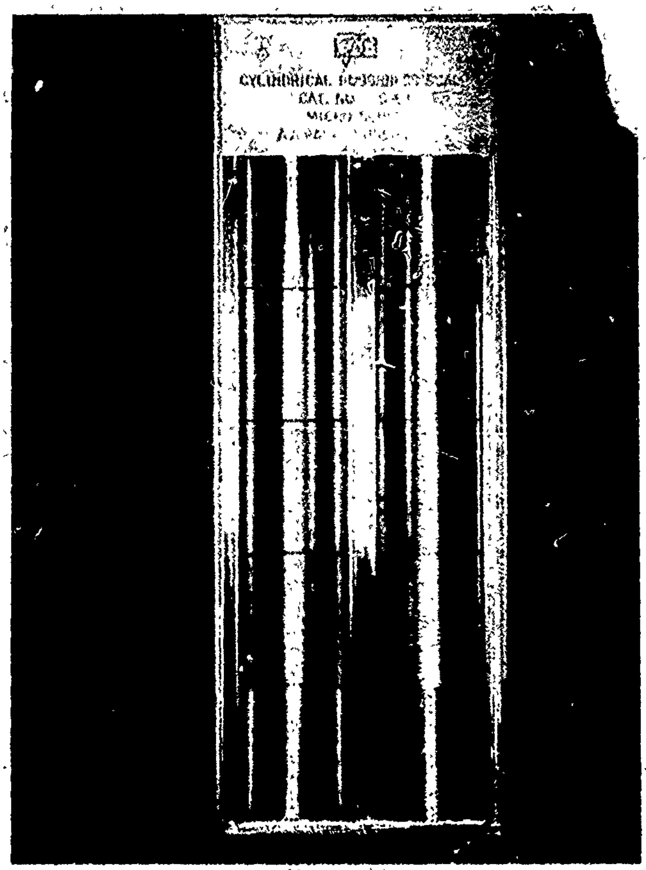


FIGURE 9 - THE GAR "MICROFINISH COMPARATOR"

VIII. SURFACE TEXTURE

Surface texture specifications generally state that "the finished hole shall be free of rifling, scratches, chatter marks, burrs, tears, laps cract, etc.". Surface texture is thus addressed as a workmanship item and must be inspected by comparison to a reference visual standard or by experienced inspectors. Such inspection requires direct visual or examination with or without an optical aid. Optical aids range from simple pocket magnifiers to costly rod and fiber optics devices. For this program, we chose a inexpensive, commercially available device known as "Sight Pipes." (13) One of these devices is shown schematically in Figure 10 .

A. "Sight-Pipes":

A "Sight-Pipe" was made of crystal clear acrylic plastic and uses both the optical and light transmission characteristics of this material. One end of the device was machined to a prism shape to enable sidewall viewing of hole in the same fashion as a periscope is used. The prism end is inserted into the hole and the image viewed through the enlarged head. A deep groove is machined around the head to supplement illumination if needed. The device was provided with a 3X magnifying head for aid in viewing.

One set of these devices was purchased to provide the correct size unit for each fastener size from 1/8 inch through 5/8 inch. The units were used in direct observation, in comparison of hole finish to the reference standard and by reference to photographic comparison standards as shown in Figure

A second set of "Sight-Pipes" were purchased to provide circumferential viewing of the hole wall along its length. The prism end of these units was replaced with a cone machined into the end of rod and enabled 360^{o} viewing of the sidewall imaged by the cone. These units were particularly effective in inspection for axial anomalies such as scratches.

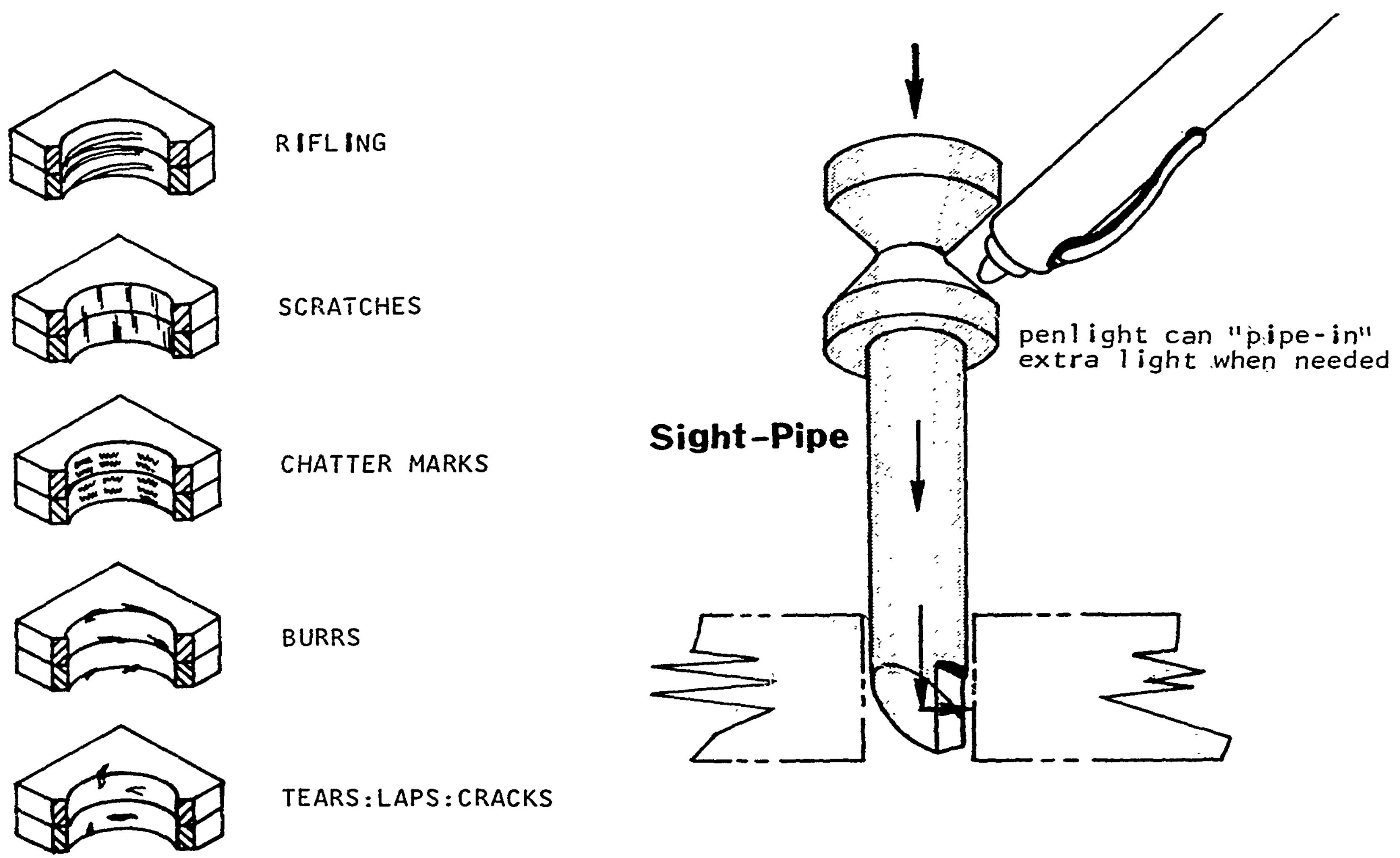
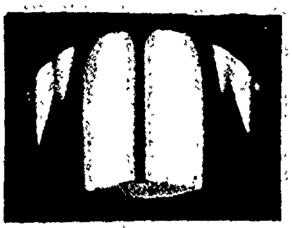


FIGURE 10 SIGHT PIPE EVALUATION OF SURFACE TEXTURE

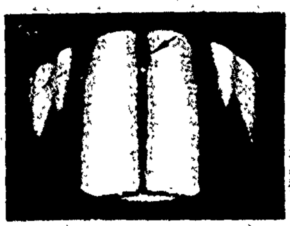
INSPECTION INSTRUCTIONS			NO. II-158
TITLE INSPECTION OF CRITICAL HOLES	REV	DATE 7-14-72	PAGE OF Appendix "A"

GROOVES — VISUAL INSPECTION



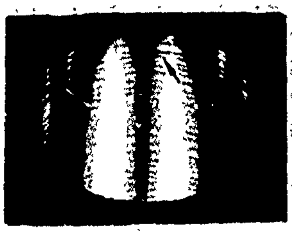
Hole free of circular grooves around circumference of hole. No visual defects.

Acceptable.



Intermittent circular grooves, none of which extend completely around circumference of hole. (Arrow)

Minimum Acceptable



Excessive circular grooves which extend completely around entire circumference of hole. (Arrows)

Unacceptable.

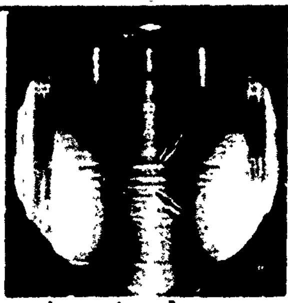
GROOVES — SIGHT PIPE INSPECTION

Hole free of circular grooves around circumference of hole. No visual defects.

Acceptable.

Intermittent circular grooves, none of which extend completely around circumference of hole. (Arrow)

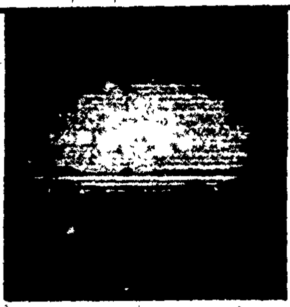
Minimum Acceptable



Excessive circular grooves which extend completely around entire circumference of hole. (Arrows)

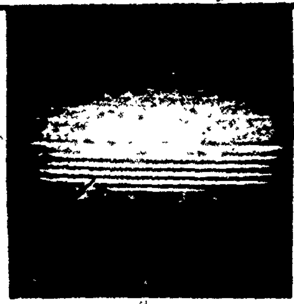
Unacceptable.

GROOVES — ROD OPTIC INSPECTION - 5X MAGNIFICATION



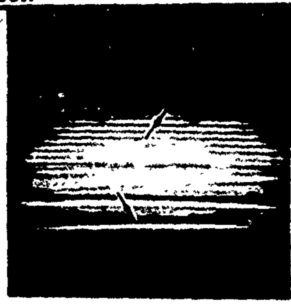
Normal machining marks (drill marks) as seen at 5X magnification. NOTE: Uniform characteristics throughout entire circumference of hole.

Acceptable.



Normal machining marks (drill marks) as seen at 5X magnification. NOTE: Uniform characteristics of hole broken by slight circular groove. (Arrow)

Minimum Acceptable



Excessive circular grooves which extend completely around entire circumference of hole. (Arrows)

Unacceptable.

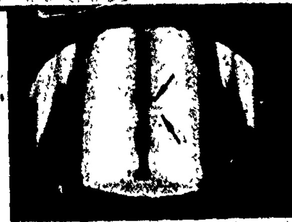
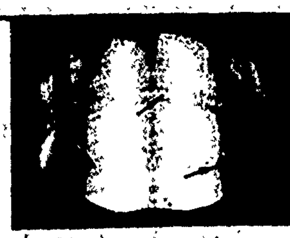
FIGURE 11-1 - VISUAL REFERENCE STANDARDS FOR SURFACE TEXTURE EVALUATION

INSPECTION INSTRUCTIONS

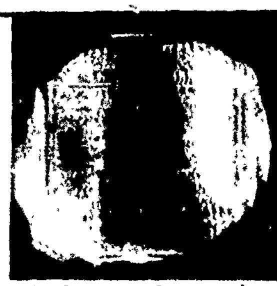
TITLE	REV	DATE	PAGE OF	NO.
INSPECTION OF CRITICAL HOLES		7-14-72	Appendix "B"	II-158

CHATTER

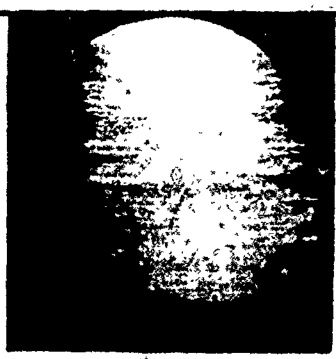
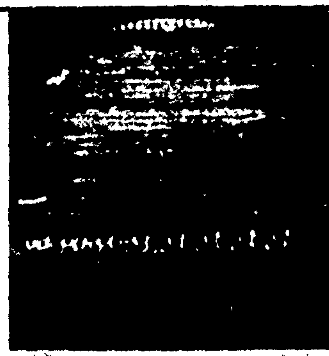
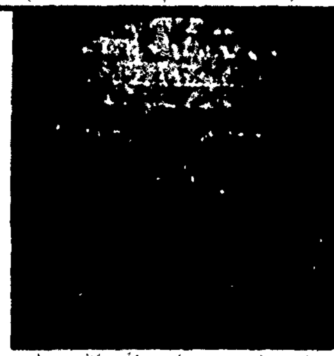
VISUAL INSPECTION

		
Hole free of visual defects. No evidence of surface imperfections. Acceptable	Photo shows slight chatter marks (arrows) which do not penetrate the root of the machining grooves. Minimum Acceptable	Photo shows excessive chatter marks (arrows) which are visible to the unaided eye. Unacceptable

SIGHT PIPE INSPECTION

		
Same hole as above except view shown is of side wall of hole as viewed with a sight pipe. Acceptable	Same hole as above when viewed with a sight pipe. Minimum Acceptable	Same hole as above when viewed with a sight pipe. Unacceptable

ROD OPTIC INSPECTION - 5X MAGNIFICATION

		
This photo shows same hole as above except side wall is magnified at 5X. Slight surface imperfections as shown shall not be cause for rejection. Acceptable	Photo shows same hole as above except side wall is magnified at 5X. Minimum Acceptable	Photo shows same hole as above except side wall is magnified at 5X. Note: The chatter marks penetrate the root of the machining grooves. Unacceptable

CHATTER

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FIGURE 11-2 - VISUAL REFERENCE STANDARDS FOR SURFACE TEXTURE EVALUATION

INSPECTION INSTRUCTIONS				NO. II-158
TITLE INSPECTION OF CRITICAL HOLES	REV	DATE 7-14-72	PAGE OF Appendix "C"	

SCRATCHES

VISUAL INSPECTION

Hole free of visual defects. No evidence of surface imperfections.

Acceptable

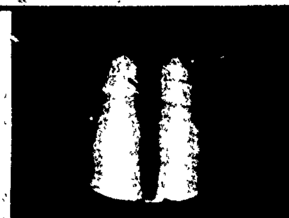


Photo shows slight surface scratches (arrows) caused during reamer extraction. NOTE: Scratches do not penetrate the root of the machining grooves.

Minimum Acceptable

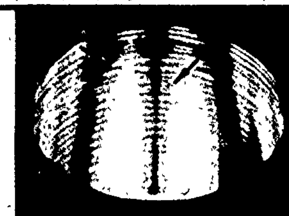


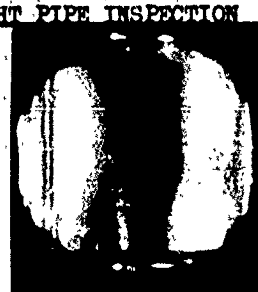
Photo shows excessive scratches (arrows) which are visible to the unaided eye.

Unacceptable

SIGHT PIPE INSPECTION

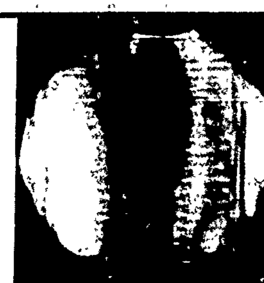
Same hole as above except view shown is of side wall section as viewed with a sight pipe.

Acceptable



Same hole as above when viewed with a sight pipe.

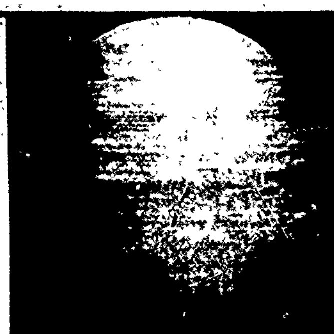
Minimum Acceptable



Same hole as above when viewed with a sight pipe.

Unacceptable

ROD OPTIC INSPECTION - 5X MAGNIFICATION



This photo shows same hole as above except side wall is magnified at 5X. Slight surface imperfections as shown shall not be cause for rejection.

Acceptable

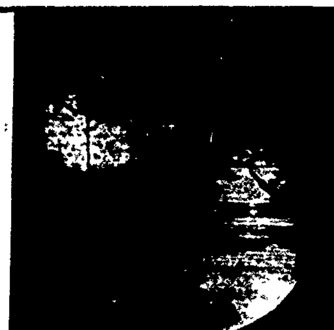


Photo shows same hole as above except side wall is magnified at 5X. NOTE: Surface scratches (arrows) which are seen at this magnification.

Minimum Acceptable

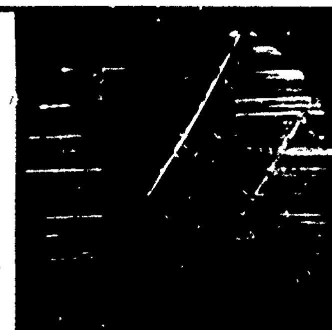


Photo shows same hole as above except side wall is magnified at 5X. NOTE: Excessive scratches (arrows) which penetrate the root of the machining grooves.

Unacceptable

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SCRATCHES

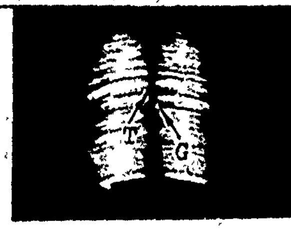
FIGURE 11-3 - VISUAL REFERENCE STANDARDS FOR SURFACE TEXTURE EVALUATION

INSPECTION INSTRUCTIONS

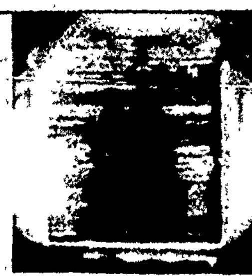
TITLE	REV	DATE	PAGE OF	NO.
INSPECTION OF CRITICAL HOLES		7-14-72	Appendix "D"	II-158

Galls-Tears

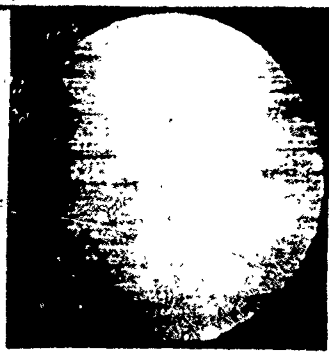
Visual Inspection

		
Hole free of visual defects. No evidence of surface imperfections.	None	Photo shows excessive galls and tears (arrows), which are visible to the unaided eye.
Acceptable	Minimum Acceptable	Unacceptable

Sight Pipe Inspection

		
Same hole as above except view shown is of side wall section as viewed with a sight pipe.	None	Same hole as above when viewed with a sight pipe.
Acceptable	Minimum Acceptable	Unacceptable

Rod Optic Inspection

		
This photo shows same hole as above except side wall is magnified at 5X. Slight surface imperfections as shown shall not be cause for rejection.	None	Photo shows same hole as above except side wall is magnified at 5X.
Acceptable	Minimum Acceptable	Unacceptable

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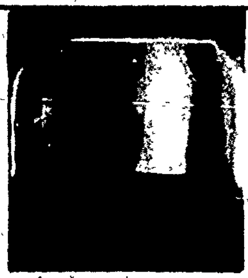
GALLS-TEARS

FIGURE 11-4 - VISUAL REFERENCE STANDARDS FOR SURFACE TEXTURE EVALUATION

INSPECTION INSTRUCTIONS				NO. II-158
TITLE INSPECTION OF CRITICAL HOLES	REV	DATE 7-14-72	PAGE OF Appendix "E"	

Exit Burr

Visual Inspection		
		
No evidence of burrs at hole exit. (arrow)	None	Photo shows burrs (arrow) at hole exit.
Acceptable	Minimum Acceptable	Unacceptable

Sight Pipe Inspection		
		
Same hole as above except view shown is of hole exit as seen with a sight pipe.	None	Photo shows excessive burrs (arrow) as seen with a sight pipe.
Acceptable	Minimum Acceptable	Unacceptable

Rod Optic Inspection		

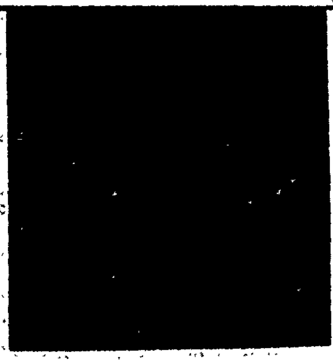



Photo shows same hole as above except edge is shown at 5X magnification.	None	Photo shows excessive burrs as seen at 5X magnification
Acceptable	Minimum Acceptable	Unacceptable

1061-A-8 NEW 7-71

EXIT BURR

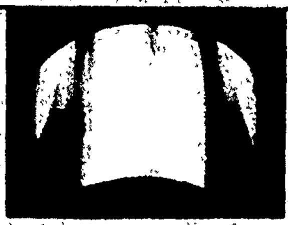
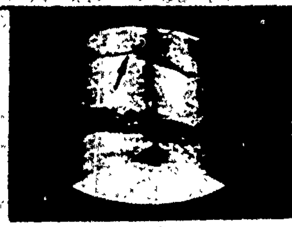
FIGURE 11-5 - VISUAL REFERENCE STANDARDS FOR SURFACE TEXTURE EVALUATION

INSPECTION INSTRUCTIONS

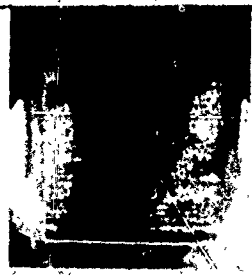
TITLE	REV.	DATE	PAGE OF	NO.
INSPECTION OF CRITICAL HOLES		7-14-72	Appendix "F"	II-158

RIFLING

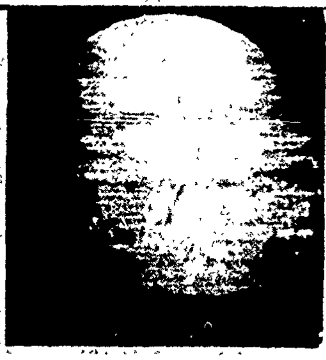
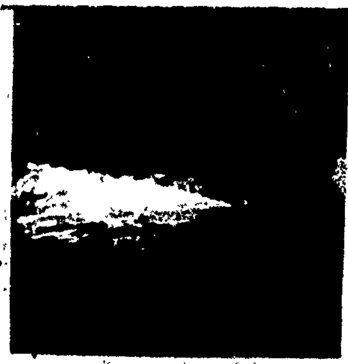
Visual Inspection

 Hole is free of visual defects. No evidence of surface imperfections. Acceptable	None Minimum Acceptable	 Photo shows excessive rifling (arrows) which are visible to the unaided eye. Unacceptable

Sight Pipe Inspection

 Same hole as above except view shown is of side wall section as viewed with a sight pipe. Acceptable	None Minimum Acceptable	 Same hole as above when viewed with a sight pipe. Unacceptable

Rod Optic Inspection

 This photo shows same hole as above except side wall is magnified at 5X. Slight surface imperfections as shown shall not be cause for rejection. Acceptable	None Minimum Acceptable	 Photo shows same hole ac above except side wall is magnified at 5X. Unacceptable

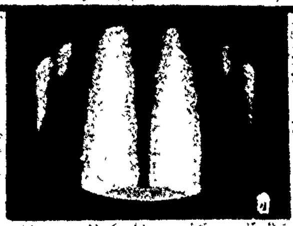
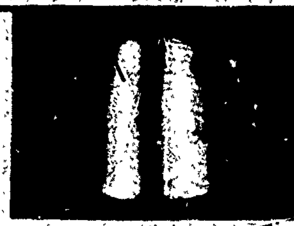
1061-A-8 NEW 7-71

RIFLING

FIGURE 11-6 - VISUAL REFERENCE STANDARDS FOR SURFACE TEXTURE EVALUATION

INSPECTION INSTRUCTIONS			NO. II-158
TITLE INSPECTION OF CRITICAL HOLES	REV	DATE 8-18-72	PAGE OF Appendix "G"

Entrance Chatter — Visual Inspection

		
No evidence of chatter at hole entrance.	Slight chatter (arrows) at hole entrance.	Excessive chatter (arrows) at hole entrance.
Acceptable	Minimum Acceptable	Unacceptable

Entrance Burr — Visual Inspection

		
No evidence of burrs at hole entrance.	None	Entrance of hole has excessive burr which must be removed prior to acceptance
Acceptable	Minimum Acceptable	Unacceptable

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ENTRANCE CHATTER
ENTRANCE BURR

FIGURE 11-7 - VISUAL REFERENCE STANDARDS FOR SURFACE TEXTURE EVALUATION

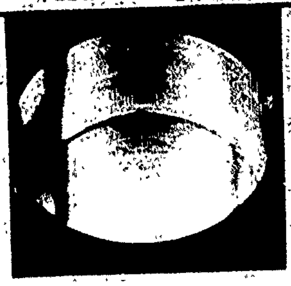
INSPECTION INSTRUCTIONS			NO. II-158
TITLE INSPECTION OF CRITICAL HOLES	REV	DATE 8/18/72	PAGE OF Appendix H

FAYING SURFACE BURRS

Visual Inspection

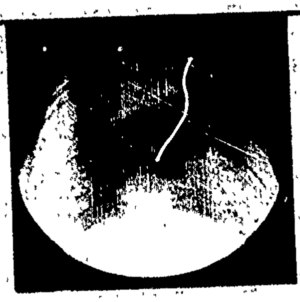
Smooth, straight line at faying surface edge with no evidence of loose burr.

