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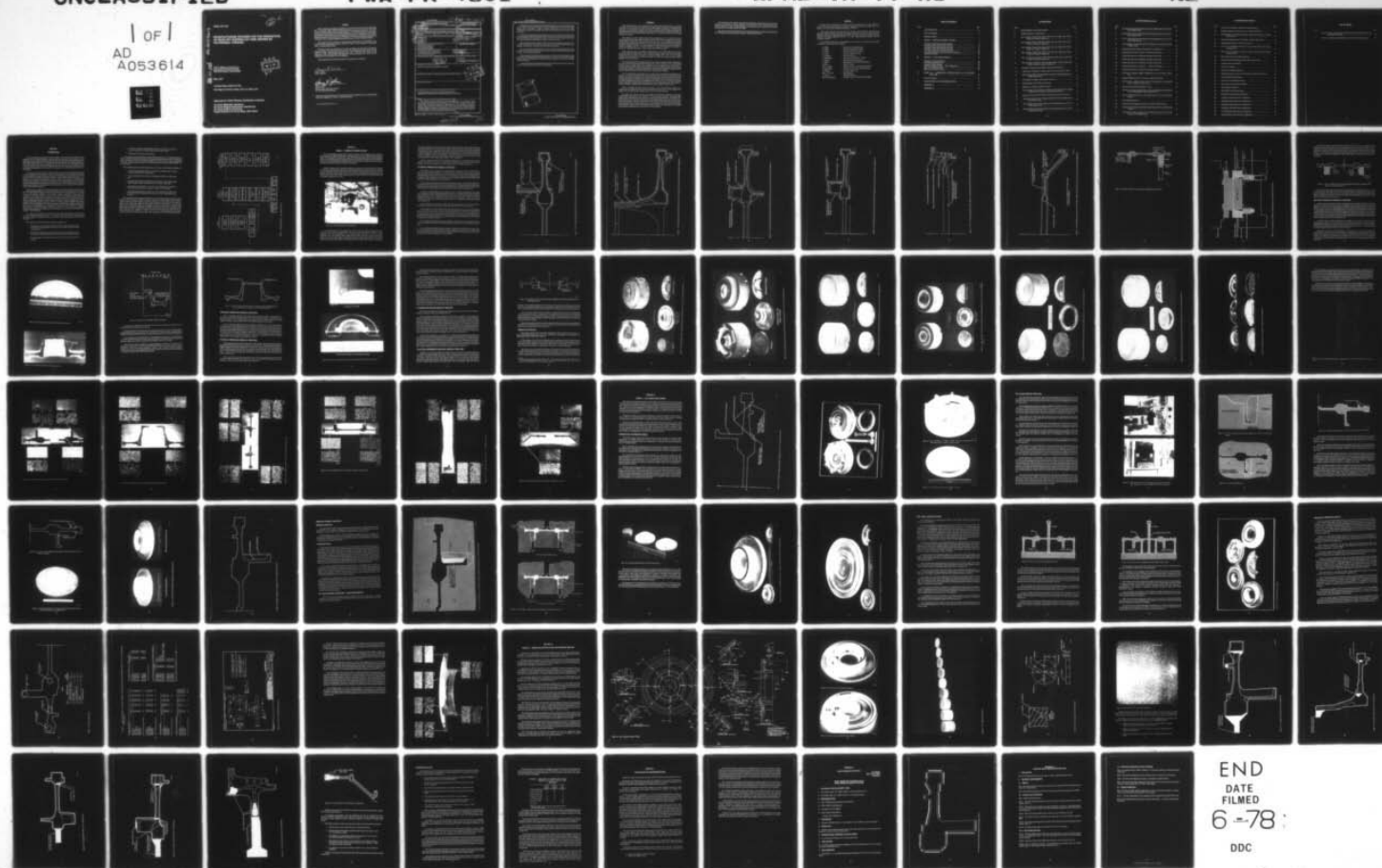
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**MANUFACTURING PROCESS FOR THE PRODUCTION
OF NEAR NET SUPERALLOY DISK SHAPES BY
ISOTHERMAL FORGING**

Pratt & Whitney Aircraft Group
Government Products Division
West Palm Beach, Florida 33402

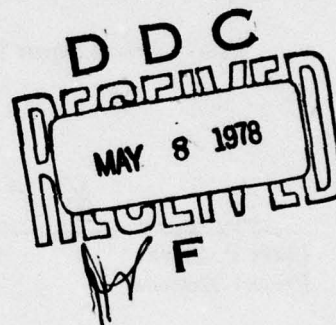
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Technical Report AFML-TR-77-80

Final Report for Period 19 May 1975 to 21 March 1977

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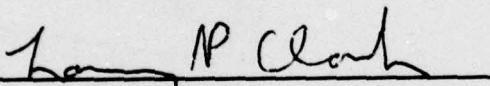
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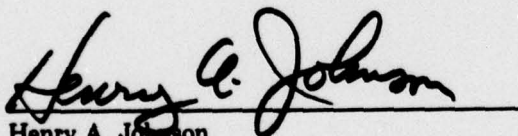
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This final report was submitted by the Pratt & Whitney Aircraft Group Government Products Division, United Technologies Corporation, West Palm Beach, Florida, under Contract F33615-75-C-5184, manufacturing methods project 278-5 "Manufacturing Process for the Production of Near Net Superalloy Disk Shapes by Isothermal Forging." Mr. Larry P. Clark, AFML/LTM, was the Laboratory Project Engineer.

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


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This program met these objectives through the demonstration of a two-step manufacturing process, billet to preform to final shape. The isothermal forging technique, used in this two-step process, allows the forging of complex, contoured shaped parts. The near net forging configurations optimized in this program were based on a 0.050-inch minimum envelope over the actual part.

The preform and final forging configurations for each of the six engine parts considered were optimized during a subscale optimization phase. Successive subscale forging iterations were made until final parts were forged with complete die fill and free of laps. Experience has shown that optimized subscale configurations are directly scalable to full-scale.

The full-scale phase of the program scaled up the optimized subscale configuration of the 1st-stage turbine disk. Five full-scale parts were forged for mechanical properties testing, sonic inspection demonstration, and release for experimental engine testing.

The two-step process produced lighter-than-current forgings which responded well to heat treatment. This response resulted in excellent mechanical properties. The properties significantly exceeded current production properties.

The sonic inspection phase demonstrated the ability to inspect the near net shape 1st-stage turbine disk. This was accomplished through extension of state-of-the-art transducer and pulser design. A major accomplishment was achieving 0.050-inch near and far surface resolution through 3 inches of material.

A cost study determined that \$20,000 per F100 engine could be saved with the incorporation of the two-step process to produce near net shape forgings.

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SUMMARY

The overall objective of this program was to develop and incorporate near net forging techniques into the production of F100 turbine disks, spacers, and seals. This program was conducted in three phases, Subscale Disk Study, Full-Scale Disk Forging, and Inspection Specifications and Economic Analysis. The six IN-100 (PWA 1073 & 1074) parts selected for this program were the 1st- through 4th-stage turbine disks, the 1-2 turbine rim spacer, and 13th-stage compressor cone seal.

The objectives of this manufacturing technology program are: (1) to reduce the cost of manufacturing IN-100 disks, seals, and spacers for the F100 engine by forging closer to finish shape thereby reducing input material and machining costs; (2) to establish a reproducible manufacturing process for the production of near net disk, seal, and spacer shapes by advanced isothermal forging techniques; (3) to demonstrate the developed process and fully laboratory qualify the forgings; and (4) to extend established nondestructive inspection techniques as required to assure full inspection of near net disk, seal, and spacer shapes.

These objectives were met through the demonstration of a two-step forging process, billet-to-preform, preform-to-final shape. The isothermal forging technique, used in this two-step process allows the forging of complex, contoured shaped parts. The near net forging configurations optimized in this program were based on a 0.050-inch minimum envelope, where possible, over the actual part.

The subscale phase of the program optimized the preform and final forging configurations for each of the six aforementioned F100 engine parts. The optimizations were accomplished through iterative forging studies where preforms of various diameters were forged until a successful part was made. When varying the preform diameter failed or lapping occurred, the die contour was modified to accomplish optimization. The subscale forgings were checked for heat treat dimensional stability and were examined for metallographic integrity.

In the second phase of the program, the 1st-stage turbine disk subscale configuration was scaled up to produce five forgings. The five full-scale parts were used for mechanical properties testing, sonic inspection demonstration, and experimental engine testing. Initially, the full-scale configuration formed the flange of the integral arm through the use of removable inserts in the die. This configuration proved to be unsatisfactory for production due to its inability to perform restrike operations. The final forging configuration for the 1st-stage turbine disk was modified to obtain a restrikable configuration. This decreased the input weight savings by 9.5 lb.

After a successful full-scale forging was made, a heat treat distortion study of the configuration was performed. Distortion was minimized by using a fixture that supported the forging at the rim and the bore during the first cycle of the heat treatment.

To qualify the two-step process for production, mechanical properties testing and metallographic examinations were performed. The mechanical properties testing included tensile, creep, stress rupture, strain control low-cycle fatigue, and bolthole low-cycle fatigue. The specimens were cut at various locations from a heat treated forging. The creep, stress rupture, and low-cycle fatigue results were all well above current production PWA 1074 properties. The tensile properties were as good or better than current material. The bolthole low-cycle fatigue results were far superior to PWA 1074 baseline results. The laboratory qualification also included metallographic examinations to assure microstructural integrity.

The third phase of the program dealt with sonic inspection improvement and an economic analysis of the production process. Extension of state-of-the-art sonic inspection techniques allowed inspection of near net shape forgings as demonstrated with a sonic reference master machined from a 1st-stage turbine disk forging.

The economic analysis showed that the two-step forging process is capable of saving \$20,000 per F100 engine plus producing parts of superior mechanical properties.

PREFACE

The final report is submitted in accordance with the requirements of Contract F33615-75-C-5184. This report details the work performed during the period from 19 May 1975 to 19 February 1977 and carries the P&WA designation of FR-8401.

This contract with the Government Products Division, Pratt & Whitney Aircraft Group, West Palm Beach, Florida, was under the technical direction of Mr. L. P. Clark, Air Force Materials Laboratory, Wright-Patterson AFB, Ohio. Mr. Bryant H. Walker, Project Materials Engineer, was program manager and Mr. L. N. Fuss, Senior Materials Engineer, was the responsible engineer.

The following personnel are acknowledged for their efforts and support which greatly contributed to the success of this program.

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SECTION I

INTRODUCTION

To meet performance demands of advanced engines, more advanced materials have been sought for use in turbine disks and other gas turbine components which operate at high temperatures. New powder metallurgy techniques now allow the use of advanced superalloys to meet these demands. However, the use of these powder metal applications is still dependent upon developing a production process compatible with the end product. Pratt & Whitney Aircraft Group Government Products Division (P&WA/Florida) has accomplished this through the use of an isothermal forging process to produce IN-100 compressor and turbine disks, and seals for the F100 engine.

This process, which has produced turbine parts for 7 years, uses hot isothermal forging and a controlled forging rate to maintain a condition of superplasticity in material previously placed in that condition by special processing techniques. By exploiting the superplastic state of the material the process allows forging of complex contoured shape disks to extremely close tolerances with no surface cracking. With this process, parts may be forged to near finished shape with minimal machining to obtain finish dimensions. This capability, relative to conventional forgings, offers significant cost reduction potential both from the standpoint of reduction of billet input weight to produce the forging and to the machining of excess material from the forging to produce the finished component.

Although input weights for IN-100 parts have been significantly reduced for the F100 engine over previous forging techniques, the potential for further reductions by forging to near net shape have not been exploited because of the required envelope to facilitate square cut outlines necessary for ultrasonic inspection. Now, however, sufficient experience in inspecting F100 components has been acquired to conclude that IN-100 powder metallurgy parts isothermally forged to near net shape can be inspected with minimal extension of state-of-the-art sonic inspection technology. Extension of state-of-the-art techniques is currently taking place under a separate AFML NDI program Contract F33615-75-C-5193, awarded to P&WA. The primary objective of this NDI program is to develop a computer controlled sonic inspection system which will allow for accurate inspection to complex contoured surfaces. This, coupled with improvements made in isothermal forging technology, made for a low risk effort to establish manufacturing techniques for producing near net shape parts that would yield a substantial cost savings for the F100 engine.

To realize this cost benefit for the F100 engine the manufacturing technology division of the Air Force Materials Laboratory funded this program which optimized the manufacturing techniques required to incorporate the near net shape isothermal forging process into F100 production.

The objectives of this manufacturing technology program were:

1. To reduce the cost of manufacturing IN-100 disks, seals, and spacers for the F100 engine by forging nearer to finish thereby reducing input material and machining costs
2. To establish a reproducible manufacturing process for the production of near net disk, seal, and spacer shapes by advanced isothermal forging techniques
3. To demonstrate the developed process and fully laboratory qualify the forgings

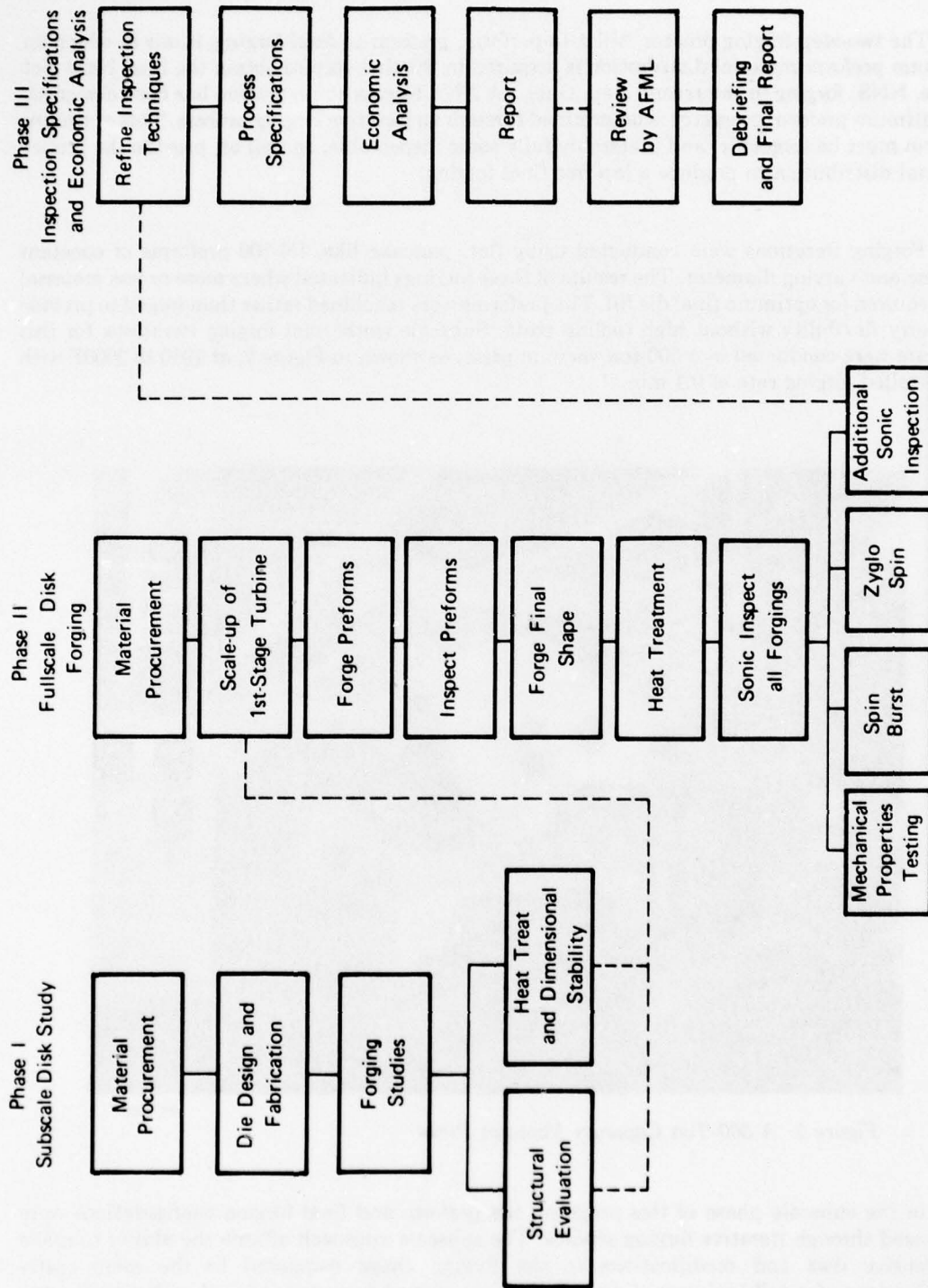
4. To extend established nondestructive inspection techniques as required to assure full inspection of near net disk, seal, and spacer shapes
5. Determine the economics of the process.

This program met these objectives through the demonstration of a two-step forging process, billet-to-preform, preform-to-final shape. The isothermal forging technique, used in this process, allows the forging of complex, contoured shaped parts. The near net forging configurations optimized in this program were based on a 0.050-inch minimum envelope, where possible, over the actual part.

The advantages of the two-step forging process over other current forging techniques are:

1. A flat pancake-like preform that can be easily and rapidly forged in a small hydraulic press (500 tons) using flat dies
2. A sonic inspection of the preform is thorough and reliable, no blind zones exist.
3. A preform step enables the material to be forged into more complex final shapes because of better material distribution without forging laps
4. An efficient heat treatment of the near net forging shapes resulting in mechanical properties that are superior to thicker section forgings
5. A reduced manufacturing cost because of less required input weight and fewer manhours to finish machine a near net part, due to less material to be removed.

This manufacturing technology program was a 21-month technical effort conducted in three phases as shown in Figure 1. Phase I consists of subscale die design, forging studies, and part evaluation of the four turbine disks, the 13th-stage compressor cone seal, and the 1-2 turbine rim spacer for the F100 engine. Phase II scaled up the subscale work of Phase I on the 1st-stage turbine disk to produce full-scale parts for laboratory evaluation and release for experimental engine testing. Phase III established acceptable nondestructive inspection procedures using refined state-of-the-art techniques to inspect the near net shape disk. Also in Phase III, an in-depth evaluation was conducted to assess the economics of incorporating near net shape isothermal forging of IN-100 superalloy disks, seals, and spacers into the F100 engine production.



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Figure 1. Phase Breakdown of Net Shape Program

SECTION II

PHASE I — SUBSCALE FORGING STUDIES

The two-step forging process, billet-to-preform, preform-to-final forging, is one in which an optimum preform material distribution is acquired in the first step to obtain the final Near Net Shape, NNS, forging in the second step. Once the NNS forging configuration has been designed, the optimum preform geometry is determined through an iterative forging process. This optimum preform must be forgeable, and preferably fully sonic inspectable, as well as, provide the proper material distribution to produce a lap-free final forging.

Forging iterations were conducted using flat, pancake like, IN-100 preforms of constant volume and varying diameter. The results of these forgings indicated where more or less material was required for optimum final die fill. The preforms were machined rather than forged to provide geometry flexibility without high tooling costs. Subscale isothermal forging iterations for this program were conducted in a 500-ton vacuum press, as shown in Figure 2, at 1950 to 2000F with a controlled forging rate of 0.1 min.^{-1}

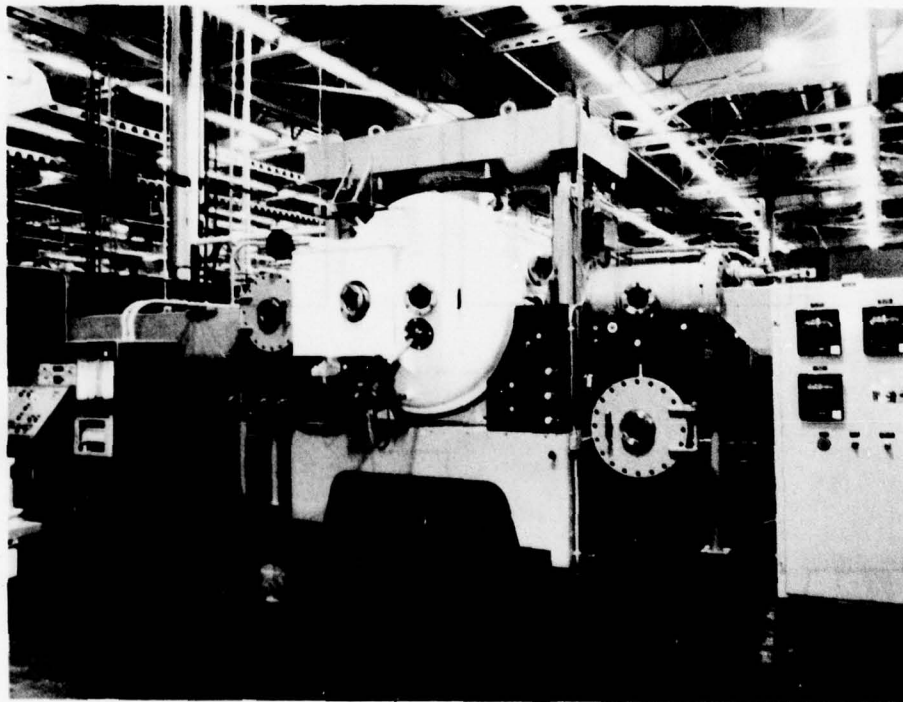


Figure 2. A 500-Ton Capacity Vacuum Press

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In the subscale phase of this program, the preform and final forging configurations were optimized through iterative forging studies. The subscale approach affords the ability to make inexpensive dies and modifications to the forging shape compared to the more costly modifications of a full-scale set of dies. Experience gained from previous subscale to full-scale studies have shown a high degree of scalability between subscale and full-scale. The forging material and parameters are identical for subscale and full-scale studies. Dimensions from the

full-scale configurations were scaled by one-third for the subscale die designs. The subscale dies were fabricated from 4- by 8-inch diameter TZM molybdenum blocks. The designs of the forging configuration for each of these parts were directed toward minimizing the forging input weight by using, where possible, a 0.050-inch forging envelope about each part. This was done while keeping in mind forgeability and sonic inspectability. This 0.050-inch envelope was established as the minimum forging envelope for this program. Figures 3 through 8 show the near net shape envelope and the current forging shape relative to the finished part.

After an optimum preform and final forging configuration was found, additional subscale forgings were made of each part. This was done to demonstrate reproducibility and to furnish forgings for heat treat dimensional stability studies and metallographic examination.

1ST-STAGE TURBINE DISK SUBSCALE ITERATIONS

The design of the 1st-stage subscale dies initially incorporated the use of die inserts to reduce the input weight for this part to a minimum. These inserts are used to form the integral arm and flange portion of the disk and occupy a volume in the die that would otherwise require additional forging material. The use of inserts to form the flange of this part was feasible because the flange extends outward from the integral arm. Thus, during forging, the material flow will be unrestricted while expanding to a larger diameter.

The 1st-stage inserts, which form a three part segmented ring made of TZM molybdenum, are seated in the lower die cavity as illustrated by Figure 9. A TZM molybdenum knockout ring, located under the inserts, was used to eject the inserts and the forged part from the lower die. These inserts were easily removed from the part after removal from the forging press.

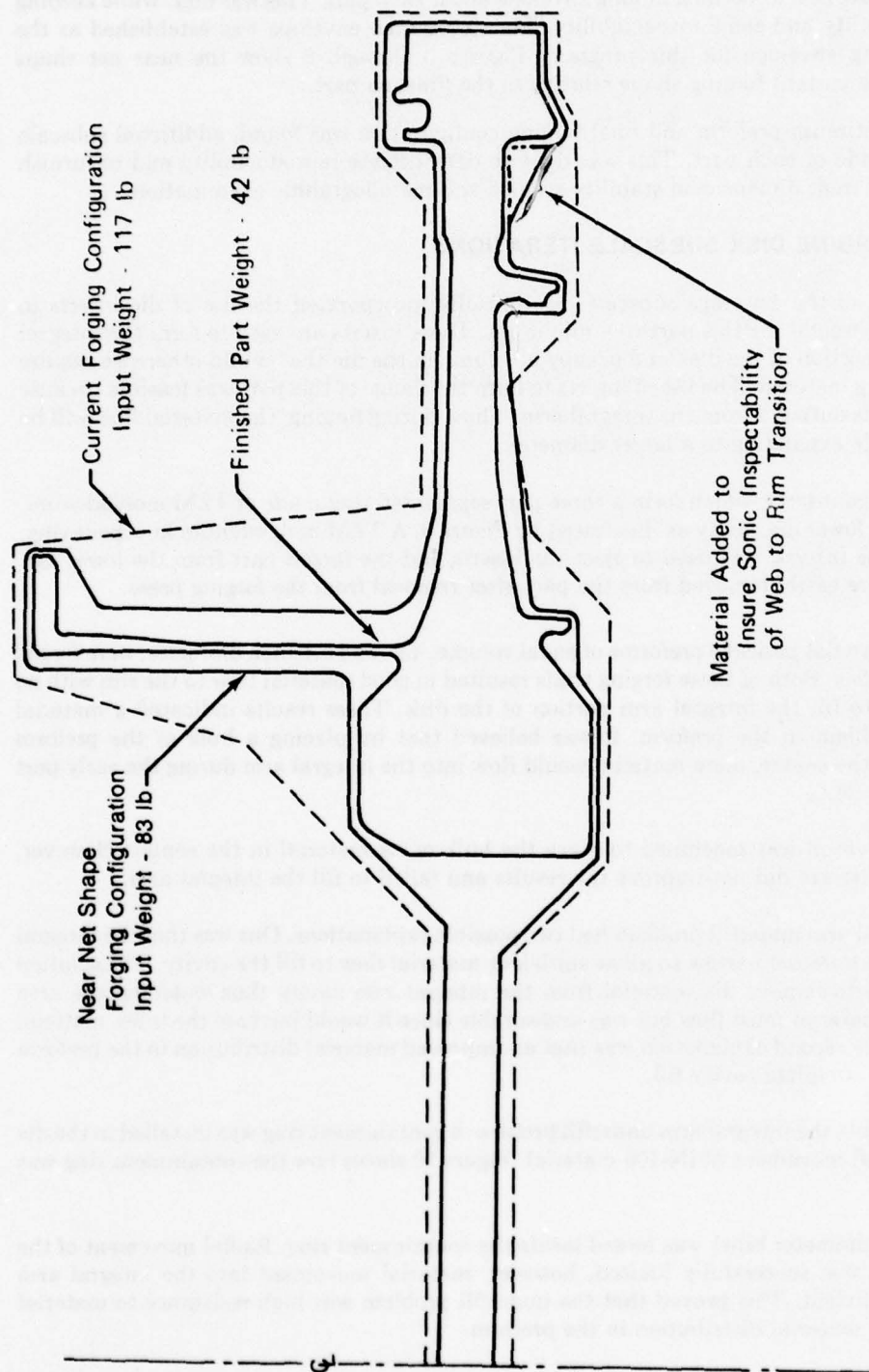
Initially, two flat pancake preforms of equal volume, 4.8- and 5.4-inch diameter, were forged in the subscale dies. Both of these forging trials resulted in good material flow to the rim with no laps but failed to fill the integral arm portion of the disk. These results indicated a material distribution problem in the preform. It was believed that by placing a bulk of the preform material nearer the center, more material would flow into the integral arm during the early part of the forging cycle.

Another preform was machined to place the bulk of its material in the center. However, forging of this preform did not improve the results and failed to fill the integral arm.

The integral arm underfill problem had two possible explanations. One was that the integral arm cavity walls were too narrow to allow sufficient material flow to fill the cavity. The solution in this case was to remove die material from the integral arm cavity thus widening the area through which material must flow but was undesirable since it would increase the billet material input weight. The second explanation was that an improved material distribution in the preform was required for complete cavity fill.

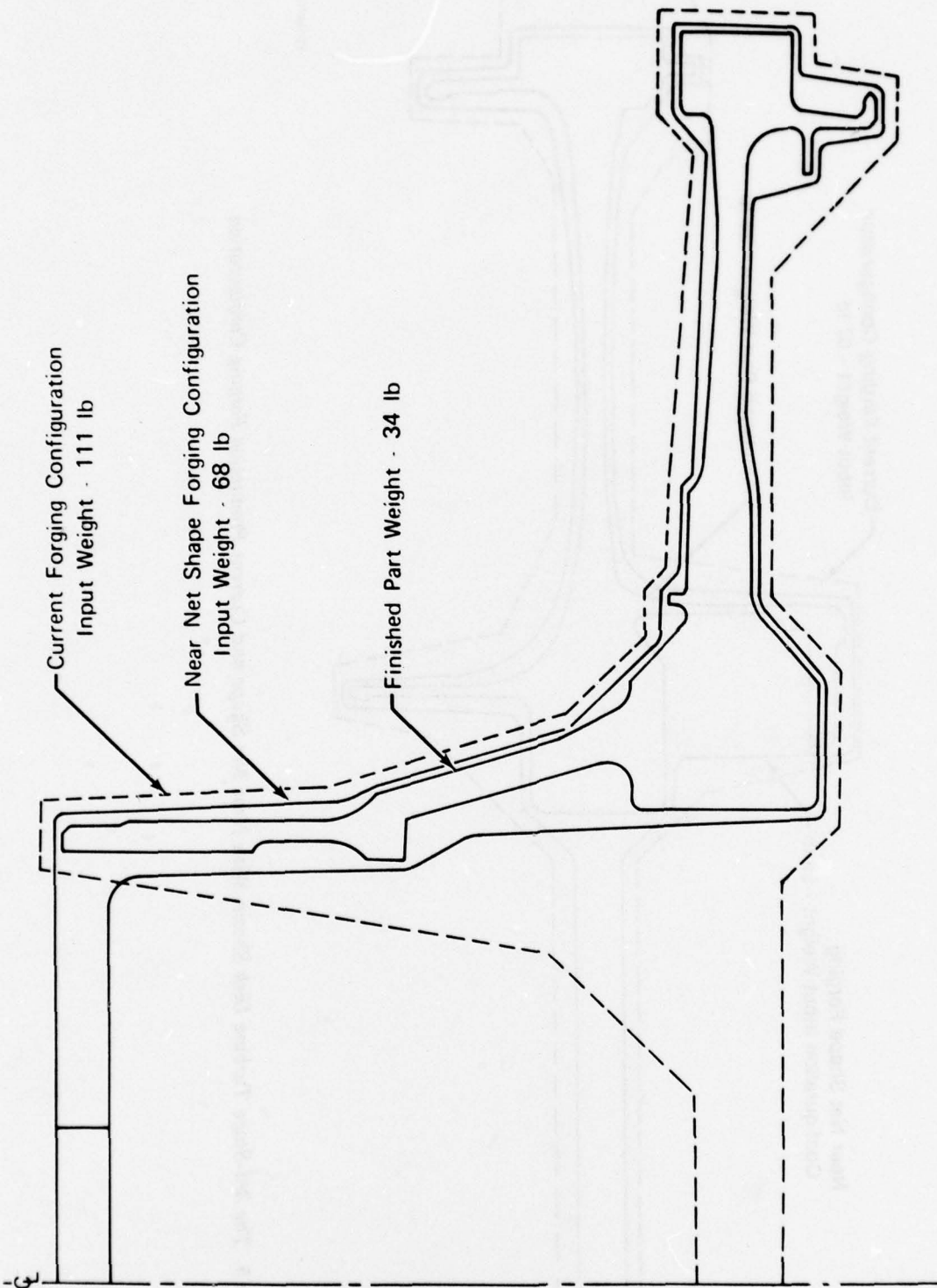
To investigate the integral arm underfill problem a containment ring was installed in the die to limit the radial movement of IN-100 material. Figure 10 shows how the containment ring was used.

A 3.7-inch diameter billet was forged inside the containment ring. Radial movement of the IN-100 material was successfully limited, however, material movement into the integral arm cavity was insufficient. This proved that the underfill problem was high resistance to material flow rather than material distribution in the preform.