Acceptable



Jagged line at faying surface edge with no evidence of loose burr extending into the hole.

Minimum Acceptable



Loose burr at faying surface edge which extends into the hole.

Unacceptable

Sight-Pipe Inspection

Photo shows same hole as above as seenwith a sight-pipe.

Acceptable

Photo shows same hole as above as seenwith a sight-pipe.

Minimum Acceptable

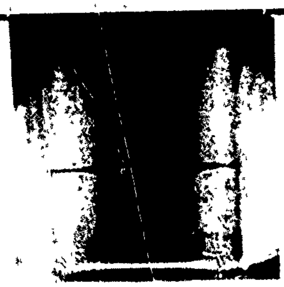
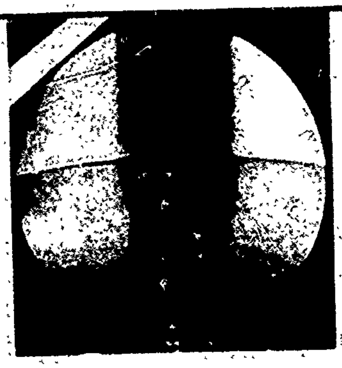


Photo shows same hole as above as seen with a sight-pipe.

Unacceptable

Rod Optic Inspection

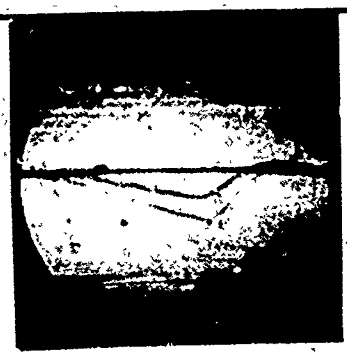


Same as above, except at 5X magnification.

Acceptable

Same as above, except at 5X magnification.

Minimum Acceptable



Same as above, except at 5X magnification.

Unacceptable

FAYING SURFACE BURRS

1061-A-8 NEW 7-71

FIGURE 11-8 - VISUAL REFERENCE STANDARDS FOR SURFACE TEXTURE EVALUATION

B. Replica Casts

Holes which exhibited particularly interesting anomalies were replicated to provide closer inspection and a record of the inspection for presentation to the host facility.

A commercially available silicone material was selected and used for replication [14]. The V-54 silicone resin and catalyst were mixed according to the manufacturers directions. This formulation yield cure in approximately two hours. The cure was accelerated for use on the production line using the following formulation.

15 cc (cubic centimeters) silicone resin
5 cc catalyst
2 drops stannous octate [15]

This formulation produced a cure in approximately 40 minutes (depending on local humidity condition). The replica was rapid enough for shadowgraph evaluation and good dimensional stability for several hours.

IX. INDUSTRY PRODUCTION LINE SURVEY

A. Approach and Philosophy:

Several industry practices and capability surveys have been completed using "round-robin" techniques. One option of this program was to provide materials to participating manufacturers and to have each drill a sample lot of holes by each method used in their respective production operations. Variations in the priority of the project, the equipment availability and the capability of personnel assigned make this sampling method non-representative of actual production practices and non-reproducible in subsequent analyses. Prospective participants expressed dissatisfaction with this method and objected to such sampling as a method of ranking specific facility production capabilities. On-site, production line evaluation by an experienced team was determined to be the most acceptable approach to participants and the most meaningful to the program objective. Since the objective was to sample and evaluate current industry production capabilities and not to rank facility capabilities it was necessary to make data collected as objective as possible and to eliminate possibility of using data collected for any alternate purpose. The following criteria was established and applied to facilitate participation by various facilities:

1. Experienced personnel would be used for all surveys.

2. A specific plan would be followed in conducting all surveys.

3. The survey team would require little support during the survey. All equipment supplies, etc., would be carried by the team.

4. Minimum disruption of the production line would be experienced.

5. The survey would be completed in a five (5) day work week period. Option was provided for second or third shift operation if desired.

6. The survey method would be "validated" prior to application in any facility.

7. Management and supervisor briefings would be held on the day of arrival prior to initiating the survey and on the day of departure to highlight results of observations during the week.

8. Data collected would be analyzed in detail and an audit report of data collected and data analysis would be provided to participants for review and validation of production details.

9. Following validation, all data was entered into a data bank and was coded with respect to the production method. All identification to the source facility was removed.

10. The cost of "escort" services for the team during the on-site survey could be paid.

Our initial contract required survey of five (5) manufacturing facilities.

B. <u>Solicitation of Participants:</u>

1. Initial Solicitation

Initial solicitation of participants was made during the proposal phase of this program. Contacts were primarily thus identified through our work in the Aerospace Industries Association (AIA). The initial letter of solicitation is included in Volume II of this report. We gratefully received tacit agreement for participation from five independent facilities during the proposal.

2. Industry Survey

Solicitation of participants was again made in our written industry survey.

3. Additional Paricipants

Contacts for additional participation were identified by Air Force Materials Laboratory personnel and by "word of mouth" communication between personnel within the industry. Verbal identification was particularly gratifying as a note of acceptance of our survey methods and the value received by participants.

C. Validation of the Survey Procedure:

1. In-House

After all equipment/supplies, etc., had been received and characterized, we moved to our own production floor to "shake down" procedures, methods, etc., and to establish basic timing. As a result, a survey "kit" was assembled for off-site evaluation.

2. Off-Site Validation

To test and validate our survey procedures, we packed up the "kit", traveled to our Baltimore facility and performed "on-line" inspections and to perfect our timing. During this exercise we identified:

a. A need to reduce the number of shipping containers;

b. The need for a portable work-stand;

c. The need for critical accessory items such as a hand tool kit, extension cord; and additional gages;

d. Changes in the calculator programs to enable deletion of erroneous data entries and random entry into a data file to add hole measurements for a given method at more than one location.

D. Survey Kit:

The tight time schedule for our surveys necessitated efficiency in operation and a compact kit. The kit was streamlined to two packing containers, one tool box and a briefcase for airline shipment. The calculator and electronic measuring unit were hand carried on the plane. One of the packing containers was equipped with flip-out casters such that all equipment could be handled by one man.

A unique, portable workstand was designed into the mobile packing container. This unit carried all equipment between inspection sites within a facility. This unit is shown in Figure 12 in both its stowed and assembled configurations.

Individual cases were provided for small items including the hand tool set, the air gage positioning tool, the "Sight-Pipes" the ball gages, alignment gage plugs, etc., for efficiency in assembly. Our efficiency was taxed on the first survey trip when the work stand container was "lost" by the airline and did not arrive until after noon on the following day.

The kit and survey format were proven on the first survey. A survey could be accomplished by two team members in five extended working days. Data could be collected and recorded for 300 holes representing ten distinct production operations. A quick data analysis could be performed in the evening to verify all data taken during the day. Data analysis and observations could be summarized for a meaningful debriefing before leaving a facility.

E. Formal Facility Solicitation:

The letter and data collection plan shown on the following pages provided a basis for understanding the task and the required commitments. Follow-up by telephone to the responsible individual was made to complete final arrangements.

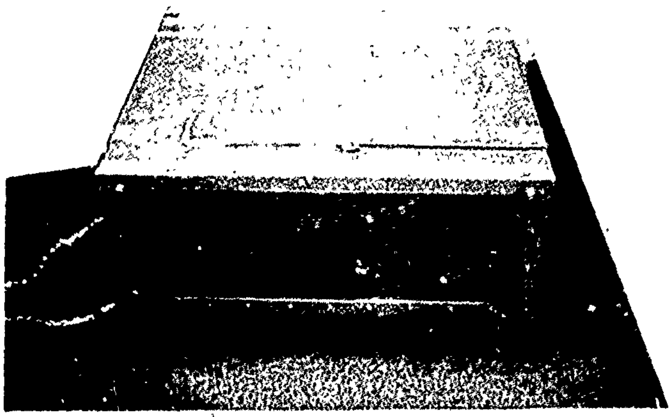


FIGURE a - PORTABLE WORK STAND IN ITS STOWED, SHIPPING CONFIGURATION

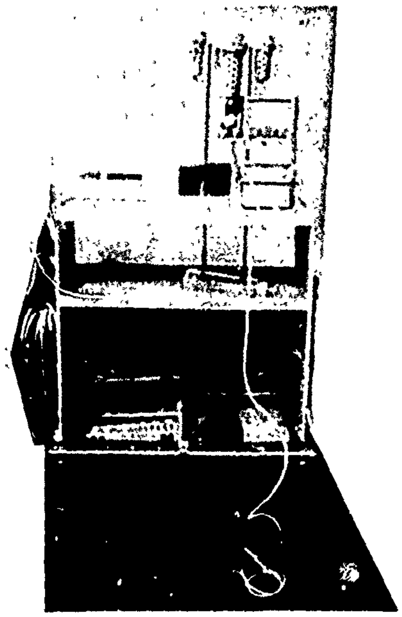


FIGURE b - PORTABLE WORK STAND IN ITS ASSEMBLED CONFIGURATION

FIGURE 12 - THE PORTABLE WORKSTAND USED IN FACILITY SURVEYS

MARTIN MARIETTA AEROSPACE

DENVER DIVISION
POST OFFICE BOX 179
DENVER, COLORADO 80201
TELEPHONE(303)973-4403

DATE

REF. NO. 77-1000-54

Mr. Host
Host Facility
Anywhere, USA XXXXX

Dear Sir:

Martin Marietta Aerospace, Denver Division, is currently under contract to the Air Force Materials Laboratory, Wright-Patterson AFB, for characterization of typical production hole quality. The primary purpose is to study characteristics of variables in manufacturing and inspection techniques for "drilled" fastener holes in aircraft structures. Characteristics of drilled holes are being studied under a separate, concurrent contract to relate variables to hole (joint) durability. The expected output of these programs will be identification of critical characteristics and a relaxation of requirements on non-critical characteristics.

The objective of the Martin Marietta Aerospace program is to provide a baseline of the capabilities of current hole production processes as a function of production method. This objective will be met by survey of on-line production aircraft and by data acquisition and analysis as a function of production method. Several facilities are being surveyed to determine characteristics which are common to the production process and to determine characteristics which are unique to a production facility.

The characterization and data collection task offers a unique opportunity for participating aircraft manufacturing facilities to assess the capabilities of their own production operations. Data collected will be as quantitative as possible. Source for data collected will be confidential to the manufacturing facility. Data collected can be used to compare capabilities of in-house operations to overall industry capabilities.

As a major producer of aircraft systems, we invite you to participate in this program. We have designed the program to meet the Air Force Materials Laboratories objectives and to provide maximum benefit to your facility. Copies of all data collected at your facility will be provided to you. We will include specific data in our data bank but will not identify any data with your facility without your specific written request. Data source identification will not be provided to the Air Force Materials Laboratory.

Data collected may not be identified to this contract by your company unless specifically approved by Martin Marietta Aerospace. In short, this is a study of production processes and every effort will be made to avoid identification of data with facilities. Our mission is in data collection analysis and reporting. Judgement of adequacy of operations for your particular products can best be made by your. We will provide objective data to your for your use in assessing process adequacy and/or in verifying confidence in your on-line operations.

In the course of data collection, Martin Marietta will require access to documents (processes, plans, etc.) by which hole production is described and controlled. Such documents will be considered confidential to your facility and will be used only for the specific purposes of data collection. Documents supplied will be returned or destroyed on completion of this program. Documents supplied will be reviewed in a limited access work area and will be protected in bonded storage facilities while at our plant.

<u>Details of the Survey</u>

1. <u>General</u> - Martin Marietta Aerospace is conducting the survey program under contract to the Air Force Systems Command, Aeronautical Systems Division. Contract F 33615-76-R-5443 dated 15, March 1977. Several surveys have been completed to date. The success and efficiency of our data collection has enabled us to add additional facilities and to extend this invitation to you.

2. <u>Objectives</u> - The objectives of this study is to characterize the variables in current production of drilled fastener holes in primary aircraft structures, and to evaluate the effectiveness of quality assurance methods applied to this production.

3. Participating Manufacturers Support - Support by participating manufacturers is required as described in the following:

a. Prior to visit Martin Marietta, personnel will become familiar with the processes used at the facility to be surveyed. This familiarization is designed to save time and minimize orientation during the survey. To accomplish this task, participants are requested to:

(1) Drawings
(2) Drawing/Design Practices/Procedures
(3) Process Specifications including personnel skill level and training
(4) Tooling Specifications/Practices/Coolants, etc.
(5) Manufacturing Planning
(6) Acceptance Criteria
(7) Quality Assurance Methods
(8) Requirements for inspection
(9) Inspection methods including personnel skill level and training
(10) Inspection Procedures
(11) Documentation providing historical basis and/or reports supporting the above

Actual documents which describe and control processing functions vary with facility and will be selected by the participant.

b. Industry Survey Questionaire - "Host Facility" operations has completed this questionaire.

c. On-Site Survey - On site survey will be scheduled by Mr. Ward D. Rummel and designated "Host Facility" personnel prior to arrival. Upon arrival, the following general support will be required by our survey team:

1) Authorization for entry of three Martin Marietta representatives with measurement/recording equipment to include one camera. Permission from your representative will be obtained for each film exposure before photographs are taken. The visit is anticipated to be completed in five working days, or less and if required, will be accomplished on a non-intereference basis to include second and third shift operations.

2) Authorization to observe hole drilling on the production line. Straight holes, in aluminum, in the 3/16 to 5/8 inch diameter range, in primary structure are the basis for survey.

3) Authorization to observe hole inspection operations on the production line.

4) Authorization and access to re-inspect production holes on the production line and collect actual hole characteristics data according to the attached plan. If inspection sampling is used as a basis for inspection, holes to be reinspected by the survey team need not be previously inspected. Normal production practices shall be used to assure that the survey sample is representative of the process as it is normally applied in the facility.

5) Facility Services - All inspection equipment will be provided by the inspection team. The host facility must supply 115 VAC, 20 Ampere electrical power and clean, dry shop air available at the inspection site.

6) Consultation - We recognize the support of the production operation that is provided and which varies with each production facility. We must include all factors which contribute to staging, performance and accepting output of the hole production processes in order to be accurate in our analyses. We therefore will request discussion and data from support groups as related to the specific production processes sampled. Consultation typically includes:

   a) Tooling

   b) Manufacturing engineering

   c) Quality

   d) Design engineering/liaison engineering

   e) Cost Management

   We fully recognize the necessity for strict confidence with respect to cost data and therefore desire to include only that data which will enable comparison of processes within your facility and within industry. Costs should be industrial engineering standards where possible and should include both direct and indirect resources specific to the production process. Typical analysis would include:

1. Average direct labor requirement and sill levels required for hole production.

2. Direct materials types and quantities including tooling and facilities.

3. Indirect labor support can reasonably be allocated to or identified with the hole production effort.

4. Indirect materials types and quantities including tooling and facilities.

Cost data shall be considered to be strictly confidential and will be used only to identify the upper and lower range of requirements as a function of production process.

4. Data Collection Schedule - A typical schedule of actions by our survey team while at your facility would be:

a. Monday - A.M., Briefing of your management on program objectives and procedures.

- P.M., Walk through your production area to select candidate processes and hardware.

b. Tuesday, Wednesday, Thursday - Data collection on your production floors.

c. Friday - A.M., Consultation with tooling, engineering, cost and personnel.

- P.M., Consultation with tooling, engineering, cost and personnel.

d. Approximately three weeks after our survey, you will receive an audit report containing our analysis of data collected while in your facility. We ask your concurrence and/or correction of items relevant to the data collected and our analyses. Upon your concurrence, source identification will be removed and the data entered into our permanent data file.

5. <u>Data Control</u> -

   a. Raw data collected at your facility is stored on magnetic tape or on Polaroid film for use in our analysis.

   b. Documents related to the process (by data lot) are identified and filed.

   c. All tapes, film and document files are stored in locked and secured cabinets at our facility. Only Project 1000 personnel have access to these cabinets.

   d. Verified data entered into the permanent file will be combined with data from other sources to enable analysis by process. Analysis of variance will be performed prior to combining data sets to determine similarity.

6. <u>Reporting</u> -

   a. You will be kept informed of program results and will be invited to a briefing at AFML prior to release of a final report.

   b. You will receive a copy of the final report.

7. <u>Expenses</u> -

We recognize that your participation in the survey will involve some direct expense for escort and support services. Reimbursable daily expenses will be agreed on between your authorized representative and Mr. Rummel, the Martin Marietta program manager prior to survey.

Approved support services are not formally recognized or subject to the same regulations as subcontract efforts and may therefore be handled at Martin Marietta by expense vouchers and can be paid promptly.

Upon completion of our survey, it is desirable to submit your expense invoice directly to Mr. Rummel for his approval and submittal to the Martin Marietta finance organization. Submittal after our visit may be made directly to Mr. Rummel or to:

Martin Marietta Corporation
P. O. Box 179
Denver, Colorado 80201

ATTENTION: Mr. W. Rummel, Mail No. 0629

REFERENCE: Project 1000

We invite and urge your participation in this most important program. Thank you for your consideration and cooperation.

Sincerely,

Ward D. Rummel

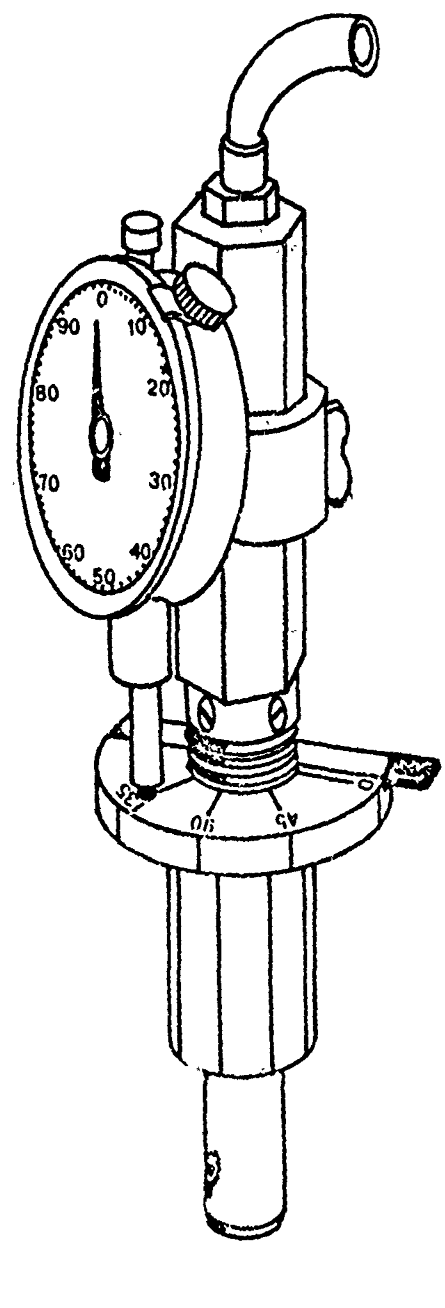
Ward D. Rummel
Program Manager
Project 1000

Martin Marietta Aerospace
Denver, Colorado Division

ATTACHMENT: Data Collection Plan

PROJECT 1000

Data Collection and Analysis Plan



DATA COLLECTION AND ANALYSIS PLAN

Martin Marietta Aerospace Data Collection and Analysis Plan is designed to provide a detailed examination of hole characteristics for purposes of the Project 1000 Program and for individual plant analysis.

1. Industry Survey - Prior to entering your facility, we have reviewed your general practices for hole production and control by your response to our industry survey.

2. Production Processes Review - Prior to entering your facility, we have received and reviewed documents specific to your production operations.

3. Hole Production Observation - On your production line, we will observe actual hole drilling operations. We desire observation for all hole

4. Hole Inspection Observation - On your production line, we will observe actual hole inspection operations and will document acceptance status on each sample lot observed.

5. Characterization of Holes - On your production line, we will inspect and characterize actual holes and document observations. For purposes of this survey we have selected the following:

   a. Dimensional Characteristics - Air Gaging with features shown in Table 1. A schematic view of the system is shown in Figure 1. A histogram output of measurements provided is shown in Figure 2. A duplicate copy of dimensions recorded and the histogram output (on paper tape) will be provided to you.

   b. Surface Finish - Profilometer, Gould Model 7100. This unit features a 1/2 mil spherical diamond stylus, a 1/8 inch stroke and an 800g load. Fixturing is provided to enable measurement of holes over the entire 3/16 to 5/8 inch range. The unit is shown schematically in Figure 3. Readings from the unit will be input to the programmable data collect system and printed on the paper tape. A duplicate copy will be provided to you.

c. Hole Perpendicularity - Will be determined by a mechanical test tool which provides verification to within 0.5 degree.

d. Hole Surface Texture - Will be visually observed with the aid of a commercially available Plexiglas rod optics device. A typical unit is shown schematically in Figure 4. Conditions representative of the sample lot and conditions unique to a specific hole may be photographed. Exposures will be accounted for in your facility and duplicate copies of unique conditions will be provided to you after processing and analysis is complete.

e. Hole Surface Replication - Conditions representative of the sample lot and conditions unique to a specific hole will be replicated using a silicone rubber compound as designated by MIL-I-83387 (without magnetic particles). Specific request will be made prior to replicating any hole.

6. Hole Production Cost Review - After review of processes and observation of hole production, we will review cost elements specific to each production method with your designated representative. Cost review will include both direct and indirect factors and will include:

   a. Tool cost, maintenance and life.

   b. Process set-up.

   c. Process performance.

   d. Process verification and inspection.

   e. Rework and rework verification.

7. Survey Schedule - Martin Marietta will schedule and perform surveys to provide minimum impact at your facility. We will work on a non-interference basis and will perform inspections on second shift if necessary. We anticipate a maximum of five working days at your facility for all measurements and on-site reviews.