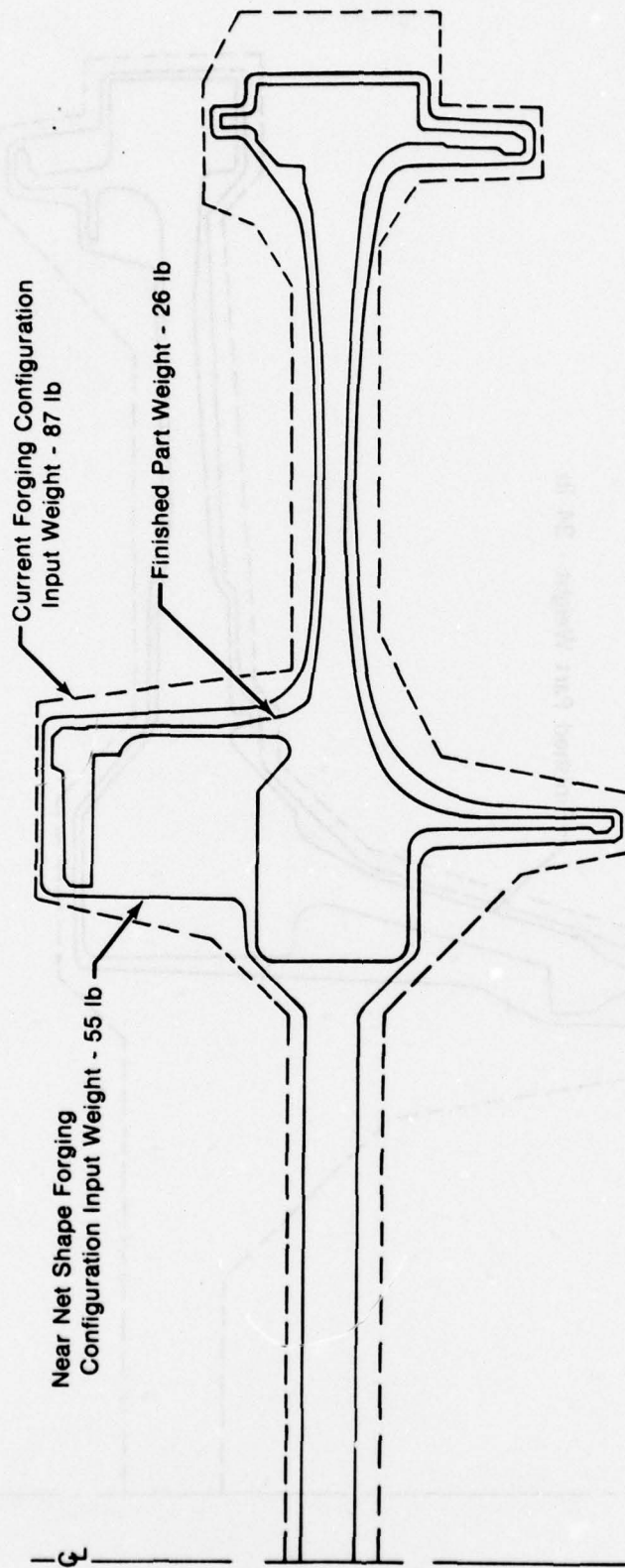
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Figure 3. The 1st-Stage Turbine Disk Shown With Near Net Shape and Current Production Forging Configuration



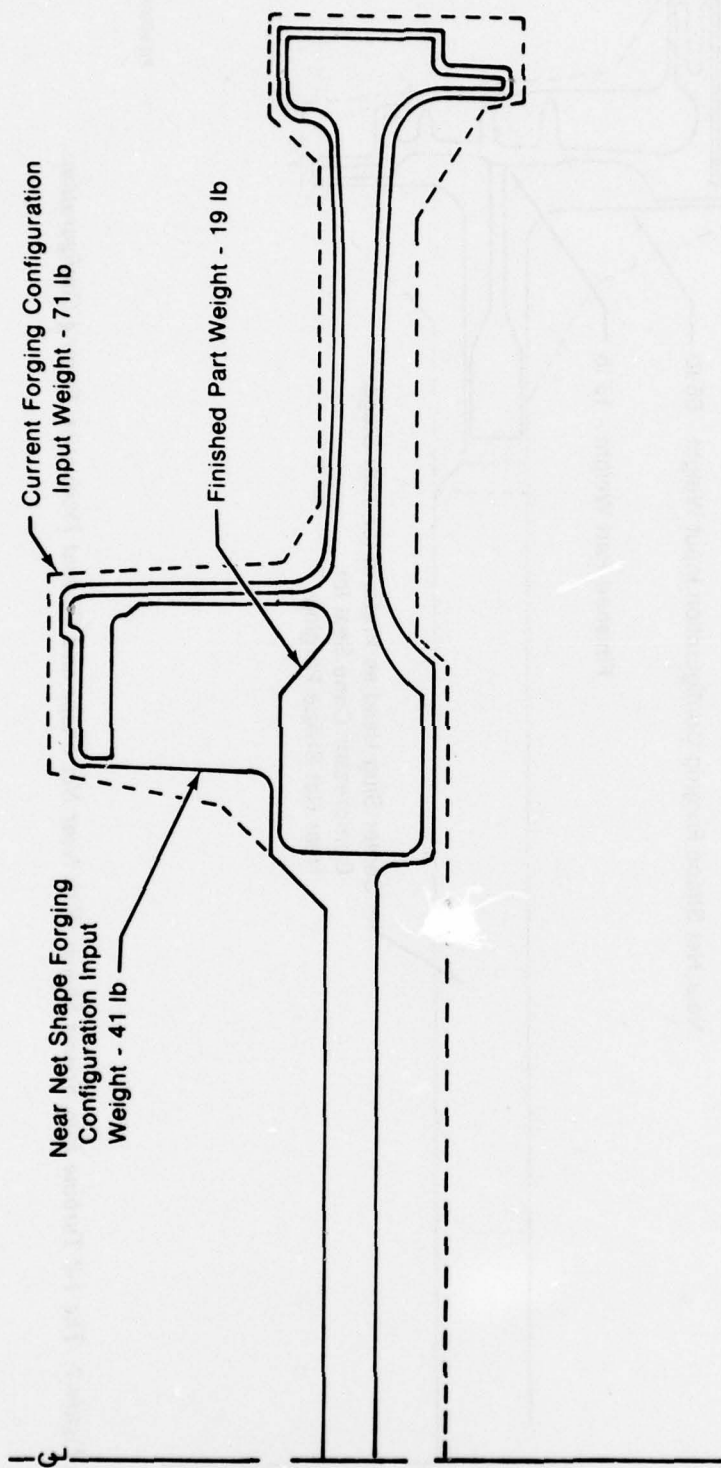
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Figure 4. The 2nd-Stage Turbine Disk Shown With Near Net Shape and Current Production Forging Configuration



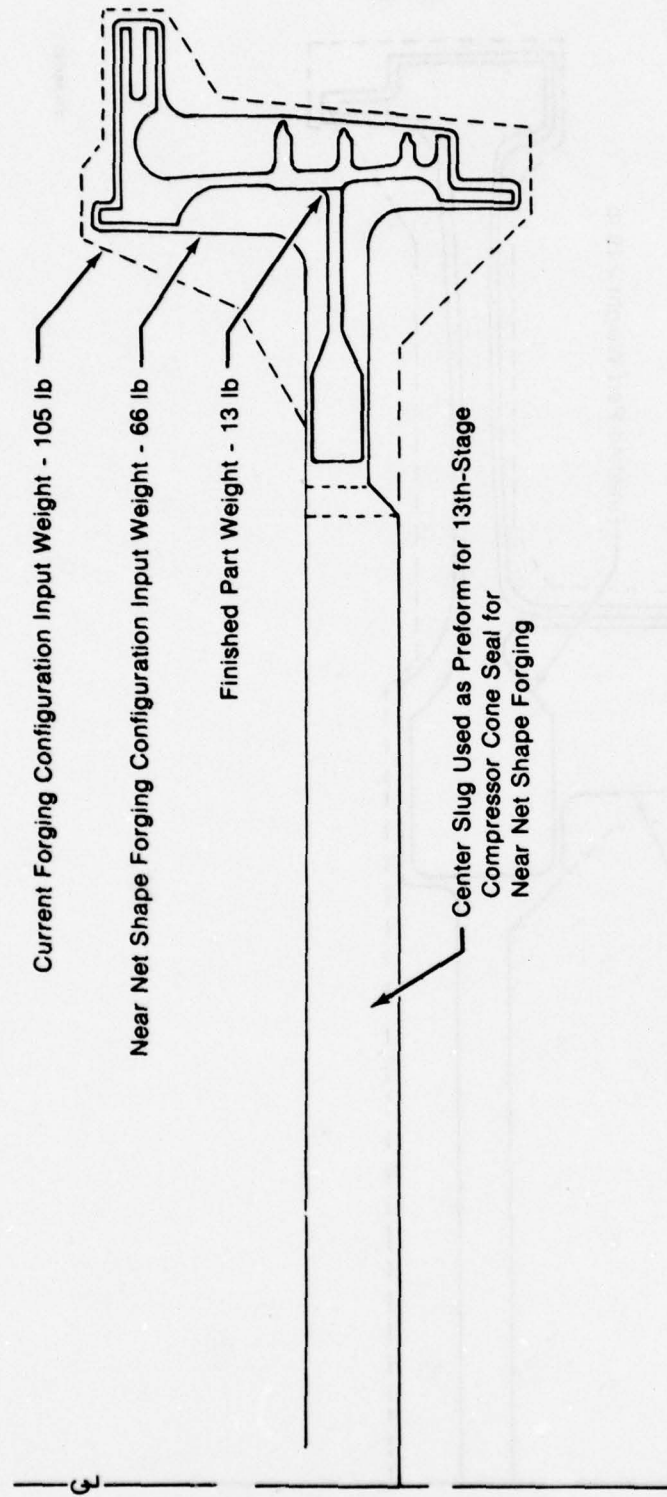
FD 9473A

Figure 5. The 3rd-Stage Turbine Disk Shown With Near Net Shape and Current Production Forging Configuration



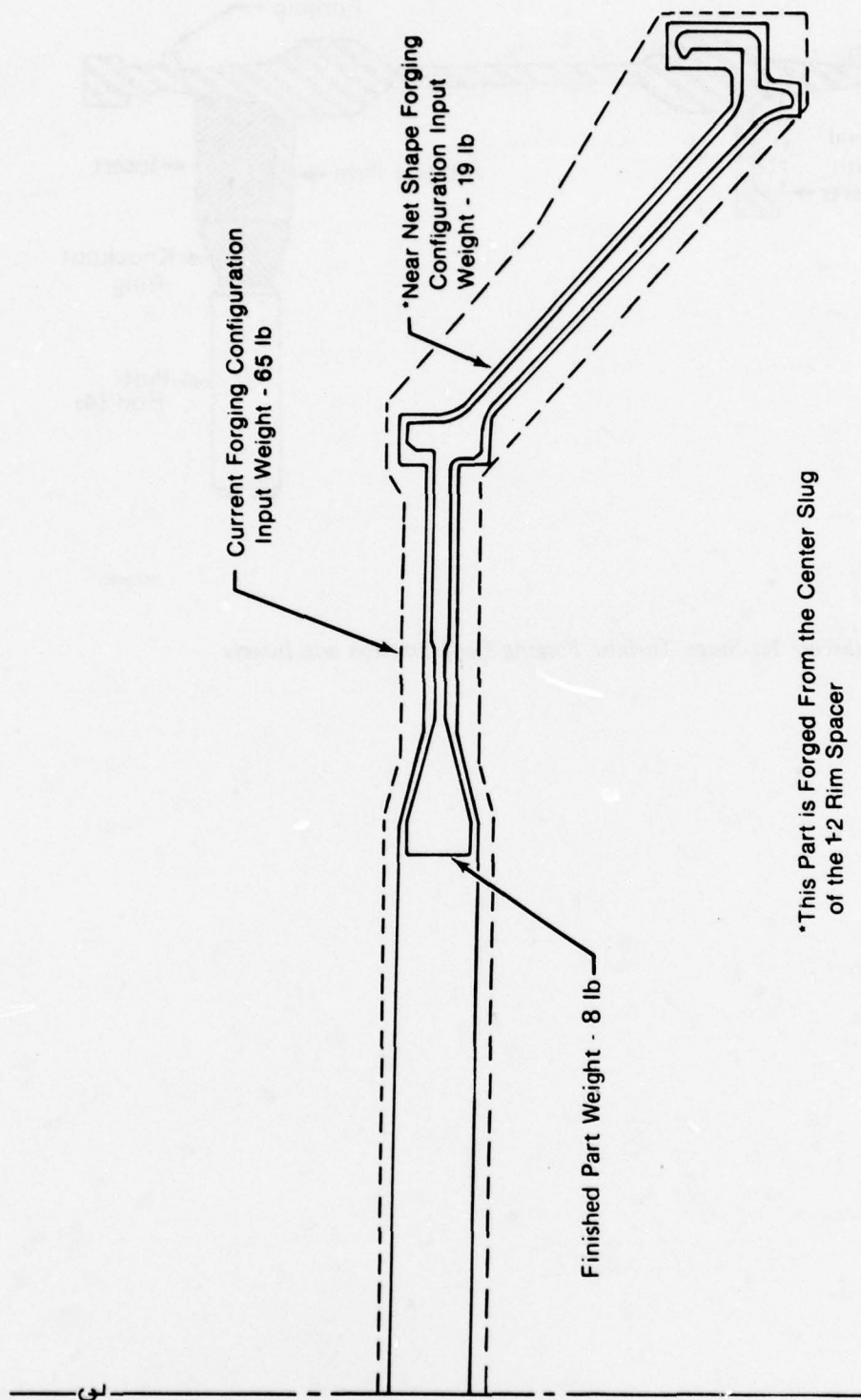
FTD 9497-4A

Figure 6. The 4th-Stage Turbine Disk Shown With Near Net Shape and Current Production Forging Configuration



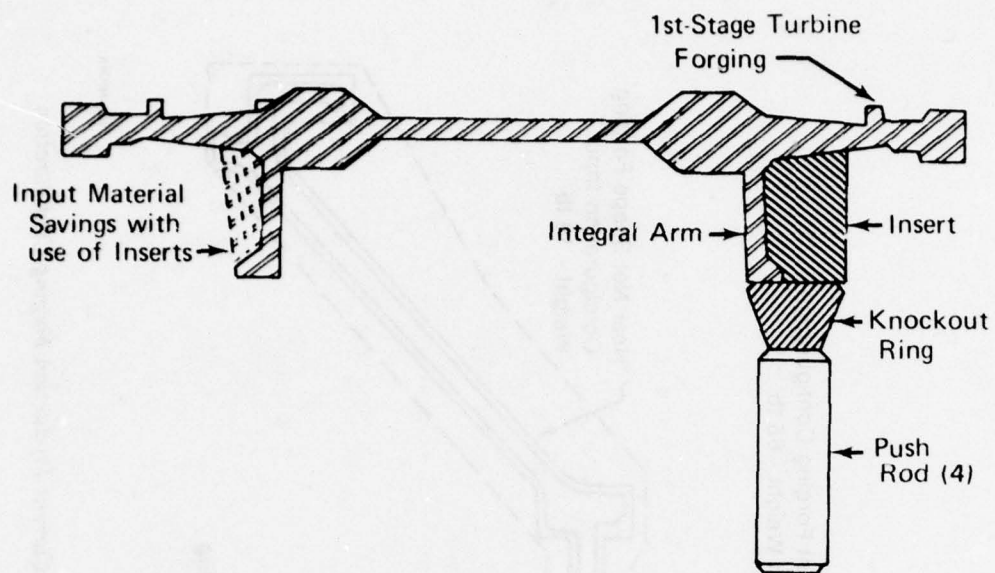
FD 94975A

Figure 7. The 1-2 Turbine Rim Spacer Shown With Near Net Shape and Current Production Forging Configuration



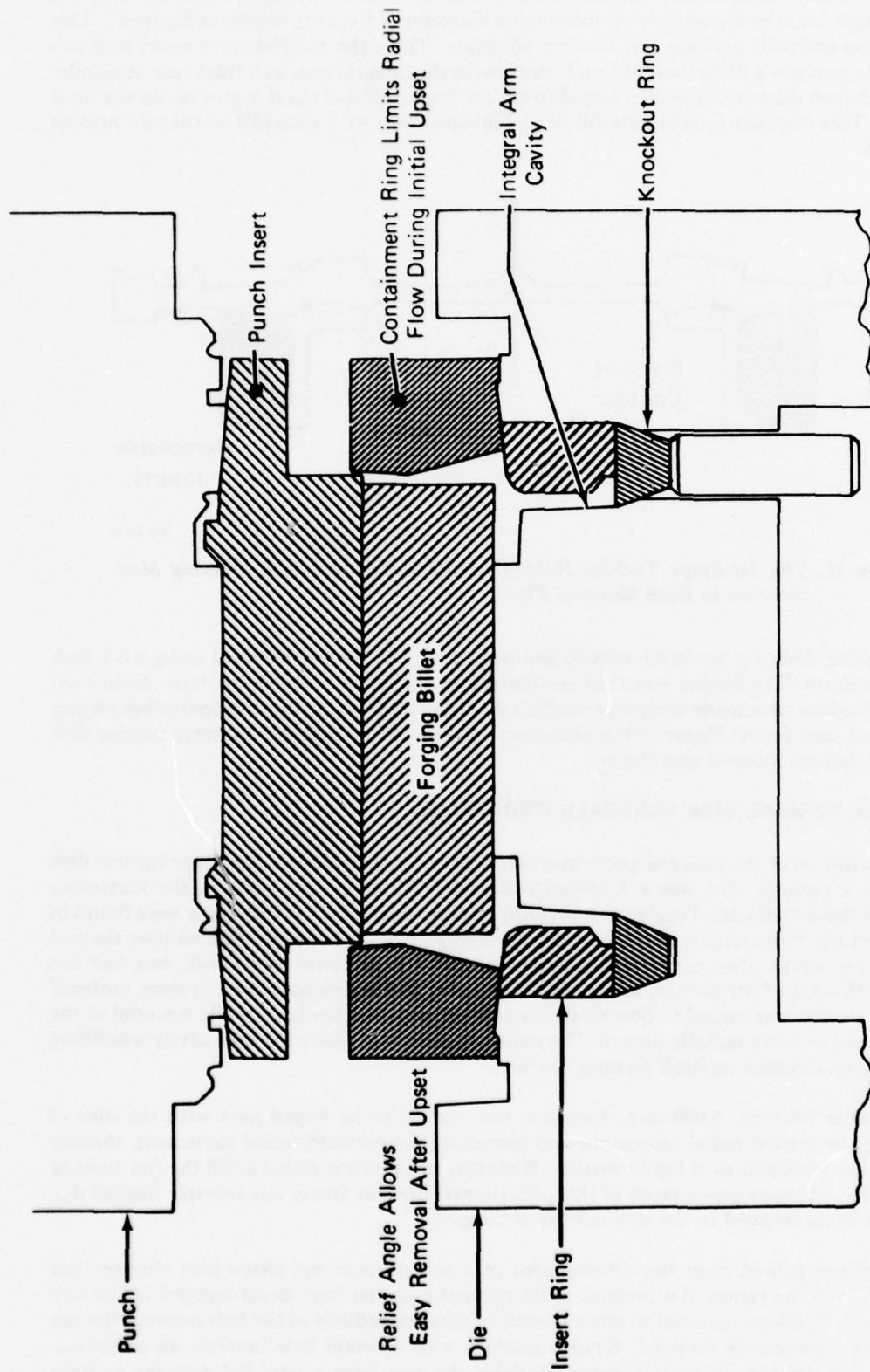
FD 94976A

Figure 8. The 13th-Stage Compressor Cone Seal Shown With Near Net Shape and Current Production Forging Configuration



FD 94977

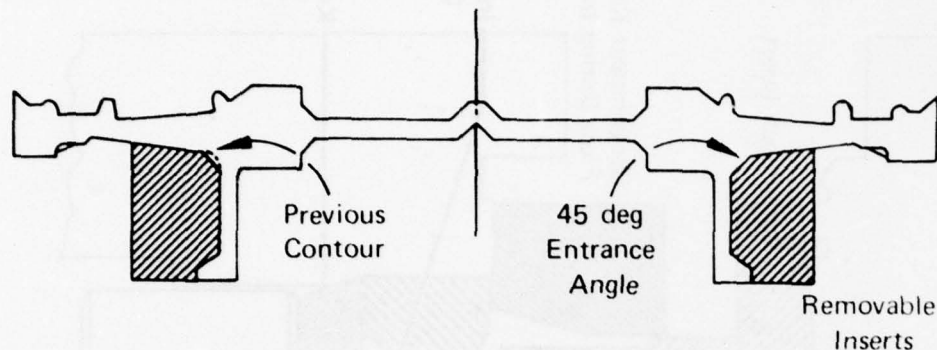
Figure 9. Subscale 1st-Stage Turbine Forging Configuration and Inserts



FD 9497A

Figure 10. Cross Section of Subscale 1st-Stage Turbine Containment Ring Tooling

The first step taken to ease the resistance to flow into the cavity was to machine a 45 deg entrance angle into the die contour on the outside diameter of the arm, shown in Figure 11. This improved the underfill problem but was not adequate. Thus, the molybdenum insert ring was machined to produce a 0.010- to 0.012-inch increase in the integral arm wall thickness. A smaller preform, 1.8-inch diameter was then forged to ensure that overfill of the rim area would not limit die travel. This resulted in complete fill of the integral arm with underfill in the rim area as anticipated.



FD 94979

Figure 11. The 1st-Stage Turbine Subscale Forging Configuration Showing Modification to Ease Material Flow

Increasing diameter preforms were forged until complete fill was attained using a 3.2-inch diameter preform. The forging was then sectioned and examined revealing no laps. Additional successful forgings were made using this 3.2-inch diameter preform proving a reproducible forging sequence had been found. Figure 12 is a photograph of a successful subscale 1st-stage turbine disk with a well defined integral arm flange.

2ND-STAGE TURBINE DISK SUBSCALE ITERATIONS

Optimization of the pancake preform configuration for the subscale 2nd-stage turbine disk began with a preform that was a 5.940-inch diameter, which is very close to the maximum diameter of the actual part. Forging this preform resulted in good die fill, but laps were found in the bore and the hub sections of the part as shown in Figure 13. Laps had formed near the end of the forging stroke after material filled the rim and hub sections of the disk, but had not completely filled the bore section, as shown in Figure 14. As the dies continued to close, material in the hub section was forced to flow down towards the web and the bore, while material in the rim was forced to move radially inward. The opposing flows met where the bore cavity was filling and the material folded on itself forming the lap.

A smaller preform, 5.000-inch diameter, was chosen to be forged next with the idea of eliminating the inward radial movement and increasing the outward radial movement, thereby decreasing the possibilities of lap formation. However, this preform failed to fill the rim areas of the die cavity. Measurements made of this part showed that die travel was severely limited due to material being trapped in the hub section of the part.

Experience gained from the development of a similar near net shape part showed that placing a hole in the center of a preform could prevent material from being trapped in the hub section. The hole allows material to move inward or outward radially in the hub section, thus die travel is not prematurely stopped. Since a preform with a center hole involves an additional machining step further efforts to successfully forge the part from a solid flat pancake preform were made.

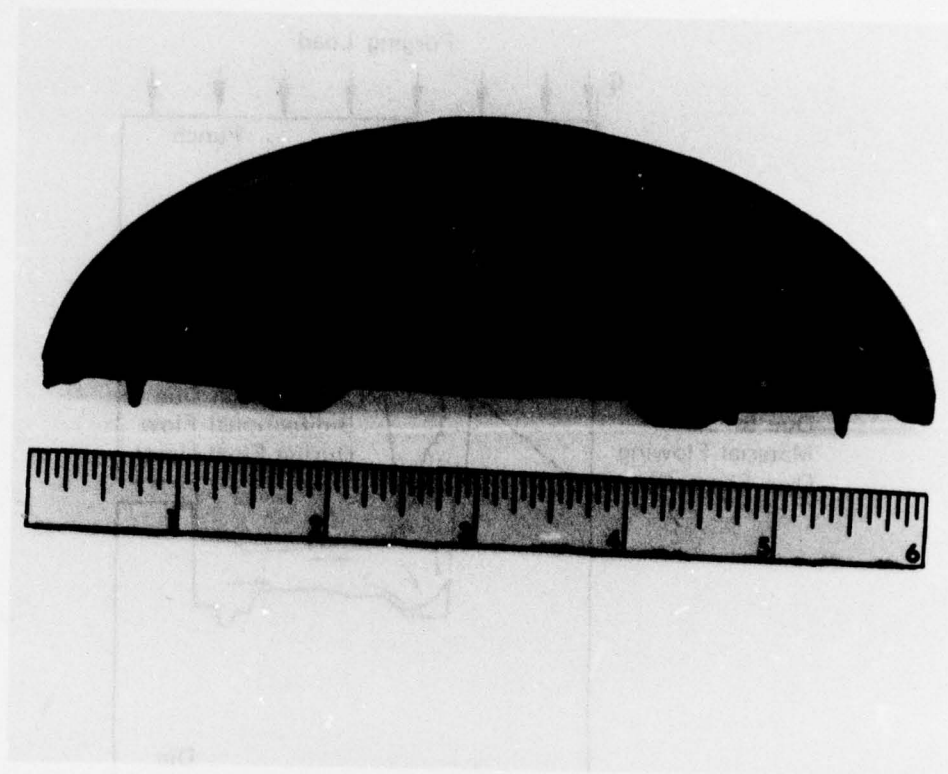


Figure 12. The Subscale 1st-Stage Turbine Disk Cross Section

FE 147249

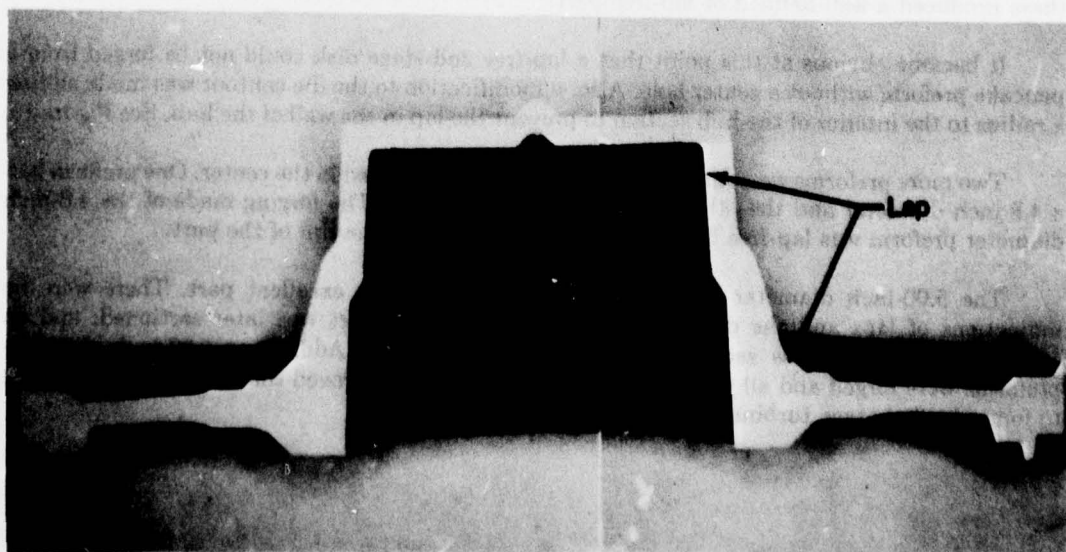


Figure 13. The 2nd-Stage Turbine Disk Lap Locations

FD 94986

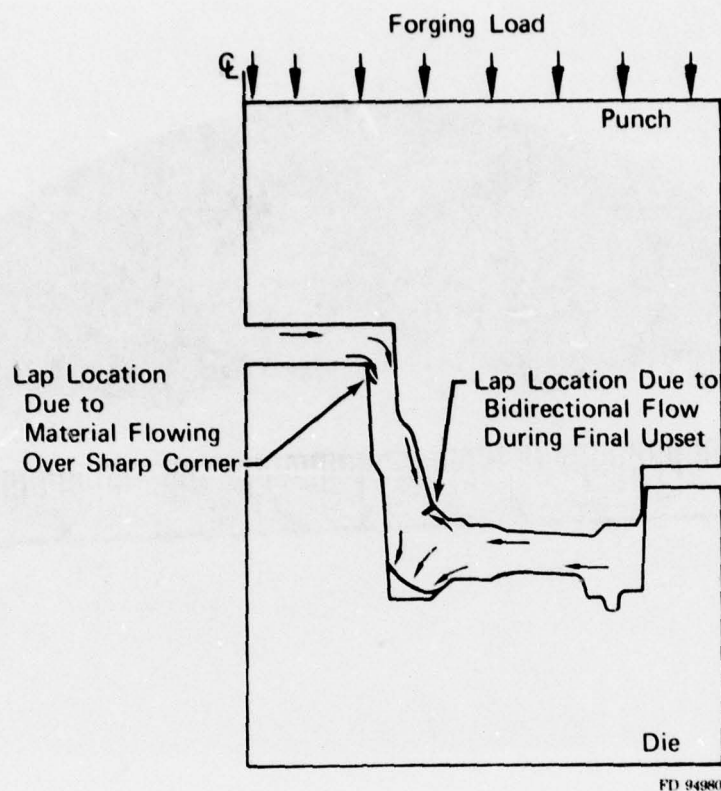


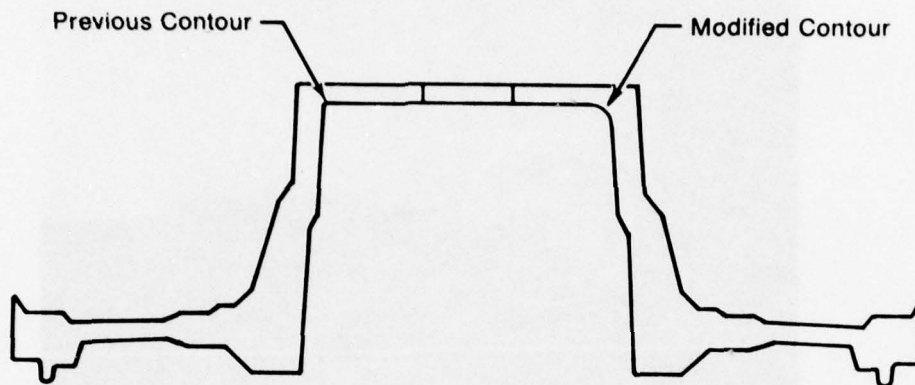
Figure 14. Schematic of 2nd-Stage Lapping Formation

Four preforms, sized between 5.000 and 5.94 inches were machined and forged. None of these produced a well defined or lap-free part.

It became obvious at this point that a lap-free 2nd-stage disk could not be forged from a pancake preform without a center hole. Also, a modification to the die contour was made adding a radius to the interior of the hub section to prevent the lap in the wall of the hub. See Figure 15.

Two more preforms were machined with $\frac{3}{4}$ -inch holes placed in the center. One preform had a 4.8-inch diameter and the other had a 5.00-inch diameter. The forging made of the 4.8-inch diameter preform was lap-free but die fill was incomplete at the rim of the part.

The 5.00-inch diameter preform was forged yielding an excellent part. There were no indications of laps and the die cavity was well filled. The part was later sectioned, and an examination of the cross section confirmed a lap-free part. Additional 5.00-inch diameter preforms were forged and all yielded well-defined parts which proved that an optimum preform to forge the 2nd-stage turbine disk had been found.



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Figure 15. The 2nd-Stage Turbine Subscale Configuration Showing Modification Made to Eliminate Lap Formation and Ease Material Flow

3RD-STAGE TURBINE DISK SUBSCALE ITERATIONS

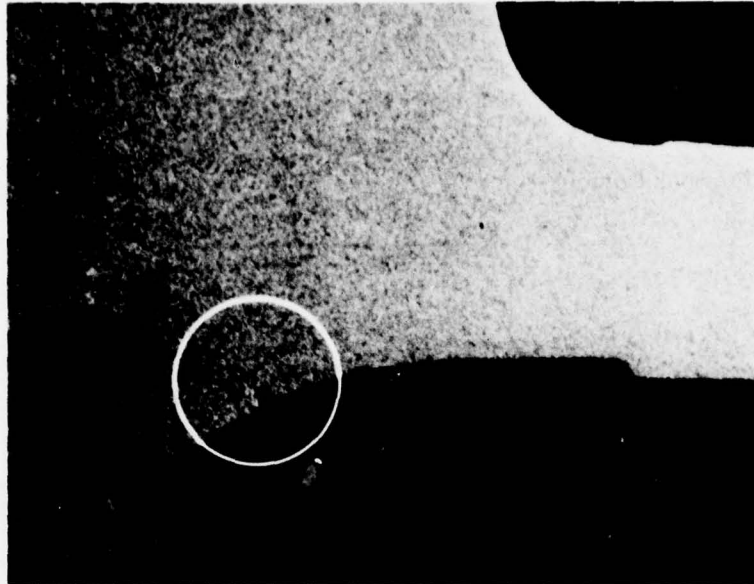
Due to experience gained on the subscale parts previously forged in this program, the optimization of the preform configuration for the 3rd-stage turbine disk was completed after five forging iterations. The iterations began with a small diameter preform followed by larger diameter preforms of equal volume until a well-defined lap-free part was made.