8. Data Use - Data collected from your facility will be tested for similarity and will be combined with data from other facilities performing similar processes. The primary goal of the program is to analyze data by process. No reference to data source is necessary. Analysis of characteristics by process is intended to provide an improved basis for selection and control of production processes to specific design requirements.

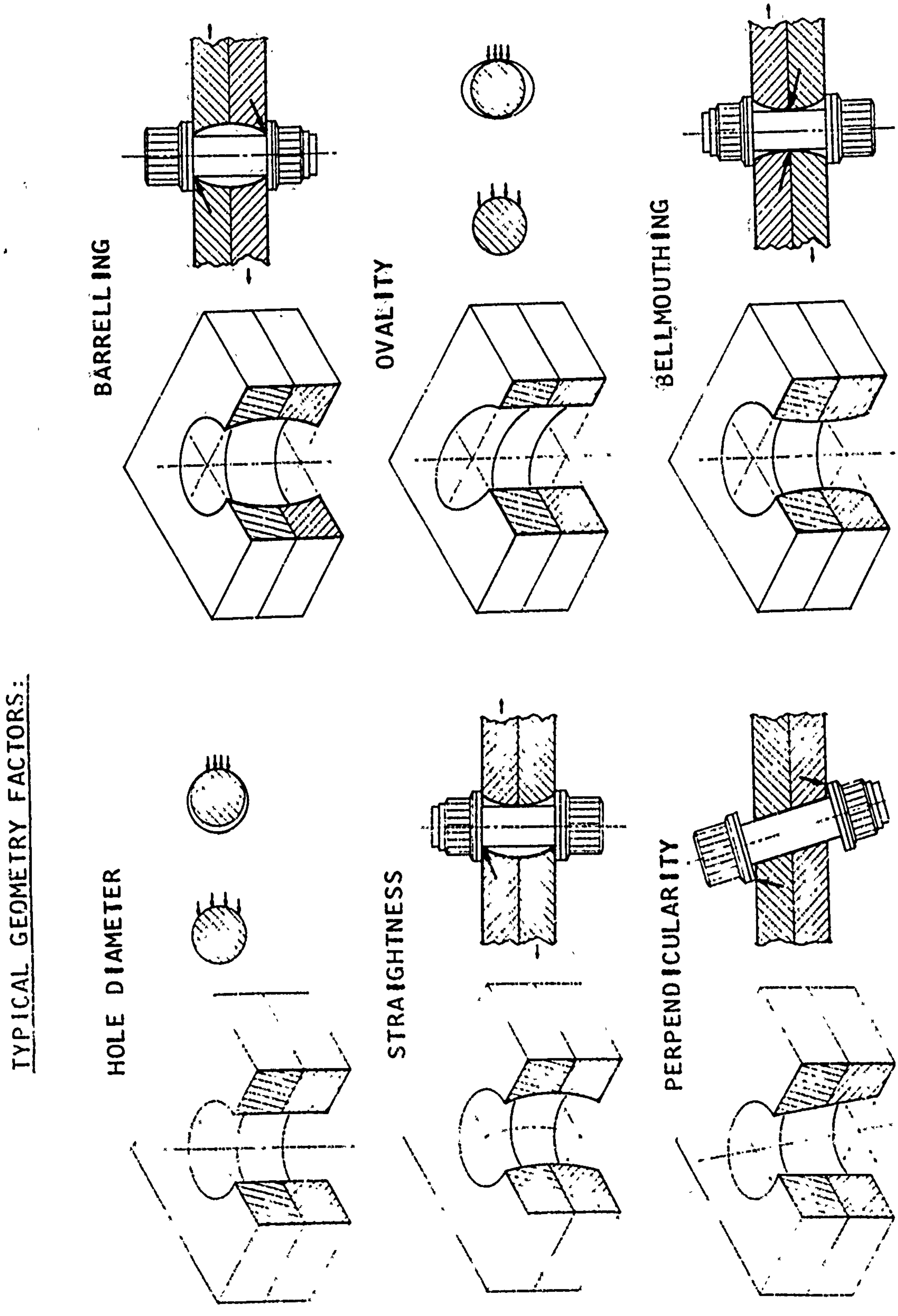
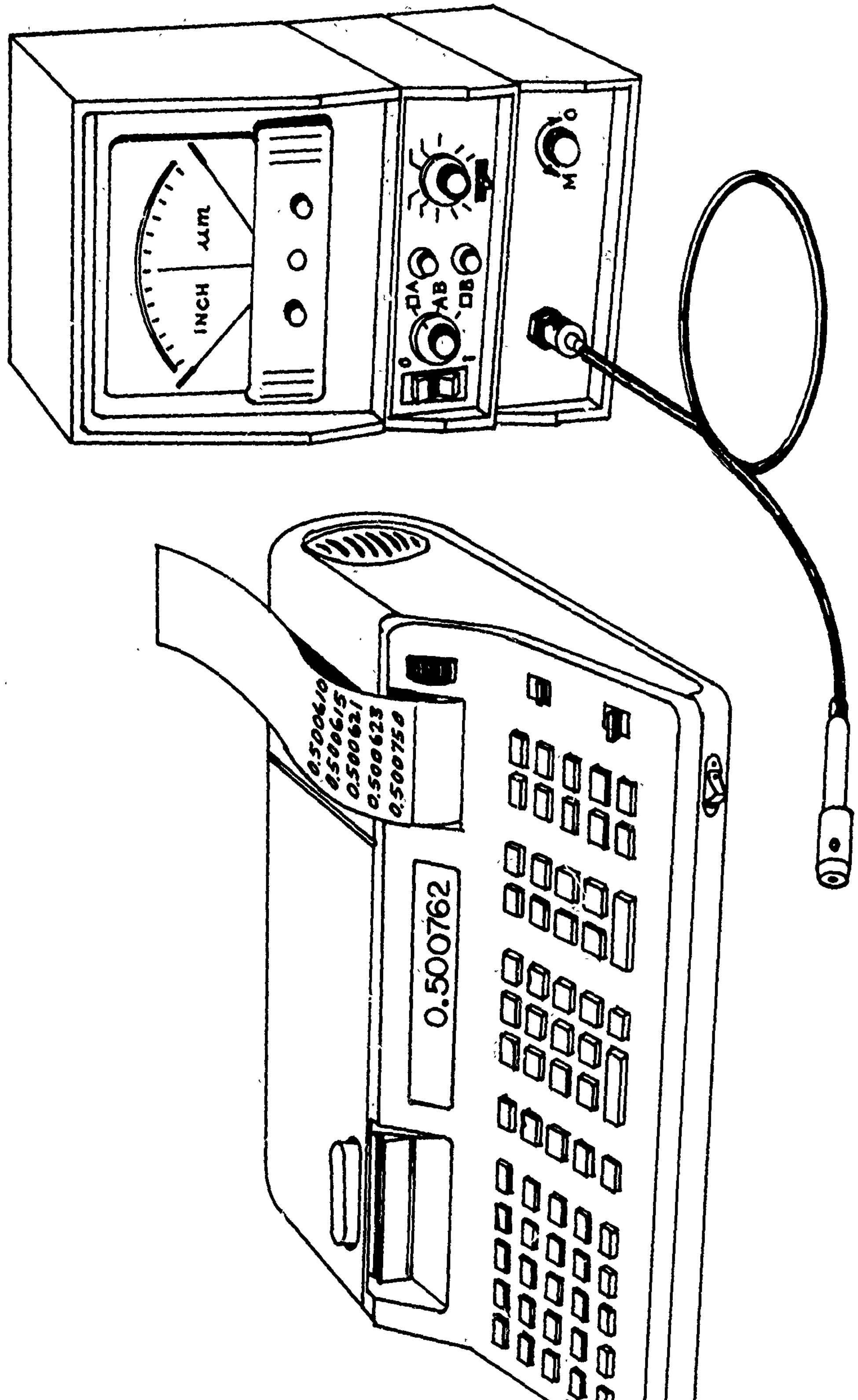


FIGURE 13 - TYPICAL GEOMETRY FACTORS



PROGRAMMABLE MEASURING SYSTEM

FIGURE 14 - PROGRAMMABLE MEASURING SYSTEM

```
HOLE NO.          1
= = = = = = = =
36  DATA ENTRIES
= = = = = = = =

HOLE SIZE*
  UPPER LIMIT=
    0.252000
  LOWER LIMIT=
    0.249000
= = = = = = = =

HIGHEST READING=
    0.252649
        ***
LOWEST READING=
    0.249422
        ***
MAX. OVERSIZE=
    ++++0.000649
        ***
MAX. UNDERSIZE=
    ----0.000000
= = = = = = = =

RANGE OF THE LOT
    0.003227
= = = = = = = =

ARITH. MEAN=
    0.250070
STD. DEV.=
    0.000785
STD. ERROR=
    0.000131
= = = = = = = =

MAX. OVAL. 0-90=
    0.002063
  AT LEVEL       9
        ***
MAX.OVAL 45-135=
    0.001276
  AT LEVEL       9
* * * * * * * *
```

PROGRAM OPERATIONS -
This sequence performs basic statistical analyses on the data, calculates the maximum ovality, and prints out the results of analyses.

TABLE V-1 - TYPICAL DATA OUTPUT FROM THE PROGRAMMABLE MEASURING SYSTEM

```
NOMINAL SIZE=
   0.250000
DESIGN TOLERANCE
 LOWER LIMIT=
   0.249000
 UPPER LIMIT=
   0.252000
* * * * * * * *
   0.249500
   0.249466
   0.249422
   0.249474
   0.249578
   0.249509
   0.249448
   0.249491
   0.249595
   0.249560
   0.249500
   0.249543
   0.249853
   0.249759
   0.249621
   0.249724
   0.249819
   0.249716
   0.249690
   0.249784
   0.250138
   0.249828
   0.249778
   0.250086
   0.250466
   0.249888
   0.250026
   0.250422
   0.251767
   0.250500
   0.250060
   0.251629
   0.252649++++
   0.250690
   0.250586
   0.251966
* * * * * * * *
  END OF DATA
      ***

= = = = = = = =
 36 DATA ENTRIES
= = = = = = = =
```

```
*.*.*.*.*.*.*.*.
PROJECT 1000
DATA ANALYSIS
FOR HOLE NO.    1

* * * * * * * *
DATE            99
DATA SOURCE    999
DATA LOT      9999
```

PROGRAM OPERATIONS -
This sequence prints identification information and actual data entries in the sequence acquired.

TABLE V-2 - TYPICAL DATA OUTPUT FROM THE PROGRAMMABLE MEASURING SYSTEM

```
HOLE NO.        1
* * * * * * * *
0  DEG. ALIGNMT
     0.249500
     0.249578
     0.249595
     0.249853
     0.249819
     0.250138
     0.250466
     0.251767
     0.252649

45 DEG. ALIGNMT
     0.249466
     0.249509
     0.249560
     0.249759
     0.249716
     0.249828
     0.249888
     0.250500
     0.250690

90 DEG. ALIGNMT
     0.249422
     0.249448
     0.249500
     0.249621
     0.249690
     0.249778
     0.250026
     0.250060
     0.250586

135 DEG. ALIGNMT
     0.249474
     0.249491
     0.249543
     0.249724
     0.249784
     0.250086
     0.250422
     0.251629
     0.251966
* * * * * * * *
      ***
```

PROGRAM OPERATIONS -
This sequence separates data into the respective azimuth orientation locations within the hole and prints data entries in the sequence acquired.

TABLE V-3 - TYPICAL DATA OUTPUT FROM THE PROGRAMMABLE MEASURING SYSTEM

```
HOLE NO.       1
* * * * * * * *
--HOLE PROFILE--
0 DEG. ALIGNMT
*              0
*              1
*              1
*              4
*              3
*              6
*X             0
*XX            3
*XXX           1

45 DEG. ALIGNMT
*
*
*
*00
*00
*000
*0000
*0000000000
*000000000000

90 DEG. ALIGNMT
*
*
*
*0
*00
*000
*000000
*000000
*00000000000

135 DEG. ALIGNMT
*              0
*              0
*              1
*              2
*              3
*              6
*              9
*XX            2
*XX            5
* * * * * * * *
```

PROGRAM OPERATIONS -

This sequence separates data into respective azimuth orientations, subtracts the lowest value entry in the list from the remaining entries and plots a histogram of the difference in values.

The result is a cross section profile of the hole at the respective azimuth orientations. Differences in entry values are plotted in 0.0001 inch increments as "0" characters or in 0.001 inch increments as "X" characters with the additional 0.0001 inch variations printed in the right hand column.

The histogram shown is typical of a tapered hole configuration.

TABLE V-4 - TYPICAL DATA OUTPUT FROM THE PROGRAMMABLE MEASURING SYSTEM

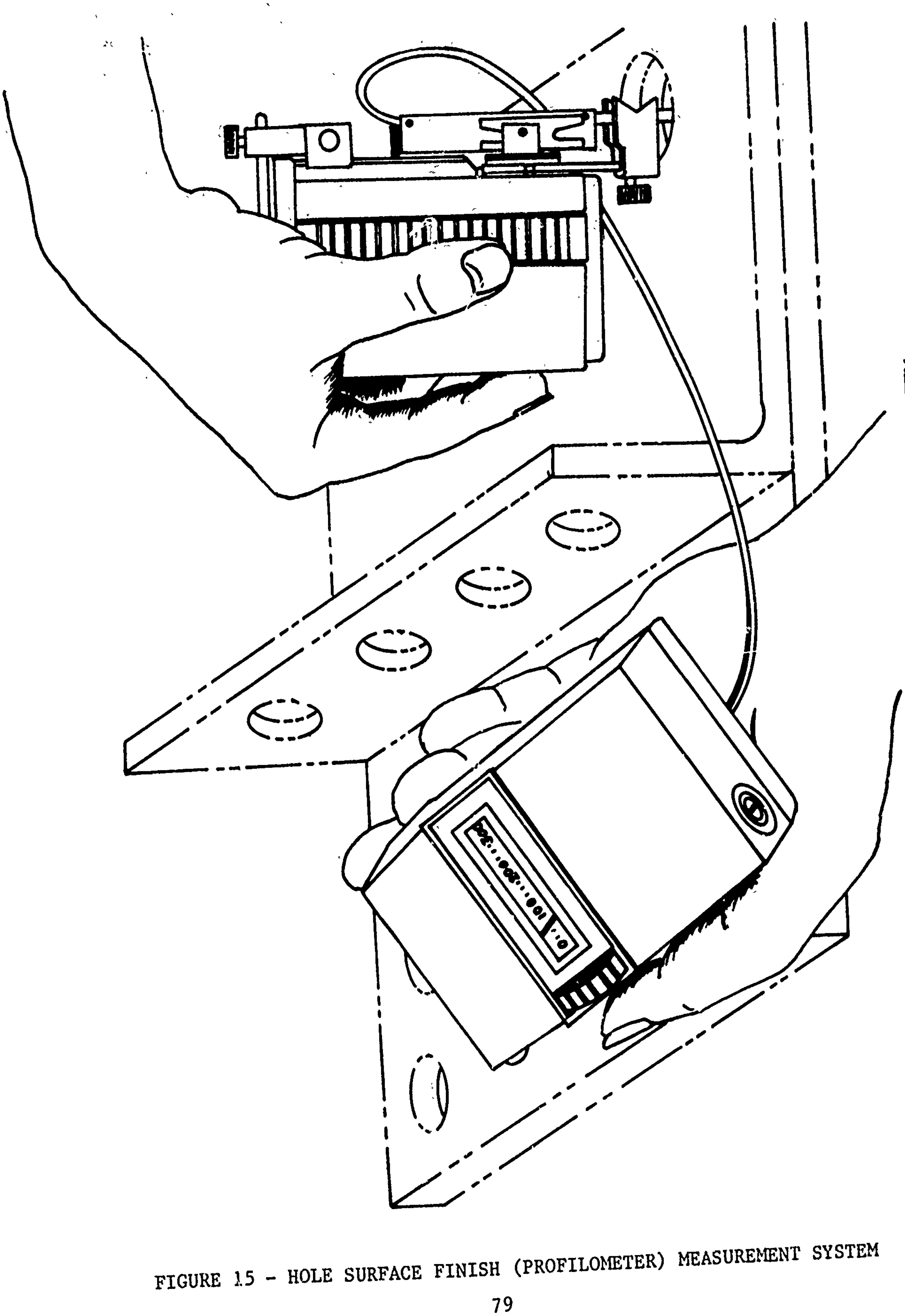
```
================
   HISTOGRAM
    OF DATA
  DISTRIBUTION
 FOR HOLE NO.  1

================

+
+
+
L.L.=VV=0.249000
+
+
+
+
+**
+********
+*****
+*****
+******
+*
O=VV=   0.250000
+*
+***
+
+
+*
+**
+*
+*
+
+
O=VV=   0.251000
+
+
+
+
+
+
+*
+
+*
+
+*
U.L.=**=0.252000
+
+*
+
  + = .0001 INCH
* * * * * * * *
```

PROGRAM OPERATIONS -
This sequence plots a histogram of data in 0.0001 inch increments. Each "*" symbol denotes a single data entry. An "0" symbol is used at the end of the line when the number of entries exceeds 15 at a single value.

TABLE V-5 - TYPICAL DATA OUTPUT FROM THE PROGRAMMABLE MEASURING SYSTEM



HOLE SURFACE FINISH (PROFILOMETER) MEASUREMENT SYSTEM

FIGURE 15 - HOLE SURFACE FINISH (PROFILOMETER) MEASUREMENT SYSTEM

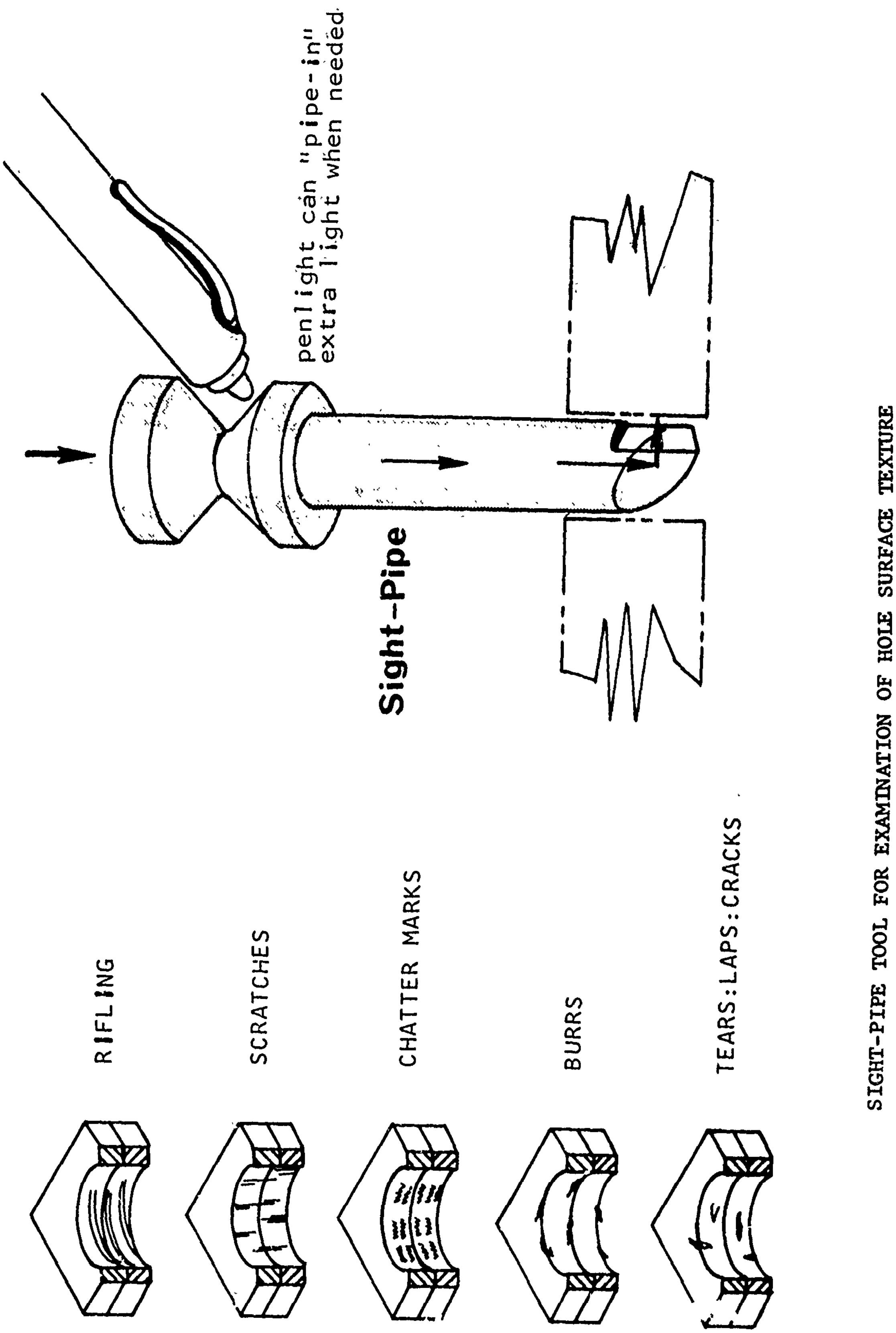


FIGURE 16 - SIGHT PIPES

X. HOLE PRODUCTION ANALYSIS

A. Overview:

Life-cycle cost management begins with design engineering of a structure and is carried through with tool design and application, production process development and application, inspection process development and application and in service maintenance. Production fastener holes are relatively inexpensive to produce but expensive to maintain. Additional resources and care during design and production could potentially result in considerable savings in maintenance and operating costs.

Improvement over present standards costs money. The lowest bid for production may not be the lowest cost bid. The problem is further complicated when differences in cost include recognized but intangible factors such as tool inspection, operator training, process audit and tool cleaning. After a facility is on contract, these same factors are favorite items for "cost reduction" and increased short-term return on investment.

Hole quality may also be impacted by:

1. Timing of resources available for rigid tooling.

2. Skill and craftsmanship of production personnel.

3. Competition of production resources with increasing imposed procedural, control, audit and social requirements.

4. Changes in configuration due to changes in criteria or model change.

Fastener hole production constitute a major element in the overall cost of hardware. Fastener holes are major elements in system reliability and life cycle cost. Timing and adequacy of resources for hole production has been and will continue to be a significant systems management challenge. The potential long term return merits attention to and perhaps changes in systems procurement and management philosophies.

B. <u>Hole Quality in Design:</u>

1. General

Engineering design requires assumption of physical behavior and boundary conditions for performance of complex structures. Fastener joint design assumptions may include:

a. Equal loading of all fasteners;

b. Uniform load distribution on a single fastener;

c. No bending load at the fastener;

d. No movement (slippage) of the joint;

e. No residual stress around the fastener, etc.

Such assumptions are verified by test and service performance and are translated into drawing tolerances and requirements, material requirements and process requirements by drawing notations.

Predictions of fastener joint performance by coupon test and by test of major structural members exhibit major uncertainties. A part of these uncertainties may be due to a failure to provide actual test data to support hole specification and tolerance requirements. Uncertainties in criteria based on part service performance may be due to differences in predicted or actual service requirements. Better design methods are required to predict actual service conditions, to predict actual structures behavior and to understand the impact (criticality) joint production processes and characteristics on structure behavior and service performance. The work reported herein aids understanding of production processes and characteristics of current production.

2. Hole Size and Tolerance

Hole size and tolerance are specified on virtually every aircraft structure drawing. Designation of tolerances for "close tolerance" or "critical" holes varies with design organization. Close tolerance specification may be imposed to meet requirements for interface and/or interchangeability or may be imposed by past practices and production experience. Production cost will increase when close tolerance is specified. The magnitude of the cost increase and real benefits from close tolerance specification will depend on the interpretation and execution of the requirements.

Close tolerance requirements specifications may result in:

a. Increase in inspection sampling;

b. Increase in inspection tasks, i.e., check for ovality, surface finish inspection or surface texture inspection;

c. Increase in process control tasks;

d. Change in the inspection and gaging methods; or

e. Change in the production process, tooling and inspection.

3. Hole Edge Distance and Spacing

Hole edge distance and spacing are designated by part dimensioning or drawing notes. Edge distance and spacing are controlled in production by rigid tooling or by locating templates. At two facilities, edge spacing variations of substructure (ribs, spars, etc.) was located during a pre-scan to determine exact position in space. Data was stored for computer control of the drill unit manipulated during actual drilling.

4. Hole Workmanship

Surface finish, surface texture, hole shape, etc., are most frequently noted on a drawings a workmanship item notes. Criteria is predominantly qualitative and performance to the established previous level is assumed.

5. Interface Requirements

Interface points, hinge points, etc., are specified by location and dimensioning and by drawing notes. Such points are normally controlled by hard (rigid) tooling and by increased drill process control.

6. Perpendicularity

Perpendicularity of holes is assumed or may be stated with tolerances up to $\pm 1^{\circ}$. No fatigue data has been identified to support the tolerance. General production practices and tooling are assumed to be sufficient to control perpendicularity.

7. Other Factors

Drawing specifications at some facilities provide for acceptance of a discrepant hole in a pattern if it is not adjacent to a second discrepant hole. Some drawings further limit the number of discrepant holes in a pattern. Standard repair/rework instructions are included in the drawing notes if the discrepancy "acceptance" criteria are not met. Repair usually involves reaming to accommodate the next larger fastener size.

8. Application

CONFORMANCE TO REAL AND/OR ASSUME CRITERIA IS SOLELY DEPENDENT ON THE TYPE, RELIABILITY AND CONTROL OF THE PROCESS USED IN PRODUCTION.

C. Hole Quality in Production

1. General

The legendary "perfect hole" is round, cylinderical, perpendicular and smooth. Factors which are known the support this goal include:

a. Stiffness in the structure/tooling.

b. Good clamp-up - must exceed drill bit pressure.

c. Sharp, properly ground tools which "machine" the hole.

d. Good chip removal.

e. Adequate material/tool cooling during the drilling/reaming operations.

f. Cleanliness of tools and of the production area.

g. De-Stack and De-Burr.

h. De-Stack.

i. De-Burr.

2. Process Selection

Selection of a drilling process is often based on experience and available tooling used on the previous production program for similar structure.

a. Interface points are generally drilled and reamed with rigid tooling and positive feed equipment.

b. Built-up structures are generally supported in rigid tooling and drilled by hand, tractor feed or lazy arm drill control methods.

c. Structures assembly are generally drilled by hand or by the "Spacematic" methods.

Cost of the initial tooling and recurring costs of multiple step operation greatly influence the process selection. The minimum process is selected to meet engineering criteria. More costly tooling and processes may be selected for operations which have been troublesome at a particular facility during past programs.

3. Tooling/Fixturing

a. Interchangeability

Tooling is critical to both hole characteristics and to the subsequent structures performance. Tooling provides precision in hole locations and is frequently imposed by interchangeability or interface requirements. Tooling also may provide for rigidity in the structure workpiece and for clamp-up during the drilling operation.

b. Clamp-Up

During the drilling process, the rigidity and clamp-up of the structure should be similar to that attained in a machineshop set-up. The clamp-up should exceed the drill point pressure such that the stack is dynamically equivalent to a solid block of material. The drill point grind changes drill point pressure, thus clamp-up requirements will vary with process, tool grind and tool wear. If clamp-up exceeds drill point pressure, a roll over burr will not be generated at a stack interface and de stack and de burr will not be generated at a stack interface and de stack and de burr operations will not be required.

c. <u>Rigidity</u>

Rigidity in the set-up is necessary to avoid structure movement during the drilling operation. movement during drilling may result in chatter and thus an undesirable hole texture condition; or may result in unpredictable hole shape characteristics. Surface texture variations produced by tool chatter are not readily apparent in visual inspection. Likewise, resultant hole shape variations are not necessarily detectable by normal production inspection methods.

d. <u>Other Characteristics</u>

In addition, to servicing the basic tooling function, the tool must provide for operator access and visibility, adequate chip clearance, adequate coolant flow etc. Tolerance build-up must be addressed by tool design of structures' pinning points and of drill location points. Tooling tolerances are normally one-half the production tolerances.

e. <u>Tool Acceptance and Maintenance</u>

After a tool is built, its integrity must be maintained by initial inspection, by periodic inspections and by verification of capability by detailed inspection of production articles. First article inspection is commonly used for verification. Such inspection must include not only those drawing characteristics normally verified during production acceptance of an article but also compatibility with master tool/interface tool pinning points and with contour requirements. A record of actual measurements is useful for comparison with duplicate tooling sets and for trend analysis of tooling changes during the life of the tool.

4. <u>Drill Equipment</u>

Selection, acceptance, usage, storage and maintenance of drilling equipment contribute to process reliability. Wide variability in drill equipment selection and handling was noted among facilities. Items of specific interest include:

a. Bearing run-out is normally not stated by equipment manufacturers. Bearing run-out is not routinely measured by users. Wobble control is assumed to be by the drill bushing.

b. Acceptance of new equipment and inventory equipment is made by functional test on test material or on production hardware.

c. Maintenance varies from extensive periodic maintenance to maintenance on demand after a series of discrepant holes are produced.

Some producers "kit" equipment and tools for critical drilling operations and perform extensive inspection and test after a predetermined series of holes are drilled. Positive feed drill units are given extra maintenance attention since work hardening of a structure may occur if feed varies due to loss of fluid pressure.

5. Drill Tools/Reamers

a. Procurement

A wide variety of drill types and grind configurations are in use. Variation is due to differing production philosophies, differences in materials and differences in hole depth. The majority of drills are purchased in standard, off the shelf configurations and may be inspected and/or reground before being issued. Vendor drawings may be incorporated into the process specifications.

b. Drill Tool Selection

Drill bit selection is based on the type of hole, type of materials, type of process and experience of manufacturing engineering personnel. Many combinations may be used to achieve the same end goal. Rationale and factors to be considered in the selection vary among facilities and are beyond the scope of this program. Qualification of the tool by demonstration in a process is required.

c. Tool Regrind

Requirements for tool regrind are determined primarily by the production operator. Regrind may be performed in-house or by an outside vendor. Location is based on cost and performance. Several choices for regrind equipment are available for in-house grind. Some facilities do total regrind in-house. The majority of facilities survey use the same regrind vendor.

6. Operator Training

Operator training varies significantly from total on-the-job training to extensive class room and laboratory training. Training required depends somewhat on the local and previous background of personnel and the type of operations to be performed.

7. Process Application

Process application tooling, equipment, drill tools, coolant, application parameters, etc., are described in written processes and are controlled by the production operator, by written procedure, by supervision and by inspection. The results vary among facilities and among operators within a facility. Rigid tooling and positive feed equipment is less influenced by operator variables and thus results in less variability in output.

8. Deburring

Deburring was the most variable part of hole production process observed between facilities and within facilities. Deburring tools varied from an over-sized drill to a pocket knife.

D. Inspection Quality in Hole Production

1. General

Inspection reliability can be as significant as process reliability in actual hardware performance. Indeed if the inspection is reliable and critical, economics will force process reliability. If inspection is critical, but not reliable, economics will force inspection reliability. If an inspection is not reliable but is not critical, it will have little effect on the process. The effectiveness of an inspection can be measured if:

a. Critical characteristics and acceptance criteria are identified;

b. If the inspection addresses the critical characteristics, and;

c. If confidence in the inspection method and application can be demonstrated.

Many inspection tasks are performed in industry to access workmanship factors. Characteristics measured may be accouterments to critical characteristics and may therefore serve as an undefined measure of process consistency. The concept that a "bad process" is recognized by the company it keeps has served well in providing consistency of performance to undefinable criteria.

Hole tolerance is the most frequently specified characteristic for assessment of hole quality. Some fatigue data relating fastener interference level to joint life has been generated. The impact of a specified tolerance in given structure is however, not known in the majority of analyses.

A part of the continuing use of tightened hole tolerances in qualitative identification of hole criticality has been in its interpretation by manufacturing engineering and by inspection engineering. The cost of rigid tooling and positive feed equipment can be easily justified for critical interface holes. Justification of such costs are more difficult for holes of lesser specified tolerances.

Inspection of "critical" close tolerance holes is generally interpreted as a requirement for an increased number of inspections to "assure" confidence. Increased sampling in turn, forces increased process control and hopefully, improved hole quality. The characteristic measured is not however, directly correlatable to structures performance.

In like manner, workmanship items such as surface finish, and texture are not directly correlatable to structures performance.

2. Hole Tolerance Measurement

a. The Plug Gage

The universal tool for hole tolerance measurement is the plug gage. A typical plug gage is shown in Figure 17 . Figure 18 shows typical application of a plug gage in hole assessment. Plug gage acceptance as a tool has been due to its ease in use, low cost and direct correlation to hole diameter.

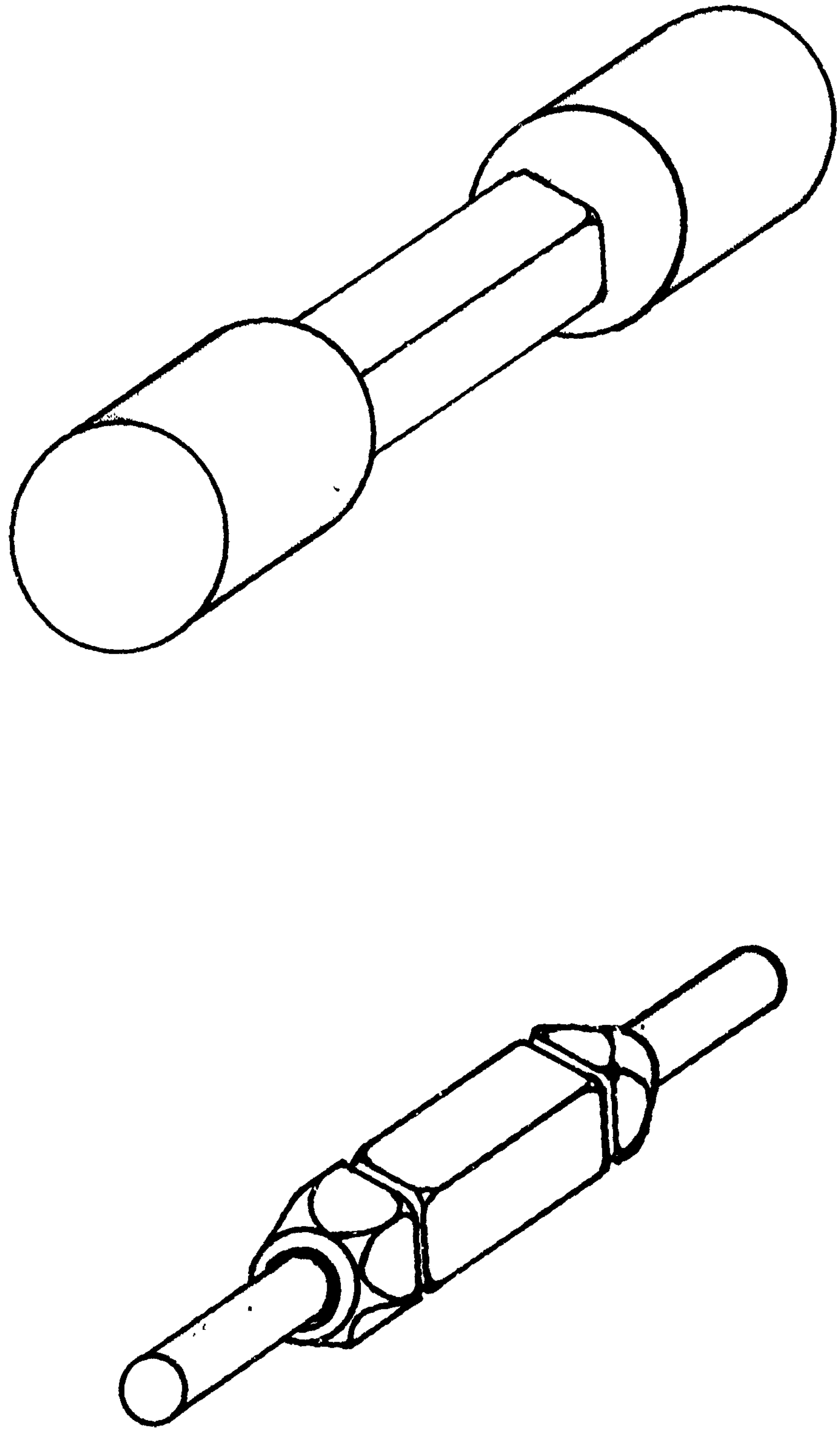


FIGURE-17 ical Plug Gage Configurations

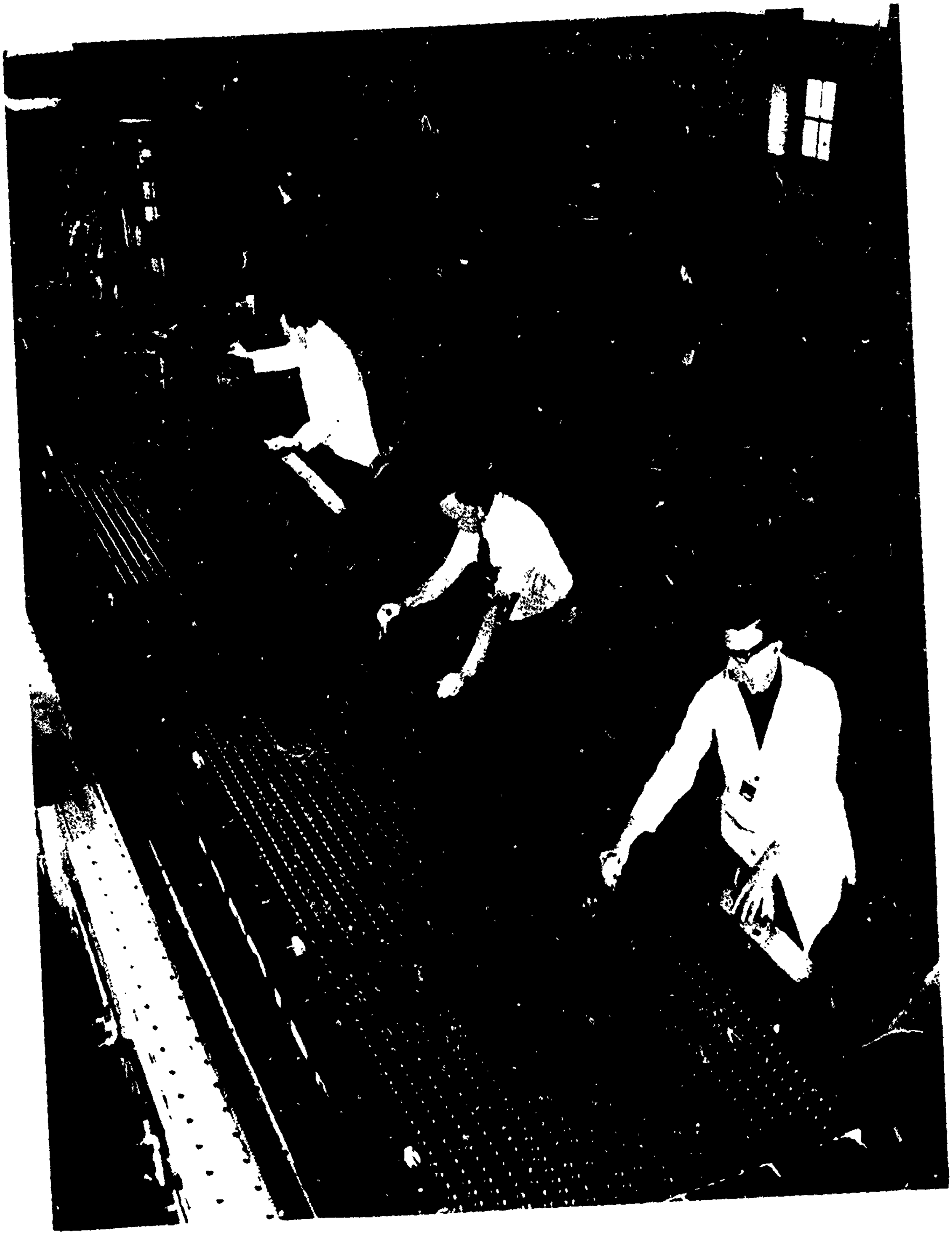


FIGURE 18 - TYPICAL PLUG GAGE INSPECTION

The gage is constructed so that the pin diameter is equal to the minimum or maximum hole diameter acceptable. The minimum diameter plug is inserted into the hole to provide an indicator that the hole diameter is above the minimum tolerance value (Go-Check). Insertion of the maximum diameter plug is attempted. If the plug cannot be inserted, the hole diameter is judged to be below the maximum tolerance value (No-Go-Check). The plug gage actually indicates that no part of a hole is smaller than a minimum diameter and that the entrance to a hole has some point which is smaller than the maximum tolerance value. A square hole may be acceptable using the plug gage method of acceptance.

b. Modified Plug Gage

Modified plug gages were used at some facilities to provide an assessment of the ovality of a hole. A typical configuration is shown in Figure 19 .

c. Ball Gage

Use of ball gages was observed infrequently on the production line. Primary use noted was as a referee and analysis method after a problem hole had been identified.

d. Air Gage

Infrequent use of air gaging was observed. The method was applied to critical intertace holes produced at specific work stations with rigid fixturing and positive feed equipment.

3. Hole Surface Finish Measurement

Specific hole surface finish values are specified on some drawings. Evaluation throughout industry was by visual comparison to a real or imagined reference standard. In no case was actual profilometry measurement observed.

4. Hole Texture

Hole texture, along with surface finish were assessed by visual inspection. In some cases, a flash light and a pocket magnifier were used as evaluation aids. Photographic reference standards were available at some locations for comparison.

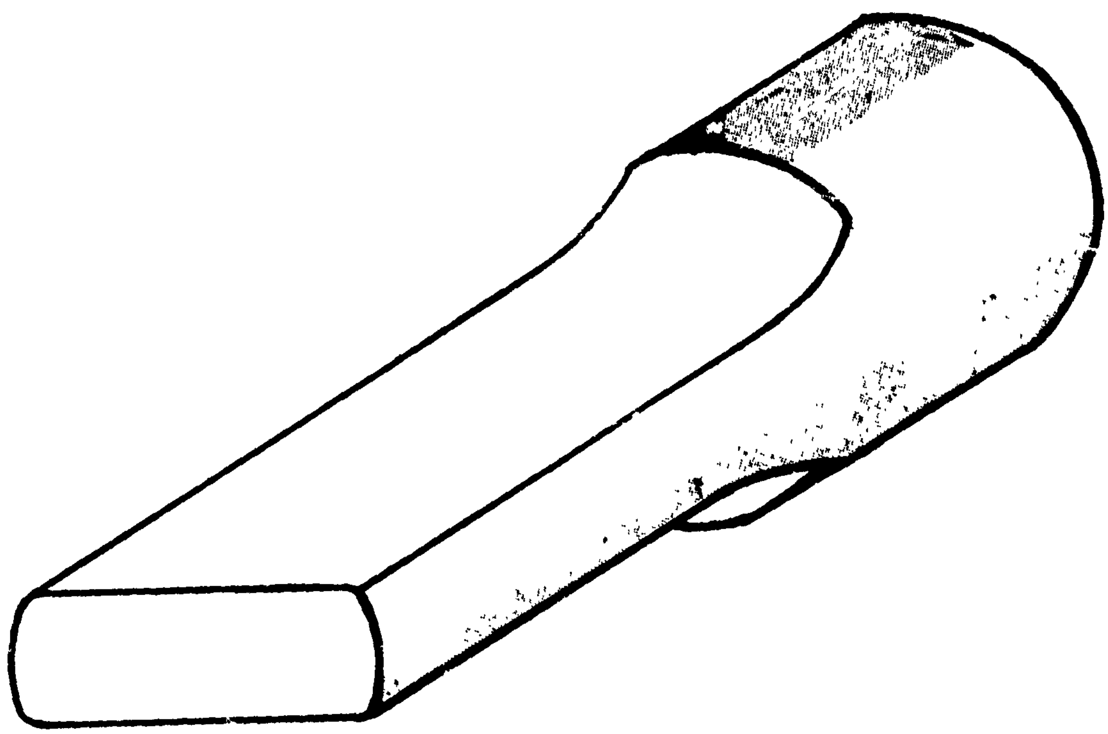


FIGURE - 19 Modified Plug Gage Used to Evaluate the Ovality of a Hole

5. Hole Alignment

Hole alignment is specified on some drawings but is rarely measured on the production line. The only method observed on the line was inspection under a fastener head with a feeler gage after fastener installation. This inspection was combined with assessment of fastener clamp-up.

6. Inspector Training

Inspector training is on the job at most facilities.

E. Production Cost and Hole Quality

The relationship of production cost to hole quality could not be directly assessed or quantified during this program. No direct relationship between cost and hole quality is judged to be meaningful. Such judgement is based on the fact that hole quality factors and life cycle prediction are in an infant state of development. Precise definition of hole quality, its impact on life-cycle performances and its cost of production are necessary before meaningful cost analysis can be considered. Indeed many of the problems in life cycle cost management can be attributed to the funding levels and procurement practices in production facility selection. General observations with respect to cost and performance include the following:

1. Tooling is a prerequisite to precision hole production. Tooling funds must be available at the onset of a program if precision in hole (and joint) production are required.

   The "fly-off" demonstration article (recent procurement practices) cannot be used as a representative fatigue on life-cycle test article. Fly-off models are produced by model shop techniques which may vary significantly with production techniques.

2. Hole production recurring labor costs are similar by all production methods. Most facilities do not discriminate by method in estimating costs.

3. Recurring labor costs for precision holes may increase in proportion to the number of additional finishing steps required, i.e., cold working, reaming, burnishing, etc.

4. Inspection costs increase with the increase in precision specified.

5. Rework costs increase proportionally with the tightness of the inspection tolerance and with the use of less rigid tooling.

X'. PRODUCTION FACILITIES SURVEY ANALYSIS

A. Facilities Surveyed

Our original contract required survey of five (5) facilities. Efficiencies in survey and industry acceptance enabled survey of ten (10) facilities within the project budget. One additional survey was performed under direct contract to the Air Logistics Command, United States Air Force and the data was included in our analysis. The survey was expanded to include material stack containing aluminum and steel, titanium and composite materials. Additional expansion included examination of holes during rework operations and examination of cold worked fastener holes.

11 facilities were surveyed

89 operations (lots) were evaluated

2,352 quantitative data entries

67,190 measurements were recorded and entered into the data bank.

Holes examined were limited to straight shank close tolerance holes in nominal fastener sizes from 3/16 inch through 5/8 inch. No rivet or other hole filling fastener holes were included.

B. Structures Surveyed

Structures surveyed included light aircraft, commercial aircraft and military aircraft. Material stacks included all aluminum and aluminum in combination stacks with steel, titanium and graphite. Structures assembly typed included.

FUSELAGE	EMPENNAGE	WINGS
Bulkheads	Fin	Root
Carry Thru	Rudder	Front Spar

FUSELAGE	EMPENNAGE	WINGS
Floor	Stabilizer	Center Spar
Nosewheel Gear	Elevator	Rear Spar
Engine Mount	Fuselage Mounting for Fin/Stabilizer	Upper Panels
Airscoop		Lower Panels
Nacelle		Flaps
		Engine Mounts
		Hinge Points

Holes in basic structure as well as critical interface and hinge structures were included in each facility survey where available.