The first preform forged was 4.46-inch diameter compared to the 5.812-inch diameter preform final part. This forging resulted in incomplete die fill. The diameter of the preform was too small for the forging material to fill the rim details of the die cavity. Three more preforms, with successively increasing diameters up to 5.0 inches were machined and forged. Each of these also failed to fill the rim areas yielding incomplete parts. Another preform was machined with a 5.1-inch diameter. The forging of this preform resulted in a well-defined part with no apparent laps. This part was sectioned and examined to reveal that it was lap-free. Thus, the subscale forging trials of the 3rd-stage turbine disk were complete.

4TH-STAGE TURBINE DISK SUBSCALE ITERATIONS

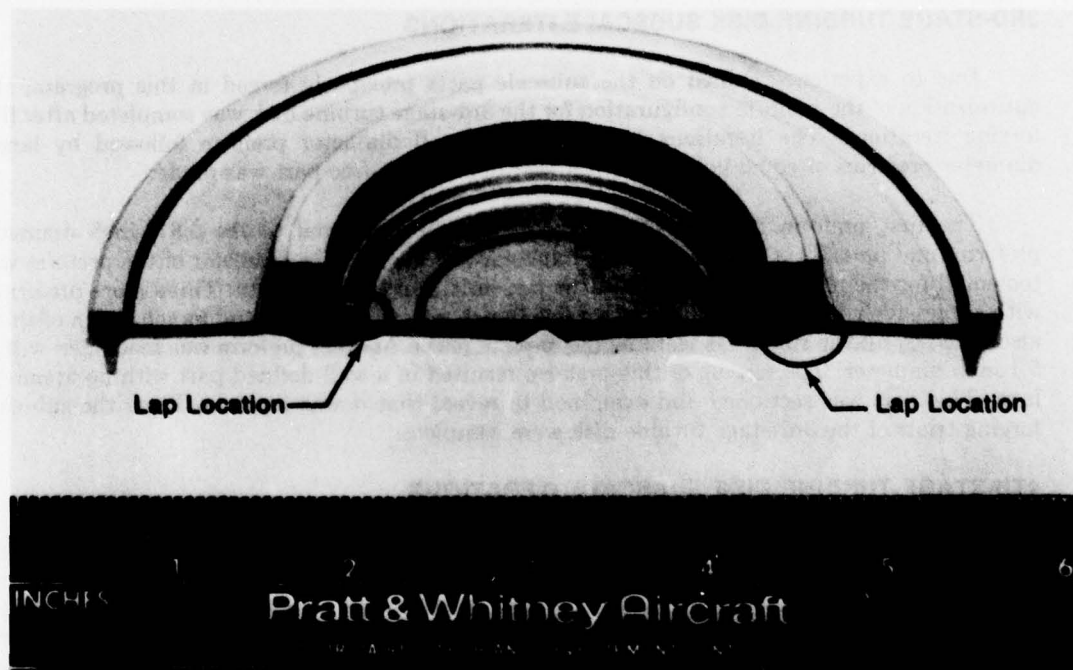
The forging iterations for the 4th-stage turbine disk subscale optimization began with three flat pancake preforms with diameters of 4.00, 4.40, and 4.80 inches. The forging results of the two smaller preforms were severely underfilled in the rim area of the part while the 4.8-inch diameter preform resulted in good die fill with the exception of small surface laps. The forging was sectioned for polishing and etching of the lapped areas. Figure 16 is a photo made of the prepared surface. Figure 16a demonstrates that the laps were small while Figure 16b shows the exact location of these laps.

The cause for the underside lap was the same as with the 2nd-stage turbine disk subscale iterations. Bidirectional flow was taking place while material filled the integral arm cavity resulting in a lap on the underside opposite the integral arm.



Mag: 10X

a. Closeup of Lap Area



b. Sectioned 4th-Stage Turbine Subscale Forging

FD 94987A

Figure 16. Sectioned 4th-Stage Turbine Subscale Forging and Closeup of Lap Area

To forge this part without laps it was decided to make two small die contour modifications and then continue to optimize the preform configuration by varying the diameter of the preform after each iteration.

The modifications made to the die contour included a 45-degree entrance angle and the relocation of a transition contour on the underside of the part to a 0.100-inch larger diameter as shown in Figure 17. Total elimination of the underside lap was deemed impractical because the die contour modification necessary would severely increase the input forging weight. The relocation of the underside transition contour was done to minimize the lap and place it a sufficient distance from the actual part for easy removal by the standard skin cutting operation during full-scale production.

The first flat pancake preform that was forged in the modified dies had a diameter of 4.600 inches, with a small increase in volume to account for the die modifications. This iteration resulted in a forging with a minimum of laps, but die fill was inadequate at the rim. A 4.700-inch diameter preform was machined and forged next with the idea that a slightly larger preform would permit the rim to fill. This forging filled the die cavity very well; however, the underside lap increased severely. A 4.65-inch diameter preform was forged next which proved to be an optimum diameter preform. Die fill was complete, and the underside lap was at a minimum. Good results were repeated with the forging of another 4.65-inch diameter preform, proving this preform was an optimum for the 4th-stage turbine disk subscale development.

1-2 TURBINE RIM SPACER SUBSCALE ITERATIONS

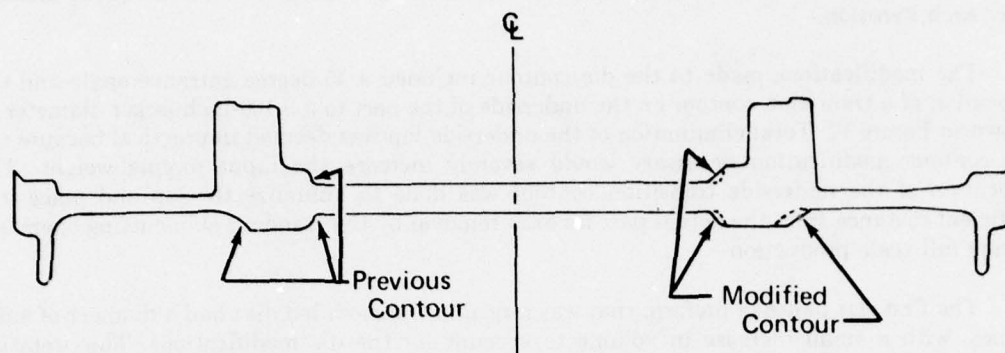
As with the other parts in this program, the forging iterations were made with flat pancake preforms of constant volume and varying diameters.

The first preform forged had a diameter of 5.300 inches compared to the finished part diameter of 6.320 inches. This forging resulted in very poor die cavity fill at the outside diameter with no material flow into the narrow flange area of the rim. These results pointed to a larger diameter preform, so a 5.58-inch diameter preform was machined and forged. This iteration had some improvements in die cavity fill with material moving about 1/3 of the way into the flange at the rim of the part. Again, a larger preform, 5.87-inch diameter, was machined and forged. This iteration was no improvement over the last. It was apparent that the underfill problem was a flow resistance problem and not preform material distribution since the preform diameter, 5.87-inch, was as large as the die cavity would allow. This necessitated a die contour modification which would increase the width of the flange cavity to ease the material flow.

After this die modification was completed, a 5.58-inch diameter preform that had given the best results of the previous three forging trials was machined and forged. This forging resulted in an incomplete part, since the forging material had failed to fill the rim details. The next preform diameter was sized as large as the die cavity would allow, 5.87 inches. The forging of the preform gave good results. The forging material filled all the details of the die cavity with no apparent laps. This part was sectioned for examination and no laps were revealed. Therefore, the preform and forging configuration for the 1-2 turbine rim spacer had been optimized.

13TH-STAGE COMPRESSOR CONE SEAL SUBSCALE ITERATIONS

Originally, the source of the preform to forge the cone seal was to be the center slug from the 1-2 turbine rim spacer forging. This center slug is removed during normal finish machining operations. A center slug, 4.385-inch diameter, was trepanned from a subscale 1-2 turbine spacer and forged in the cone seal dies. This forging resulted in a very poor die fill. This underfill situation was attributed to the extremely thin cross section of the cone seal forging configuration and the resultant high resistance to material flow. Two more preforms, 4.80- and 5.00-inch



FD 94984

Figure 17. 4th-Stage Turbine Subscale Forging Configuration Showing Modifications to Ease Material Flow

diameter, were machined and forged. In both cases the forgings failed to fill the rim area of the die cavity. The preform diameter was then increased to the full 5.4-inch diameter of the die cavity. The forging of this larger preform resulted in a well defined part that was free of laps.

Due to the large diameter preform required to successfully forge the near net configuration of the 13th-stage cone seal, a modification to the original plan was necessary. The trepanned center slug from the 1-2 turbine spacer forging will still be the material source for the cone seal preform. However, a flat die forging step will be necessary to upset the center slug to the diameter required before final forging.

Figures 18 through 23 show the optimized subscale preforms and final forging configurations together with the subscale dies for each part. Figure 24 is a closeup of all of the subscale parts which were sectioned to reveal the cross section.

SUBSCALE EVALUATION

After subscale preform and final forging configurations were optimized for each of the six parts, additional forgings were made for metallurgical examination and evaluation of dimensional stability during heat treatment.

Three forgings of each subscale configuration were machined to obtain reference surfaces which would readily indicate distortion. Each forging was then dimensionally matched prior to heat treatment. Subsequent to receiving the PWA 1073/74* heat treatment, the forgings were again dimensionally checked for comparison to the preheat treatment dimensions.

The subscale distortion analysis showed that the configurations were generally dimensionally stable during heat treatment. Unfortunately, the behavior of the subscale part during heat treatment is not directly applicable to the full-scale part because of the large mass difference. Thus, the small distortions noted are only indications toward the behavior of the full-scale parts.

* The PWA 1073/74 heat treatment consists of: heat to $2050 \pm 15^\circ\text{F}$ for 2 hours and oil quench, heat to $1600 \pm 15^\circ\text{F}$ for 40 ± 5 min. and cool below 700°F , heat to $1800 \pm 15^\circ\text{F}$ for 45 ± 5 min. and cool below 700°F , heat to $1200 \pm 15^\circ\text{F}$ for 24 hours and air cool below 700°F , heat to $1400 \pm 15^\circ\text{F}$ for 4 hours and air cool.

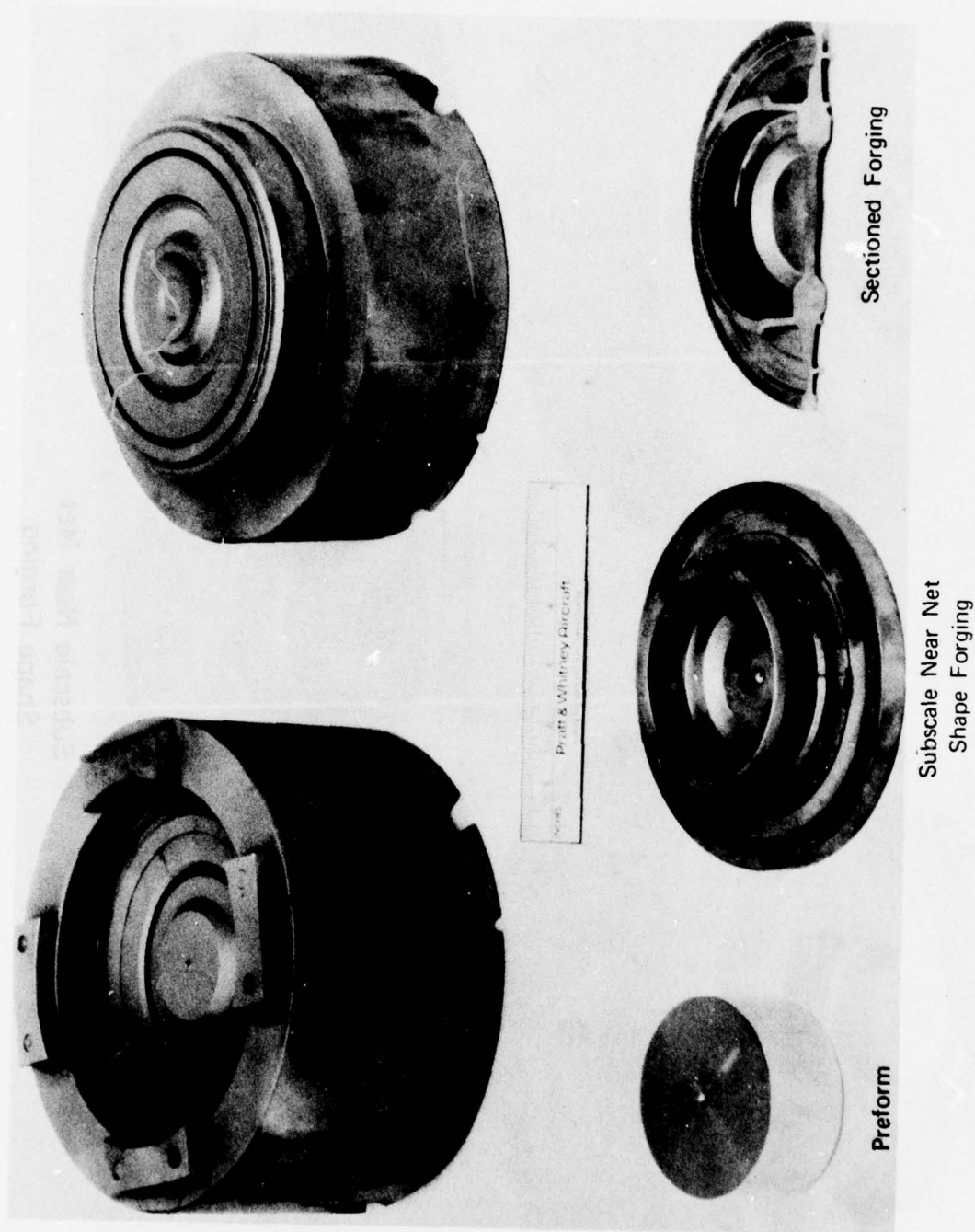
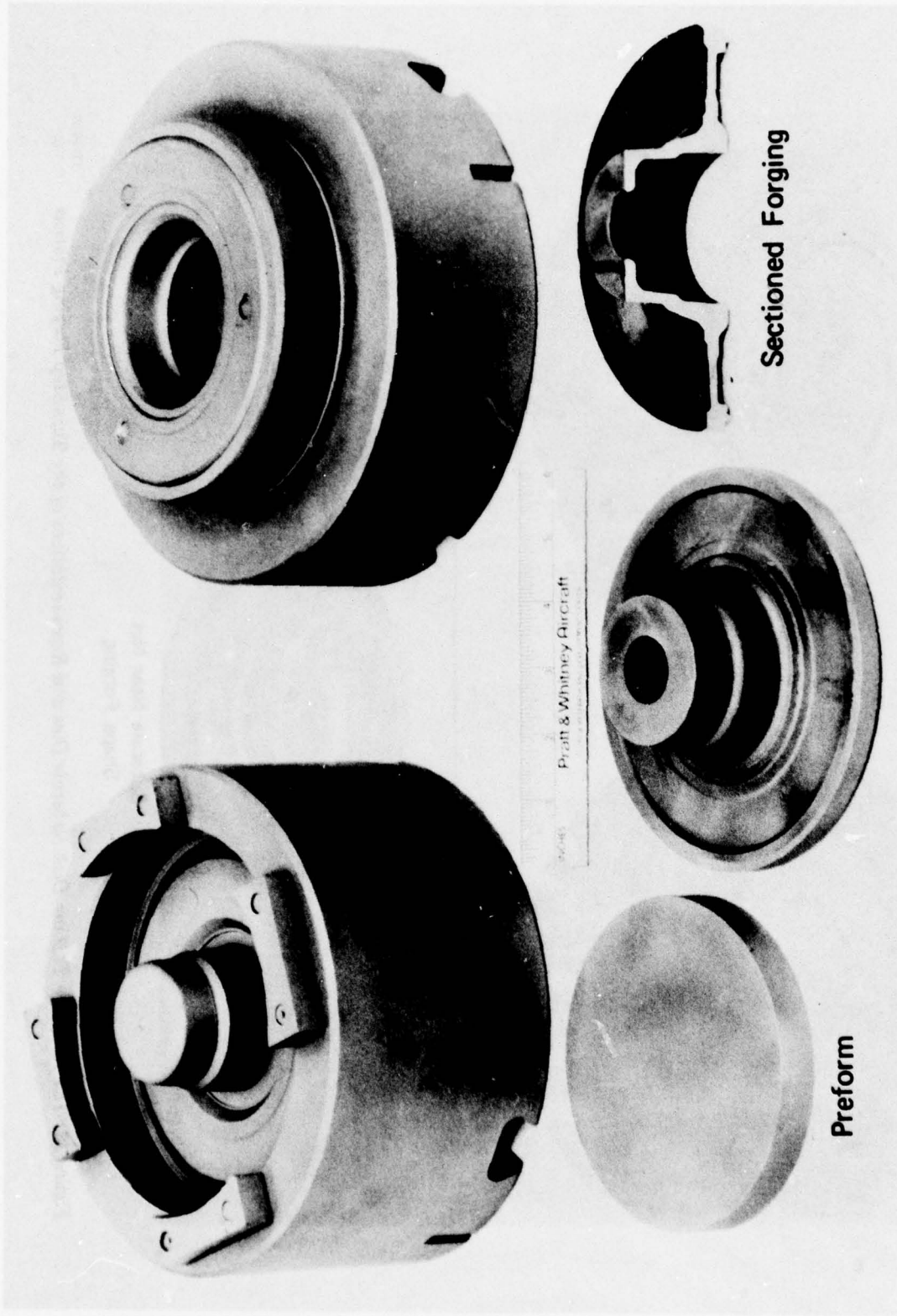


Figure 18. The 1st-Stage Turbine Disk Subscale Dies and Representatives of the Two-Step Forging Process

FD 95727



**Subscale Near Net
Shape Forging**

Sectioned Forging

Preform

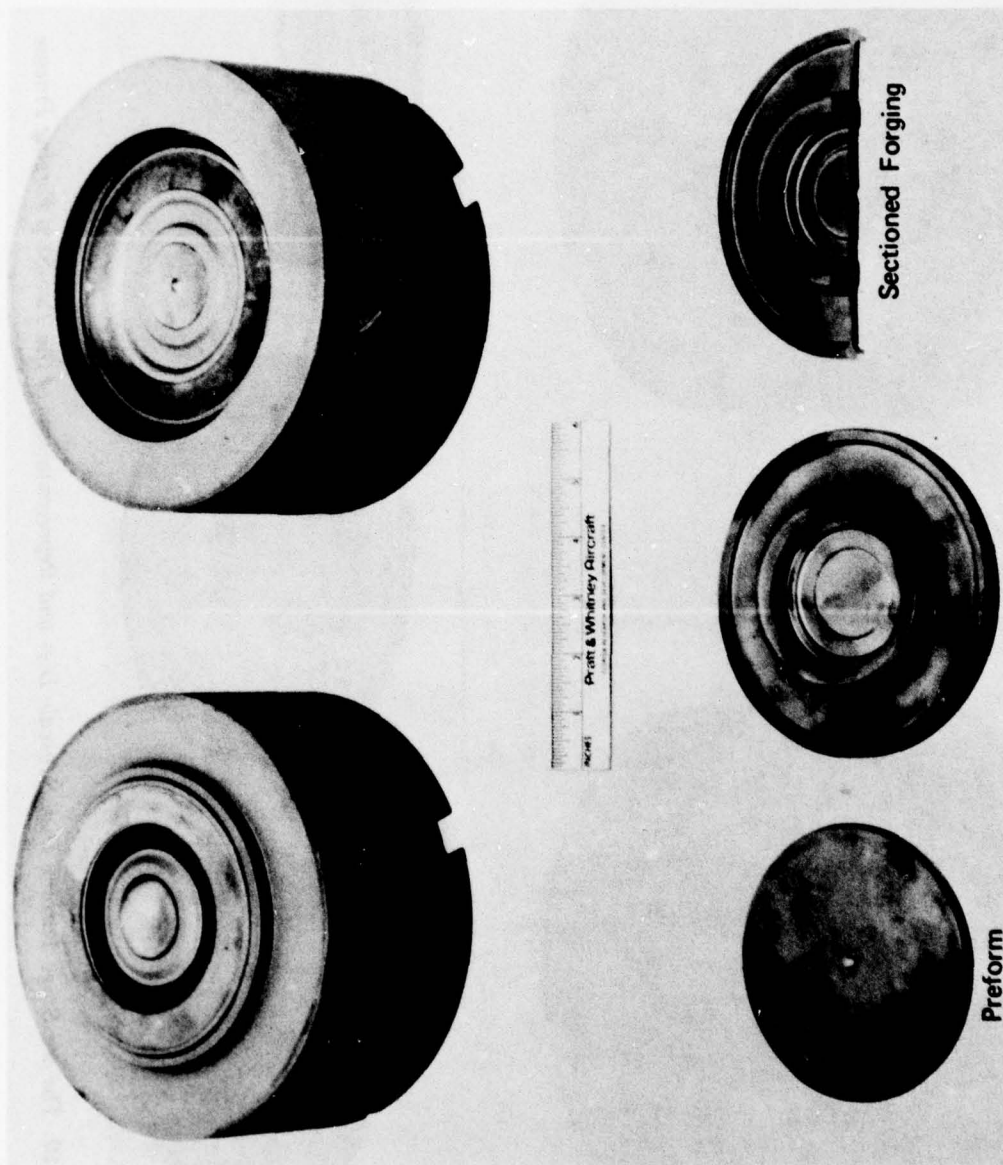
FD 96728

Figure 19. The 2nd-Stage Turbine Disk Subscale Dies and Representatives of the Two-Step Forging Process



FE 146329

Figure 20. The 3rd-Stage Turbine Disk Subscale Dies and Representatives of the Two-Step Forging Process



FD 95730

Figure 21. The 4th-Stage Turbine Disk Subscale Dies and Representatives of the Two-Step Forging Process

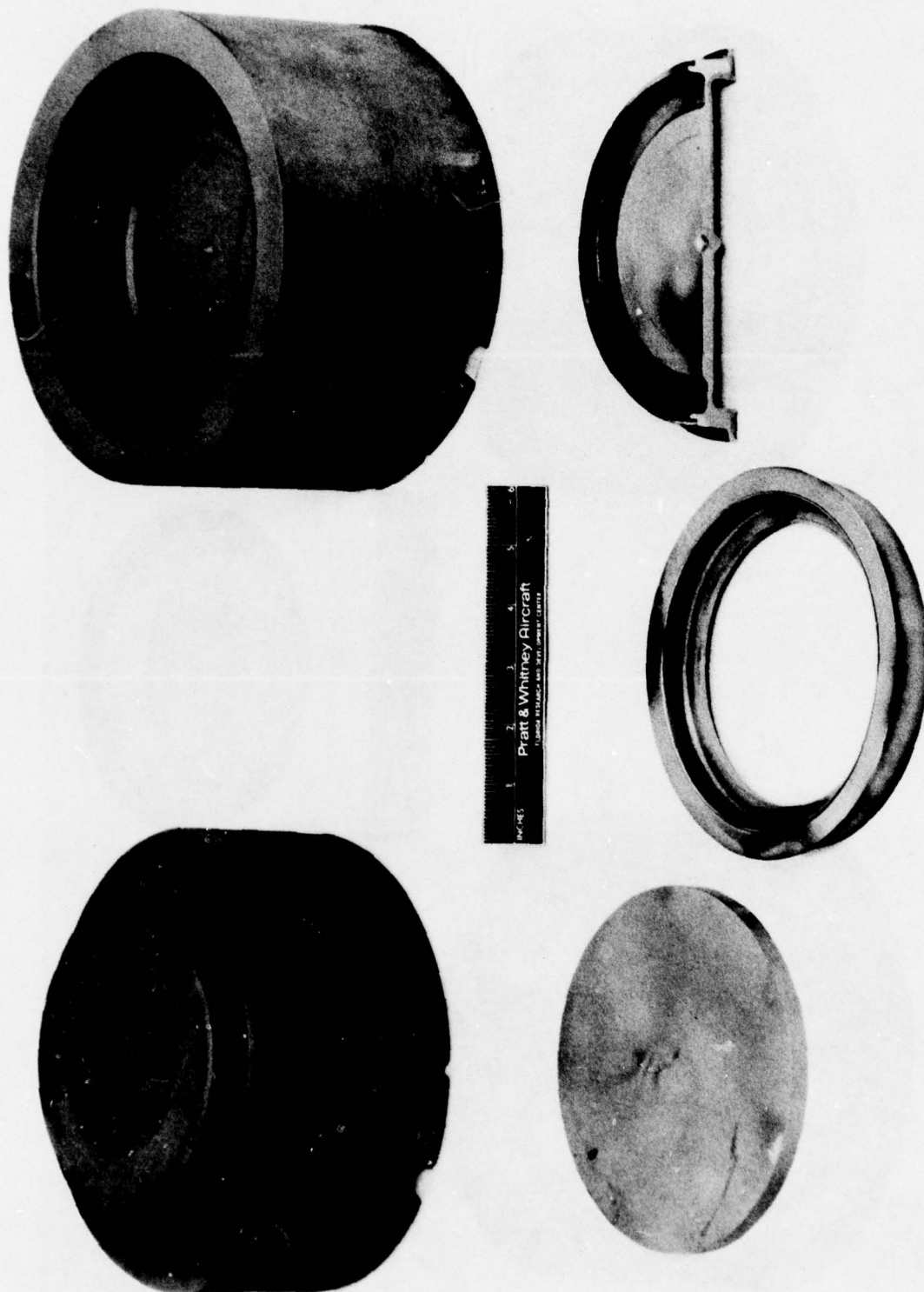
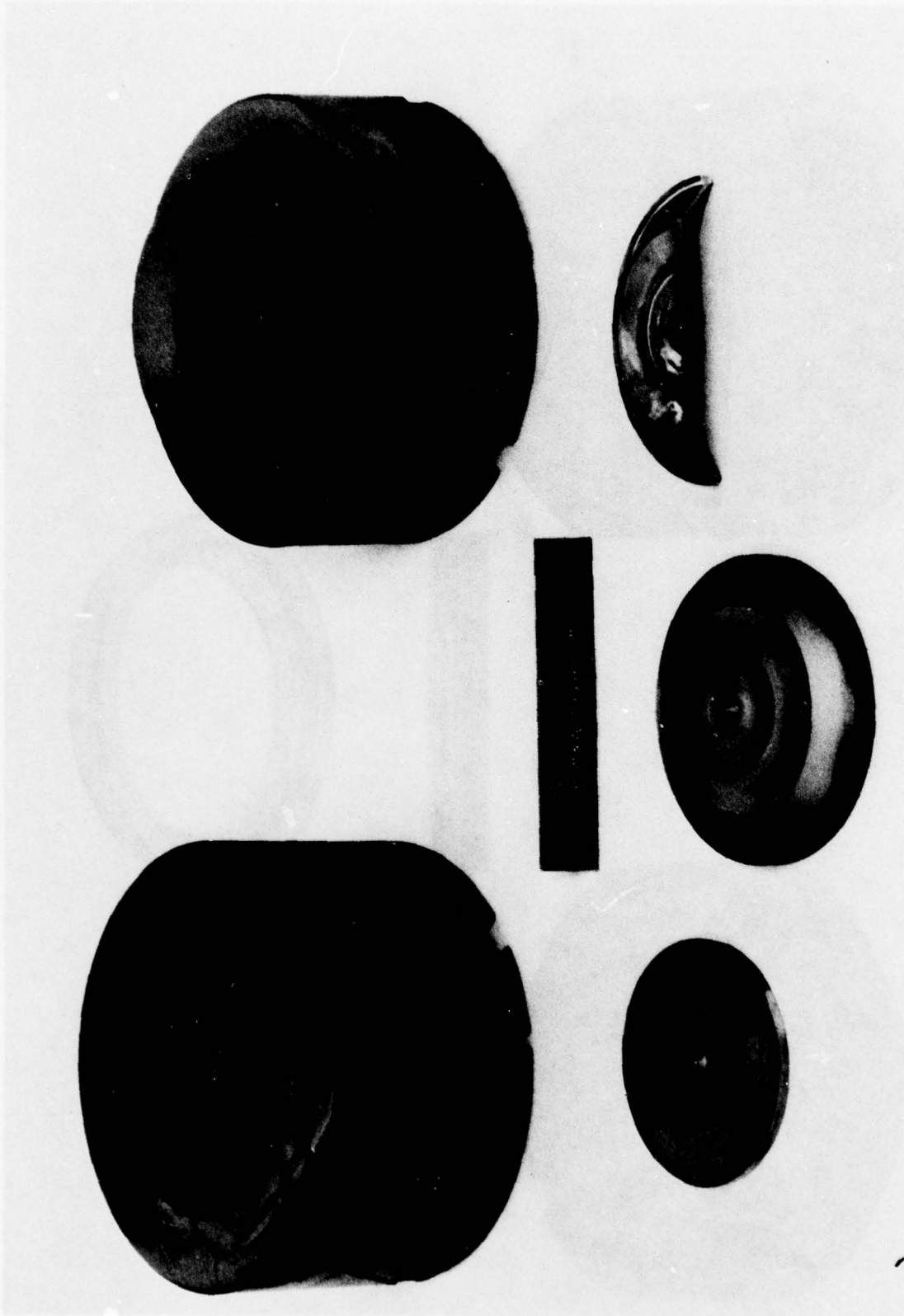


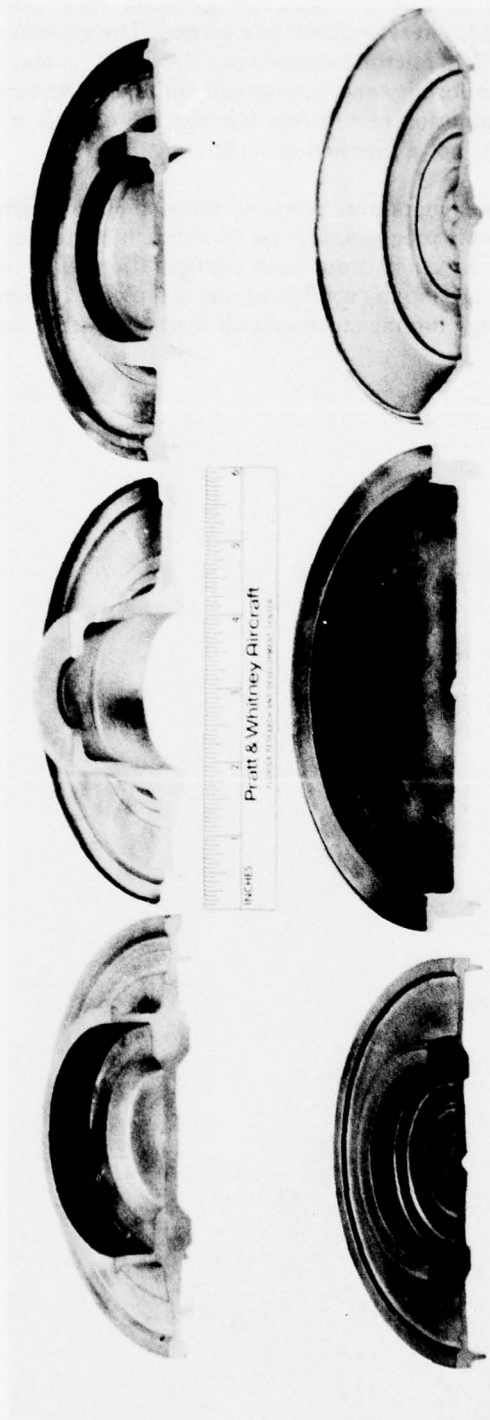
Figure 22. The 1-2 Turbine Rim Spacer Sub-scale Dies and Representatives of the Two-Step Forging Process

FE 149473



FE 148472

Figure 23. The 13th-Stage Cone Seal Subscale Dies and Representatives of the Two-Step Forging Process



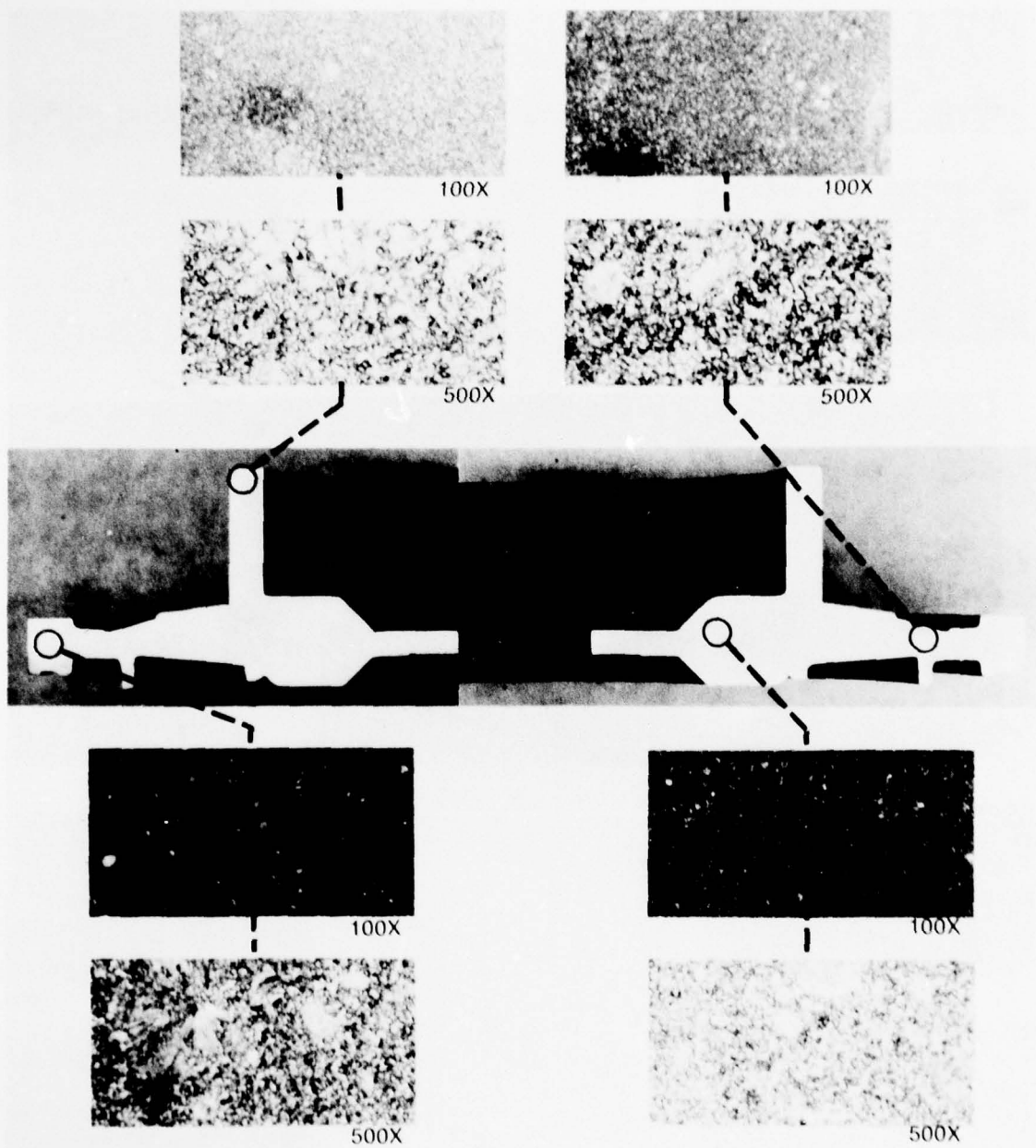
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Figure 24. Optimized Subscale Forgings of Program Part Configurations

The metallurgical examination checked for proper metallographic microstructure and material homogeneity throughout each subscale forging configuration. Heat treated forgings were sectioned and the cross section surfaces were polished and etched. The examination revealed all configurations to meet the PWA 1073/74 microstructural specification**. A macroexamination of the prepared surfaces revealed the uniformity and homogeneity of microstructure to be excellent. The results of metallographic examination of subscale forgings are directly applicable to full-scale forgings since microstructure is not a function of scale.