C. Production Methods Surveyed

A sampling of as many types of processes as possible was made at each facility. Processes sampled included the following:

1. Hand Held Drill - Hand Held Reamer.
2. Hand Held Drill - No Reaming.
3. Spacematic - One Shot - No Reaming.
4. Spacematic Drill - Hand Reaming.
5. Positive Feed (Quackenbush 47) System - Hand Reaming.
6. Positive Feed System - Drill and Ream.
7. Positive Feed System - One Shot (Drill/Reamer - Dreamer).
8. Track Mounted/Machine Shop Equipment.

D. Data Collection and Analysis

1. Data Records

Hole dimensional measurements at each facility were collected and stored on magnetic tape. Hofe surface finish, hole texture, hole alignment, hole inspection, and other factors related to the structure and production method were collected in written form. Anomalies noted on the production-line were reported to the cognizant facility representative and a "rough" data analysis output provided to him on-site.

2. Hole Size and Shape Summary

Analysis of dimensional measurement data from a given facility was initiated by print-out of all data by hole for a given sample lot (single production method). Typical analysis by hole was described in Chapter V and shown in Table II of this report. A summary of dimensional measurement by sample lot was performed to provide a basis for comparison of production methods. A narrative descrption of the structure, production method and observations was written for each lot sampled. The narrative summary, sample lot data analysis summary and, data analyses by hole constitutes our record of hole characteristics assessment. Compilation of these records formed the basis for our audit report to the respective host facility management and is the basis for analyses completed in this report. A typical example of a lot sample analysis report is included in Appendix A, of this report volume. A complete tabulation of all lot sample analysis reports has been submitted to the Air Force Materials Laboratories. The large volume of data collected does not warrant general distribution.

3. Ranking of Data Lots

Ranking of hole quality as a function of production method may or may not be meaning due to the variety of structures, materials, hole depths, etc., sampled. After considerable discussion, we selected ranking by the standard deviation of measurements within a lot.

This method biases data with respect to hole size, depth, material, etc., and is offered only to provide a basis for assessing current industry practices and not capability of a technique. Ranking by standard deviation is shown in Table VI. Data lot summaries by rank for all holes is included in Volume II of this report. Comparison by production method is shown in Table VII.

TABLE VI- RANKING BY STANDARD DEVIATION

PROCESS & RANKING NUMBER	STANDARD DEVIATION	NOMINAL HOLE SIZE	ENG. TOLERANCE	MEASURED RANGE	MATERIAL THICKNESS	NUMBER OF HOLES	NUMBER OF READINGS	METHOD
SE-1	.000071	.246	+.000 -.001	.00075	.5625	29	1044	SPACEMATIC DRILLING COLD WORK SPLIT SLEEVE MANDREL EXPANSION FINAL HAND REAMING
Q2-2	DELETED		INACCURATE STATISTICS					
Q3-3	.000087	.627	+.001 -.000	.000741	.5625	29	1064	QUACKENBUSH HOLE DRILLING & REAMING COLD WORK ROLLER BURNISHING
SE-4	.000090	.246	+.004 -.000	.001405	.5625	29	1044	SPACEMATIC DRILLING COLD WORK SPLIT SLEEVE/MANDREL EXPANSION FINAL HAND REAMING
SE-5	.000110	.246	+.004 -.000	.000879	.5625	29	1044	SPACEMATIC DRILLING COLD WORK SPLIT SLEEVE/MANDREL EXPANSION FINAL HAND REAMING
SE-6	.000127	.246	+.004 -.000	.000819	.500	29	928	SPACEMATIC DRILLING COLD WORK SPLIT SLEEVE/MANDREL EXPANSION FINAL HAND REAMING
Q2-7	.000133	.4375	+.003 -.000	.001362	.625	17	676	QUACKENBUSH DRILLING AND REAMING
SE-8	.000137	.246	+.004 -.000	.001095	.5625	29	1044	SPACEMATIC DRILLING COLD WORK SPLIT SLEEVE/MANDREL EXPANSION FINAL HAND REAMING
Q3-9	.000152	.377	+.002 -.000	.000948	.250	29	464	QUACKENBUSH ONE SHOT "DREAMER" DRILL AND REAM
Q1-10	.000162	.312	+.006 -.000	.001060	.1875	29	348	QUACKENBUSH DRILLING HAND HELD AIR DRIVEN DRILL MOTOR POWERING A PILOTED REAMER

TABLE VI- RANKING BY STANDARD DEVIATION

PROCESS & RANKING NUMBER	STANDARD DEVIATION	NOMINAL HOLE SIZE	ENG. TOLERANCE	MEASURED RANGE	MATERIAL THICKNESS	NUMBER OF HOLES	NUMBER OF READINGS	METHOD
SE-11	.000173	.246	+.004 -.000	.001770	.5625	29	1044	SPACEMATIC DRILLING COLD WORK SPLIT SLEEVE/MANDREL EXPANSION FINAL HAND REAMING
Q2-12	.000192	.200	+.002 -.001	.001284	.5625	29	1044	QUACKENBUSH DRILLING QUACKENBUSH REAMING
Q3-13	.000217	.5645	+.003 -.000	.001328	.4375	29	812	QUACKENBUSH ONE SHOT "DREAMER" DRILL AND REAM
Q2-14	.000223	.250	+.003 -.000	.001491	.625	29	1156	QUACKENBUSH DRILLING QUACKENBUSH REAMING
H2-15	.000241	.190	+.004 -.000	.001153	.3125	29	580	HAND HELD DRILLING HAND HELD REAMING
Q2-16	.000242	.250	+.003 -.000	.001490	.625	29	1160	QUACKENBUSH DRILLING QUACKENBUSH REAMING
S1-17	.000263	.312	+.003 -.000	.001805	.3125	29	580	SPACEMATIC ONE SHOT DRILLING AND COUNTER SINKING NO REAMING
H2-18	.000265	.250	+.003 -.000	.001784	.125	29	232	HAND HELD DRILLING HAND HELD REAMING
S2-19	.000305	.246	+.004 -.000	.002017	.4375	29	809	SPACEMATIC DRILLING HAND HELD REAMING
Q3-20	.000312	.3775	+.003 -.000	.001439	.375	29	696	QUACKENBUSH ONE SHOT "DREAMER" DRILL AND REAM
Q2-21	.000315	.625	+.001 -.000	.003164	.75 TO 1.5	19	1508	QUACKENBUSH DRILLING QUACKENBUSH REAMING
Q2-22	.000319	.375	+.0005 -.0005	.002043	.5625	29	1036	

TABLE VI- RANKING BY STANDARD DEVIATION

PROCESS & RANKING NUMBER	STANDARD DEVIATION	NOMINAL HOLE SIZE	ENG. TOLERANCE	MEASURED RANGE	MATERIAL THICKNESS	NUMBER OF HOLES	NUMBER OF READINGS	
H1-23	.000332	.250	+.004	.002491	.5625	29	1044	HAND HELD DRILLING NO REAMING
S1-24	.000338	.246	+.004	.002155	.250	29	464	SPACEMATIC DRILLING "ONE SHOT" NO REAMING
S1-25	.000347	.310	-.002 +.003	.001991	.500	29	928	SPACEMATIC DRILLING "ONE SHOT" NO REAMING
H1-26	.000367	.187	-.002 +.001	.001905	.125	29	232	HAND HELD AIR POWERED DRILL NO REAMING
MS-27	.000369	.186	-.0005 +.001	.002172	.250	29	464	TRACK MOUNTED AIR POWERED DRILLING AND REAMING
Q2-28	.000374	.625	+.005	.001733	.750	12	576	QUACKENBUSH DRILLING QUACKENBUSH REAMING
S2-29	.000389	.310	±.001	.003078	.4375	29	812	SPACEMATIC DRILLING HAND HELD REAMING
H2-30	.000393	.1885	+.0025 -0.00	.003241	.375	29	696	HAND HELD DRILLING HAND HELD REAMING
Q1-31	.000409	.246	+.004 -0.00	.001973	.625	29	1160	QUACKENBUSH DRILLING HAND HELD REAMING
Q3-32	.000415	.248	+0.00 -.003	.002345	.250	29	464	QUACKENBUSH ONE SHOT "DREAMER" DRILL AND REAM
S1-33	.000415	.246	+.004 -0.00	.001986	.250	29	464	SPACEMATIC ONE SHOT DRILLING NO REAMING
Q2-34	.000428	.246	+.004 -.000	.002409	.4525	29	1144	QUACKENBUSH DRILLING QUACKENBUSH REAMING
MS-35	.000441	.624	+. -.0005	.004491	1.4375	27	2472	VERTICAL DRILL PRESS HORIZONTAL BROACHING

TABLE VI- RANKING BY STANDARD DEVIATION

PROCESS & RANKING NUMBER	STANDARD DEVIATION	NOMINAL HOLE SIZE	ENG. TOLERANCE	MEASURED RANGE	MATERIAL THICKNESS	NUMBER OF HOLES	NUMBER OF READINGS	METHOD
Q2-36	.000456	.200	+.002 -.001	.002267	.125	29	232	QUACKENBUSH DRILLING QUACKENBUSH REAMING
MS-37	.000457	.312	+.002 -.000	.003853	.875	29	1624	VERTICAL DRILL PRESS HAND REAMING
Q1-38	.000459	.200	+.002 -.001	.003052	.250	29	464	QUACKENBUSH DRILLING HAND HELD REAMING
Q1-39	.000475	.625	+.001 -.0005	.003517	.3125	29	580	LAZY ARM VERTICAL FARNHAM DRILL HAND HELD REAMING
H1-40	.000483	.2495	+.0085 -.000	.003250	.4375	29	808	HAND HELD DRILLING NO REAMING
H3-41	.000488	.310	+.003 -.001	.003586	.625	29	1068	HAND DRILLING, COLD WORKED, HAND REAMING
MS-42	.000490	.5005	+.001 -.000	.002284	.500	29	928	NUMERICAL CONTROLLED MILLING AND BORING
H1-43	.000496	.190	+.004 -.000	.003267	.4375	29	812	HAND HELD DRILLING NO REAMING
MS-44	.000519	.500	+.0005 -.0005	.002690	.0625	29	116	VERTICAL DRILL PRESS W/REAMING
Q3-45	.000519	.312	+.0015 -.000	.004922	.3125	29	584	QUACKENBUSH DRILLING FINAL SIZED W/QUACKENBUSH CORE DRILL
Q2-46	.000532	.5005	+.002 -.000	.001981	1.375	19	1416	QUACKENBUSH DRILLING COLD WORKED QUACKENBUSH REAMING
Q2-47	.000547	.250	+.003 -.000	.003086	.625	29	1160	QUACKENBUSH DRILLING QUACKENBUSH REAMING
Q2-48	.000548	.312	+.003 -.000	.003871	.3125	29	580	QUACKENBUSH DRILLING QUACKENBUSH REAMING

TABLE VI- RANKING BY STANDARD DEVIATION

PROCESS & RANKING NUMBER	STANDARD DEVIATION	NOMINAL HOLE SIZE	ENG. TOLERANCE	MEASURED RANGE	MATERIAL THICKNESS	NUMBER OF HOLES	NUMBER OF READINGS	METHOD
Q2-49	.000549	.375	+.0005 -.0005	.002043	.125	14	112	QUACKENBUSH DRILLING QUACKENBUSH REAMING
H2-50	.000557	.250	+.0015 -.0005	.004784	.375	29	696	HAND HELD DRILLING HAND HELD REAMING
Q1-51	.000559	.375	+.004 -.000	.003690	.875	29	1623	QUACKENBUSH DRILLING HAND HELD REAMING
Q1-52	.000562	.310	+.003 -.002	.004983	.625	29	1160	QUACKENBUSH DRILLING HAND HELD REAMING
H1-53	.000600	.250	+.004 -.000	.003345	.5625	29	1044	HAND HELD DRILLING NO REAMING
Q2-54	.000605	.250	+.004 -.000	.003503	.3125	29	580	QUACKENBUSH DRILLING QUACKENBUSH REAMING
S2-55	.000636	.246	+.004 -.000	.003129	.500	29	928	SPACEMATIC DRILLING HAND HELD REAMING
H1-56	.000670	.187	+.001 -.002	.003690	.1875	29	348	HAND HELD DRILLING NO REAMING
H2-57	.000680	.250	+.004 -.000	.003328	.1875	29	348	HAND HELD DRILLING HAND HELD REAMING
H2-58	.000680	.376	+.002 -.000	.006371	.4375	29	811	HAND HELD DRILLING HAND HELD REAMING
H3-59	.000687	.250	+.003 -.001	.003750	.250	6	96	HAND DRILLING; COLD WORKED; HAND REAMING
S1-60	.000701	.246	+.004 -.000	.003595	.3125	29	580	SPACEMATIC DRILLING NO REAMING
S2-61	.000703	.310	+.001 -.001	.003931	.500	29	927	SPACEMATIC DRILLING HAND REAMING
S1-62	.000711	.250	+.004 -.000	.002664	.1875	29	348	SPACEMATIC DRILLING NO REAMING

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PROCESS & RANKING NUMBER	STANDARD DEVIATION	NOMINAL HOLE SIZE	ENG. TOLERANCE	MEASURED RANGE	MATERIAL THICKNESS	NUMBER OF HOLES	NUMBER OF READINGS	METHOD
Q1-63	.000716	.500	+.0006 -.0009	.005271	.1875	29	348	QUACKENBUSH DRILLING HAND HELD REAMING
S1-64	.000730	.246	+.004 -.000	.003543	.4375	29	812	SPACEMATIC DRILLING NO REAMING
H1-65	.000811	.187	+.001 -.002	.007198	.250	29	464	HAND HELD DRILLING NO REAMING
Q1-66	.000815	.250	+.004 -.001	.004966	.500	29	928	QUACKENBUSH DRILLING HAND HELD REAMING
S1-67	.000827	.187	+.001 -.002	.003983	.125	29	232	SPACEMATIC DRILLING NO REAMING
Q2-68	.000859	.500	+.003 -.001	.006172	.1875	29	349	QUACKENBUSH DRILLING QUACKENBUSH REAMING
H2-69	.000867	.250	+.003 -.000	.006224	.1875 TO .250	29	388	HAND HELD DRILLING HAND HELD REAMING
Q2-70	.000867	.500	+.005 -.000	.005672	.500	19	716	QUACKENBUSH DRILLING QUACKENBUSH REAMING
Q1-71	.000886	.375	+.004 -.000	.004362	.9375	29	1740	QUACKENBUSH DRILLING HAND HELD REAMING
Q2-72	.000888	.375	+.005 -.000	.004379	.250	29	472	QUACKENBUSH DRILLING QUACKENBUSH REAMING
Q2-73	.000909	.4375	+.005 -.000	.006017	.4375	20	688	QUACKENBUSH DRILLING QUACKENBUSH REAMING
H3-74	.000945	.251	+.004 -.000	.003422	.4375	12	336	HAND DRILLING COLD WORKED HAND REAMING
Q2-75	.000946	.3125	+.003 -.000	.005431	1.125	29	2088	QUACKENBUSH DRILLING QUACKENBUSH REAMING

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PROCESS & RANKING NUMBER	STANDARD DEVIATION	NOMINAL HOLE SIZE	ENG. TOLERANCE	MEASURED RANGE	MATERIAL THICKNESS	NUMBER OF HOLES	NUMBER OF READINGS	METHOD
S2-76	.001012	.310	+.001 -.001	.004791	.6875	29	1276	SPACEMATIC DRILLING HAND HELD REAMING
H2-77	.001026	.250	+.000 -.003	.004448	.0625	29	116	HAND HELD DRILLING HAND HELD REAMING
Q1-78	.001055	.250	+.004 -.000	.004560	.6875	29	879	QUACKENBUSH DRILLING HAND HELD REAMING
S1-79	.001137	.187	+.003 -.001	.004328	.4375	29	812	SPACEMATIC DRILLING NO REAMING
H3-80	.001138	.246	+.002 -.001	.004491	.3125	18	440	HAND DRILLING COLD WORKED HAND REAMING
H2-81	.001190	.190	+.003 -.000	.007681	.3125	29	504	HAND HELD DRILLING HAND HELD REAMING
Q1-82	.001213	.375	+.004 -.000	.004672	.4375	29	812	QUACKENBUSH DRILLING HAND HELD REAMING
H2-83	.001221	.250	+.0015 -.0005	.005905	.3175	29	580	HAND HELD DRILLING HAND HELD REAMING
Q1-84	.001223	.250	+.004 -.000	.005922	.3175	29	580	QUACKENBUSH DRILLING HAND HELD REAMING
H2-85	.001228	.3125	+.004 -.000	.006362	.375	20	480	HAND HELD DRILLING HAND HELD REAMING
H3-86	.001249	.625	+.0005 -.0005	.005043	1.125	8	576	HAND HELD DRILLING COLD WORKED HAND HELD REAMING
S1-87	.001358	.3125	+.0055 -.000	.004853	.3125	12	240	SPACEMATIC DRILLING NO REAMING
Q1-88	.001535	.250	+.004 -.000	.006362	.3125	29	580	QUACKENBUSH DRILLING HAND HELD REAMING
H3-89	.001647	.437	+.003 -.002	.006552	.8125	6	336	HAND HELD DRILLING COLD WORKED HAND HELD REAMING

TABLE VII- RANKING BY PROCESS

HAND HELD DRILLING; NO REAMING

RANKING NUMBER	STANDARD DEVIATION	NOMINAL HOLE SIZE	ENGINEERING TOLERANCE	MEASURED RANGE	MATERIAL THICKNESS	NUMBER OF HOLES	NUMBER OF READINGS
H1-23	.000332	.250	+.004 -.000	.002491	.5625	29	1044
H1-26	.000367	.187	-.002 +.001	.001905	.125	29	232
H1-40	.000483	.2495	+.0035 -.000	.003250	.4375	29	808
H1-43	.000496	.190	+.004 -.000	.003267	.4375	29	812
H1-53	.000600	.250	+.004 -.000	.003345	.5625	29	1044
H1-56	.000670	.187	+.001 -.002	.003690	.1875	29	348
H1-65	.000811	.187	+.001 -.002	.007198	.250	29	464

TABLE VII- RANKING BY PROCESS

HAND HELD DRILLING; HAND HELD REAMING

RANKING NUMBER	STANDARD DEVIATION	NOMINAL HOLE SIZE	ENGINEERING TOLERANCE	MEASURED RANGE	MATERIAL THICKNESS	NUMBER OF HOLES	NUMBER OF READINGS
H2-15	.000241	.190	+.004 -.000	.001153	.3125	29	380
H2-18	.000265	.250	+.003 -.000	.001784	.125	29	232
H2-30	.000393	.1885	+.0025 -.000	.003241	.375	29	696
H2-50	.000557	.250	+.0015 -.0005	.004784	.375	29	696
H2-57	.000680	.250	+.004 -.000	.003328	.1375	29	348
H2-58	.000680	.376	+.002 -.000	.006371	.4375	29	811
H2-69	.000867	.250	+.003 -.000	.006224	.1875 TO .250	29	388
H2-77	.001026	.250	+.000 -.003	.004448	.0625	29	116
H2-81	.001190	.190	+.003 -.000	.007681	.3125	29	504
H2-83	.001221	.250	+.0015 -.0005	.005905	.3175	29	580
H2-85	.001228	.3125	+.004 -.000	.006362	.375	20	480

TABLE VII- RANKING BY PROCESS

HAND HELD DRILLING; COLD WORKED; HAND HELD REAMING

RANKING NUMBER	STANDARD DEVIATION	NOMINAL HOLE SIZE	ENGINEERING TOLERANCE	MEASURED RANGE	MATERIAL THICKNESS	NUMBER OF HOLES	NUMBER OF READINGS
H3-41	.000488	.310	+.003 -.001	.003586	.625	29	1068
H3-59	.000687	.250	+.003 -.001	.003750	.250	6	96
H3-74	.000945	.251	+.004 -.000	.003422	.4375	12	331
H3-80	.001138	.246	+.002 -.001	.004491	.3125	18	440
H3-86	.001249	.625	+.0005 -.0005	.005043	1.125	8	576
H3-89	.001647	.437	+.003 -.002	.006552	.8125	6	336

TABLE VII- RANKING BY PROCESS

SPACEMATIC "ONE SHOT"; NO REAMING

RANKING NUMBER	STANDARD DEVIATION	NOMINAL HOLE SIZE	ENGINEERING TOLERANCE	MEASURED RANGE	MATERIAL THICKNESS	NUMBER OF HOLES	NUMBER OF READINGS
S1-17	.000263	.312	+.003 -.000	.001805	.3125	29	580
S1-24	.000338	.246	+.004 -.000	.002155	.250	29	464
S1-25	.000347	.310	-.002 +.003	.001991	.500	29	928
S1-33	.000415	.246	+.004 -.000	.001986	.250	29	464
S1-60	.000701	.246	+.004 -.000	.003595	.3125	29	580
S1-62	.000711	.250	+.004 -.000	.002664	.1875	29	348
S1-64	.000730	.246	+.004 -.000	.003543	.4375	29	812
S1-67	.000827	.187	+.001 -.002	.003983	.125	29	232
S1-¯9	.001137	.187	+.003 -.001	.004328	.4375	29	812
S1-87	.001358	.3125	+.0055 -.000	.004853	.3125	12	240

TABLE VII- RANKING BY PROCESS

SPACEMATIC DRILLING; HAND HELD REAMING

RANKING NUMBER	STANDARD DEVIATION	NOMINAL HCLE SIZE	ENGINEERING TOLERANCE	MEASURED RANGE	MATERIAL THICKNESS	NUMBER OF HOLES	NUMBER OF READINGS
S2-19	.000305	.246	+.004 -.000	.002017	.4375	29	809
S2-29	.000389	.310	±.001	.003078	.4375	29	812
S2-55	.000636	.246	+.004 -.000	.003129	.500	29	928
S2-61	.000703	.310	+.001 -.001	.003931	.500	29	927
S2-76	.001012	.310	+.001 -.001	.004791	.6875	29	1276

TABLE VII- RANKING BY PROCESS

SPACEMATIC W/EXPANSION

RANKING NUMBER	STANDARD DEVIATION	NOMINAL HOLE SIZE	ENGINEERING TOLERANCE	MEASURED RANGE	MATERIAL THICKNESS	NUMBER OF HOLES	NUMBER OF READINGS
SE-1	.000071	.246	+.000 -.001	.000750	.5625	29	1044
SE-4	.000090	.246	+.004 -.000	.001405	.5625	29	1044
SE-5	.000110	.246	+.004 -.001	.000879	.5625	29	1044
SE-6	.000127	.246	+.004 -.000	.000819	.500	29	928
SE-8	.000137	.246	+.004 -.000	.001095	.5625	29	1044
SE-11	.000173	.246	+.004 -.000	.001770	.5625	29	1044

TABLE VII- RANKING BY PROCESS

QUACKENBUSH DRILLING; HAND HELD REAMING

RANKING NUMBER	STANDARD DEVIATION	NOMINAL HOLE SIZE	ENGINEERING TOLERANCE	MEASURED RANGE	MATERIAL THICKNESS	NUMBER OF HOLES	NUMBER OF READINGS
Q1-10	.000162	.312	+.006 -.000	.001060	.1875	29	348
Q1-31	.000409	.246	+.004 -.000	.001973	.625	29	1160
Q1-38	.000459	.200	+.002 -.001	.003052	.250	29	464
Q1-30	.000475	.625	+.001 -.0005	.003517	.3125	29	580
Q1-51	.000559	.375	+.004 -.000	.003690	.875	29	1623
Q1-52	.000562	.310	+.003 -.002	.004983	.625	29	1160
Q1-63	.000716	.500	+.0006 -.0009	.005271	.1875	29	348
Q1-66	.000815	.250	+.004 -.001	.004966	.500	29	928
Q1-71	.000886	.375	+.004 -.000	.004362	.9375	29	1740
Q1-78	.001055	.250	+.004 -.000	.004560	.6875	29	879

TABLE VII- RANKING BY PROCESS (CONT.)

QUACKENBUSH DRILLING; HAND HELD REAMING

RANKING NUMBER	STANDARD DEVIATION	NOMINAL HOLE SIZE	ENGINEERING TOLERANCE	MEASURED RANGE	MATERIAL THICKNESS	NUMBER OF HOLES	NUMBER OF READINGS
Q1-82	.001213	.375	+.004 -.000	.004672	.4375	29	812
Q1-84	.001223	.250	+.004 -.000	.005922	.3175	29	580
Q1-88	.001535	.250	+.004 -.000	.006362	.3125	29	580

TABLE VII- RANKING BY PROCESS

QUACKENBUSH DRILLING; QUACKENBUSH REAMING

RANKING NUMBER	STANDARD DEVIATION	NOMINAL HOLE SIZE	ENGINEERING TOLERANCE	MEASURED RANGE	MATERIAL THICKNESS	NUMBER OF HOLES	NUMBER OF READINGS
Q2-2	DELETED						
Q2-7	.000133	.4375	+.003 -.000	.001362	.625	17	676
Q2-12	.000192	.200	+.002 -.001	.001284	.5625	29	1044
Q2-14	.000223	.250	+.003 -.000	.001491	.625	29	1156
Q2-16	.000242	.250	+.003 -.000	.001490	.625	29	1160
Q2-21	.000315	.625	+.001 -.000	.003164	.75" TO 1.5"	19	1508
Q2-22	.000319	.375	+.0005 -.0005	.002043	.5625	29	1036
Q2-28	.000374	.625	+.005 -.000	.001733	.750	12	576
Q2-34	.000428	.246	+.004 -.000	.002409	.5625	29	1144
Q2-36	.000456	.200	+.002 -.001	.002267	.125	29	232

TABLE VII- RANKING BY PROCESS

QUACKENBUSH DRILLING; QUACKENBUSH REAMING

RANKING NUMBER	STANDARD DEVIATION	NOMINAL HOLE SIZE	ENGINEERING TOLERANCE	MEASURED RANGE	MATERIAL THICKNESS	NUMBER OF HOLES	NUMBER OF READINGS
Q2-46	.000532	.5005	+.002 -.000	.001981	1.375	19	1416
Q2-47	.000547	.250	+.003 -.000	.003086	.625	29	1160
Q2-48	.000548	.312	+.003 -.000	.003871	.3125	29	580
Q2-49	.000549	.375	±.0005	.002043	.125	14	112
Q2-54	.000605	.250	+.004 -.000	.003563	.3125	29	580
Q2-68	.000859	.500	+.003 -.001	.006172	.1875	29	349
Q2-70	.000867	.500	+.005 -.000	.005672	.500	19	716
Q2-72	.000888	.375	+.005 -.000	.004379	.250	29	472
Q2-73	.000909	.4375	+.005 -.000	.006017	.4375	20	688
Q2-75	.000946	.3125	+.003 -.000	.005431	1.125	29	2088

TABLE VII- RANKING BY PROCESS

QUACKENBUSH "ONE SHOT" DREAMER

RANKING NUMBER	STANDARD DEVIATION	NOMINAL HOLE SIZE	ENGINEERING TOLERANCE	MEASURED RANGE	MATERIAL THICKNESS	NUMBER OF HOLES	NUMBER OF READINGS
Q3-2	.000087	.627	+.001 -.000	.000741	.5625	29	1064
Q3-9	.000152	.377	+.002 -.000	.000948	.250	29	464
Q3-13	.000217	.5645	+.003 -.000	.001328	.4375	29	812
Q3-20	.000312	.3775	+.003 -.000	.001439	.375	29	696
A3-32	.000415	.248	+.000 -.003	.002345	.250	29	464
Q3-45	.000519	.312	+.0015 -.000	.004922	.3125	29	584

TABLE VII- RANKING BY PROCESS

MISCELLANEOUS SYSTEMS

RANKING NUMBER	STANDARD DEVIATION	NOMINAL HOLE SIZE	ENGINEERING TOLERANCE	MEASURED RANGE	MATERIAL THICKNESS	NUMBER OF HOLES	NUMBER OF READINGS	METHOD
MS-27	.000369	.186	-.0005 +.001	.002172	.250	29	464	TRACK MOUNTED AIR POWERED DRILLING & REAMING
MS-35	.000441	.624	±.0005	.004491	1.4375	27	2472	VERTICAL DRILL PRESS HORIZONTAL BROACHING
MS-37	.000457	.312	+.002 -.000	.003853	.875	29	1624	VERTICAL DRILL PRESS HAND REAMING
MS-42	.000490	.5005	+.001 -.000	.002284	.500	29	928	NUMERICAL CONTROLLED MILLING AND BORING
MS-44	.000510	.500	±.0005	.002690	.0625	29	116	VERTICAL DRILL PRESS W/REAMING

Holes with smallest standard deviation in dimensional measurements were produced by the spacematic method, cold worked by expansion sleeve technique and hand reamed to final size. Cold working appeared to be of benefit in dimensional control. Variability in cold worked holes was significantly less than for those produced by Spacematic drill and hand ream without cold working.

Quackenbush holes were not consistent overall and is regarded by our survey team as the most consistent method overall. Holes of note were produced by the Quackenbush method and then roller burnished.

E. <u>Summary of Production Observations</u>

1. Round, cylindrical smooth holes are produced by those processes which "cut" the material. A sharp uniform chip is good indiator of hole quality. Tool grind, feed, speed and coolant application are key factors in good cutting.

2. Taper was the most frequently observed shape feature in close tolerance holes. Taper is believed to be due primarily to efficiency in chip removal. Deep holes intensify chip removal difficulty.

3. Stacks of mixed materials present special drilling problems in chip removal, particularly when a harder material, such as titanium, is located below an aluminum layer. Feed, speed and tool grind are selected for the harder material. Chip must be efficiently removed to avoid gouging of the softer aluminum material. Oil hole, cobalt drills with a 550 point in a Quackenbush tool produced the most uniform holes observed in an aluminum-titanium-steel stack.

4. Double margin split point, 1180, step drills were used to produce the most uniform holes observed by the hand drilling method.

   Variations between hand drilling operations and hole quality produced are attributed to the degree of clamp-up and structural stiffness. Guide bushings, drill blocks or portable aids such as the "Sheridan Adapter"(18) were used in hand drilling operations at all facilities.

5. Precision holes were produced by Quackenbush drill and ream at all facilities. At one facility, a combination drill and ream tool called the "Dreamer" [19] was applied successfully in precision hole production.

6. Age of touch-labor production workers is being addressed throughout the aircraft industry. The facility which relied most heavily on hand drilled holes, also had a force of experienced craftsman.

   A operator training at one facility was credited as a reason for low cost, low reject rate and smooth integration of workers into the production force. This same facility had the most comprehensive tool control and maintenance program found during this study.

   Operator training and integration of new workers at another facility was addressed by test and bench instruction of tool kits at a crib which was operated by an experienced worker. Training in application was done on the job by a co-worker or supervisor.

   At another facility, training was done, on the job, by an experienced co-worker who was the crew chief for a work area. The crew chief was responsible for the quality of work in the area and was an active worker for performing "tough" tasks in the work area. Worker satisfaction was high at this facility.

7. Coolants and/or lubricants were used in drilling approximately half of the holes sampled. Fewer problems with chip clearance were noted where a coolant/lubricant was used. Cetyl alcohol in solid form was used at several facilities where bonding and/or sealant were required. Freon TB-1 mist was used at other facilities for the same purpose. Various fluid lubricants were used in other operations.

8. Rigid tooling and good clamp-up were present for operations which produced most uniform holes.

9. Hole size sample checks by the production operator are frequently called out on processes. Plug-gage check of every fifth hole is common. Sampling was observed on the line infrequently.

10. Deburring operations stand out as the single factor which varies significantly among facilities. Some detailed deburring instructions are included in some process specifications. In other cases, deburring is considered to be a workmanship item and, instructions are provided on the job by co-workers and by supervision.

Deburring tools ranges from a modified "vixen block" to a pocket knife or oversize drill.

11. Use of close tolerance holes as tool jig support points and as attachment points for movement of subassemblies was observed in several facilities. Insert bushings were not provided to minimize hole damage in some cases. When printed out, these practices were recognized as being undesirable and were reported to the facility management for action.

12. Most facility process specifications require that drills and reamers continue turning on withdrawal from a hole. Nonconformance was frequently observed.

13. Shift of a material stack during drilling was frequently observed when a series of holes were drilled in a structure which was not rigidly clamped during drilling. "Cleco" clamps do not prevent such shift. Fasteners were used in some cases to avoid stack shift and provide local clamp-up. Surface damage was observed in several structures as a result of fastener removal.

14. Rigid tooling, clamp-up and positive feed equipment processes were less influenced by operator variables. Counterbalancing of the positive feed drill units was necessary to minimize evidence of side (gravity) loading in the hole shape analysis.

F. Summary of Production Inspection Observations

1. The distinguishing factor between critical holes and close tolerance holes at most facilities was increased hole inspection. Inspection requirements for critical holes varied from a 50% sampling to a 100% sampling.

2. Training of inspectors is minimal at most facilities.

3. The plug-gage is the universal tool for inspecting hole size.

4. Use of the plug gage varies. Some facilities prohibit rotation of a plug gage in a hole. Cleanliness of the gage is noted in some specifications. Inspection of the gage for nicks, burrs, etc., is called out and is controlled in some facilities by crib issue of the

gage on a single shift basis and check of the plug against a master ring gage. Private, tool box gages were frequently observed where crib locations were remote, where check out involved time consuming paperwork and where crib lines were visible.

Inspection with a plug-gage from both sides of a stack is called out frequently.

5. While no specific data was taken on inspection performance, i.e., repeative inspection and comparison of results, analysis of the hole characteristics (2,352 holes 67,190 measurements) the plug gage should have detected approximately 192 errors (8.2% (oversize and undersize conditions). The air probe used by the survey team shows 416 holes (17.7%) with values out of tolerance. These additional conditons could not be detected by the plug gage at all.

   One of the most significant findings of this survey is the high lighting of hole characteristics approaching or exceeding engineering limits which cannot be detected by the inspection techniques in use. These characteristics may be important in determining the ability of a process to produce in tolerance hardware (Early detection of going out of control).

   It should also be pointed out that many of the oversize holes would probably be allowed to stand as is because the out of tolerance condition is not through the entire hole so that the rejection percentage for the plug gage technique would most likely be less than 5%.

   The survey team is of the opinion that the currently in use inspection techniques are not adequate to evaluate parameters which could be indicators of problems downstream.

6. Inspection aids such as the "Sight-Pipes" and the "GAR, Microfinish Comparator" were either not available or were not used in inspection of hole surface-finish and hole texture. Few problems were observed, by the survey team regarding these factors.

G. Isolated Incidents of Note

An independent audit of operations is particularly useful when "fit, form and function" characteristics are measured. Isolated incidents are often revealed during audit but must not be regarded as indicative of the performance capability of a facility or process. Our survey team was particularly gratified by the reception, interest and "problem solving" attitude of personnel involved at all facilities. Incidents noted were given prompt management attention as "lessons learned" and are reported herein to stimulate thought by the reader and to present items of intangible value which may be revealed by an audit.

1. The single structure sampled in which hole perpendularity was out of tolerance, was observed on a fuselage structure at a skin joint-to-stringer interface. Holes were drilled and reamed using a three point (trivet) type drill block. The block was positioned across the splice joint and the resulting holes were drilled off axis.

2. Oversized holes in a hinge fitting prompted check of the drill bushing. The bushing was 0.013 inch oversize at the exit side. Maintenance was corrected.

3. Oversize holes in a hinge fitting produced by the Quackenbush method were noted and correction was proposed by counterbalancing the drill units.

4. Oversize holes in a steel to aluminum hinge fitting were produced by using an incorrect reamer size. The steel chips build up severely gouged the aluminum hole to produce a barrelling condition which was beyond the range of our air gages. Suggested process improvements included better lighting in the work area.

5. Holes produced by a single operator on a difficult structure were identified at one location and a detailed measurement and comparison requested. Our measurement revealed that the holes were similar to those produced by other operators but that reaming was performed from the opposite side of the structure. Plug-gage inspection at the exit side accepted holes with a significant taper. Tooling changes were recommended.

6. Variability of holes produced by a single operator using the Spacematic method was evaluated. Variance was attributed to side loading by the operator in anticipation of the next hole location.

7. A 0.013 inch undersize condition was identified for interference fit fastener holes in a critical fitting joint. The error was called out on the drawings and implemented in production and inspection. The joint proved to be particularly troublesome in service and redesign was underway.

8. Shift of a heavy stack containing close tolerance holes prevented entry of an air gage which was 0.003 inch undersize. Evaluation revealed a ± 0.0005 inch hole tolerance on the structure and a ± 0.001 inch tolerance on tooling pins. Correction was implemented.

9. Deep, close tolerance holes in an assembly were determined to be tapered. The initial hole was produced by the Quackenbush method using rigid tooling but was finished by a piloted hand reamer without the aid of a bushing or lubricant.

XII. EVALUATION OF THE EQUIPMENT USED IN THE SURVEY

A. General

We learned much as a result of the surveys performed. The methods and procedures developed were useful and pertinent to the characterization task at hand. All equipment functioned well. No lost time was experienced due to equipment malfunction. Great interest was generated by the measurement system operation and it was readily accepted by personnel at all facilities.

A few changes would be made if we were starting the program with benefit of the experience gained. These include the following:

B. Dimensional Measurement System

1. General -

Overall the dimensional measurement system worked very well. The system was transported to several locations across the country, with differing air and power systems and with differing industrial environment. Low voltage at one motel location prevented use of the calculator at night. No other difficulties in operation were expereinced.

2. 9815A Calculator -

The Hewlett-Packard, 9815A calculator had one failure of the tape drive system a short time after its 90 day warranty had expired. Repair was expensive. No other functional failures were experienced.

The thermal printer tape-output is acceptable for a real-time record, but fades rapidly and is not acceptable as a permanent record. Further, the tape format is difficult to incorporate into a written report. In future use, the unit will be interfaced to a line printer for permanent data output.

3. Alina-Pretec Measurement System -

The Alina system also functioned satisfactorily throughout the program. Calibraton check is accomplished with the aid of a calculator program tape which is supplied with the unit. Minor adjustments were necessary throughout the program.

Measurement calibration set-up on the job is awkward. The amplifier must be balanced by one adjustment on the front of the panel and alternately by a second, screwdriver adjustment on the back side of the unit. Both adjustments must be made while viewing the panel meter. Although the adjustments can rapidly be made by an experienced operator, the unit is poorly human engineered.

Analog to digital conversion in this unit is tied to the meter readout. The meter must settle before an accurate digital reading is obtained. Once recognized, this feature may be easily accommodated in actual measurement. An alternate, direct conversion independent of the meter would be desirable for more rapid data acquisition.

The air-converter also functioned without difficulty. Connection to an air supply along with transportation and maintenance of the filter-dryer system was bothersome. An alternate system which utilizes an internally generated air supply was located but was not evaluated during this program. The "Wilson Airless Airgage" features a precision blower located inside the electronic control box as the air supply, is compatible with "standard" air gage probes and provides a BCD compatible interface output.

4. Air-Gage Probes -

The Western air gage probes worked well throughout the program. A single connector extension handle would have simplified our usage, but the dual units were readily adapted to our manipulation tool with a bushing sleeve.

5. Program Software -

The program software worked well throughout the program and analysis tasks. It is unique to this program but uses principles and logic which are readily adaptable to other tasks.

C. Hole Alignment Gage

The hole alignment gage worked well throughout the program. No changes in this technique are offered.

D. Surface Finish Measurement

Surface finish measurement using the GAR, Micro Finish Comparator was satisfactory and is recommended for general use. It is inexpensive, durable and provided a good basis for comparison.

E. Surface Texture

The "Sight Pipes" used for "in hole" inspection of surface finish and surface texture worked well. The units require care in handling, but were a significant asset to our evaluation. We recommend them for general shop usage

F. "Diatest" Split Ball Gages

The "Diatest" split ball gages provided excellent capability for rapid gaging of holes on the production line. The direct reading, small footprint, and non-abrasive characteristics of these units were readily recognized and accepted. The units require reasonable care in handling but are recommended for general shop usage.

We do not recommend interface of the split ball gages to the electronic readout system due to difficulty in centering the gage.

G. Replica Material

Although holes were seldom replicated during the actual surveys, the material worked very well for those applications where it was used. The host facility retained the replicas in most cases to aid in internal discrepancy evaluation.

XIII. SUMMARY AND CONCLUSIONS

A. General

Hole production is a multi-step process. We observed "good" holes and "bad" holes produced by every process. No endorsement can be made for any single process as the critical factor in close tolerance hole production. No endorsement can be made for:

1. Specific engineering design criteria;

2. Tooling;

3. Drilling equipment;

4. Drill bits, reamers, etc. (type or grind);

5. Coolant;

6. Process;

7. Deburring method;

8. Inspection method;

9. Fastener installation method; or

10. Maintenance method.

Superior results may be obtained by optimizing all factors to the specific application. The industry is in general meeting or exceeding the criteria established. Tooling is the single factor where improvement in the hole production process realiability could be obtained. Tooling is a significant initial investment and must be factored into each program.

Good holes can be produced by an experienced craftsman with substand tooling. "Nothing is impossible for the man who doesn't have to do it." However, process reliability in general production includes adequate and rugged tooling.

B. Hole Quality as a Function of Process

A complex relationship exists between hole quality and hole production processes. Any one factor in the process can result in "out of tolerance" holes. Ranking of hole dimensional parameters by process, Table IV provides a basis for comparison of methods and resultant trends in variability. Data were plotted in various ways in an attempt to further establish trends. Figures 20 through 27 are plots of (σ) standard deviation in dimensions as a function of stack material and hole depth. No conclusion trends are revealed. Data scatter is attributed not only both the production method and application of the method. Judgement must be applied to proficiency in application of the methods.

Our qualitative judgement is that the "Quackenbush method" provides best overall consistency in hole quality as witnessed across the industry. We attribute the consistency of the method to the rigidity and clamp-up required by this method, to the inherent features of the method and to the fact that hole tolerance criteria are generally tighter where this method is applied. The method allows less operator influence than all other methods.

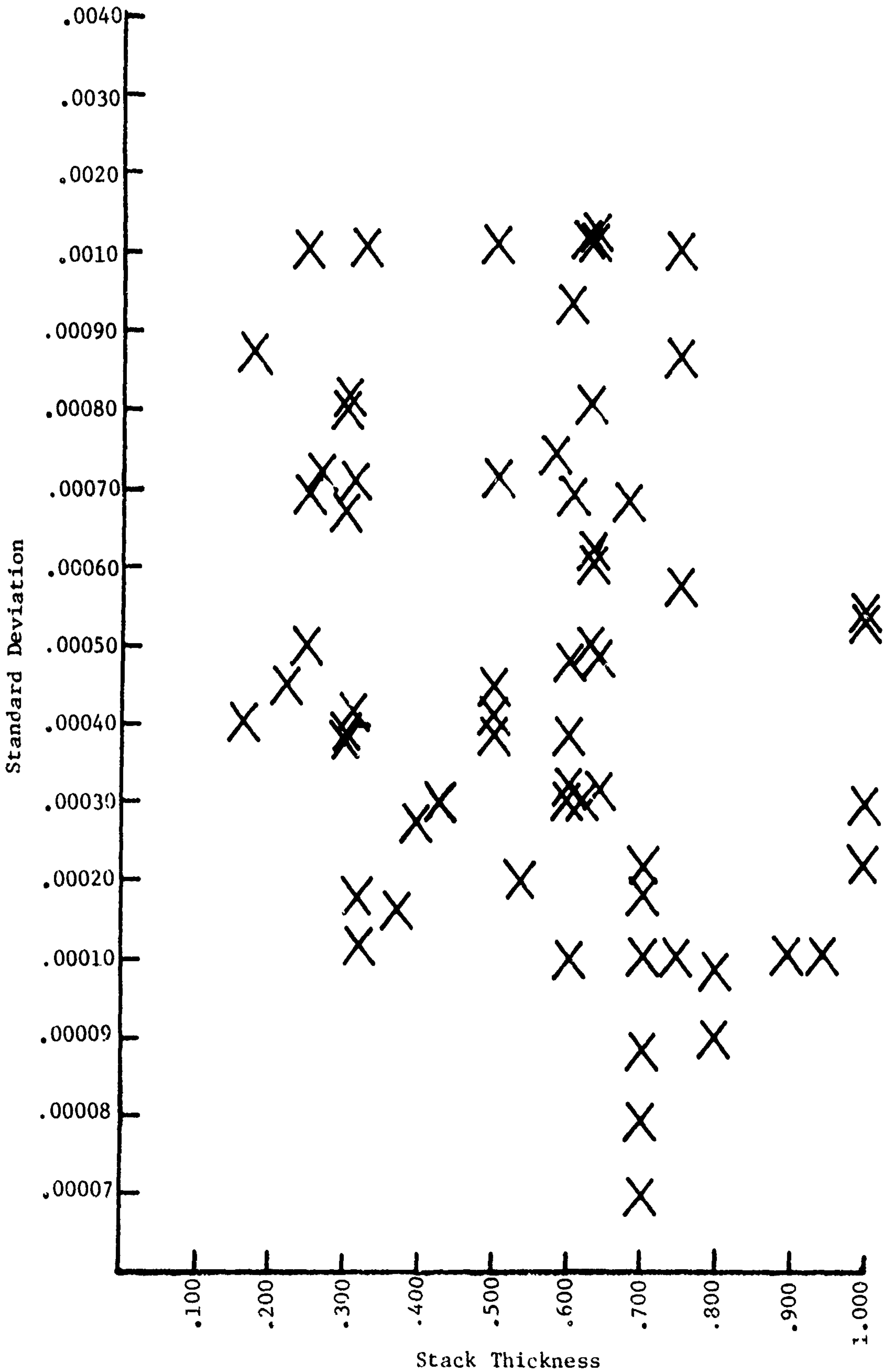

FIGURE 20 - Stack Thickness vs. Standard Deviation (Aluminum)