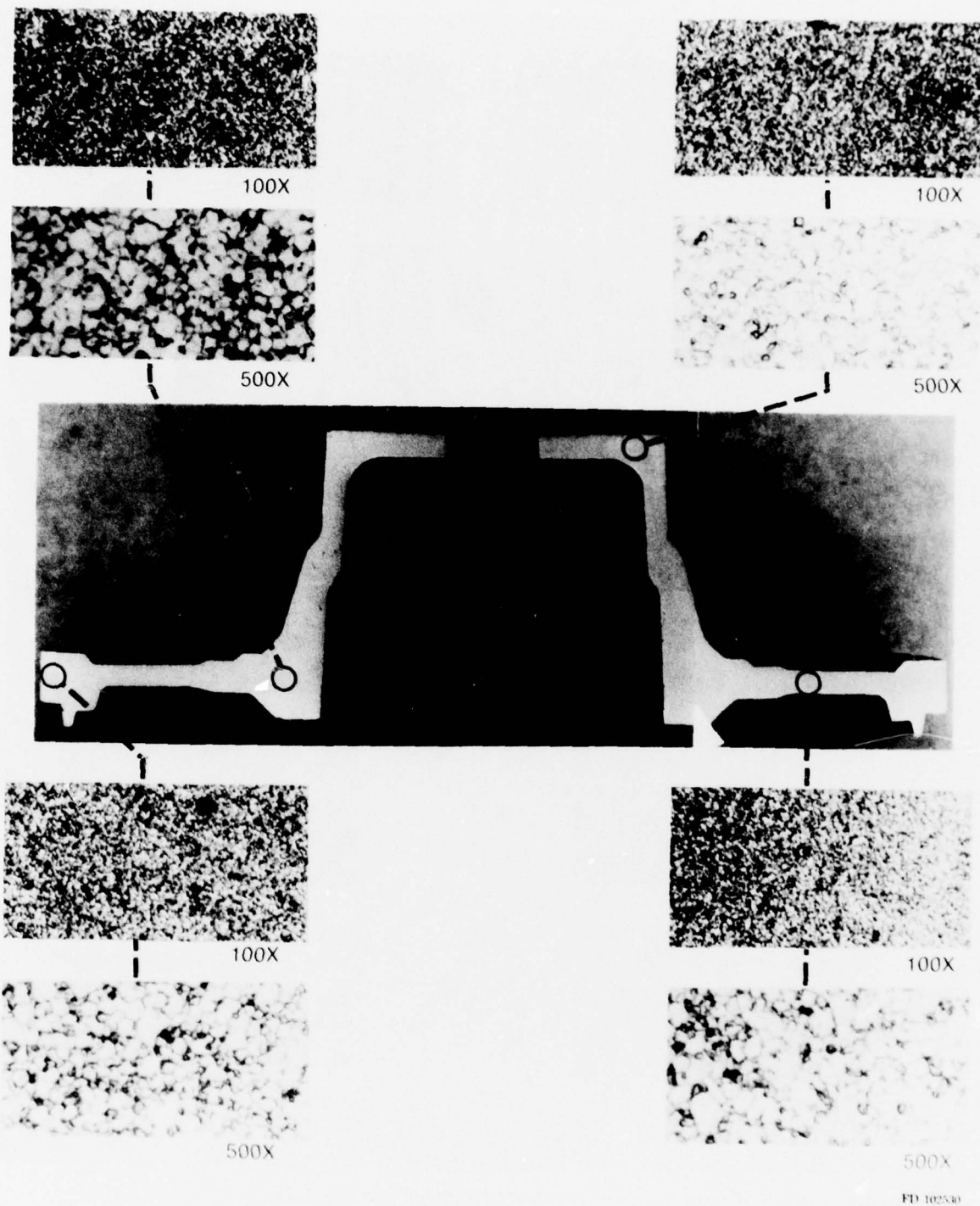
Homogeneity of microstructure layouts were prepared for each of six forging configurations optimized in the subscale phase of this program. Figures 25 through 30 display 100X and 500X photomicrographs taken at various locations from each configuration. The consistency of the microstructure observed throughout the forging configurations is typical of the isothermal forging process when using powder metallurgy forging stock and all inert processing techniques.

** PWA 1074/75 grain size shall be predominantly recrystallized grains of 10.5 or finer with no segregation of coarse or fine areas.



FD 1025/29

Figure 25. Typical Microstructure of Subscale 1st-Stage Turbine Disk



FD 102530

Figure 26. Typical Microstructure of Subscale 2nd-Stage Turbine Disk

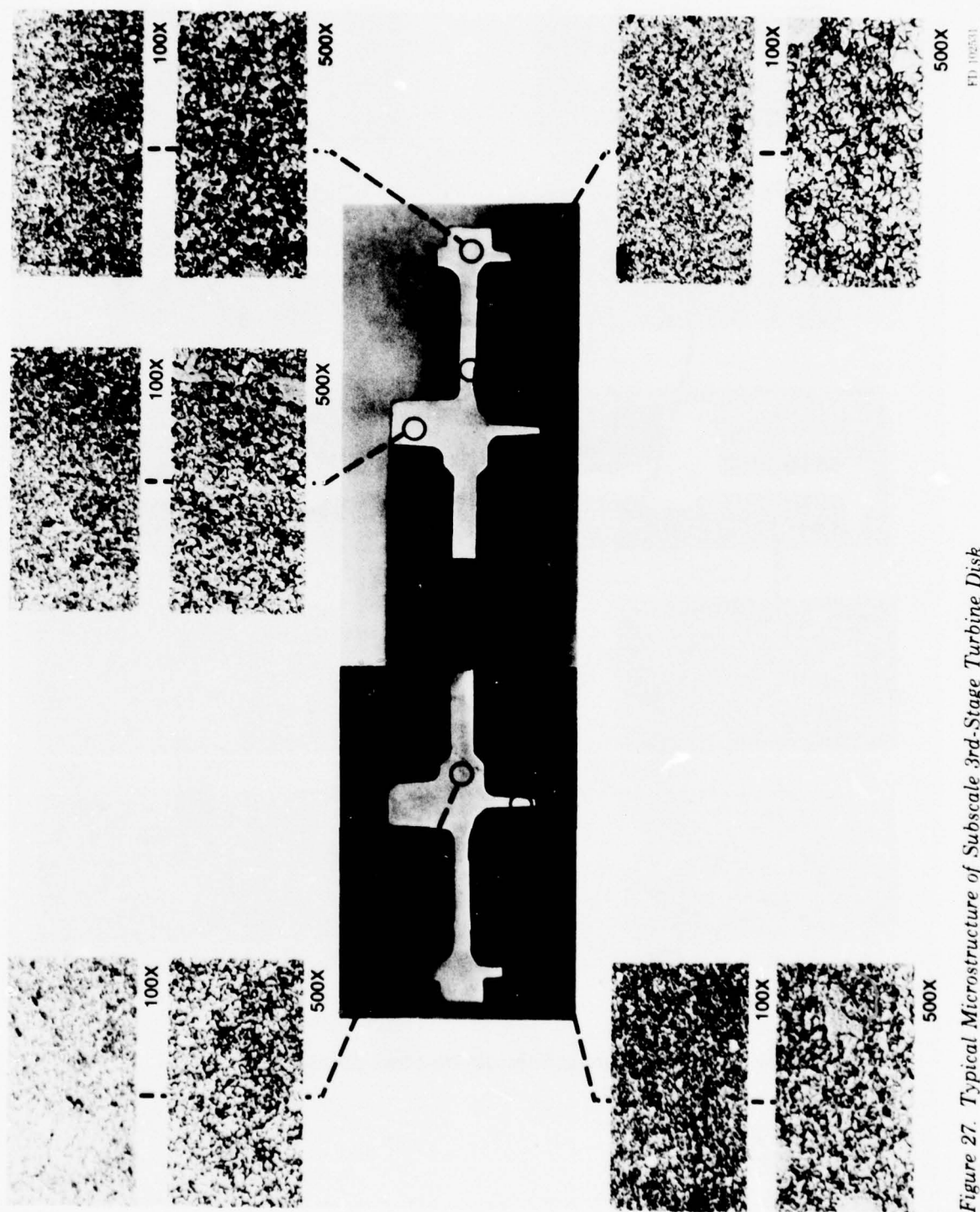
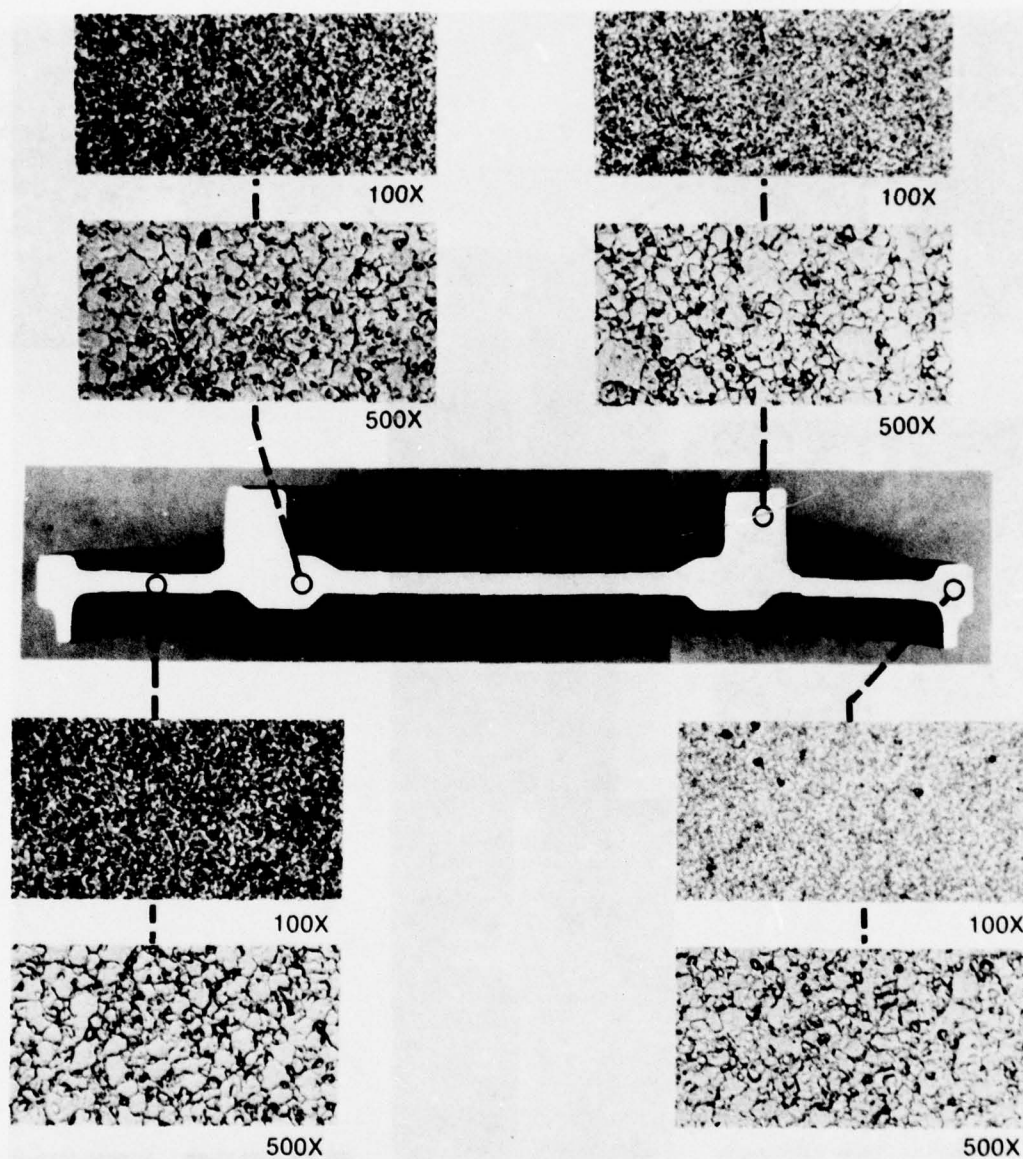
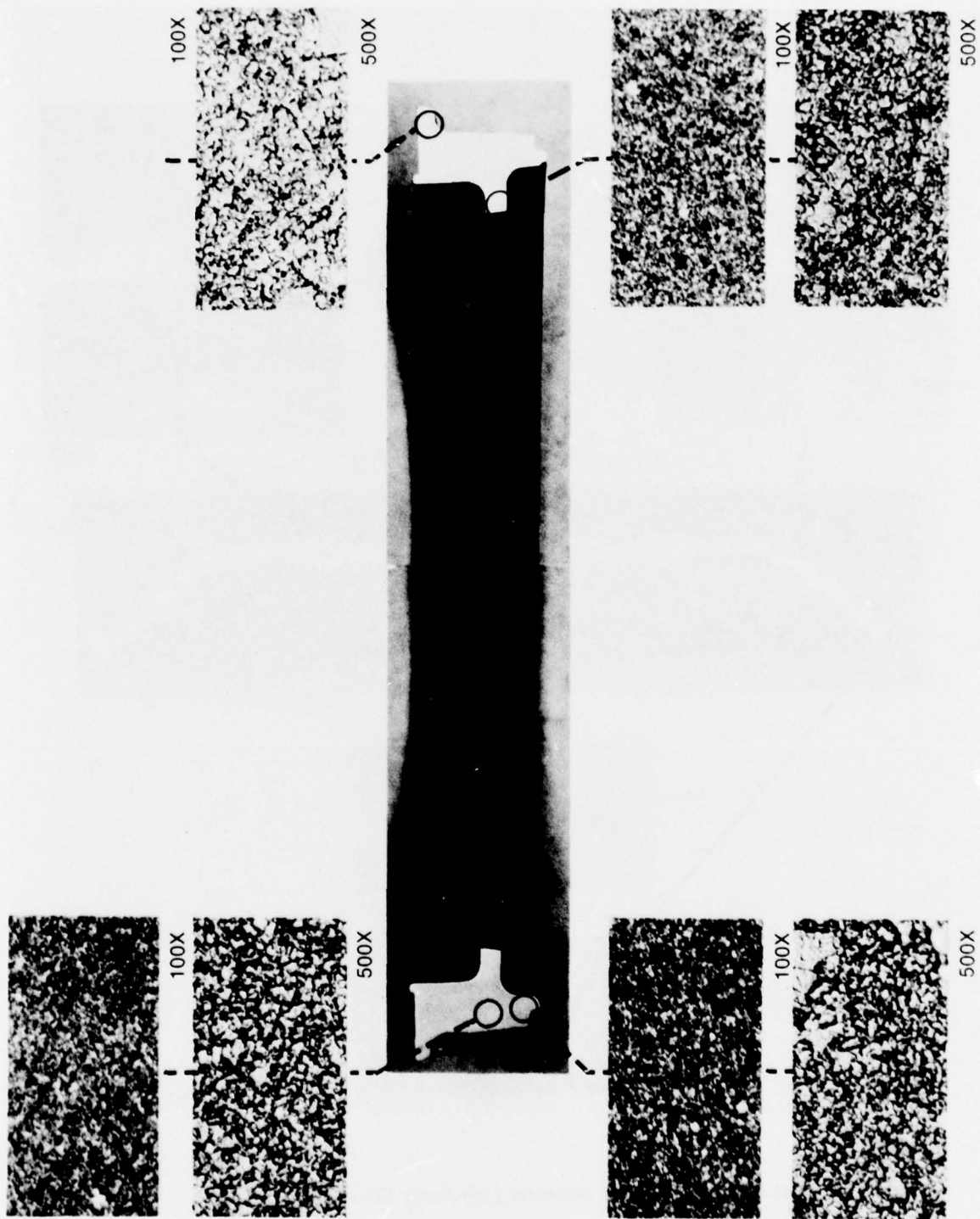


Figure 27. Typical Microstructure of Subscale 3rd-Stage Turbine Disk



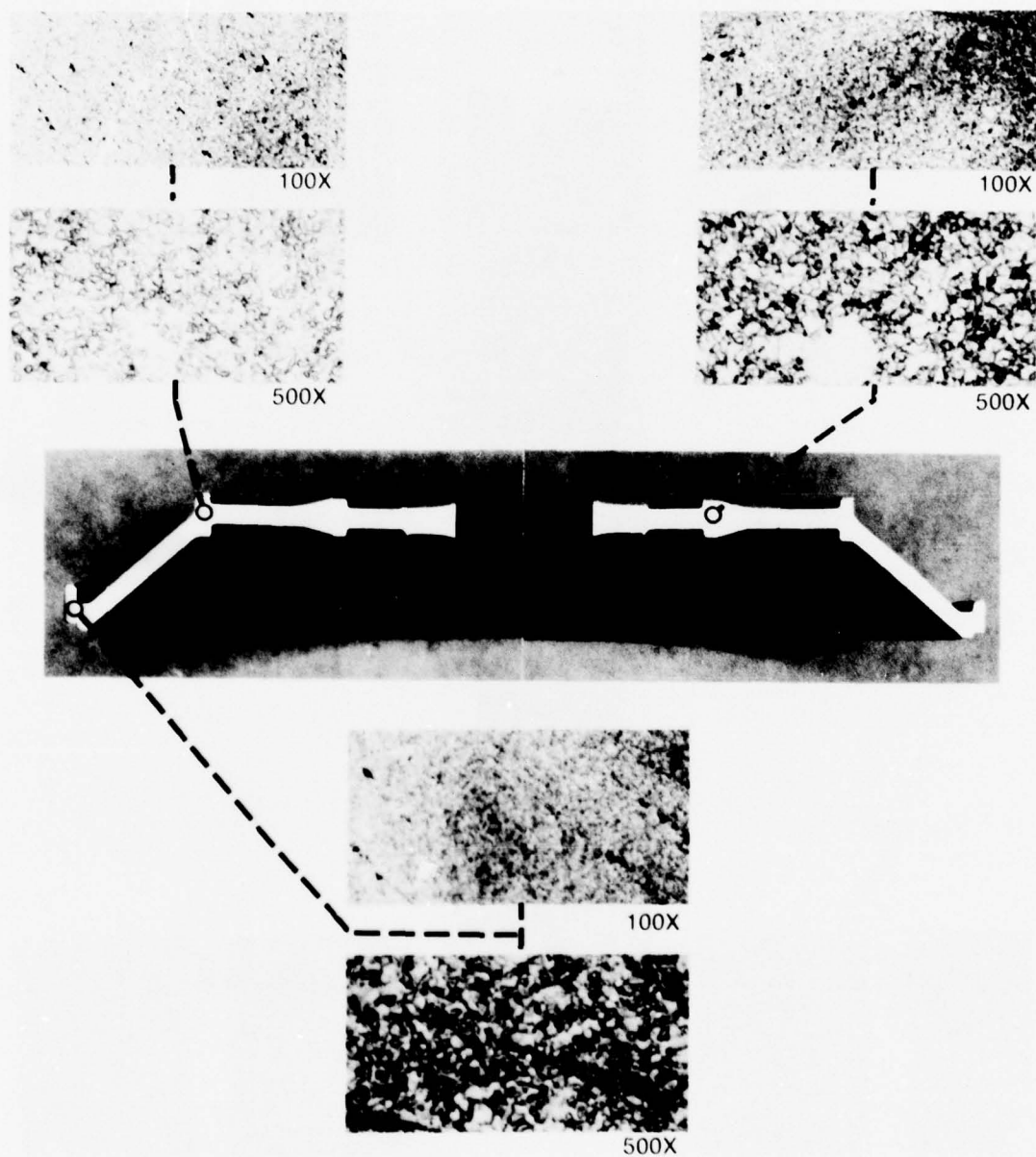
FD 102532

Figure 28. Typical Microstructure of Subscale 4th-Stage Turbine Disk



FD 102533

Figure 29. Typical Microstructure of Subscale 1 - 2 Turbine Rim Spacer



FD 102534

Figure 30. Typical Microstructure of Subscale 13th-Stage Cone Seal

SECTION III

PHASE II — FULL-SCALE DISK FORGING

The full-scale demonstration phase of this program involved the scale-up of the subscale 1st-stage turbine disk forging configuration. Full-scale dies were fabricated and forging iterations were made until an optimum full-scale preform and forging configuration were found. Following this, a heat-treat study examined the dimensional stability of the configuration. Mechanical properties tests were then undertaken to qualify the process. Metallurgical evaluation included macrostructure and microstructural examination and inspection of sections from the cut-up disk to assure structural uniformity.

During the scale-up of the forging configuration, material was added at two locations as shown in Figure 31 to ensure adequate sonic inspectability. Otherwise, where possible, the forging configuration incorporates the 0.050-in. minimum envelope over the actual part.

The dies to forge the full-scale 1st-stage turbine disk were fabricated from 24-inch TZM molybdenum blocks. Figure 32 displays the completed die set. This set used the segmented insert ring to allow the forging of the integral arm flange like that used during Phase I. Figure 33 shows how the segments are seated in the die cavity and the blocks pinned around the upper circumference of the die cavity. These blocks were installed as guides to engage the punch with the die early in the forging stroke to minimize eccentric material flow.

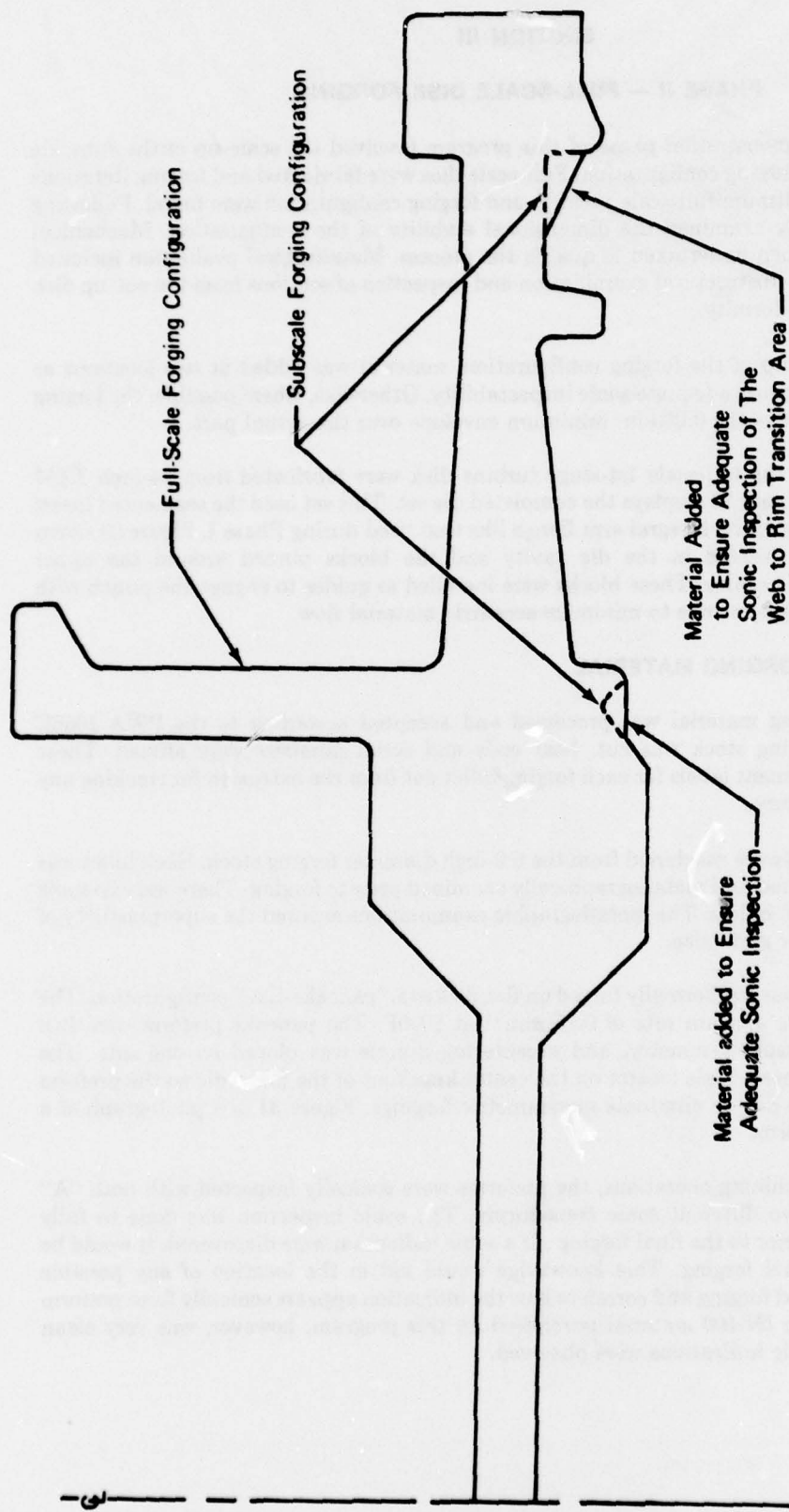
PREPARATION OF FORGING MATERIAL

The IN-100 forging material was processed and accepted according to the PWA 1056E specification. The forging stock was cut, heat code and serial numbers were affixed. These numbers become permanent labels for each forging billet cut from the extrusion for tracking any facet of the billet's history.

The IN-100 billets were machined from the 6.2-inch diameter forging stock. Each billet was thoroughly sonic inspected and metallographically examined prior to forging. There were no sonic indications in any of the billets. The metallographic examinations ensured the superplasticity of the material and proper grain size.

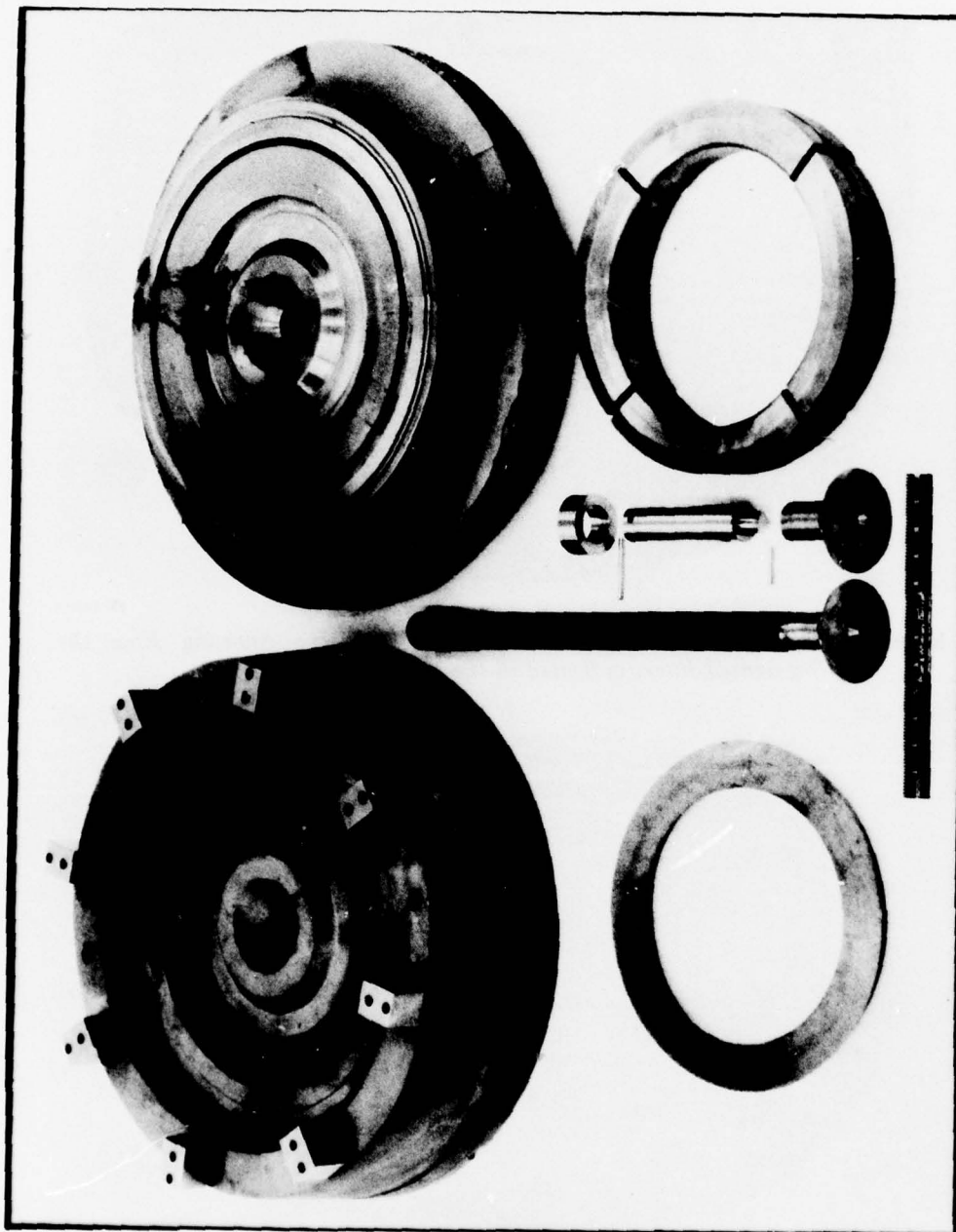
Next, each billet was isothermally forged on flat dies to a "pancake-like" configuration. The forging parameters were a strain rate of 0.15 min^{-1} at 2000F. The pancake preform was then lightly machined to ensure symmetry, and a centering dimple was placed on one side. The centering dimple matches a male locator on the center knockout of the lower die so the preform will be centered on the die, to eliminate unsymmetric forgings. Figure 34 is a photograph of a prepared pancake preform.

Following the machining operations, the preforms were sonically inspected with both "A" and "C" scans with two different sonic transducers. The sonic inspection was done to fully evaluate the material prior to the final forging. If a sonic indication were discovered, it would be followed through to final forging. This knowledge would aid in the location of any possible indication in the finished forging and correlate how the indication appears sonically from preform to finished forging. The IN-100 material purchased for this program, however, was very clean since no significant sonic indications were observed.



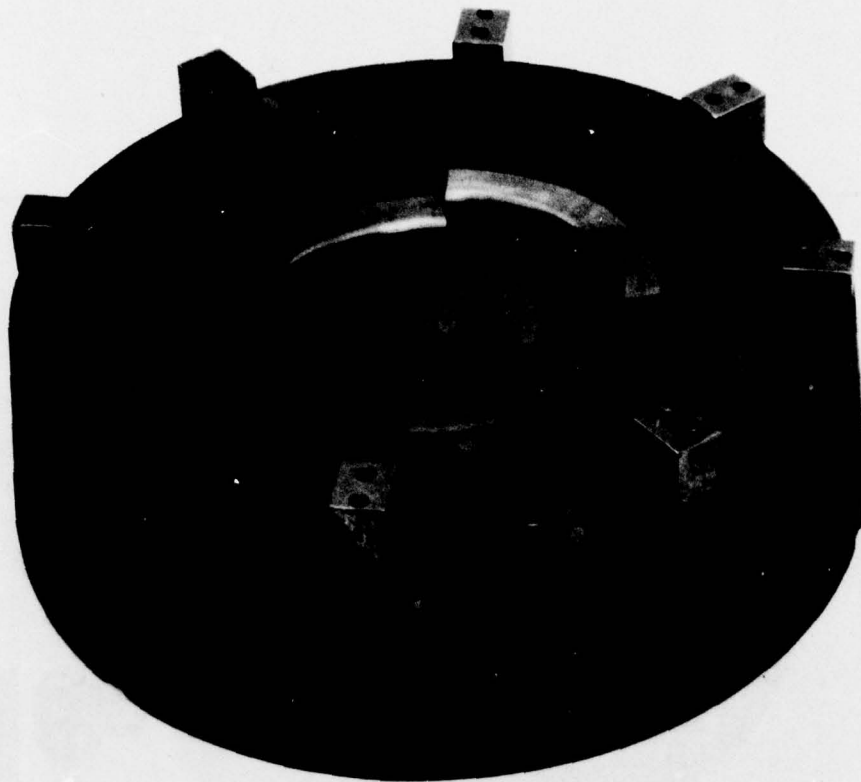
FD 9495

Figure 31. Full-Scale vs Subscale Forging Configurations for the 1st-Stage Turbine Disk



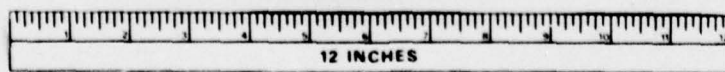
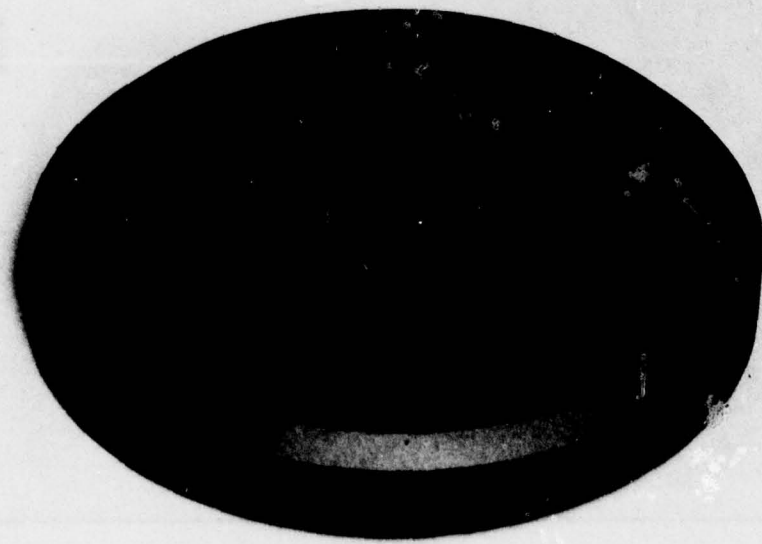
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Figure 32. Finished TQM Moly Die Set To Forge 1st-Stage Turbine Disk



FE 149129

Figure 33. The Full-Scale 1st-Stage Turbine Disk Die Showing How the Segmented Insert is Seated in the Die Cavity



FE 153926

Figure 34. Full-Scale Pancake Preform Ready To Forge

FULL-SCALE FORGING ITERATIONS

The full-scale forging operations began with the preparation of the dies. The dies and associated parts were grit blasted and then lubricated with boron nitride. Proper lubrication was especially important with this particular die set due to the snug fit of the segmented insert ring in the die cavity.

The full-scale forging iterations proceeded at 2000F and a strain rate of 0.1 min^{-1} , and were conducted in P&WA/Florida's 1650-ton HPM press shown in Figure 35. The first preform had a 9.8-inch diameter and was 3.700-inch thick. At the completion of the forging stroke the dies were separated to review the forging. The forging material had flowed to the outside diameter of the die but the part lacked complete detail, necessitating restriking or reapplying the forging load.

Three restrikes were made before flash could be seen at the outer diameter and the part ejected from the die cavity. The segmented insert ring came out of the die cavity with the part and then fell away from the part.

It could be seen that the part was generally well defined, with the exception of the integral arm. Material had flowed down the integral arm cavity formed by the insert ring, but had only moved about a third of the way into the flange portion of the cavity, as illustrated in Figure 36.

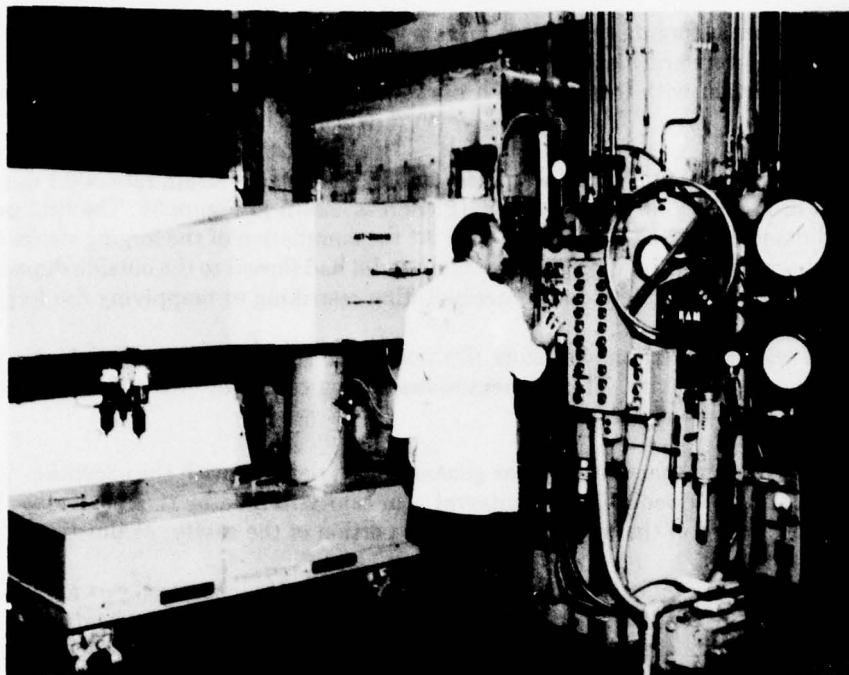
The part was metallographically examined. A grain size inspection was made to ensure that an overtemperature condition had not occurred in the preform during the heating of the die stack. The dominant grain size observed confirmed that no overtemperature condition had been reached.

The full-scale part was then carefully dimensionally checked to reveal any areas where die fill might be incomplete. As previously mentioned, the only area lacking definition was the flange of the integral arm.

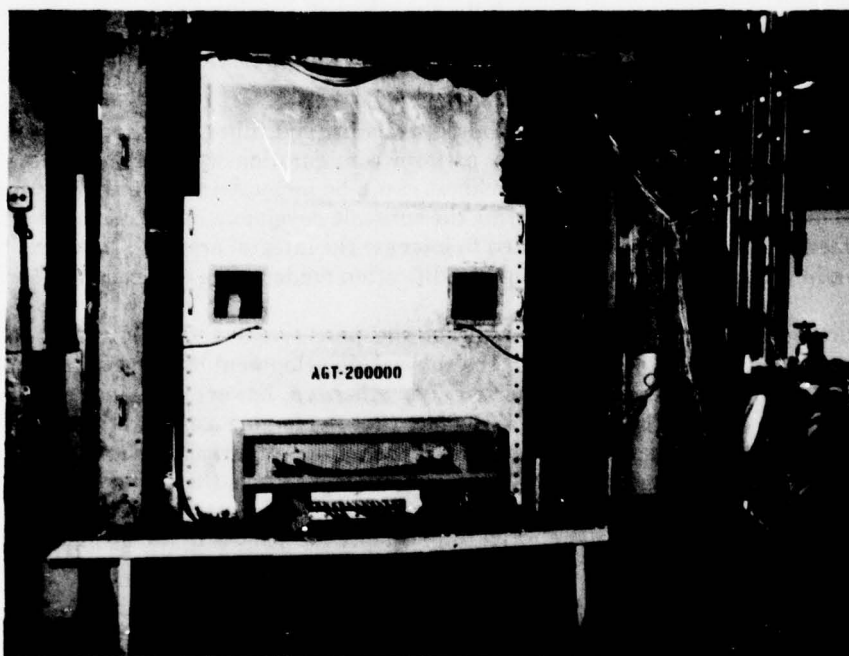
Since the material was well distributed, reaching and filling the rim, and nearly filling the integral arm flange, no changes to the preform configuration were planned. To aid filling the flange cavity, the integral arm wall thickness could be increased to ease flow resistance into the cavity. This had proven successful during the subscale development of 1st-stage turbine disk. So, the segmented insert ring was machined to increase the integral arm wall thickness by 0.040-inch as shown in Figure 37. This was the only modification made before the second full-scale iteration.

Further examination of the surface of the part revealed that laps had formed in two locations as shown in Figure 38. From the subscale development of this part, the possibility of a lap in the punch side flange was expected. The other lap, however, was not experienced during subscale development. This was due to the fact that the forging configuration was altered during scale-up to ensure adequate sonic inspection of the web-to-rim transition area. Neither of the laps appeared to be severe, and because of the particular locations they would be easily eliminated from the part by slight die contour modifications. These modifications were not made at this time since the immediate goal of these initial full-scale iterations was to fill the flange of the integral arm.

The second full-scale forging iteration used the same preform configuration as the first forging. As with the first iteration, this forging trial was restruck three times to obtain flash around the outside diameter of the part. After the part was removed from the die set, it was observed that the part was generally well defined with the exception of the flange of the integral arm; however, some improvement had been made. The flange cavity was over half filled, but like the first iteration, laps were observed in the same locations.



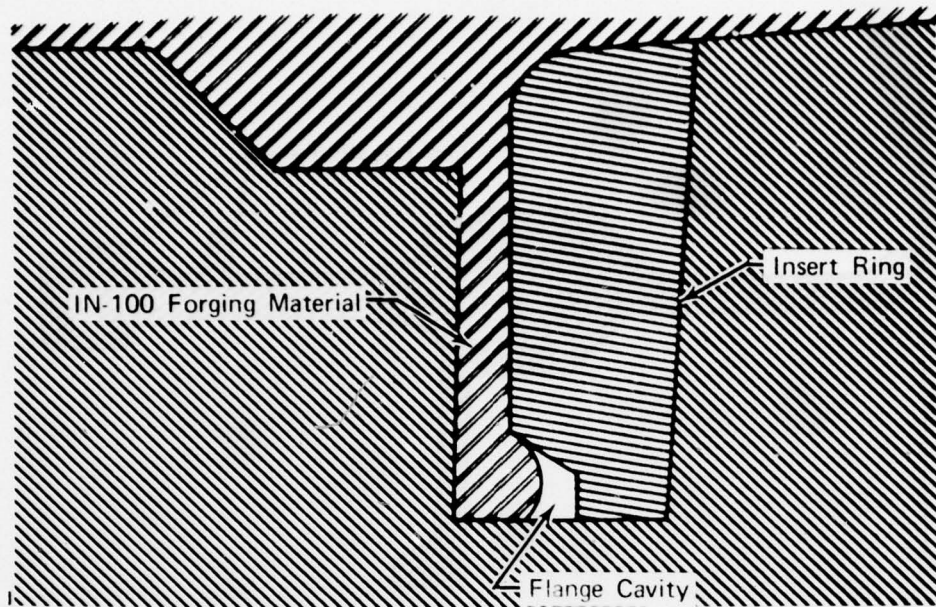
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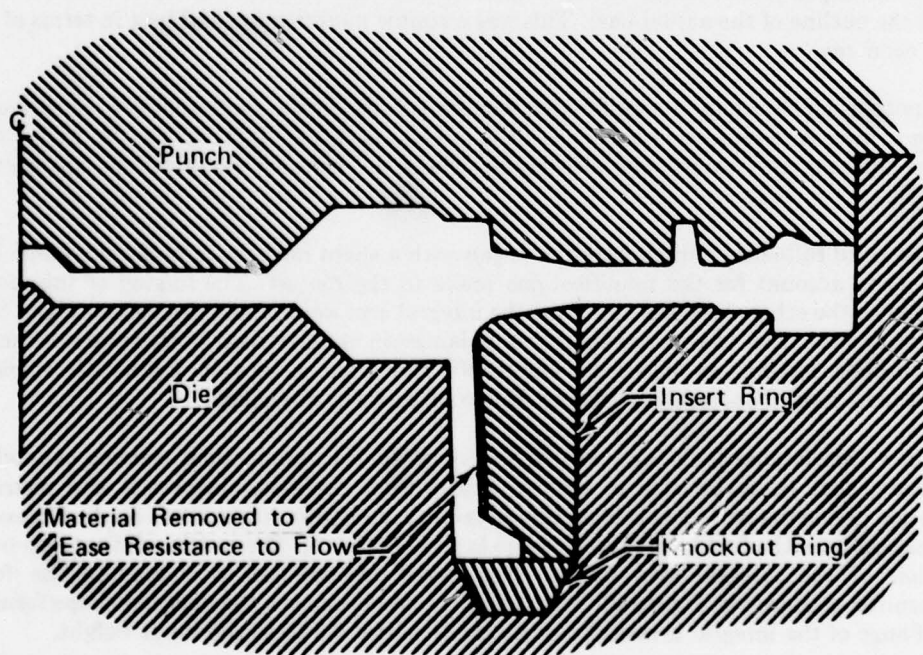
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Figure 35. 1650-Ton Press Used for the Production of Advanced Military Rotor Hardware by the GATORIZING™ Brand Forging Process



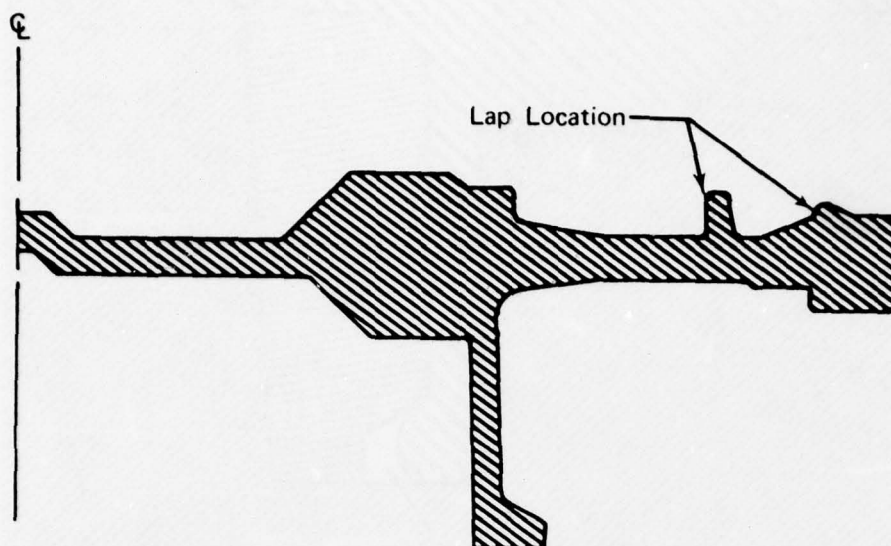
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Figure 36. The IN-100 Material Flow Into the Flange Cavity of the First Full-Scale Forging



FD 97256

Figure 37. Insert Ring Modification



FD 97257

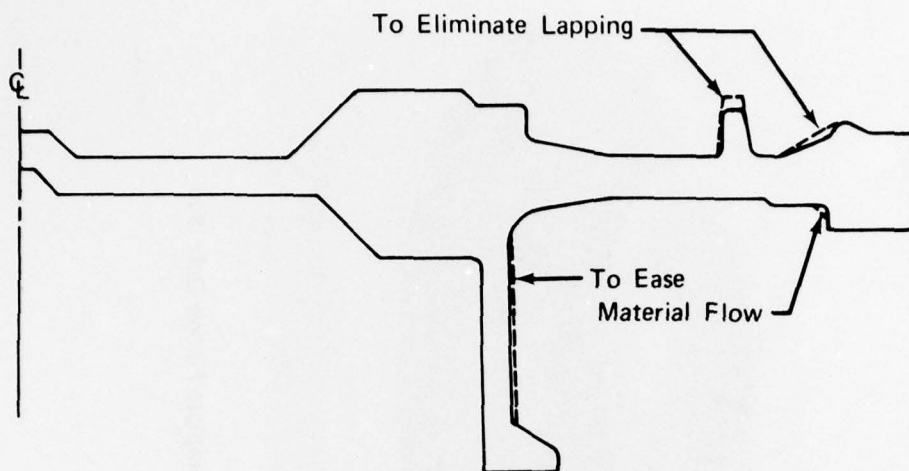
Figure 38. Locations Where Lapping Occurred in the First Full-Scale Forging

To eliminate the lap that was forming in the punch-side flange, a modification was made to increase the depth of this flange cavity a distance sufficient to allow the lap to form outside, or beyond the outline of the actual part. This was a simple modification and best in terms of input weight economy.

Another lap elimination modification was smoothing the die contour at the transition from the web to rim. A modification to increase the integral arm wall thickness to ease material flow into the integral arm cavity was also made. These die contour modifications are shown in Figure 39.

The third full-scale forging iteration began with a slight increase in preform volume (same diameter) to account for the modifications made to the die set. The forging of this preform proceeded as the others had, but this time the integral arm was defined throughout about 80% of its circumference. This forging was slightly unbalanced in material distribution and was therefore an incomplete forging, as shown in Figure 40. However, as seen in Figure 41, significant improvement toward successfully forging, this configuration was made.

Since this forging technique will be incorporated into production, restrike capability is mandatory, that is, to be able to remove a part from the press, inspect it and restrike to completely define the part. To evaluate this capability, a restrike attempt was made. Excess flash was removed from the first forging so as not to inhibit die travel. The restrike did not improve the definition of the integral arm flange. This result necessitated a change to the forging configuration as shown in Figure 42. This modification eliminated the near net shape formation of the flange of the integral arm and unfortunately added 9.5 lb to the input weight.



FD 97258

Figure 39. The Die Contour Modifications Made to Ease Material Flow and to Eliminate Lapping



FE 149474

Figure 40. The Third Full-Scale 1st-Stage Turbine Disk Showing the Die Fill in the Flange of the Integrated Arm



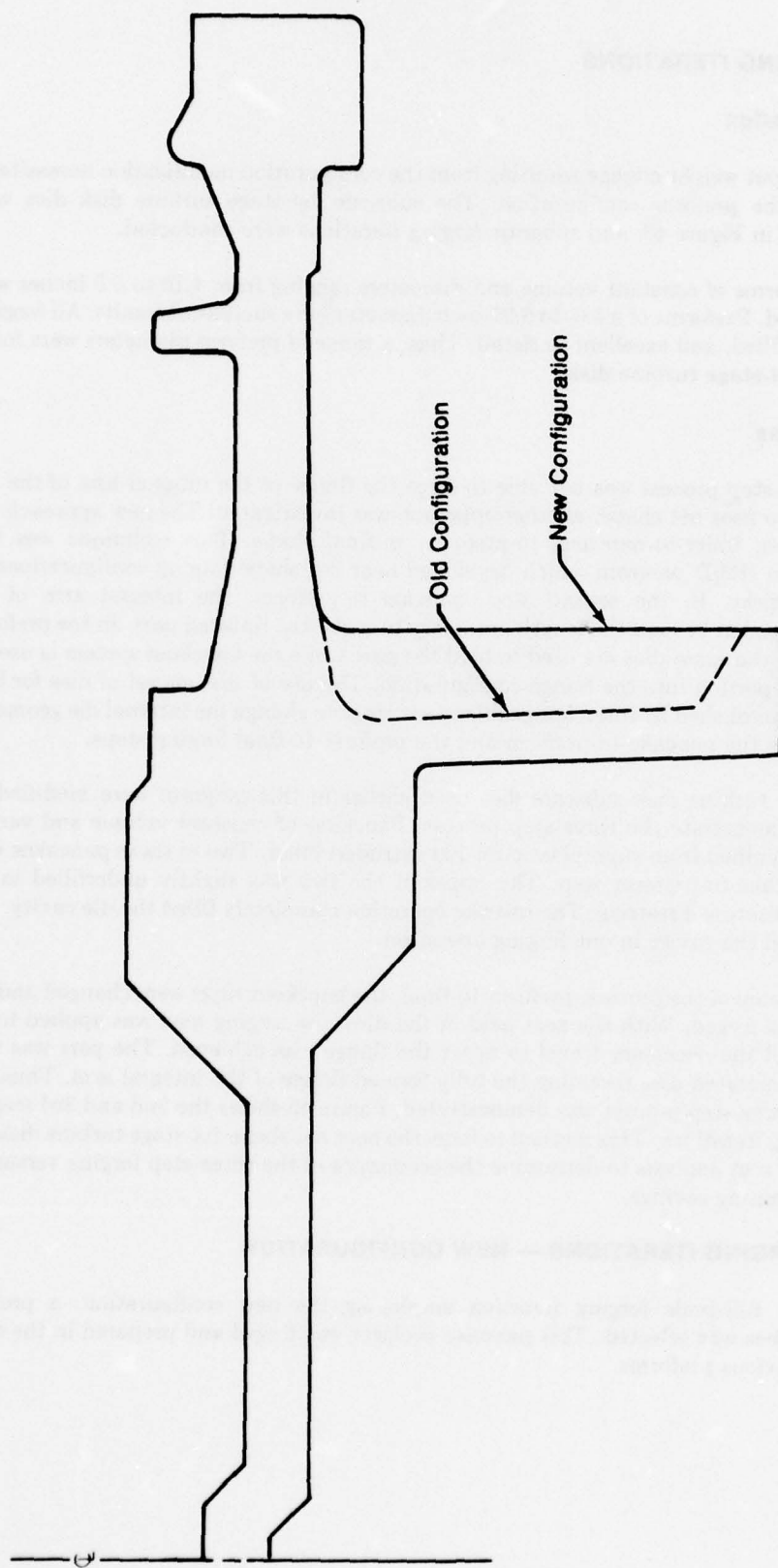
Incomplete Flange Definition



80% Complete Flange Definition

FD 124361

Figure 41. First and Third Flanged Configuration Forging Iterations



FD 124364

Figure 42. Forging Configuration Change for the 1st-Stage Turbine Disk

SUBSCALE FORGING ITERATIONS

Modified Configuration

The forging input weight change resulting from the configuration modification necessitated reoptimization of the preform configuration. The subscale 1st-stage turbine disk dies were modified, as shown in Figure 43, and subscale forging iterations were conducted.

Subscale preforms of constant volume and diameters ranging from 4.10 to 5.5 inches were machined and forged. Preforms of a 4.6- to 5.25-inch diameter gave successful results. All forgings were lap free, well filled, and excellent in detail. Thus, a range of preform diameters were found to yield subscale 1st-stage turbine disks.

Three-Step Process

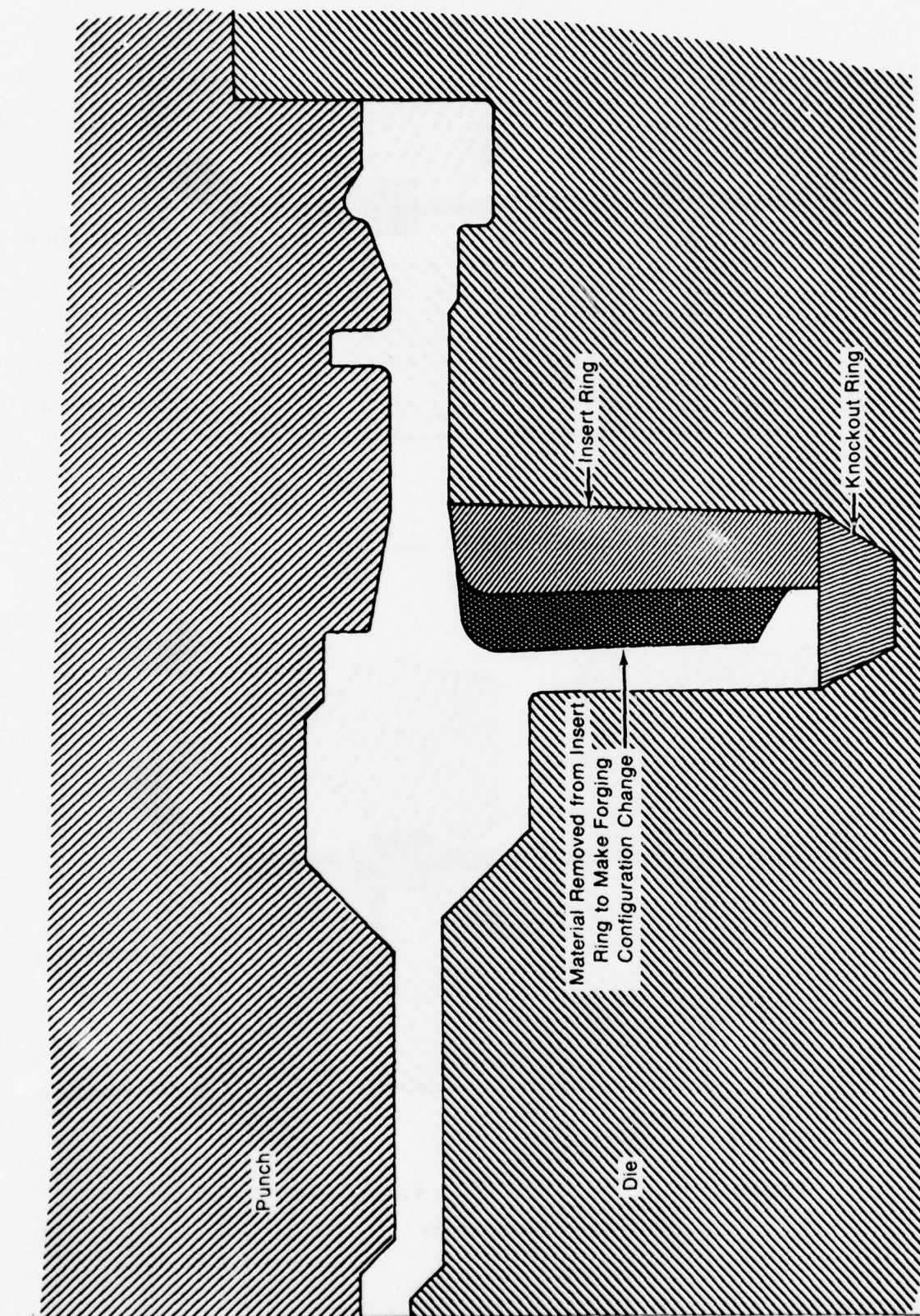
Since the two-step process was not able to forge the flange of the integral arm of the 1st-stage turbine disk to near net shape, another approach was investigated. The new approach was a three-step process; billet-to-pancake, to-preform, to-final shape. This technique was first demonstrated on an IR&D program which developed near net shape forging configurations for F100 compressor disks. In the second step, pancake-to-preform, the integral arm of the configuration is extruded beyond the length necessary to make the finished part. In the preform-to-final shape step, the same dies are used to hold the part while the knockout system is used to upset the extruded portion into the flange configuration. The use of the one set of dies for both forging steps is accomplished by interchangeable insert rings to change the internal die geometry. Figure 44 illustrates the pancake-to-preform and the preform-to-final forging steps.

The 1st-stage turbine disk subscale dies used earlier in this program were modified for forging trials to demonstrate the three-step process. Pancakes of constant volume and various diameters were machined from superplastic IN-100 extruded billet. Two of these pancakes were forged in the pancake-to-preform step. The larger of the two was slightly underfilled in the integral arm necessitating a restrike. The restrike operation completely filled the die cavity. The other pancake filled the cavity in one forging operation.

For the third step of the process, preform-to-final, the knockout rings were changed and one of the preforms was forged. With the part held in the dies, the forging load was applied to the knockout pins until the necessary travel to upset the flange was achieved. The part was then ejected from the separated dies revealing the fully formed flange of the integral arm. Thus, the feasibility of the three-step process was demonstrated. Figure 45 shows the 2nd and 3rd steps of the subscale forging iterations. This method to forge the near net shape 1st-stage turbine disk will be included in the cost analysis to determine the economics of the three-step forging versus the material and machining savings.

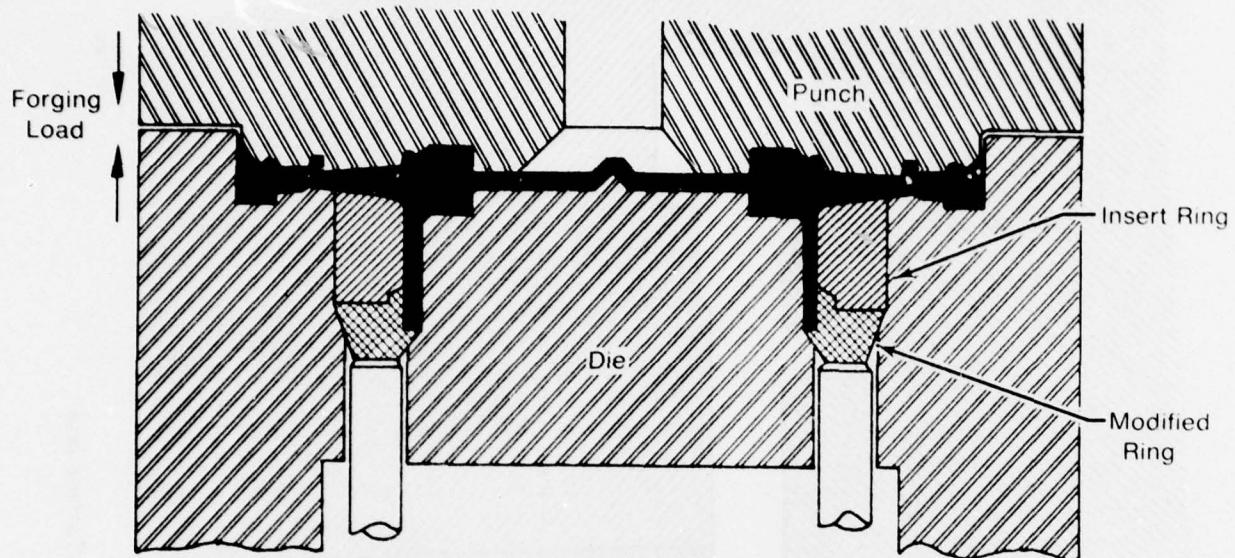
FULL-SCALE FORGING ITERATIONS — NEW CONFIGURATION

For the first full-scale forging iteration employing the new configuration, a preform diameter of 15 inches was selected. This pancake preform was forged and prepared in the same manner as the previous preforms.