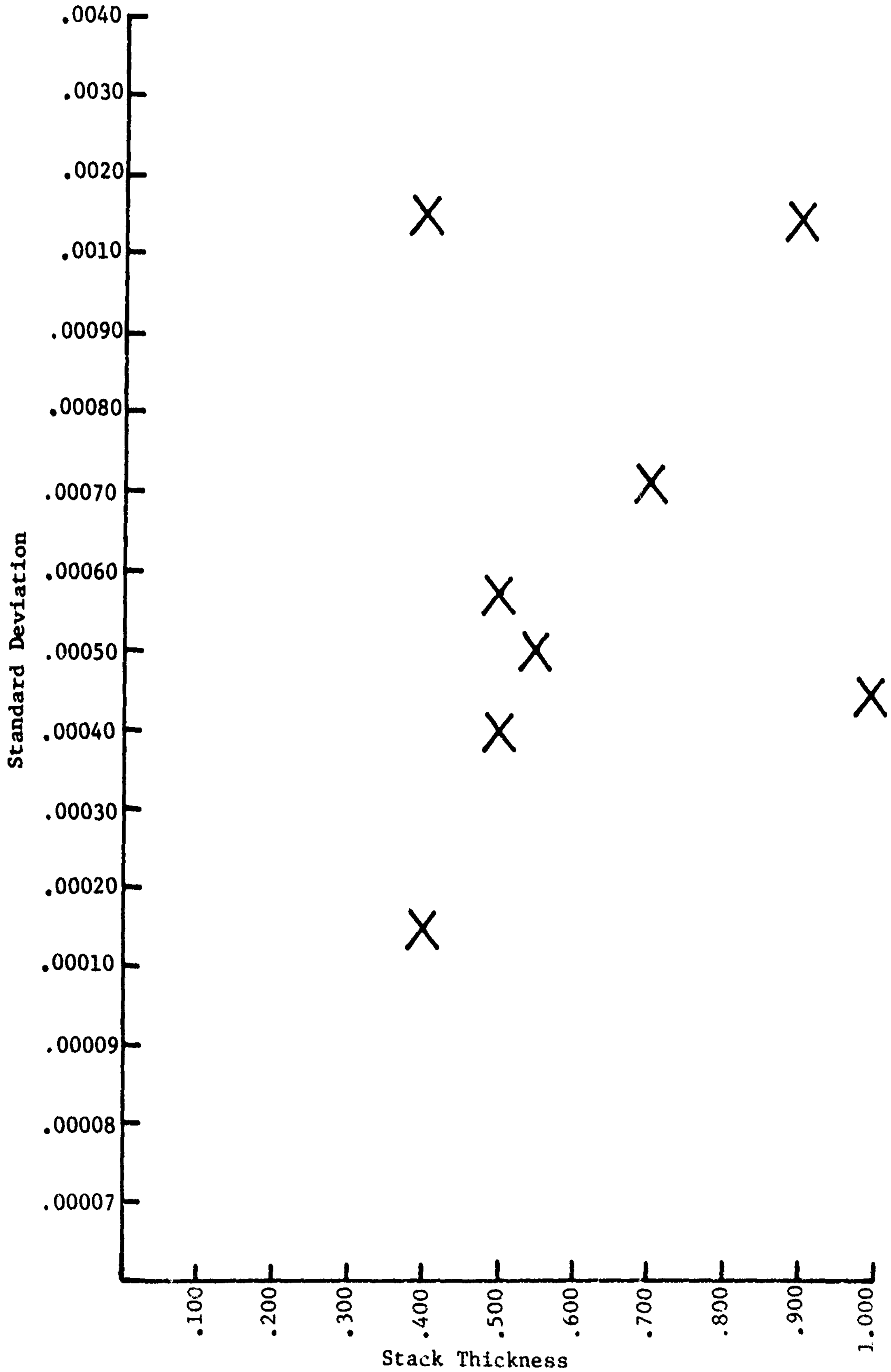

FIGURE 21 - Stack Thickness vs. Standard Deviation (AL-Steel)

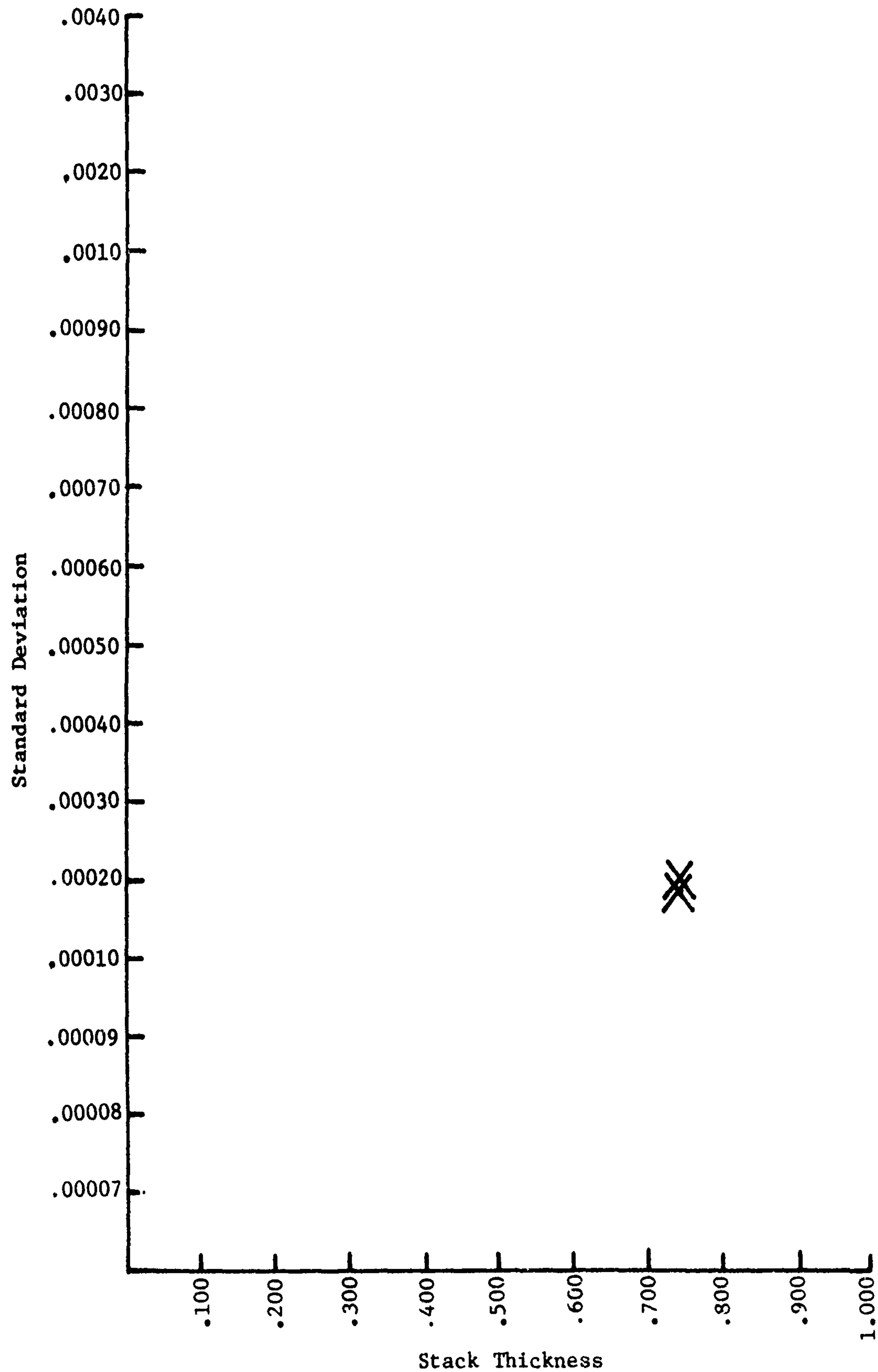

FIGURE 22 - Stack Thickness vs. Standard Deviation (AL-Titanium-Steel)

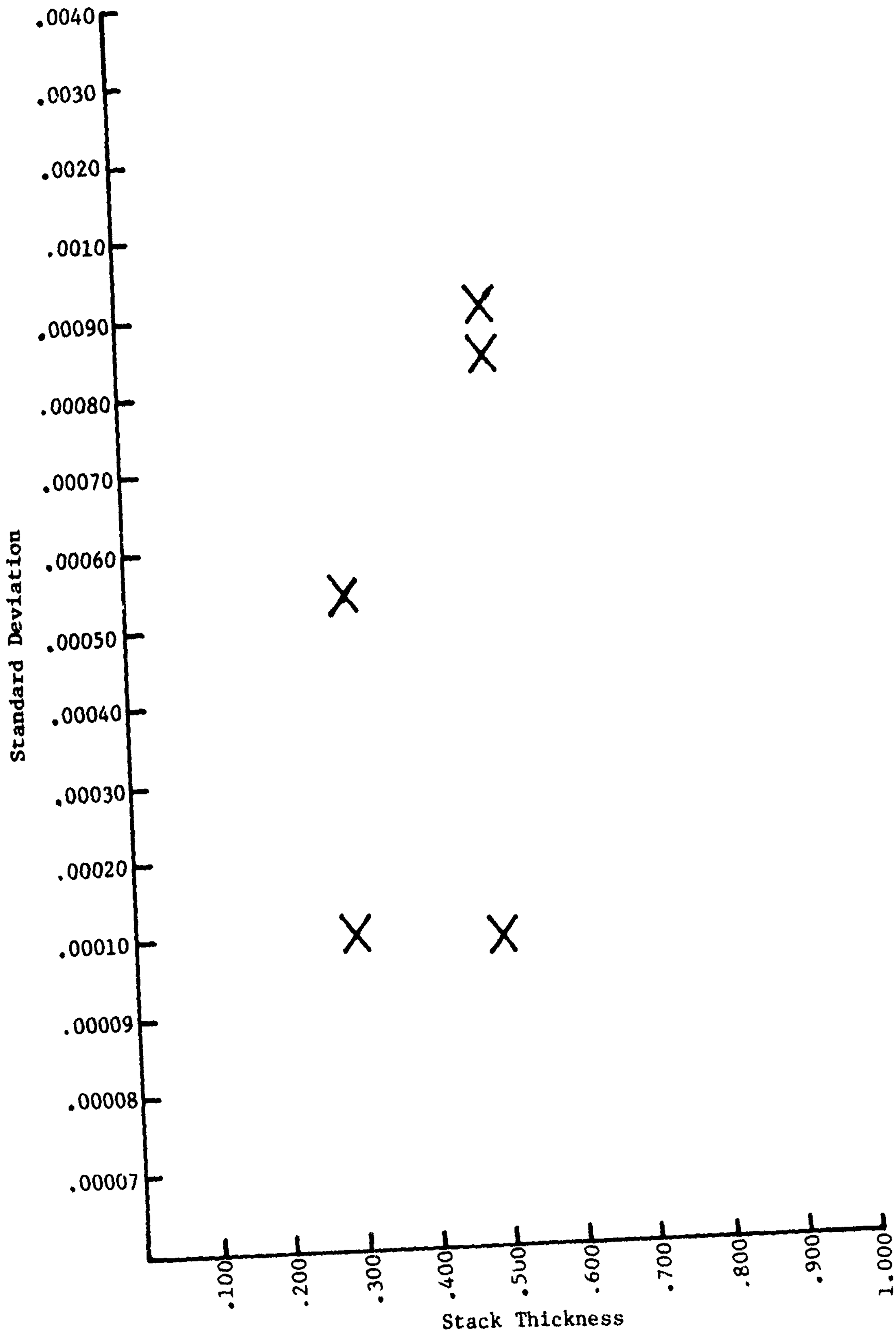

FIGURE 23 - Stack Thickness vs. Standard Deviation (Titanium)

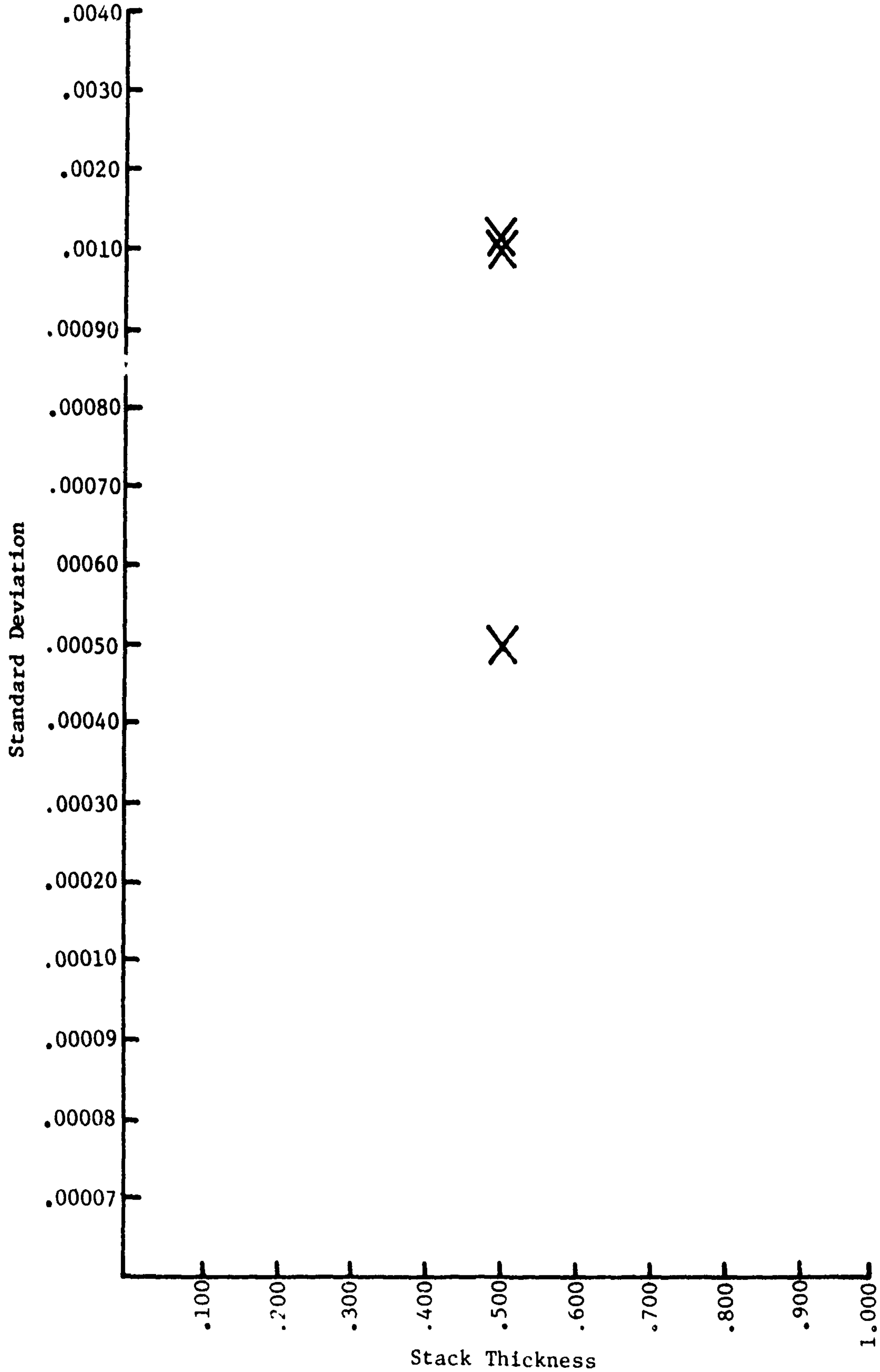

FIGURE 24 - Stack Thickness vs. Standard Deviation (Steel)

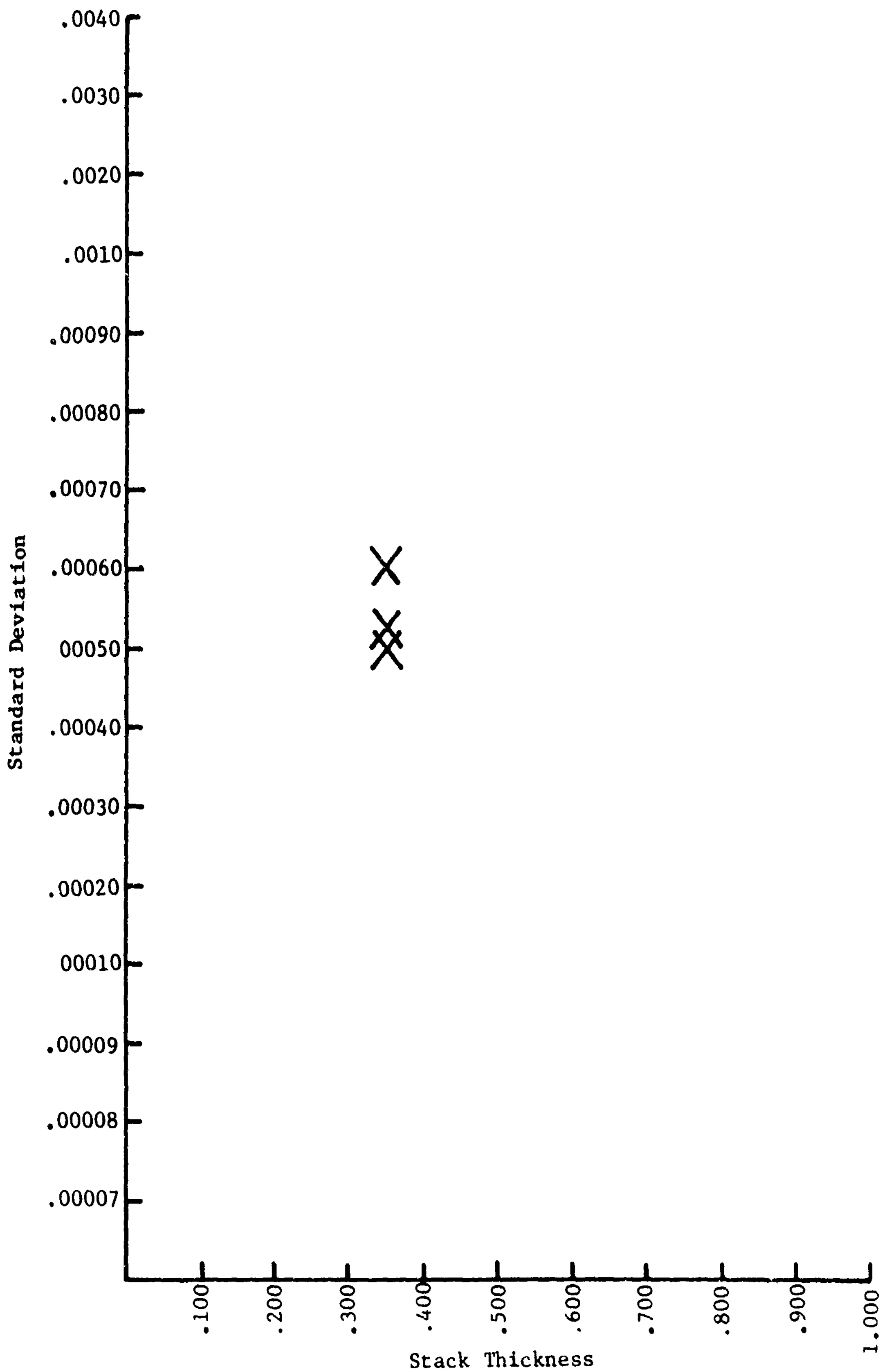

FIGURE 25 - Stack Thickness vs. Standard Deviation (Aluminum Graphite)

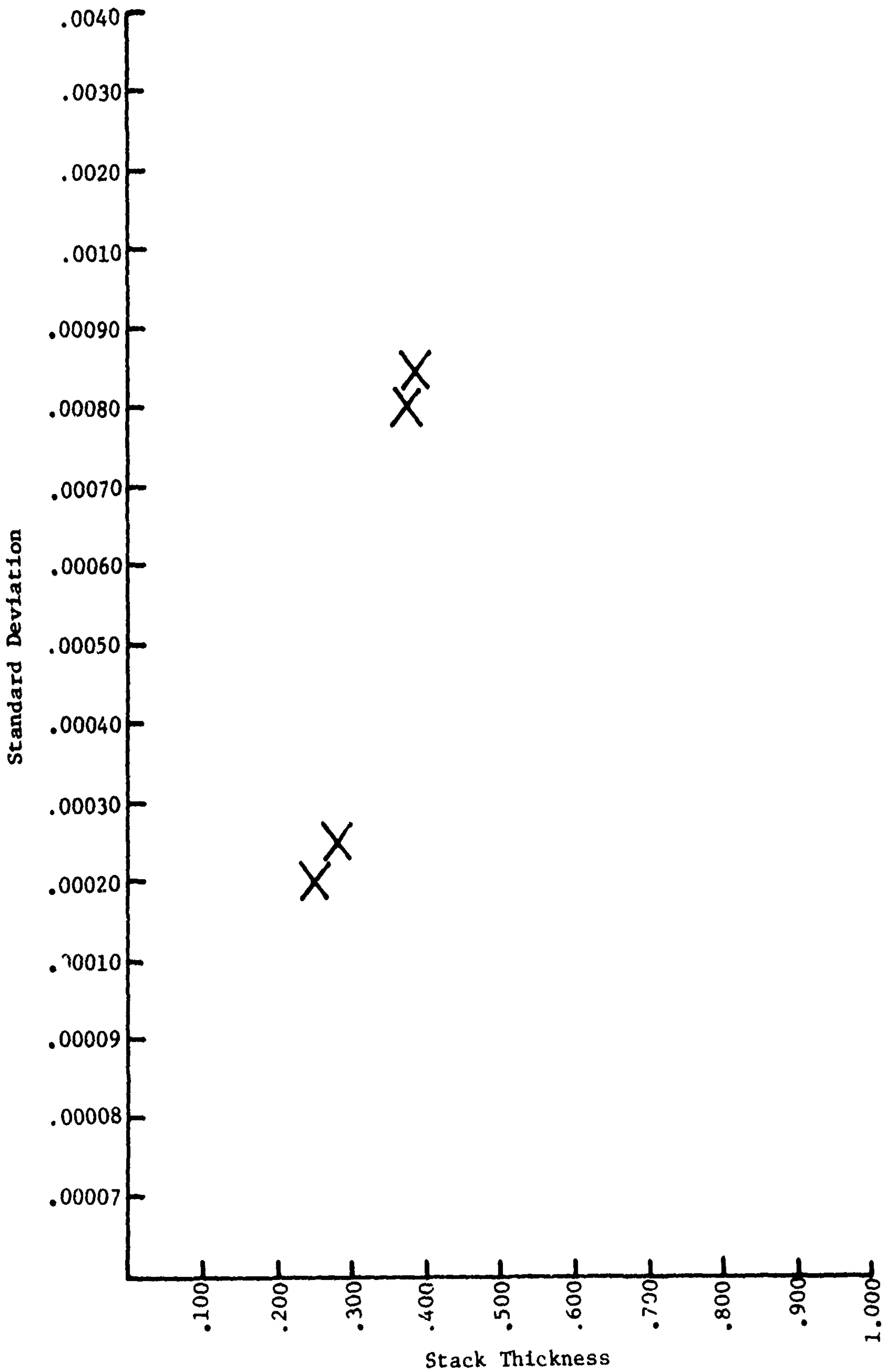

FIGURE 26 - Stack Thickness vs. Standard Deviation (Aluminum Titanium)

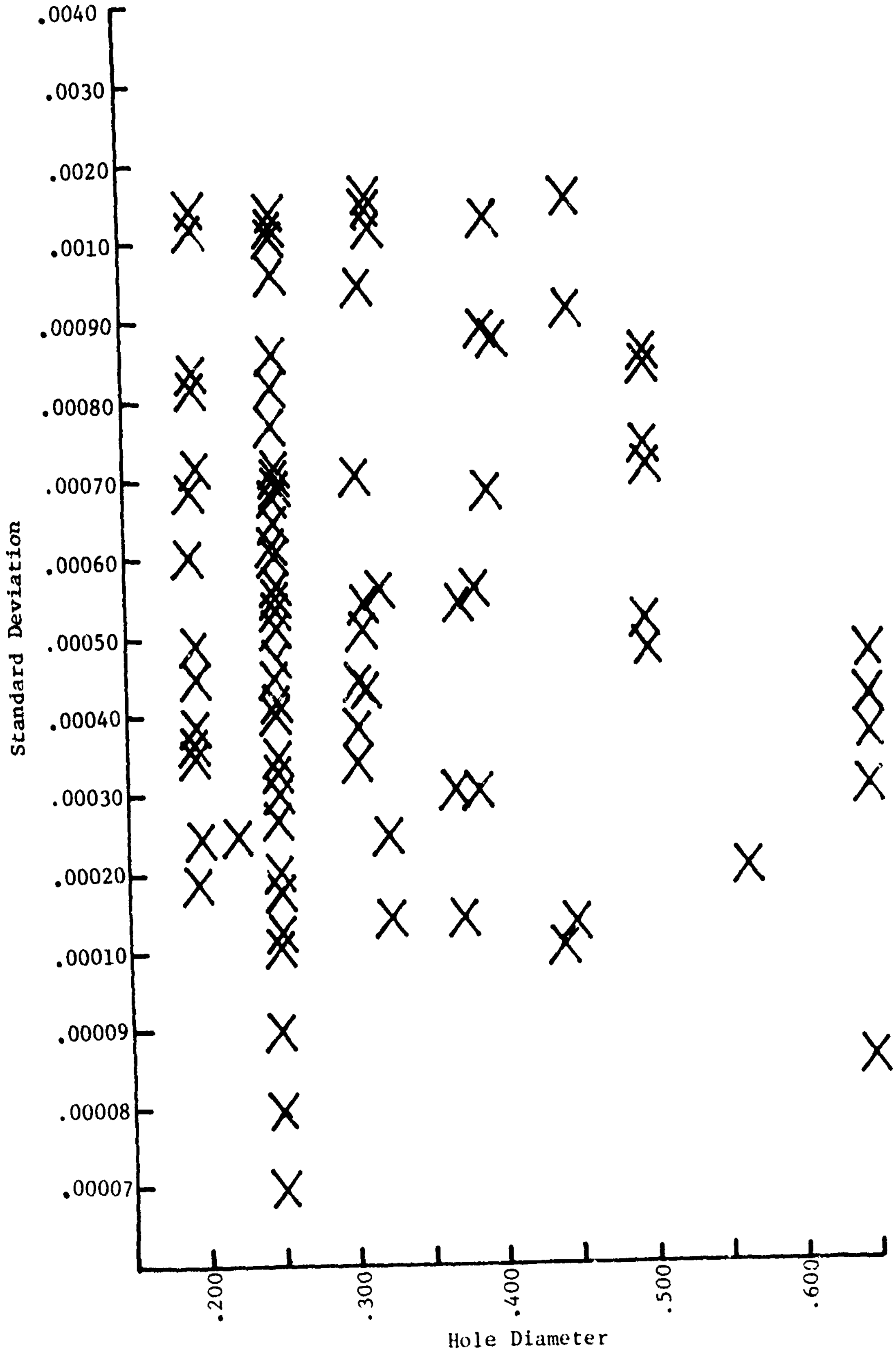

FIGURE 27 - Holesize vs. Standard Deviation

Equal (or better) results can be obtained by the "Spacematic" method and by hand drilling if structures rigidity and clamp-up are controlled.