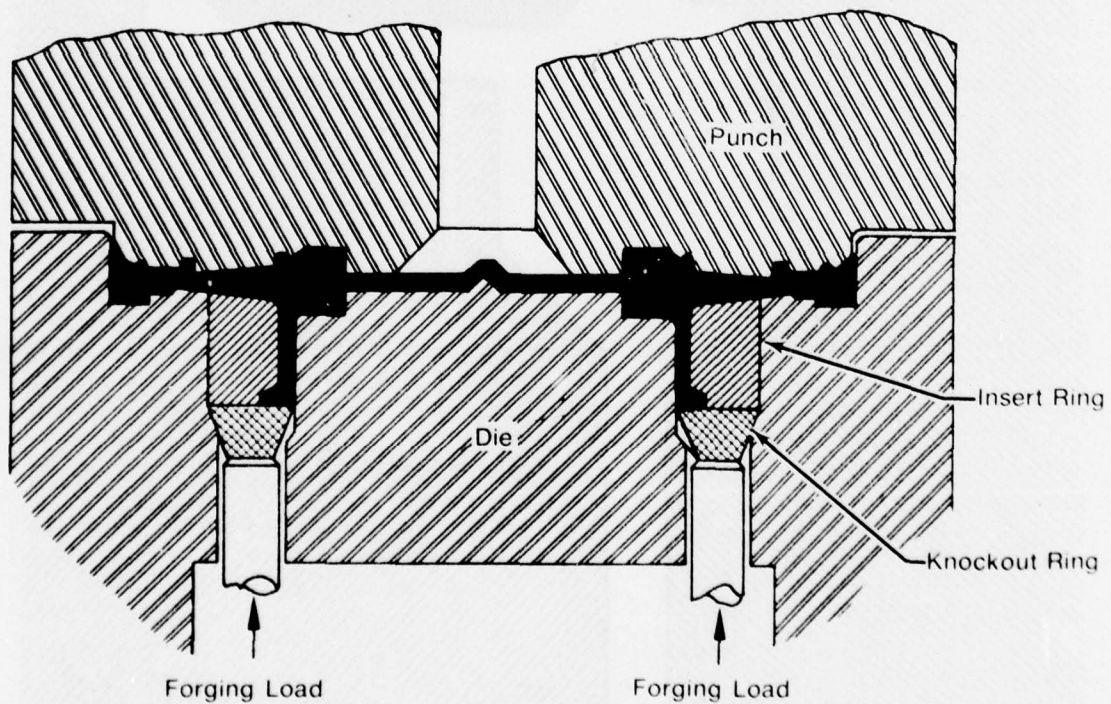


FD 124963

Figure 43. Die Modification to Incorporate Forging Configuration Change for 1st-Stage Turbine Disk



(a) Pancake-To-Preform Step



(b) Preform-To-Final Step

FD 124362

Figure 44. Three-Step Forging Scheme for Subscale 1st-Stage Turbine Disk

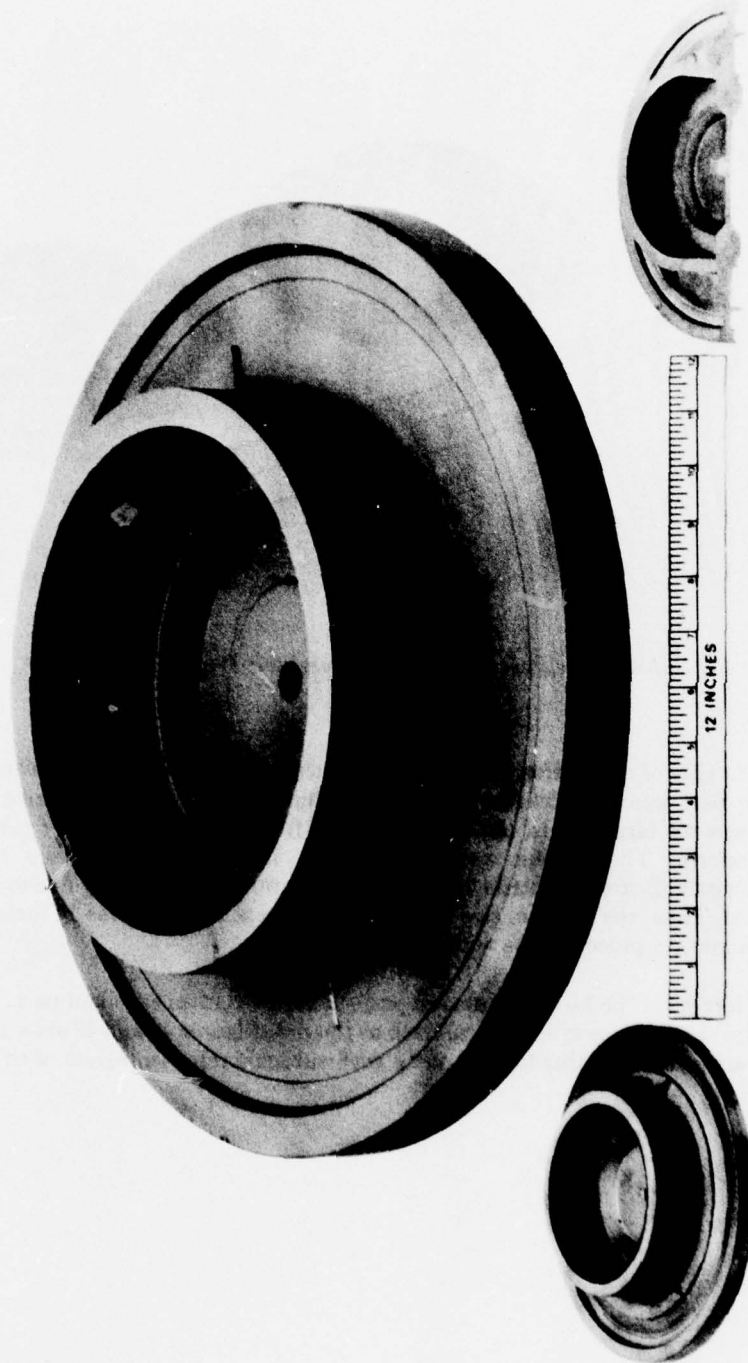


FE 152817

Figure 45. Subscale Representatives of Three-Step Process

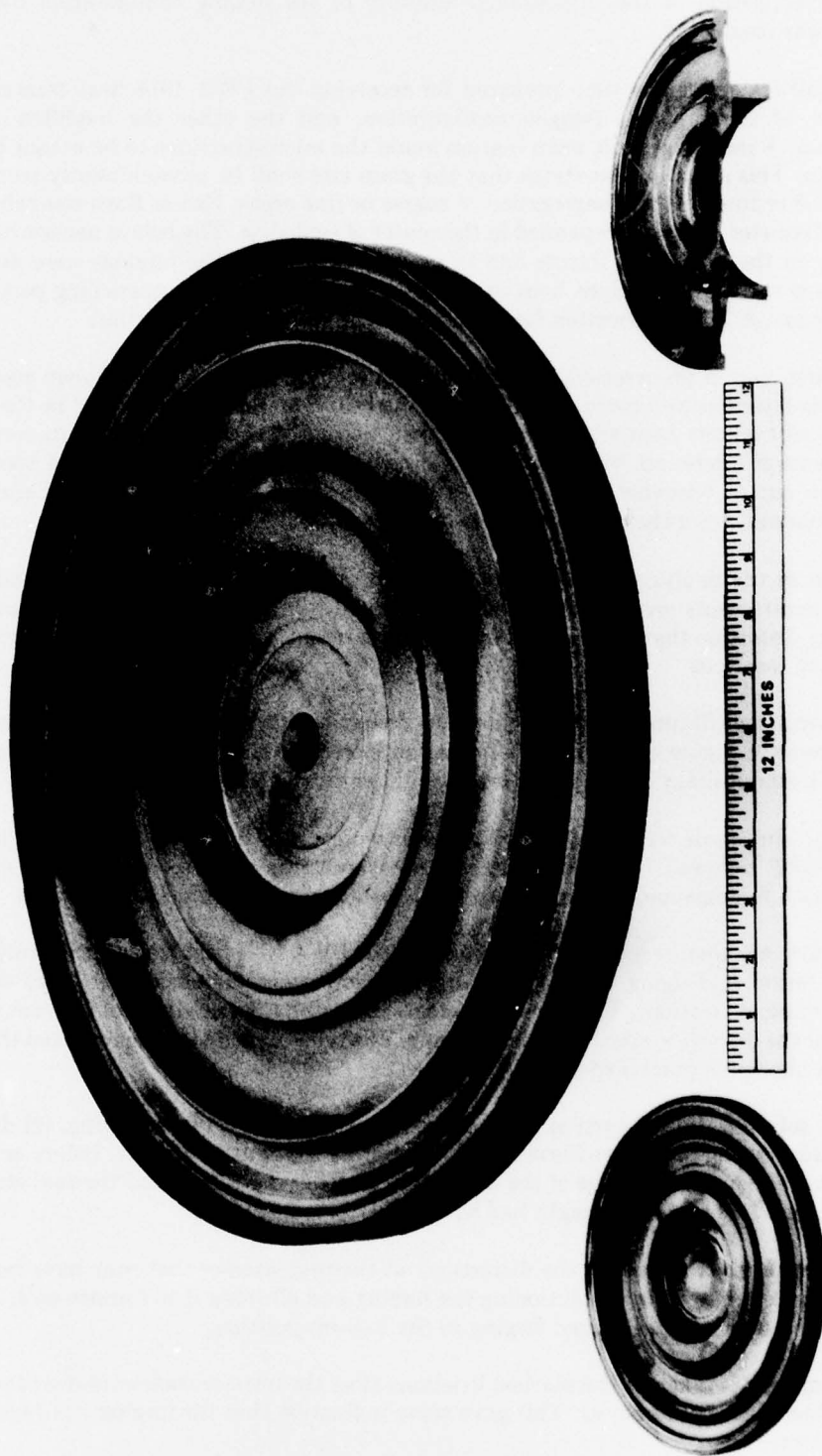
The forging of this preform resulted in an incomplete die fill of the integral arm cavity. The rim of the part was well defined and had an abundance of flash indicating that the preform diameter was too large. Thus, the insufficient die fill was due to improper material distribution in the preform. The forging was measured to ascertain if a restrike was feasible. The measurements indicated a restrike could not fill the integral arm cavity due to improper material distribution. Thus, the preform size selected for the next iteration was 14 inches. The remainder of the preparation proceeded as with previous preforms.

The forging of the 14-inch diameter preform resulted in an excellent part. The die cavity was well filled and there was symmetrical flash at the rim. Figures 46 and 47 show the excellent detail that was achieved with this forging along with subscale representatives of this configuration.



FE 14761

Figure 46. Top View of Unflanged Full-Scale Turbine Disk and Subscale Representatives



FE 14052

Figure 47. Bottom View of Unflanged Full-Scale 1st-Stage Turbine Disk and Subscale Representatives

HEAT TREAT DISTORTION STUDY

An investigation of the dimensional stability of the forging configuration during heat treatment was conducted.

The full-scale forgings were prepared for receiving the PWA 1074 heat treatment. One forging was of the previous flanged configuration, and the other the modified unflanged configuration. A metallographic examination found the microstructures to be within PWA 1074 specification. This specification states that the grain size shall be predominantly recrystallized grains of 10.5 or finer with no segregation of coarse or fine areas. Excess flash was removed and a 2.5-inch diameter hole was trepanned in the center of each disk. The hole is necessary to mount the forging on the heat treat fixture and to prevent distortion. The forgings were deburred to remove sharp corners that might behave as crack starters during the quenching portion of the heat treatment. A Zygo inspection found no cracks or surface abnormalities.

The first step in preparation for the distortion study is a dimensional layout made of each forging. This layout served two purposes. First, the initial measurements would be the reference dimensions to evaluate heat treatment distortion. Secondly, these measurements were used to check dimension tolerances with the forging drawing. Two diameters of the die contour were found to be out of tolerance by 0.020 to 0.030 inch. This situation was easily corrected by removing material from the dies at these two locations.

To aid in the analysis of heat-treat distortion, a more specific layout was made of each forging. Measurements were made at several marked locations on the forgings which would indicate any distortion that may occur. After heat treatment, the forgings were measured at these same marked locations.

The heat-treat fixture used throughout the distortion study was a post, spider, and support ring arrangement. Figure 48 illustrates a forging supported on the fixture. The forging was placed in the hub-down position so the larger mass would enter the oil quench first.

The two full-scale forgings received the solution cycle of the PWA 1074 heat treatment (2 hours at 2050F followed by an oil quench). Measurements made of the solutioned forgings indicated both forgings had distorted with the hub moving down relative to the rim.

Both forgings then received the remainder of the PWA 1074 heat treatment, which includes the precipitation and aging cycles. The forgings were again dimensionally laid out at the previously marked locations. These measurements indicated the remainder of the heat treatment did not alter the distortion status of either forging. The remaining distortion rendered the forgings unable to yield finish machined parts.

Three solutions to a distortion problem are: (1) adding mass to the forging, (2) designing a holding or supporting heat treat fixture, and (3) altering the heat treatment. Before any solution could be implemented, the cause of the distortion, whether it was residual thermal stress or the forging sagging under its own weight had to be determined.

To investigate the cause of the distortion, all thermal stresses that may have remained in the forging were removed by resolutioning the forging and allowing it to furnace cool. This cycle was performed using the unflanged forging in the hub-up position.

Measurements taken at the marked locations after the furnace cooling showed that some of the distortion had been removed. This gave some indication that the forging was sagging under its own weight.

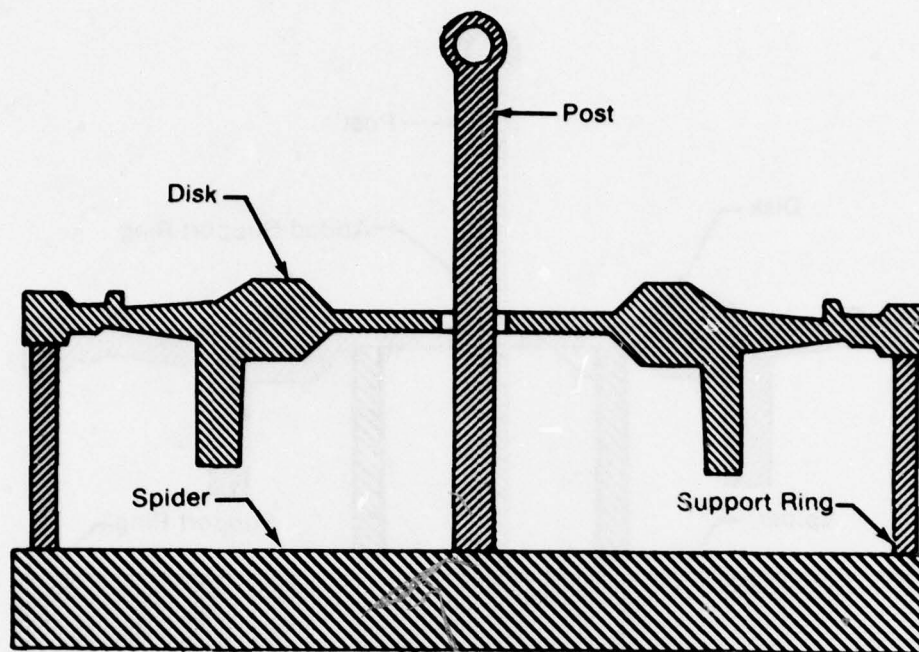


Figure 48. Heat-Treat Fixture and Forging Placement

FD 99113

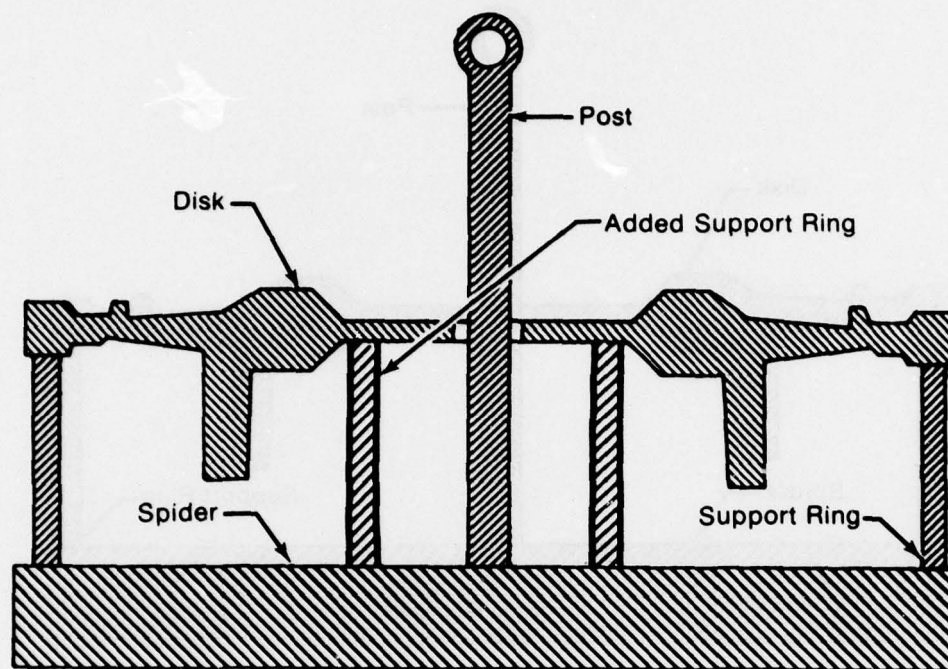
With thermal stresses removed, the next step was to solution and oil quench the forging in the hub-up position. Measurements taken after this cycle showed no significant movement within the disk. Thus, it appeared the solution to the distortion problem was to place the forging in the hub-up position during heat treatment.

Another full-scale forging was prepared for heat treatment to prove this solution. This forging was placed on the heat-treat fixture in the hub-up position and received the solution and oil quench cycle. Measurements taken from the forging revealed that the disk had distorted and showed that the hub section had moved down relative to the rim.

Thus, the primary cause of the distortion was the forging sagging under its own weight. The solution to the problem was to add a ring to the heat-treat fixture to support the center section of the forging. Figure 49 illustrates the modification made to the fixture.

A virgin 1st-stage turbine disk forging was heat treated on this modified fixture. The postheat treatment dimensional layout revealed only slight distortion around the rim, but no sagging. The rim distortion was minimal and would not interfere with this forging, yielding a finished part.

The heat-treat distortion study revealed another phenomena. Postheat-treat measurements revealed the forgings were shrinking, both radially and axially. The radial shrinkage was much greater than the axial, amounting to approximately 0.050-inch on the outer diameter of the forging.



FD 99114

Figure 49. Heat-Treat Fixture Modification With Added Support Ring

The shrinkage took place during the solution cycle of the heat treatment. The precipitation and age cycles did not contribute any further shrinkage.

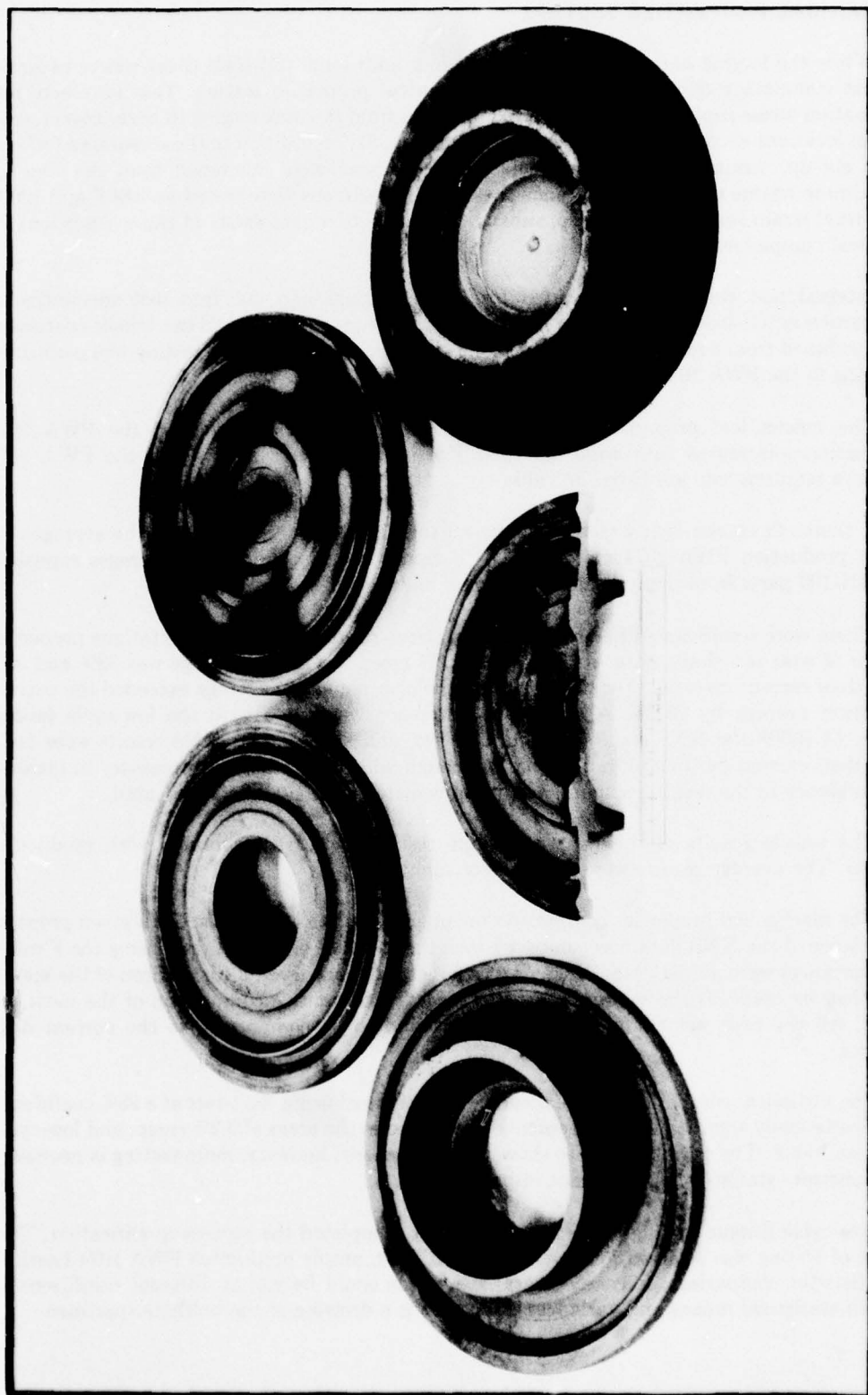
To compensate for the shrinkage, several diameters of the die cavity were increased by 0.050-inch. Increasing the outer diameter eliminated the desired tolerance between the punch and die. To regain this tolerance, a molybdenum coating was applied to the perimeter of the punch by plasma spraying. The coating was applied to an overthick condition and machined until the desired punch-die tolerance was obtained.

Since the heat-treat fixture modification solved the distortion problem, no major changes to the forging configuration were necessary. The forging of the additional disks proceeded to fulfill the obligations of the contract. Five full-scale 1st-stage turbine disks were required for demonstration of sonic inspection capabilities, mechanical properties testing, and process qualification testing.

Four more billets were forged into 14-inch preforms at 1900F and forge rate of 1.5-in./min. The remaining preparation proceeded as with the previous preforms. No indications were located in the preforms during sonic inspection.

After the four full-scale forgings were made, two were found able to yield finish machined parts while the other two had underfilled areas sufficient to necessitate restriking. The restrike operation significantly improved both forgings.

Dimensional layouts then showed these two forgings able to yield finish machined parts. All four forgings were heat treated to the PWA 1073/74 specification. Figure 50 displays the five forgings made which completed the full-scale contractual obligations.



FE 152012

Figure 50. Complete Full-Scale Forgings

MECHANICAL PROPERTIES TESTING

While the forging and heat treating of the four additional full-scale disks was in progress, the first complete forging was cut-up for mechanical properties testing. Tensile, creep, and combination stress rupture specimens were machined from the disk forging in bore, spacer, web, and rim locations according to the plan shown in Figure 51. In addition to these required tests for a disk cut-up, strain control low-cycle fatigue specimens were machined from the rim. To approximate engine operating conditions the fatigue specimens were tested at 1000F and 1200F at the total strain range of 1.0%. Also, substantial production data exists at these conditions for statistical comparisons.

Integral test rings were machined from two forgings and cut into test specimens. A combination notch-smooth stress-rupture specimen, a creep specimen, and two tensile specimens were machined from each test ring. The tensile, creep, and stress-rupture testing was performed according to the PWA 1074 specification.

The mechanical properties of the near net shape material surpassed the PWA 1074 specification minimums with wide margins. The individual test results and the PWA 1074 minimum requirements are listed in Table 1.

A thorough comparison was made between the near net shape data and the averages for current production PWA 1074 material. The current production property averages represent many IN-100 parts from many heats of material, and several vendor sources.

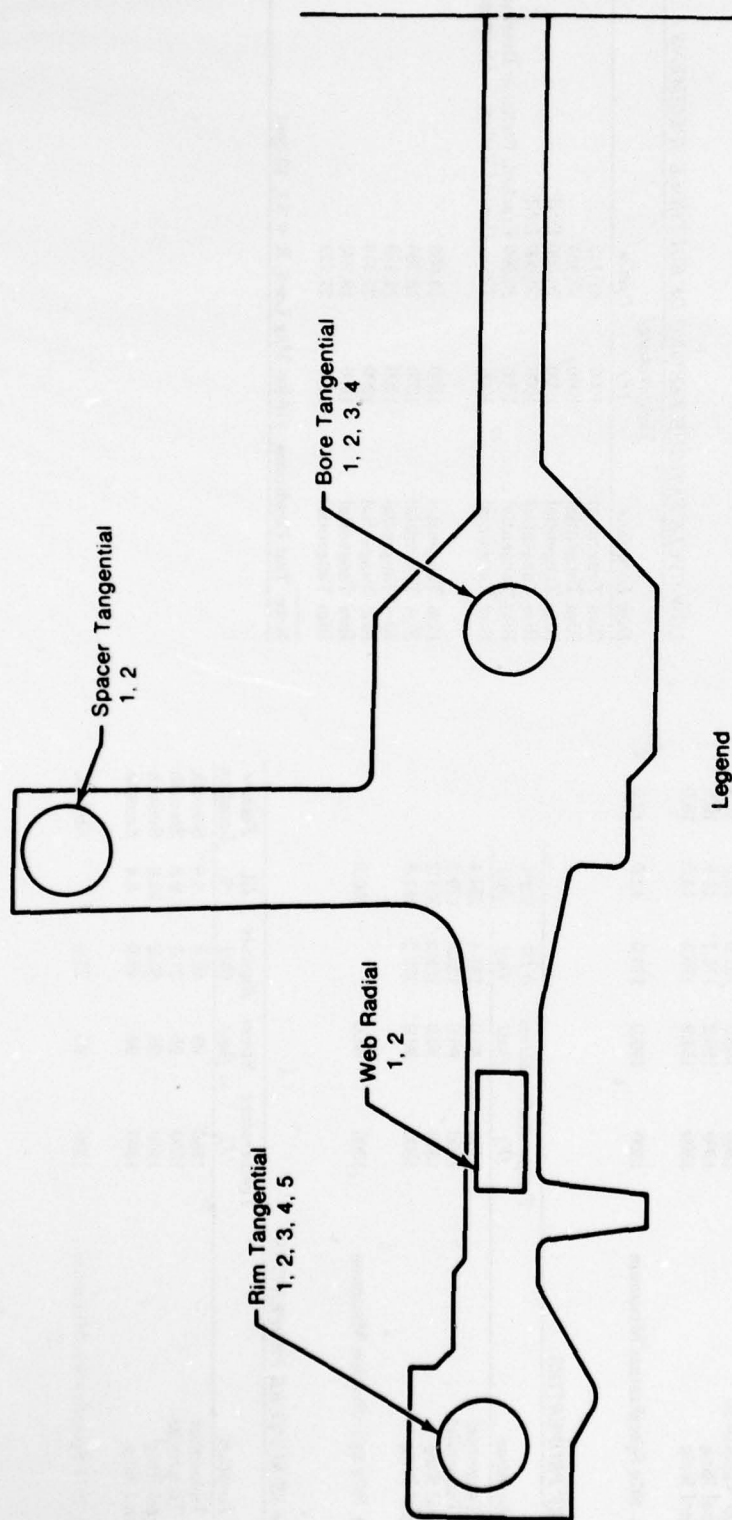
There were significant differences in creep, stress-rupture and low-cycle fatigue properties in favor of near net shape data. At 0.1% and 0.2% creep, the NNS average was 32% and 38% better than current material. For stress-rupture the near net shape average exceeded the current production average by 28.5%. A significant difference was noted with the low-cycle fatigue testing. At 1000F the NNS results were 10% better, and at 1200F the NNS results were 140% better than current production fatigue life. Although additional testing is necessary to increase the confidence in the results, a significant improvement in fatigue life is indicated.

The tensile results of the near net shape testing compared favorably with production material. The average results were the same or slightly better.

The mechanical properties comparison included a statistical analysis. For a given property the variance of the NNS data was compared with the variance of current data using the F-ratio. If the variances were statistically the same at a 95% confidence level, a comparison of the means could then be made. If the variances are statistically different, a comparison of the means is invalid. All the near net shape variances were found to be comparable to the current data variances.

The statistical comparison of the means was performed using the t-test at a 95% confidence level. Statistically significant improvements were found in the areas of 0.2% creep, and low-cycle fatigue at 1000F. The other properties showed improvement; however, more testing is necessary to demonstrate statistically significant improvements.

Low-cycle fatigue testing of bolthole specimens completed the process qualification. This method of testing was selected for several reasons. First, ample production PWA 1074 baseline data exists for comparison. Second, several specimens could be run at different conditions to establish statistical means and variances. Figure 52 is a drawing of the bolthole specimen.



Legend

Key	Specimen Type	Total Specimens
1	Room Temperature Tensile	8
2	Hot Tensile	8
3	Hot Combination S/R	4
4	Creep	4
5	Strain Control LCF	4

FD 102535

Figure 51. Disk Cut-Up Scheme

TABLE 1. NEAR NET SHAPE 1ST-STAGE TURBINE DISK MECHANICAL PROPERTIES DISK CUT-UP AND INTEGRAL TEST RINGS

TENSILE PROPERTIES					
Disk Location	Temperature (F)	YS (ksi)	UTS (ksi)	EL %	RA %
Web Radial	RT	165.3	233.0	22.5	32.1
Rim Tangential	RT	164.4	233.5	20.5	20.2
Bore Tangential	RT	168.5	235.0	22.5	28.2
Spacer Tangential	RT	171.0	235.0	21.0	23.0
Integral Ring	RT	171.3	237.6	23.0	28.7
Integral Ring	RT	169.7	236.0	23.0	24.6
PWA 1074 Specification Minimum	RT	154.0	223.0	15.0	15.0
Web Radial	1300	155.0	183.3	21.0	32.8
Rim Tangential	1300	161.9	181.8	19.5	20.4
Bore Tangential	1300	157.9	181.1	23.0	24.9
Spacer Tangential	1300	156.0	182.0	20.5	24.4
Integral Ring	1300	156.2	175.7	14.5	19.6
Integral Ring	1300	154.9	175.5	14.5	16.9
PWA 1074 Specification Minimum	1300	150.0	174.0	12.0	12.0
CREEP PROPERTIES					
Disk Location	Temperature (F)	Stress (ksi)	0.1% (hr)	0.2% (hr)	
Rim Tangential	1300	80.0	181.1	234.4	
Bore Tangential	1300	80.0	122.7	179.2	
Integral Ring	1300	80.0	258.2	331.2	
Integral Ring	1300	80.0	203.2	261.5	
PWA 1074 Specification Minimum	1300	80.0		100.0	
STRESS-RUPTURE PROPERTIES					
Disk Location	Temperature (F)	Stress (ksi)	Rupture (hr)	EL %	Failure Location
Rim Tangential	1350	95	42.8	6.6	Smooth
Bore Tangential	1350	95	27.5	9.8	Smooth
Integral Ring	1350	95	65.2	10.6	Smooth
Integral Ring	1350	95	49.9	8.4	Smooth
PWA 1074 Specification Minimum	1350	95	23.0		Smooth

LOW-CYCLE FATIGUE AT 1% TOTAL STRAIN

Disk Location	Temperature (F)	Cycles
Rim Tangential	1000	3,030
Rim Tangential	1000	5,300
Rim Tangential	1000	10,872
Rim Tangential	1000	11,582
Rim Tangential	1000	5,800
Rim Tangential	1200	6,891
Rim Tangential	1200	7,054
Rim Tangential	1200	11,946
Rim Tangential	1200	12,119

No PWA 1074 LCF Specification

LOW-CYCLE FATIGUE TESTING OF BOLTHOLE SPECIMENS

Disk Locations	Temperature (F)	Cycles
Rim Tangential	1000	42,112
Rim Tangential	1000	62,164
Rim Tangential	1000	70,000 DNF
Rim Tangential	1000	70,000 DNF
Rim Tangential	1000	25,000 Cracked, Failed in Overload
Rim Tangential	1000	Temp Control Failure - Overtemp
Rim Tangential	1200	13,033
Rim Tangential	1200	18,785
Rim Tangential	1200	21,139
Rim Tangential	1200	27,416
Rim Tangential	1200	19,702
Rim Tangential	1200	27,723

Note: Test Conditions: 110 ksi Max Load, R = 0.1, 10 cpm

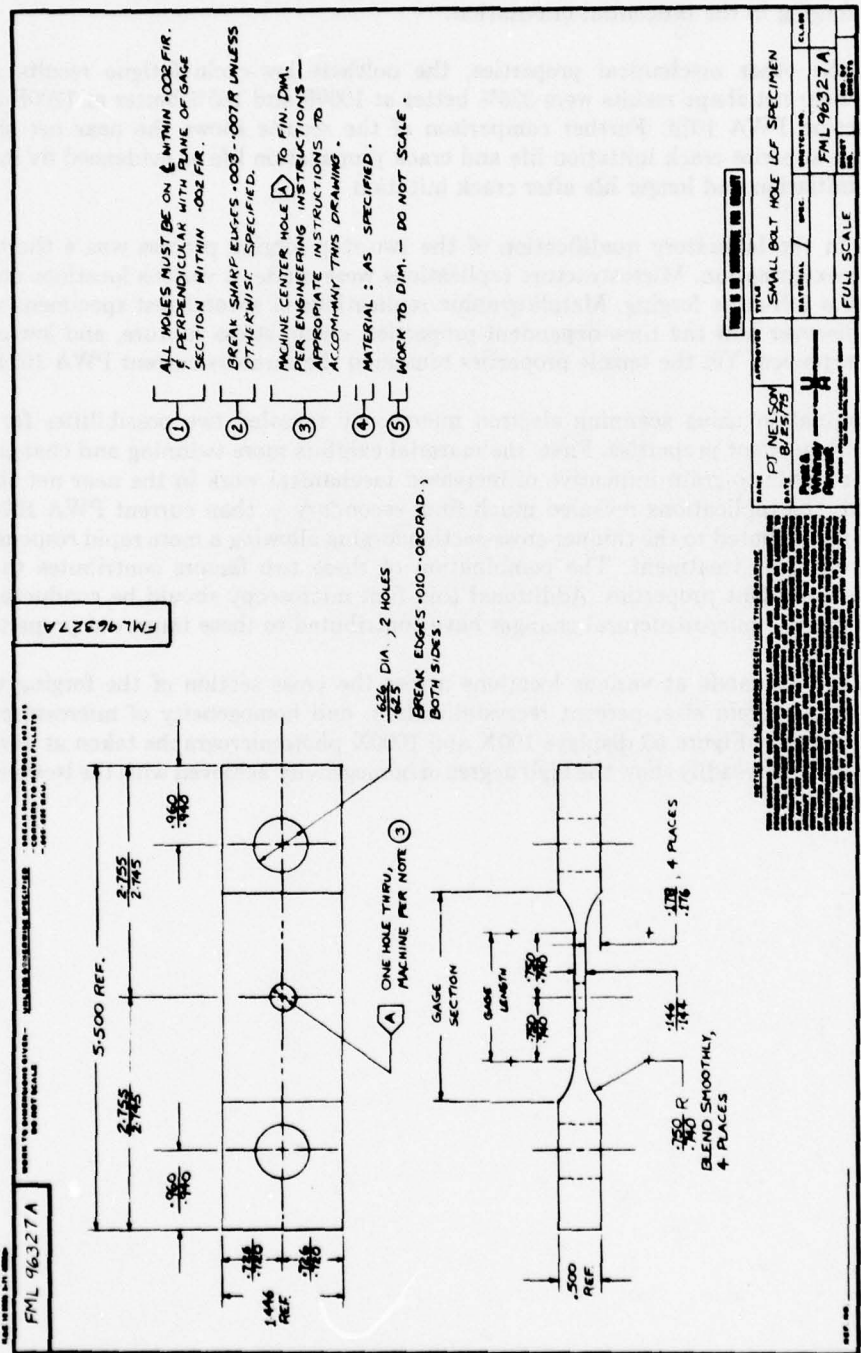


Figure 52. Strain Control Bolt-hole Specimen

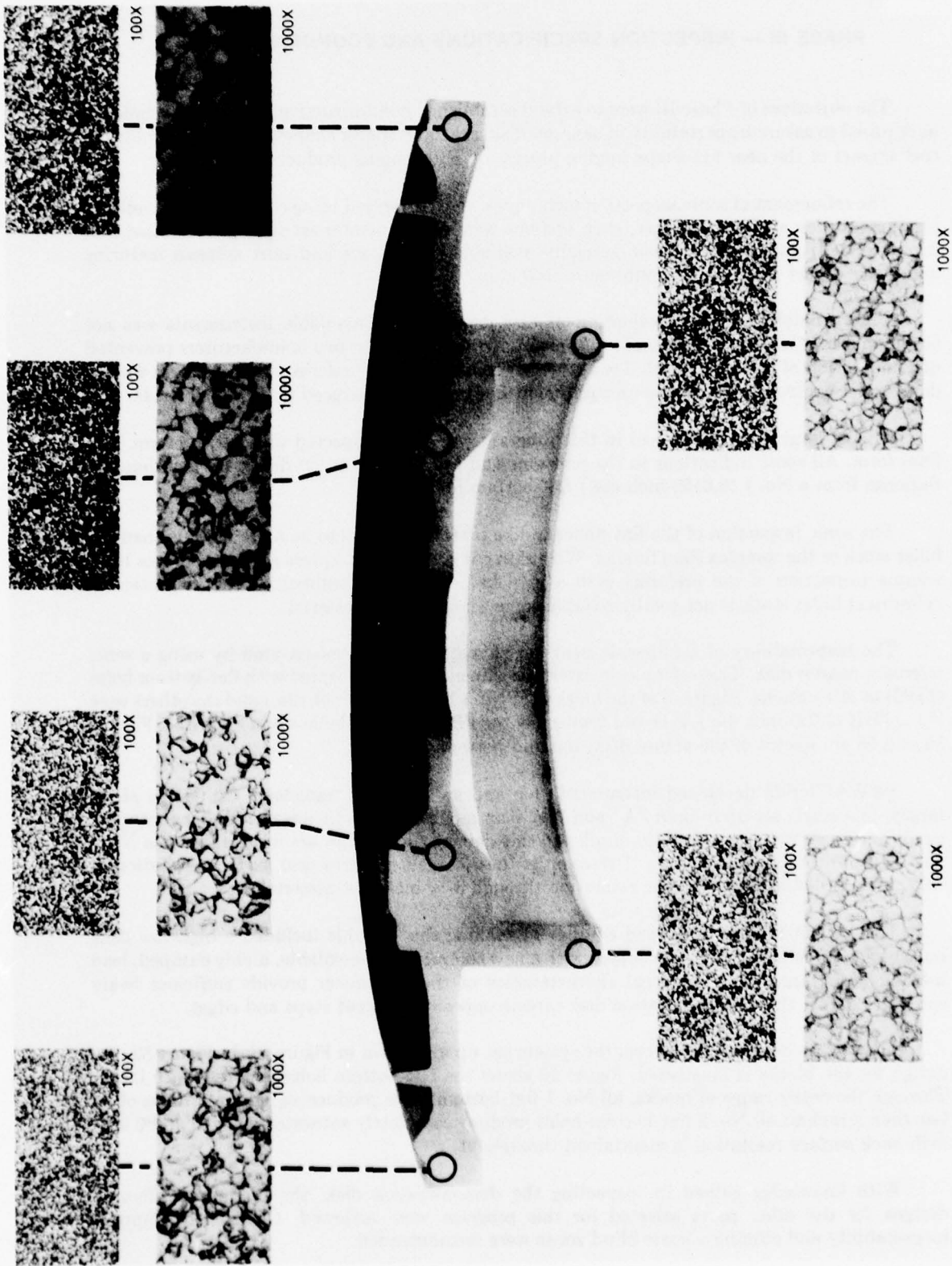
The test conditions selected were a stress level of 110 ksi to cycle at 10 cpm at 1000 and 1200F. These conditions were directly comparable to the PWA 1074 baseline testing and also correlated to actual engine operating conditions. Twelve specimens were machined from the rim of a full-scale forging in the tangential orientation.

As with the other mechanical properties, the bolthole low-cycle fatigue results were excellent. The near net shape results were 335% better at 1000F and 165% better at 1200F than current production PWA 1074. Further comparison of the results shows the near net shape material to have superior crack initiation life and crack propagation life as evidenced by longer time to crack initiation and longer life after crack initiation.

Included in the laboratory qualification of the two-step forging process was a thorough metallographic examination. Microstructure replications were made at various locations on the cross section of a full-scale forging. Metallographic replications of several test specimens were also made to discover how the time-dependent properties, creep, stress rupture, and low-cycle fatigue, were improved. Yet the tensile properties remained the same as current PWA 1074.

This examination using scanning electron microscopy revealed two possibilities for the improved time-dependent properties. First, the material exhibits more twinning and changes in orientation from grain-to-grain indicative of increased mechanical work in the near net shape forging. Second, the replications revealed much finer secondary γ' than current PWA 1073/74 material. This is attributed to the thinner cross-section forging allowing a more rapid response to quenching during heat treatment. The combination of these two factors contributes to the improved time-dependent properties. Additional thin-film microscopy should be conducted to explain how these two microstructural changes have contributed to these improved properties.

The replications made at various locations across the cross section of the forging were examined for proper grain size, percent recrystallization, and homogeneity of microstructure throughout the forging. Figure 53 displays 100X and 1000X photomicrographs taken at various locations. These photos readily show the high degree of homogeneity achieved with the isothermal forging process.



FD 1025.96

Figure 53. Typical Microstructure Layout for Full-Scale 1st-Stage Turbine Disk

SECTION IV

PHASE III — INSPECTION SPECIFICATIONS AND ECONOMIC ANALYSIS

The objectives of Phase III were to extend established nondestructive inspection techniques as required to assure inspectability of near net disk, seal, and spacer shapes, and to determine the cost impact of the near net shape forging process on F100 engine production.

The refinement of sonic inspection techniques were performed using commercially available instrumentation systems. Further, such systems were to be operator set-up and controlled (not computerized) and consist of commercially available transducers and tank systems featuring automatic preset indexing and automatic flaw stop.

Unfortunately, the full evaluation of new commercially available instruments was not accomplished. Continual component failures in new systems from two manufacturers prevented documentation of their potential. Thus, the inspection of billet, preform, and final form was all done under controlled conditions on equipment designed and produced by P&WA/Florida.

All the forging material used in this program was sonic inspected in billet, preform, and final form. All sonic indications in the preforms and the demonstration disk were less than the response from a No. 1 (0.0156-inch dia.) flat-bottom hole.

The sonic inspection of the flat pancake-like preforms proved to be more reliable than the billet stock or the complex final forging. With skin cut surfaces and square edges, there was 100% volume inspection of the preforms with a very high degree of confidence. The inspection of cylindrical billet stock is not totally reliable since sonic blind zones exist.

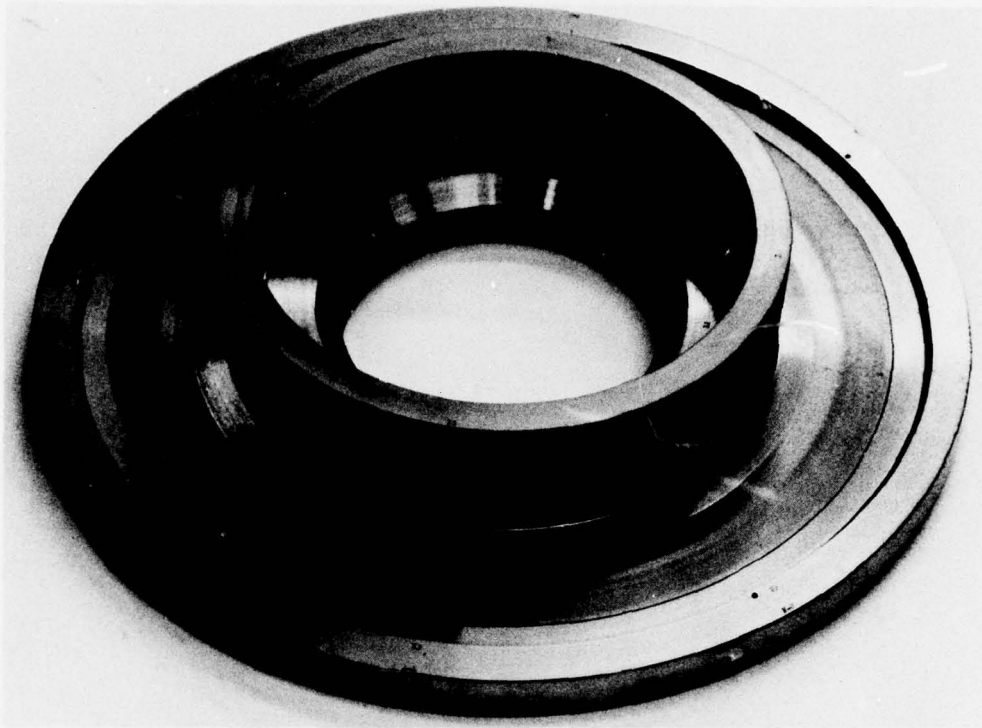
The inspectability of a full-scale near net shape part was demonstrated by using a sonic reference master disk. This reference master was skin cut and then drilled with flat-bottom holes (FBH) at 36 locations. Eighteen of the holes were No. 1 FBH (0.015-inch dia.) and the others were No. 2 FBH (0.030-inch dia.). A layout drawing of the FBH locations is shown in Figure 54. Figures 55 and 56 are photos of the actual disk, top and bottom views.

P&WA/Florida developed instrumentation and an advanced transducer for testing all 36 targets in a single set-up in both "A" and "C" scan modes. This indicates that under controlled conditions, near net shape forgings similar to this demonstration disk are inspectable to a No. 1 flat-bottom hole acceptance limit. Detection of these targets requires near surface resolution to 0.050-inch and similar far surface resolution through 3-1/4 inches of material.

The P&WA/Florida developed equipment making this possible included a high-rise time pulser and a broadband receiver coupled with a new commercially available, highly damped, lead metaniobate transducer. The focal characteristics of the transducer provide sufficient beam spread to detect those demonstration disk targets opposite adjacent steps and edges.

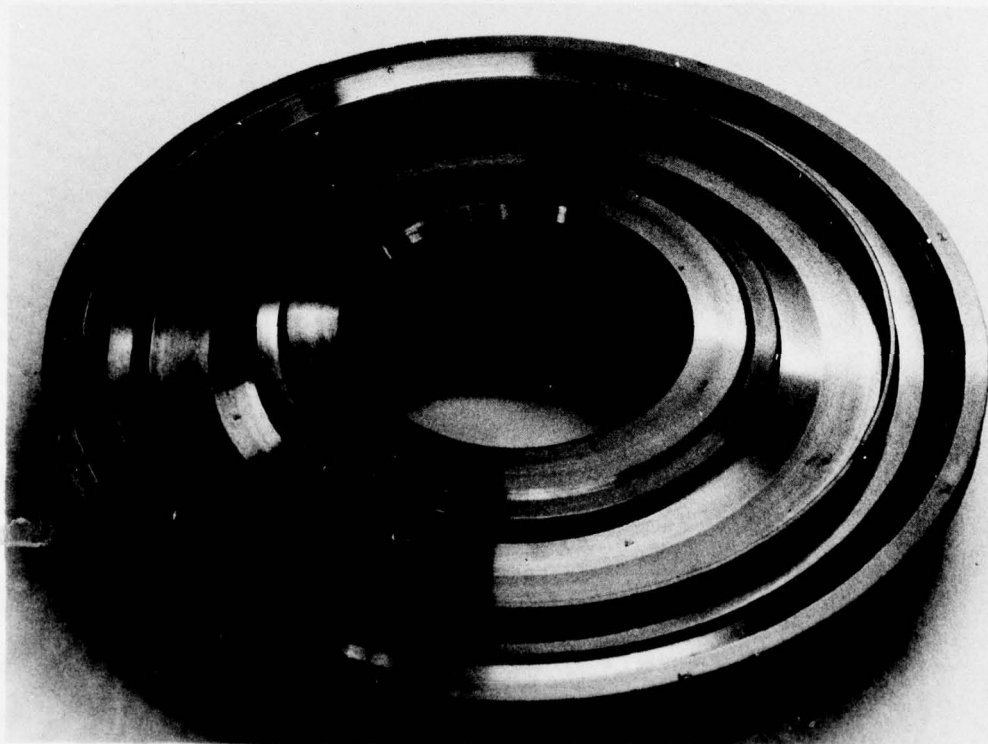
The test blocks used to perform the system set-up are shown in Figure 57. In Figure 58, the design for the blocks is illustrated. Figure 59 shows the flat-bottom holes in a reference block. Through the entire range of blocks, all No. 1 flat-bottom holes produce signal amplitudes of no less than 2 inches; all No. 2 flat-bottom holes produce completely saturated signals, and 0.050-inch back surface resolution is maintained throughout.

With knowledge gained in inspecting the demonstration disk, the preliminary forging designs for the other parts selected for this program were reviewed. Changes to improve inspectability and eliminate sonic blind zones were recommended.



FE 156383

Figure 55. Top View of Sonic Reference Master



FE 156384

Figure 56. Bottom View of Sonic Reference Master

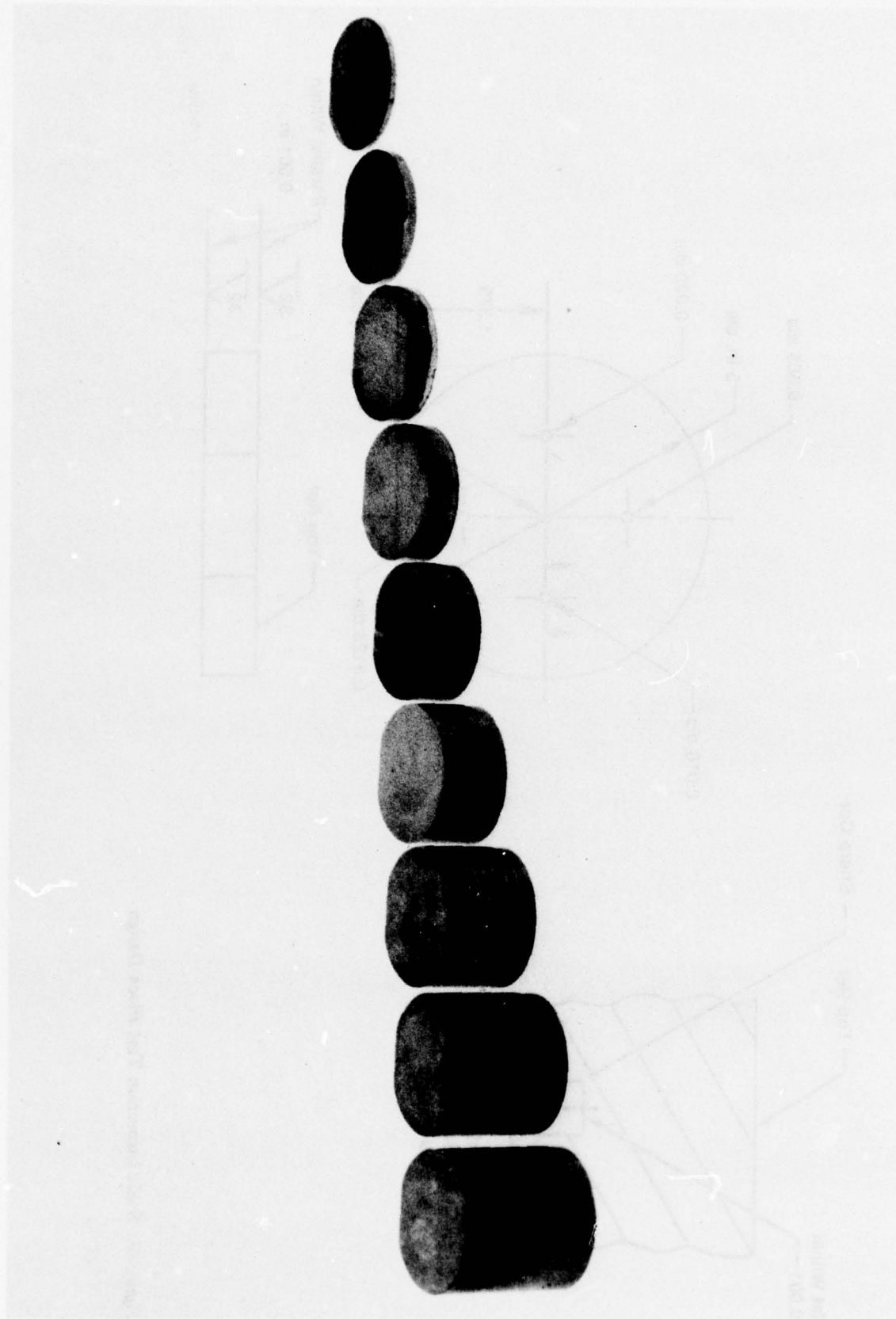
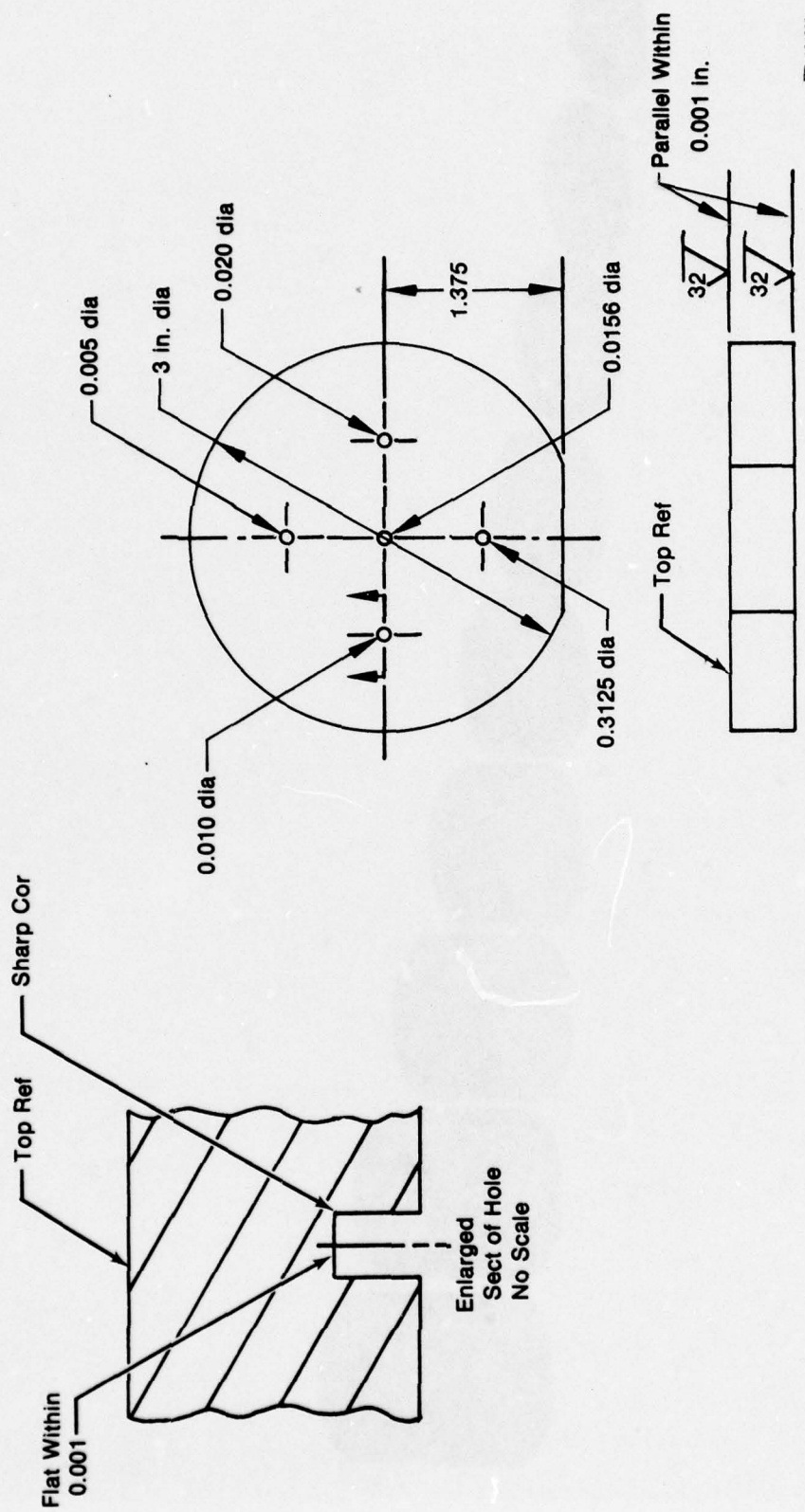
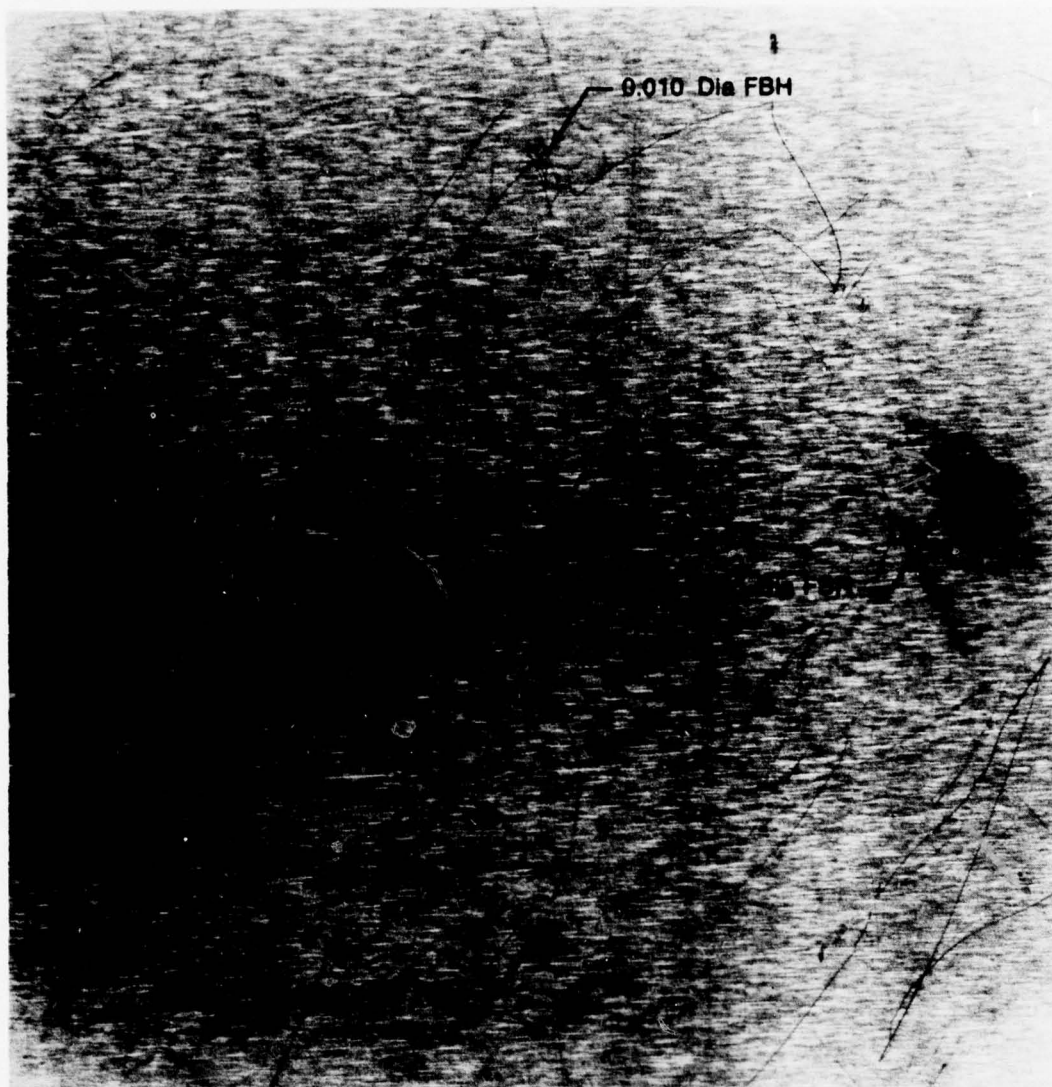


Figure 57. Sonic Reference Block Set



FD 124399

Figure 58. Sonic Inspection Test Block Design



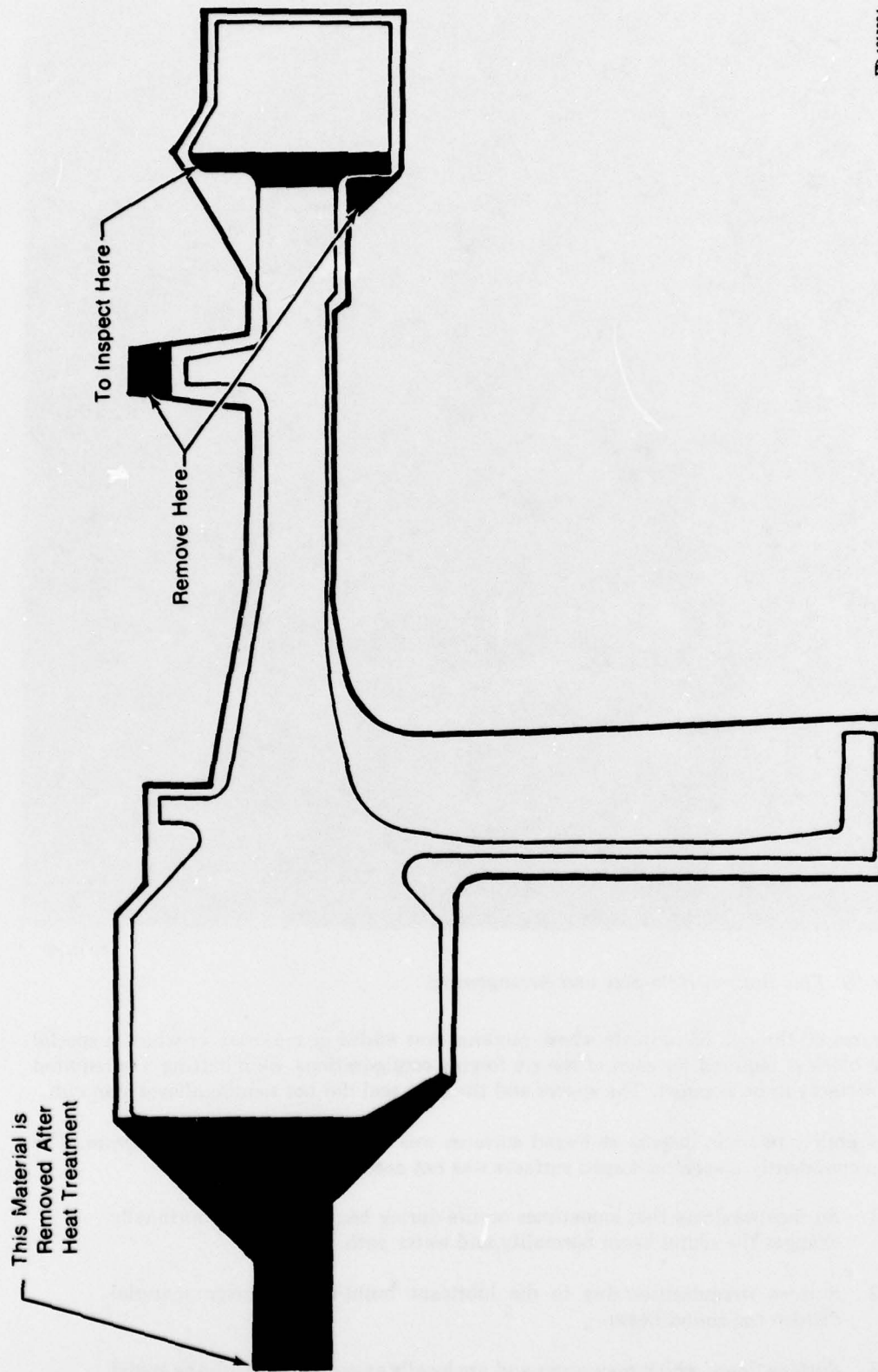
FD 124360

Figure 59. Flat Bottom Hole Size and Arrangement

Figures 60 through 65 indicate where material was added or removed, or where a special reference block is required for each of the six forging configurations. Skin cutting was required only on surfaces to be scanned. The spacer and the cone seal did not require allover skin cuts.