For close tolerance and hole shape control, reaming provides more confidence in hole conformance and is generally applied.

Detailed narrative description of structure type, production method and a statistical summary of measurement results for each data lot ranked is included in Volume II of this report. These data support the multiparameter nature of production process applications and the inherent difficulty in combining results.

C. Hole Quality as a Function of Inspection

The task of evaluating hole quality as a function of inspection method was somewhat easier. Dimensional tolerances is the primary criteria applied to hole acceptance. The plug gage is the universal standard for measurement. Confidence in conformance for critical holes is generally increased by increased sampling. We had few opportunities to directly evaluate the discrimination of inspection processes on the line. The individual skill and attention of the operator would have provided some variance but was considered significant.

A more significant analysis can be made by comparing the plug gage inspection to the air gage technique used in this survey. Out of 2352 holes, initially analyzed, 8.2% could have been identified as "out-of-tolerance" by the plug gage method while 17.7% were identified as out of tolerance by the air gage method. Out of tolerance conditions not detectable by the plug gage method were primarily shape related conditions. Out of tolerance hole shape characteristics are not necessarily detrimental to the performance of the structure but are significant indicators of process control.

D. Hole Quality as a Function of Cost

1. General

Differences in cost collection producers, differences in direct versus indirect costs and variability of hole production practices did not enable quantitative cost assessment. Response to a question on drilling a 1/4 inch diameter hole in a 1/4 inch aluminum stack varied from 0.08 to 0.183 standard manhours.

2. Process Steps Versus Cost

All facilities recognize additional cost with additional processing steps, for example, ream, countersink burnishing etc. All facilities recognize additional cost in hand-drill operations without the aid of templates, positioning jigs or fixed guide bushings. All facilities recognize increased cost with increasing hole depth and with increasing material toughness, i.e., aluminum, steel, titanium.

3. Ranking By Process

Some disagreement in ranking of cost by process was found. In general, hand-drill is recognized as having the highest recurring cost per hole, followed by Quackenbush and Spacematic. One facility rated Spacematic at highest cost. This same facility reported high maintenance costs for the Spacematic equipment.

High volume producers favored rigid tooling jigs with fixed bushings with hand drill or for positive feed equipment.

4. Cost Versus Tolerance

A question identifying close hole tolerance versus cost produced surprising response. Higher reject rate was a primary concern while additional processing and inspection steps were identified as related factors.

E. Deburring

Deburring stands out as the single most variable factor in hole production between production facilities. There is considerable controversy over the requirement to deburr. The predominant practice is to destack and deburr.

As a factor which can have great effect on final hole loading, deburring is given relatively little attention.

One facility clearly defined that up to 20% of the hole depth could be disregarded for purposes of diameter variations due to deburring. A complete absence of criteria for inspection after deburring was found. Many operations, however, had planning instructions directing deburring.

F. Hole Registration

Air gaging requires use of air probes of a diameter near that of the hole. In air gaging a series of adjacent holes, the probe would frequently not fit through all holes in a line. In some cases, more forceful clamp-up solved the problem. In many cases, the difficulty was due to a shift in the registration of layers within a stack due to varying structural stiffness or to varying clamp-up during the drilling operation. If identified as a "no go" condition during plug-gage inspection, such holes were often re-reamed to "get acceptable holes." If not re-reamed, the stack could result in a local skin buckle condition as shown schematically in Figure 28.

We have been unable to locate any analyses or test data which would quantify the effects of this condition on joint performance. We suspect that this condition may be more significant than is close diameter tolerance.

We had the opportunity to examine holes in several aircraft which had been in service to assess effects of this condition. These holes were severely fretted as compared to adjacent "smooth skin" holes. We recommend that this condition be addressed in future studies.

G. Cleanliness

Interference fit fasteners have enable sig improvements in joint efficiency in airframe structures. After a hole has been prepared and accepted for fastener installation, the fastener is positioned at the entrance to the hole and is driven in with a rivet gun. The attachment collar assembly is pulled or spun into place to a predetermined tensile (clamp-up) load value.

Axial scratches within a hole were shown to have significant effect on fatigue life in a recent study program(4). Microscopic scratches are difficult to see visually, thus process control was recommended to minimize the effect. It is difficult to imagine that similar or more significant scratching may occur when the fastener is driven into place. Smoothness and dimensional control of the fastener are important to this process. Nicks due to fastener handling and foreign particles on the fastener will multiply the effect.

Cleanliness of drilling equipment, of gaging equipment, of the prepared hole and of the fastener are believed to be worthy of attention in analysis and test. Of particular concern are holes containing interface sealant and fasteners which are installed wet. The elastomeric material attracts and traps debris and is frequently stored (used) in an open condition adjacent to chip producing operations. Steel and titanium chips are known to gouge aluminum during drilling of dissimilar material stacks and would therefore expected to be contributors to flaw initiation as imbedded particles.

XIV. RECOMMENDATIONS

A. Engineering Tolerances

Engineering tolerance in hole diameter is considered to be a primary cost factor in hole production. If tolerances in hole size can be relaxed, decreased cost of production and decreased rework could be realized. Additional testing is recommended to develop and support criteria.

B. Hole Registration

Testing is in order to establish the effect, if any, on misregistration of multiple holes in a joint array.

The condition does exist in production and should be quantified.

Rigid tooling and clamp-up are not currently specified but are currently used to produce "critical holes." It is our opinion that close tolerance (diameter) is specified in some applications to force adequate tooling when a lesser tolerance could meet functional requirements.

C. Cleanliness

We recommend tests to quantify the effects of particulate contamination on joint durability.

D. Deburring

Rigidity in tooling and clamp-up along with good process control are known to decrease the need for deburring. Standard deburring methods are required for cases where deburring cannot be avoided. Quantitative fatigue/deburr data should be developed.

E. Process Qualification

Variations in process application and higher reject rates for close tolerance holes are indicators that a process has not been qualified for the output required. Tooling, tool grind and type, method, coolant, feeds and speeds, selected for a process should be capable of use in demonstrating a given process variability. The measurement system developed for this program may be of significant value in demonstrating capabilities as well as establishing criteria for regrind (holes/grind) and equipment maintenance. Dimensional quantification along with chip examination should be of significant aid in qualifying a process.

A recent analysis suggests that residual stress and heat generation during machining can reduce fatigue life [21]. One manufacturer's process specification contains criteria for heat generation, i.e, comfortable to the touch, for drilling operations. Aluminun alloys are known to be sensitive to overheating and develop increased hardness with slight overheat. Qualification samples may be instrumented or may be examined by microscopic techniques after sectioning.

Once process control is established, inspection sampling by a selected method is meaningful.

We recommend process qualification as an initial aid to adequate tooling and process development and spot sampling during a production run for trend monitor. The quality of a hole is dependent on the process control in producing it and not solely on factors which can be readiliy measured after the fact.

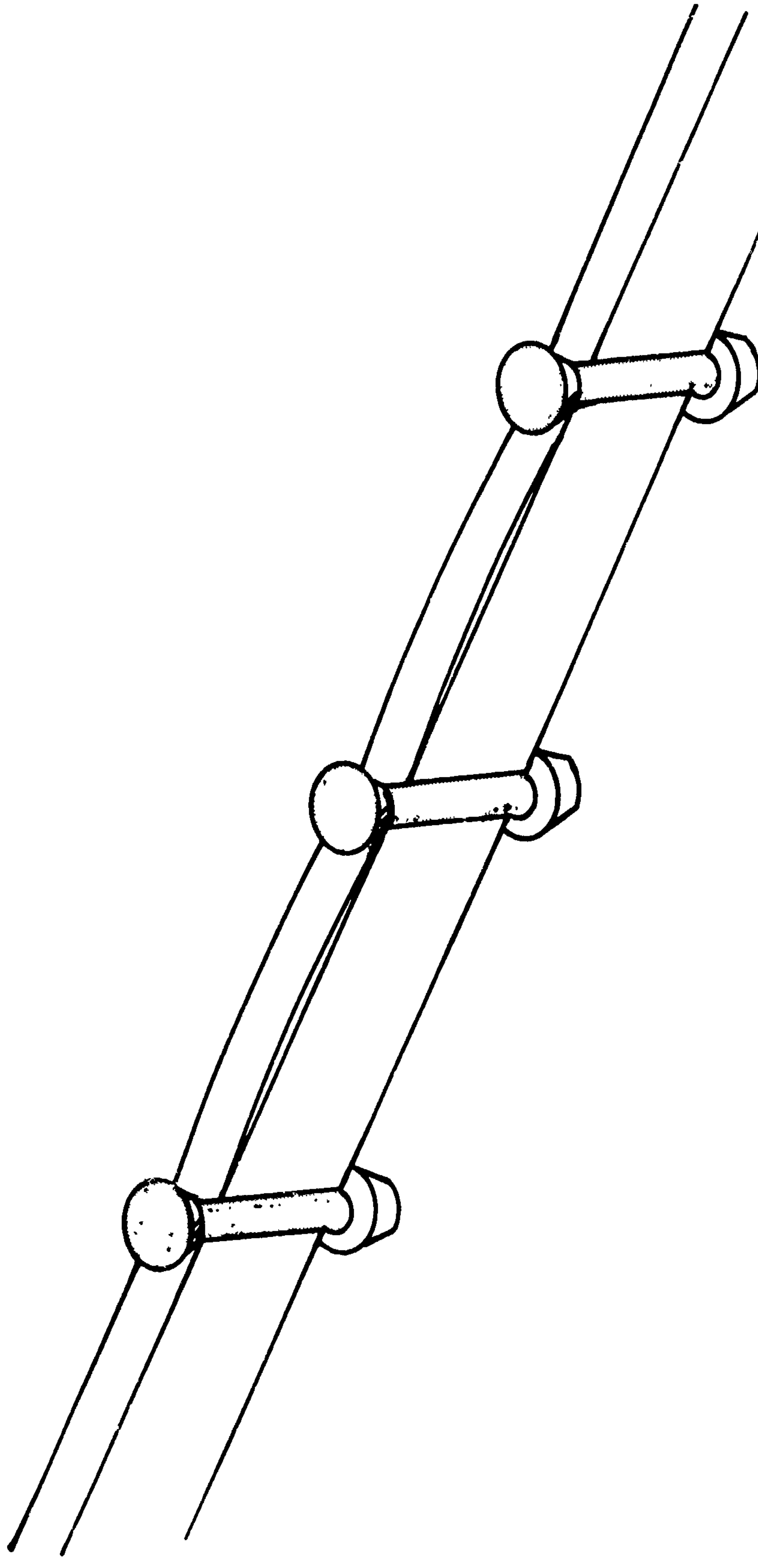

FIGURE 28 SKIN BUCKLE CONDITION

References:

1. Moore, Major Tehomas K. "Factors Believed to Influence the Fatgieu Life of Mechanically Fastened Shear Joints. AFML, Workshop on NDI, July, 1974.

2. Rudd, J. L. and T. D. Gray, "Quantification of Fastener Hole Quality," Transactions 1977 AIAA Meeting, pp. 131-137.

3. Wood, Howard A., Joseph Gallagher, Robert M. Engle and John M. Potter, "Current Practice On Estimating Crack Growth Damage Accumulation with Specific Application to Structural Safety Durability and Reliability," AFFDL-TR-75-32, Jan. 1976.

4. Contract F33615-76-C-3113 "Fastener Hole Quality," General Dynamics, Fort Worth Division.

5. Contract F33615-75-C-5173 "Verification of Production Hole Quality," Metcut Research Associates, Inc., Cincinnati, Ohio.

6. Lewis, W. H. Jr, H.S. Gibson, Jr, W. R. Hood, L. Faulkner, E. B. Trend and D. R. Walden, "Dimensional Evaluation of Tapered Fastener Systems," AFML-TR-77-203, December 1977.

7. Cooper, Leslie E. "Dimensional Evaluation of Tapered Fastener Systems." Interim Report IR-879-6A (I), Contract F33615-76-C-5283, February 77.

8. Western Gage Corporation, 8842 National Blvd., Culver City, California 90230. Telephone (213) 879-2002.

9. Diatest Gages, The Iver J. Esbenson Co. 666 Bryant Street, Denver, Colorado 80204. Telephone (303) 571-1606.

10. Alina Corporation, 175 Sunnyside Blvd., Plainview, New York, 11803. Telephone (516) 433-1000.

11. Gould, Model 7100 Surf Indicator, Measuring Devices Division, F.S. Leonard Co., P. O. Box 385, Broomfield, Colorado 80020.

12. GAR Electroforming, Division of Mite Corporation, Danbury, Conn., 06810. Telephone (202) 744-4300.

13. Sight-Pipe is a trademark of Dave Jones Machinists, 1023 South Main Street, South Bend, Indiana, 46618. Telephone (219) 288-8722.

14. SWS Silicones Corp., P. O. Box 428, Adrian, Michigan, 49221. Minimum lot buy of 30 pounds required.

15. Stannous octate is available from local chemical supply houses under its generic chemical name.

16. Spacematic is a trade name for equipment manufactured by the Deutsch Fastener Corporation, 7001 West Imperial Highway, Los Angeles, California. Spacematic equipment was formerly produced by Winslow.

17. Quackenbush is a tradename for equipment manufactured by Dresser Industries, Dallas, Texas.

18. Sheridan Products, Inc., Los Angeles, California.

19. Dreamer Tool Co., A Division of Cutting Tooling Inc., 956 Linwood Street, Brooklyn, N.Y. 11208. Telephone (212) 649-3200. Formerly distributed by Custanite Corp.

20. "Wilson Airless Airgage," Wilson Instrument Company, 587 South Hill Ave., Pasadena, California, 91106. Telephone (213) 449-4858.

21. Bates, W.F., Jr. "Entropy Sheds Light on the Behavior of Metals," Machine Design, April 20, 1978, pp 46-49.

APPENDIX A

A TYPICAL LOT SAMPLE ANALYSIS REPORT

DRILL METHOD Q-3

RANKING NUMBER 3*

HOLE SIZE: 0.6270"/0.6280"

I. OVERVIEW:

A. This set of production holes features drill, reaming and cold work roller burnishing of the Structural Fin. The structure is a very heavy machined fin skin whose thickness is tapered on both the inner and outer faying surfaces to match interfacing structure. Owing to the tapers with regard to the "thru-hole" air probe, an engagement length in the holes of approximately 0.70" was measured to avoid bleed out at the tapered faces. The subject hole is sized by Engineering at 0.6270"/0.6280".

II. SUMMARY:

A. This set of holes, roller burnished to achieve final Engineering size, is the most perfect geometrically configured and finish textured series of holes from all lots surveyed at this facility.

Twenty-nine (29) holes were available from a series of Fin Assemblies to accrue the aforenoted sampling set size. The method of production featured Quackenbush preliminary hole drilling and reaming. These operations were followed by cold worked roller-burnishing to achieve the final hole size per Engineering criterion.

B. Reference Executive Summary by Data Lot. This set discloses a measurement distribution whose arithmetical average is 0.627484" for the set of twenty-nine (29) holes. This value is an excellent feature since it resides at the mid-point of the Engineering tolerance range. All of the holes for this set meet the Engineering Criteria.

Apecific discussion on the geometric characteristics of the holes are discussed at paragraph III.

C. The Computer Statistical Printout for this series of holes provides composite clues traceable to the following for the production of excellent holes:

1. Custom designed fixturing ensures interchangeability and location reliability. Fixture is extremely heavy to accommodate roller burnishing.

2. Quackenbush drill method and accessory tooling produces very good preliminary holes prior to cold working in the following sequence:

   a. Preliminary pilot hole drilling to 0.500" diameter.
   b. Core drilling to 35/64" diameter.
   c. Dreamer combination drill/ream to 0.6265"/0.6270".

* DRILL METHOD CODING: Q-3 = Quackenbush - One shot Quackenbush, drill method and accessories; tooling, preliminary pilot hole drilling, core drilling, "Dreamer" combination.

3. Cold work roller burnishing to final Engineering size at 0.6270"/ 0.6280".

4. Planning is very good, providing adequate work instructions and definition of inspection requirements.

III. CHARACTERISTICS:

A. Hole Size: 1064 data measurements were accrued for the series of twenty-nine (29) holes. The arithmetical average for the set, 0.627484", is an ideal characteristic in regard to the Engineering criterion of 0.6270"/0.6280". This is an excellent series of holes on size, geometric features and hole finish texture.

1. Reference to Individual Computer Printout discloses an excellent overall measurement range from the highest to lowest reading within the thirty-six (36) to forty (40) measurements per hole. The range of measurements are as follows:

Hole #	Range	Hole #	Range
1	0.000362"	16	0.000319"
2	0.000414"	17	0.000517"
3	0.000448"	18	0.000391"
4	0.000491"	19	0.000267"
5	0.000414"	20	0.000319"
6	0.000319"	21	0.000353"
7	0.000466"	22	0.000293"
8	0.000405"	23	0.000440"
9	0.000475"	24	0.000500"
10	0.000267"	25	0.000422"
11	0.000440"	26	0.000353"
12	0.000276"	27	0.000388"
13	0.000388"	28	0.000595"
14	0.000672"	29	0.000440"
15	0.000388"		

Focus onto the above measurement ranges was for the purpose of drawing attention to the fact that this series of holes are nearly perfect. Several holes exhibit an extremely slight bulge enlargement generally along one (1) axis of measurements interpreted as a failure to "clean-out" due to minute concentricity differences between the Dreamer (0.6265"/0.6270") operation and final roller burnishing (0.6270"/0.6280").

2. Reference Individual Hole Computer Printouts and item III.A.1. above. Nine (9) holes exhibit a slight bulge identified via Computer Profile Printout and Measurement Data. The specific holes and bulge orientations are identified as follows:

Hold #	Axis Affected	Magnitude max. & plane level
2	135^o	.0002" at level 6 and 7
3	135^o	.0002" at level 5
4	45^o	.0002" at level 5, 6 and 7
5	135^o	.0003" at level 5, 6 and 7
7	0^o	.0002" at level 4, 5, 6 and 7
9	135^o	.0002" at level 6
14	45^o	.0003" at level 4 and 5
23	0^o	.0003" at level 5 and 6
24	0^o	.0003" at level 5

Note: In all cases, the bulge configuration was not evident as a physical mar or defect of abrupt shape and/or geometry. Very subtle finish texture identifiable by variation of light reflection identified the locations and orientation. Orientations were confirmed via hole indexing from which measurements were taken by "thru-hole" air probe. All holes, including the bulge measurements were well within the Engineering tolerance criterion. The bulges were not considered a detriment to hole quality by this analysis effort.

3. Reference to Individual Hole Histograms reveal an excellent dispersion of data elements populated about the mid-range of the hole tolerance zone. The Normal Gausian Distribution representative of this data is suggestive of tools, personnel and processes functioning in complete harmony. This series of holes, considering all geometric features and hole finish texture are excellent.

Reference Executive Summary Histogram. The data population is excellent and crowds the mid-range of the tolerance zone. Again, as per the Individual Hole Histograms, a Normal Gausian Distribution is evident signifying controlled hardware processing and notable craftsmanship on the finished product.

B. Ovality: Maximum recorded ovality within the set occurred at Hole #14 and discloses a value of 0.000672" at plane level #9 on the 45^o -135^o axes. Enlargement at the exit plane of measurements most probably is the result of irregular breakout of the Dreamer that failed to "clean-up" on roller burnishing. The ovality magnitude is well within the Engineering tolerance criterion and is not a detracting feature for hole quality.

Ovality was not a cause for concern on this set. Reference to Individual Hole Computer Printout disclosed all holes to be extremely good on the ovality measurements. None of the hole of this set exceeded the Engineering Criterion.

C. Perpendicularity: Heavy fixturing assures correct angularity of the holes with regard to faying surfaces of interfacing structure. This series of holes were checked by gaging with a 10X magnification Azimuth/Angle Gaging Device. The longitudinal axis of the hole was verified to be 5° closed with regard to the outboard machined face of the structure, measured normal (90°) to the Fin Waterline 2.000 reference and along Fin Stations 18.996 and 23.997.

D. Straightness: Straightness is within Engineering design tolerance as indicated by profile analyses.

E. Barrelling: None existent as evidenced by profile analyses.

F. Bellmouthing: None existent as evidenced by profile analyses.

G. Hole Texture: Rifling, Scratches, Chatter Marks. This set of holes exhibited a very good interior wall texture. There were no perceptible rifling traces on the hole sidewalls when inspected by Sight Pipes at 3X magnification. There were no chatter marks nor vertical scoring in these holes.

H. Burrs: This structure, drilled, reamed and roller burnished through one (1) solid flange was deburred satisfactorily in the normal process plan work instructions.

I. Surface Finish: All holes of this set exhibited a surface finish significantly superior to "63 AA" and approximating "32AA". Surface was smooth and shiny. Surface finish differences helped confirm the presence of the minute bulges described per narrative at items III.A.1. and III.A.2.

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