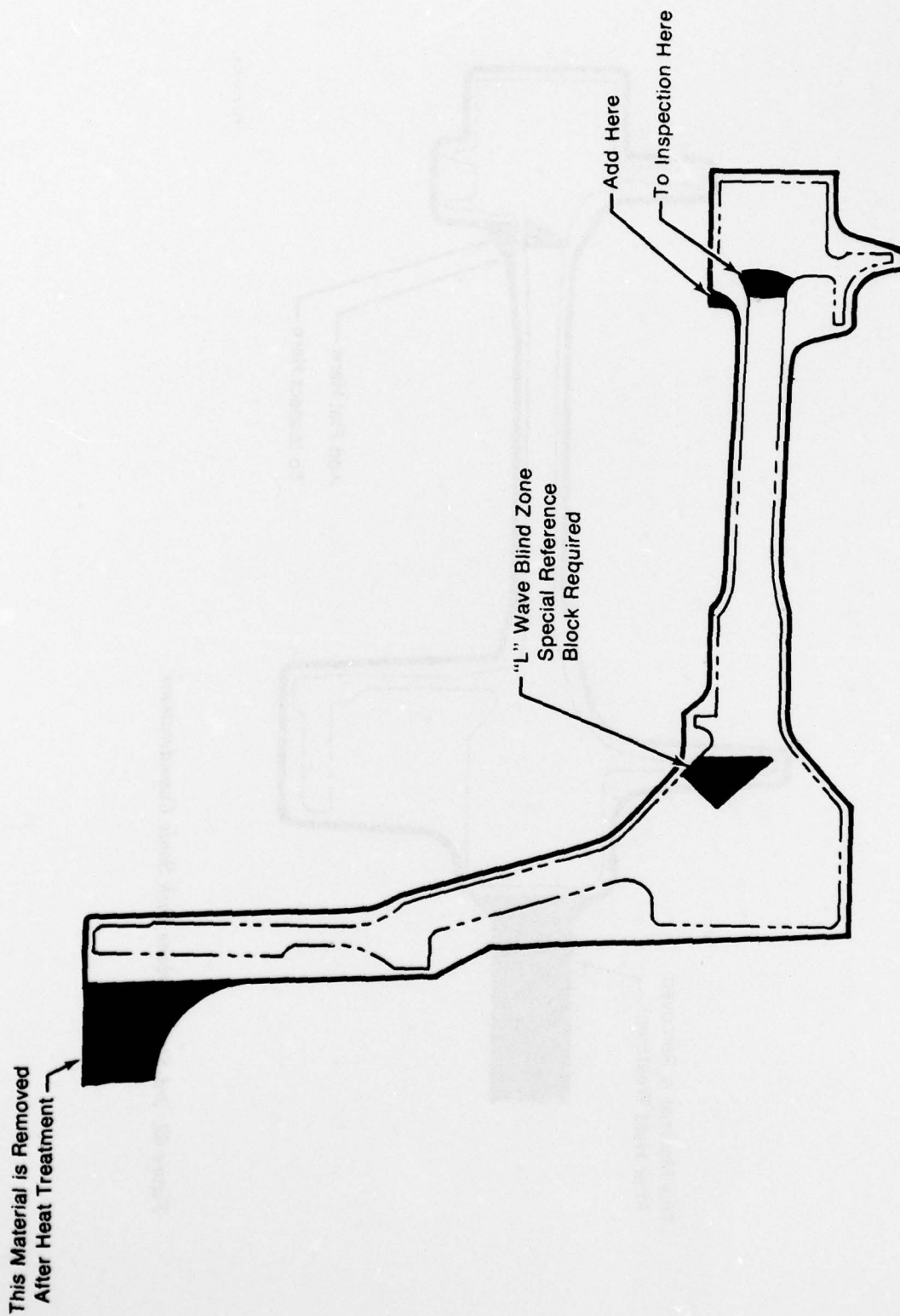
The ability to sonic inspect as-forged surfaces was also addressed in this program. The ability to confidently inspect as-forged surfaces was not accomplished because:

1. Surface waviness that sometimes occurs during heat treatment continually changes the sound beam normality and water path.
2. Surface irregularities due to die lubricant build-up or foreign material disturb the sound beam.
3. Surface flaws, which may occur and are locally smoothed, disturb the sound beam.



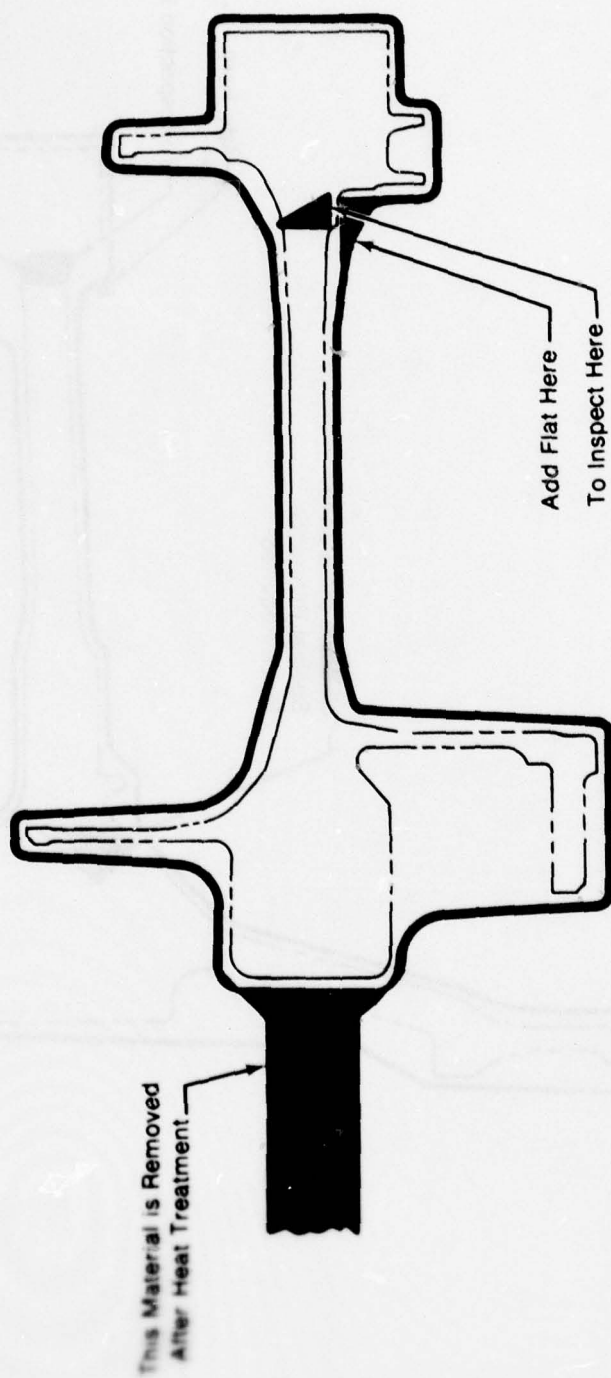
FD 101580A

Figure 60. 1st-Stage Turbine Disk Sonic Considerations



FD 101594A

Figure 61. 2nd-Stage Turbine Disk Sonic Considerations



FD 101596A

Figure 62. 3rd-Stage Turbine Disk Sonic Considerations

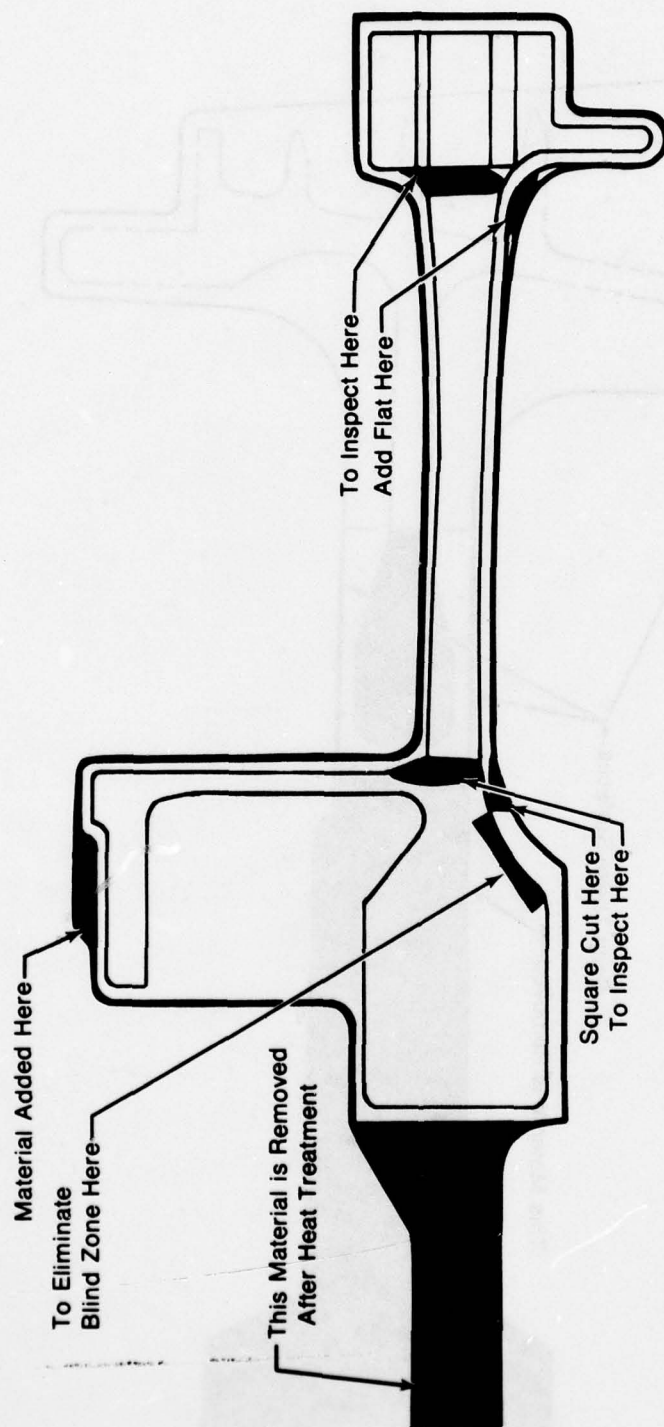
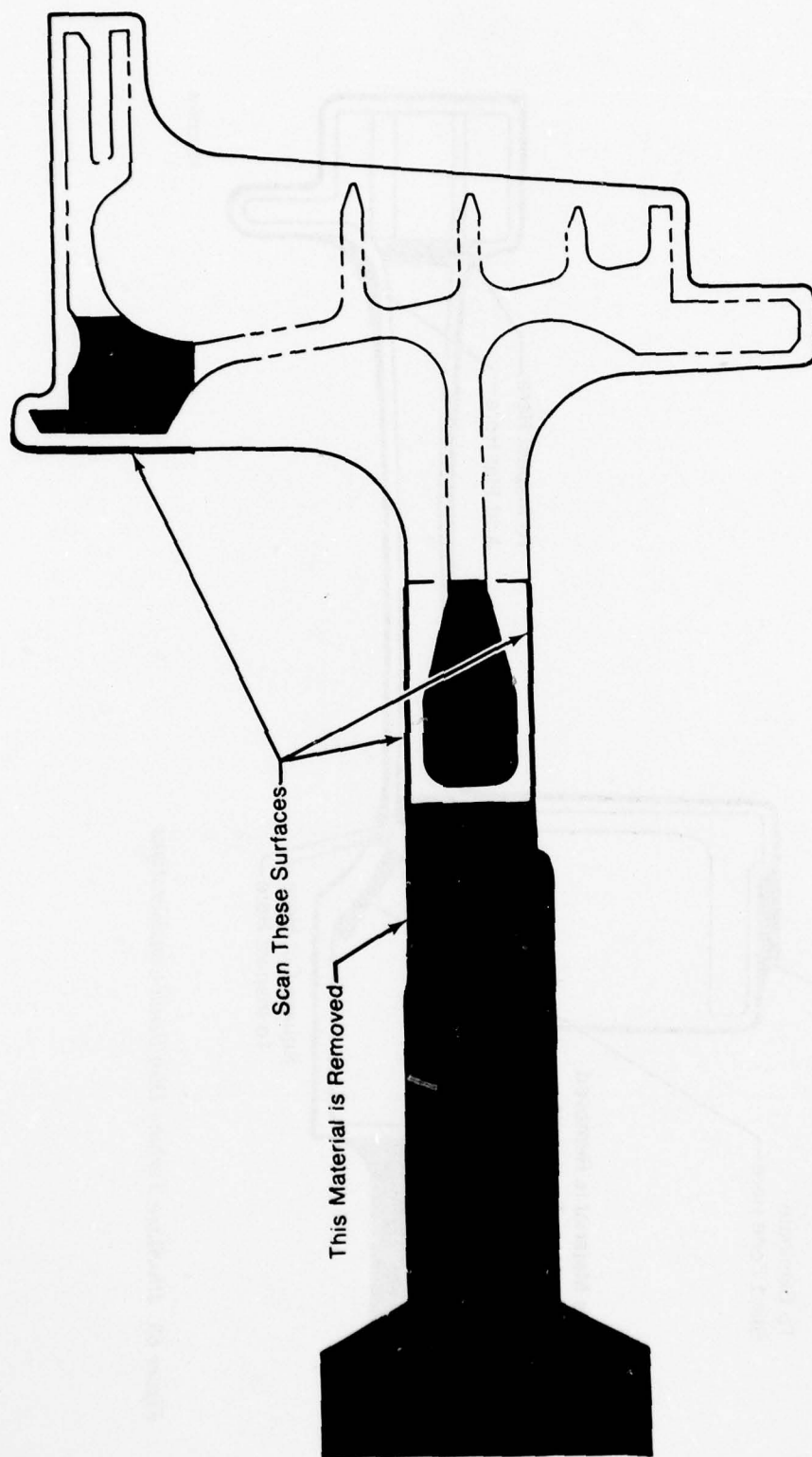
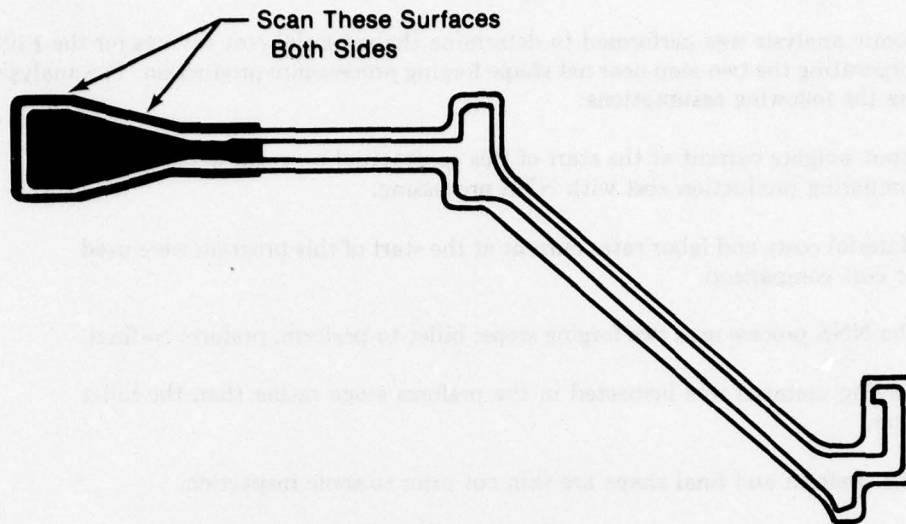


Figure 63. 4th-Stage Turbine Disk Sonic Considerations



FD 101560A

Figure 64. 1-2 Turbine Rim Spacer Sonic Considerations



FD 101599A

Figure 65. 13th-Compressor Cone Seal Sonic Consideration

Therefore, the thrust of the NDT effort was aimed toward improving techniques to inspect skin cut heat treated surfaces.

An as-forged demonstration disk was fabricated and will be available for future improvement efforts and possibly as a test disk for the inspection system being developed under Air Force Contract F33615-75-C-5193, "Production Inspection of Near Net Turbine Disk Shapes."

The results of efforts to inspect the full-scale 1st-stage turbine demonstration disk are:

1. Similar parts are sonic inspectable under controlled conditions.^A
2. Transducers and tank systems capable of performing such an inspection are now commercially available.
3. The capability of commercially available instrumentation was not proven, only P&WA designed instrumentation was used.
4. Implementation may require a new generation of sonic reference blocks at each facility, possibly including some to determine the capability at edges and adjacent or near in-line steps.
5. An inspection may be more operator dependent than current production operations.

Appendix A contains the Ultrasonic Scan Plan used to inspect the near net shape 1st-stage turbine disk.

ECONOMIC ANALYSIS

An economic analysis was performed to determine the potential cost savings for the F100 engine by incorporating the two-step near net shape forging process into production. The analysis was done using the following assumptions:

1. Input weights current at the start of this contractual program were used for comparing production cost with NNS processing.
2. Material costs and labor rates current at the start of this program were used for cost comparison.
3. The NNS process uses two forging steps; billet-to-preform, preform-to-final.
4. Forging material was inspected in the preform stage rather than the billet form.
5. The preform and final shape are skin cut prior to sonic inspection.
6. Machining estimates were based on an in-house production process, i.e., no processing done by vendors after the acquisition of raw materials.
7. The NNS full-scale input weights are based on the subscale NNS configurations optimized in this program.

The cost analysis found \$20,000 per F100 engine could be saved with the incorporation of near net shape forging into F100 production. This significant savings applies to the two-step NNS forging process to be used on all the IN-100 rotating parts in the F100 engine; the 9th-, 11th-, 13th-stage compressor disks, the 13th-stage cone seal, the 1st-, 2nd-, 3rd-, 4th-stage turbine disks, and the 1-2 turbine rim spacer.

This \$20,000 cost savings was obtained by using the methods discussed in the following paragraphs. The comparison of forging input weights between production forging and NNS forging showed the NNS process to use 444 lb less material. This equates to \$7,200 per F100 engine.

A comparison of machining efforts for the two forging practices showed a reduction of \$800 per engine for the NNS process. If, in the future, sonic inspection capabilities were extended to inspect as-forged surfaces, the skin cutting of the preform and the final shape would be eliminated. This would increase the machining savings to \$1,350 per F100 engine.

The near net shape two-step process offers another potential cost savings in the elimination of sonic inspection of the final form. This is possible due to the thorough, reliable inspection of the preform combined with the hypothesis that isothermal forging does not introduce internal flaws. Inspection experience with the two-step process will provide the means to prove the theory. If final form inspection were eliminated for the 9 parts, approximately \$1,000 per F100 engine could be saved.

The remaining \$12,000 is attributed to resourcing the production of the nine IN-100 rotating parts to an in-house operation. Resourcing the production of these parts eliminates the vendor's profit and takes advantage of the P&WA experience in near net shape forging.

The following discussion details the input weight savings realized in this program and a similar IR&D program. The three-step process discussed previously will be compared with the two-step process as applied to the 1st-stage turbine disk.

Table 2 shows the near net shape input weights compared with production input weights for the six parts chosen for this program. The NNS full-scale input weights are based on the optimized subscale near net shape configurations. For the six parts of this program, the weight saving is 233 lb per F100 engine.

TABLE 2. NEAR NET VS PRODUCTION INPUT WEIGHTS ON PARTS USED IN THIS PROGRAM

	<i>Current Forging Weight, (lb)</i>	<i>Near Net Forging Weight, (lb)</i>	<i>Net Weight Savings, (lb)</i>
1st-Stage Turbine Disk	117	83	34
2nd-Stage Turbine Disk	111	68	43
3rd-Stage Turbine Disk	77	55	22
4th-Stage Turbine Disk	71	41	30
1-2 Turbine Rim Spacer	105	66	39
13th-Stage Cone Seal	65	*	65
Total Savings			233

* The near net shape process uses the center slug material from the 1-2 turbine rim spacer forging.

Significant input weight savings were demonstrated in a recently completed IR&D program for the composite near net shape forging of the 9th-, 11th-, 13th-stage compressor disks. By combining the savings projected from the IR&D program and this program, the total input weight savings would be 444 pounds.

The detailed analysis of the production costs of the 1st-stage turbine disk forged to full-scale during this program revealed a net savings of \$740.00 per finished disk. This savings may be broken down into an input weight savings of \$610.00, and a machining savings of \$290.00.

These savings are balanced against \$160.00 cost of the preform step. This step includes forging, machining, and sonic inspection of the preform. Thus, in spite of the extra forging step, the input weight and the machining savings produce a \$740.00 cost reduction for each 1st-stage turbine disk.

As discussed earlier, the three-step process forges the flange of the integral arm of the 1st-stage turbine disk to NNS and eliminates about 10 lb of input material under the flange. The three-step process produces a configuration as shown in Figure 42 labeled "Old Configuration". A savings of \$950.00 per 1st-stage turbine disk is possible with the three-step process. Compared to the two-step process, the three-step uses \$160.00 less in raw material and \$110.00 less machining costs per disk. However, the third forging step costs approximately \$90.00 per forging. The third forging step expenses include the forging operations and additional tooling costs. The net result is \$180.00 additional savings over the two-step process, or \$920.00 total savings per finished disk.

All these savings become more significant when it is remembered that the near net shape processing yields parts of higher mechanical properties which mean longer engine life. For instance, stress rupture and 0.2% creep lives were improved by 28.5% and 38% respectively over current PWA 1074 material. An impressive low cycle fatigue improvement was revealed in bolt hole testing; i.e., at 1000F the NNS life was 335% better, at 1200F the NNS life was 165% better than current PWA 1074 material. Thus, near net shape processing produces higher quality forgings while decreasing production costs.

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

In general all objectives of the near net shape (NNS), isothermal forging program were met.

Specifically, the NNS process can reduce the production costs of nine IN-100 parts by \$20,000 per F100 engine. The process achieved this by forging to a minimum of 0.050-inch of the finished part thereby reducing forging input weight and machining time.

The process repeatedly yielded quality forgings in a manner suitable for production. After the full-scale 1st-stage turbine disk forging configuration was finalized, five forgings were produced with no problems.

In the subscale phase of the program, the two-step process demonstrated the ability to adapt to a variety of forging configurations. An optimum material distribution was found which produced lap-free, complex forgings, by simply varying the diameter of the pancake preform. The validity of the subscale approach was proven when the optimized subscale configuration for the 1st-stage turbine disk was successfully scaled up to full-scale with minimal changes.

The process was completely laboratory qualified. At each step of the process, billet, preform, and final shape, metallographic examinations checked the integrity of the microstructure. A disk cut-up was made and a variety of test specimens were machined from several disk locations. Testing included tensile, creep, stress rupture, and strain control low-cycle fatigue. To further qualify the process, bolthole low-cycle fatigue specimens were tested at two temperatures. The results from all this testing showed the NNS properties to be at least as good as and generally much improved over currently forged IN-100 material. Mechanical property improvements were particularly significant for the time-dependent properties.

This process demonstrated the two-step process to offer opportunities for high quality control. For example, the highly reliable sonic inspection of the flat pancake-like preform is superior to inspecting cylindrical billet material. Flaws which may escape a billet inspection would be detected in a preform inspection. Therefore, flawed material would be rejected prior to final forging resulting in lower rejection rate of finished forgings.

The sonic inspection phase of the program demonstrated the ability to inspect the NNS full-scale 1st-stage turbine disk. From this experience, other similar near net shape forging configurations will be inspectable. Although commercially available instrumentation was not functioning for this program, much of the equipment capable of this level of inspection is available.

Thus, the two-step isothermal forging process is able to significantly reduce the cost of producing quality IN-100 forgings of superior mechanical properties, in sonic inspectable forging configurations.

Although the objectives of this program were successfully met, areas were observed where improvements would greatly advance the near net shape technology. Specifically, these areas are:

1. Ultra sonic inspection of near net shapes
2. Material properties testing

Near net shape forging configurations will be greatly advanced when the ability to reliably inspect contours is fully developed. Air Force Contract F33615-75-C-5193 is currently developing an automatic system which will detect and follow a contour while maintaining an optimum position for the ultrasonic transducer. The ability of the system to compensate for small changes in inspected surface will allow the inspection of as-forged, heat-treated surfaces. Thus, the skin-cutting operation presently required to remove surface waviness will be eliminated resulting in a reduction of manufacturing costs.

The contour following system will also determine the dimensional references necessary to machine a part from a given forging. This information is directly applicable to computer aided machining (CAM). A demonstration of the automatic inspection system's capabilities is expected soon. We strongly recommend this system be qualified and incorporated as soon as possible.

The mechanical properties testing performed in this program has shown the two-step process to produce parts of superior quality. Additional testing will increase the statistical confidence in the comparisons of NNS material with current products. Also, other phases of material behavior such as fracture toughness and crack growth should be investigated. We suggest that testing be done to fully explore all the possible ramifications of NNS processing.

As NNS forging is put into production, vendor qualification will be necessary. Incorporating the two-step process requires just a few process changes to produce the same product as current methods. Therefore, an expensive spin burst test or an engine test are unnecessary as qualification tests. We recommend the vendors' process qualification follow the example set in this program, i. e., testing of a standard disk cut-up with extra bolthole low-cycle fatigue testing. This would be adequate to ensure mechanical integrity.

In light of the cost savings and properties improvements of the NNS process, we strongly recommend the process be incorporated into production and be considered for all engine applications where strength and part integrity are necessary.

APPENDIX A

GPD ULTRASONIC SCAN PLAN

AG-100050C
(Skin Cut For Sonic
Inspection)

SONIC INSPECTION STANDARD S1S-316 **SONIC INSPECTION METHOD S1M-308B**

1. ULTRASONIC TEST BLOCK SET G-79694

- 1.1 Near Surface Hole: No. 1 FBH in Detail 1 (0.050-inch Metal Travel)
- 1.2 Far Surface Hole: No. 1 FBH in Detail 9 (3.0-inch Metal Travel)

2. INSTRUMENTATION

- 2.1 UM-721 Reflectoscope Mainframe (Style 50B721)
- 2.2 PWA 50 HR-2 Pulser/Receiver*
- 2.3 Transigate H (Style 50E664)*
- 2.4 Relay Chassis (Style 50C434)

*Includes DAC Modification

3. TRANSDUCER

- 3.1 Harisonic I31006T S/N1220 ($\frac{3}{8}$ -inch Diameter, Tuned 10 MHz, 3-inch Focal Length)

4. WATER PATH

- 4.1 Adjust for best response between Near and Far Surface Holes, but not less than that which places the Y_1 point at the Near Surface Hole.

5. MAXIMUM INDEX INCREMENT AND SCAN SPEED

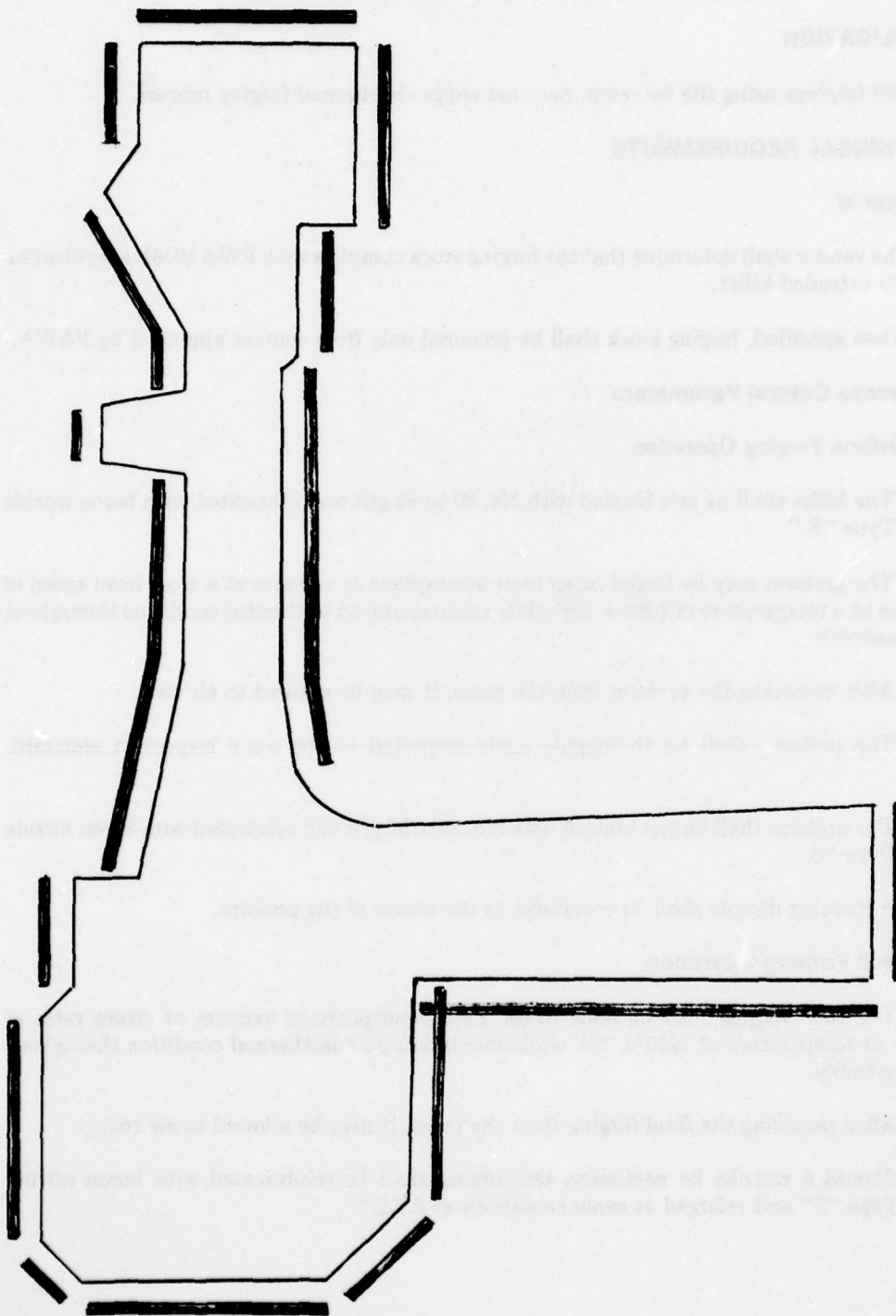
- 5.1 As determined by dynamic test on Near Surface Hole.

6. TANK SYSTEM

- 6.1 AI Model US-454 Lab Scanner (Modified) with UM-710M Manipulator with 2 ft Search Tube and 6 ft RG62B/U Cable.

7. SCAN SURFACES

- 7.1 Indicated by — for amplitude indications exceeding S1S-316, as shown on the following sketch.



Scan Surfaces for Amplitude Indications Exceeding SIS-316

APPENDIX B
NEAR NET SHAPE PROCESS SPECIFICATION

1. APPLICATION

For IN-100 forgings using the two-step, near net shape, isothermal forging process.

2. TECHNICAL REQUIREMENTS

2.1 Material

2.1.1 The vendor shall determine that the forging stock complies with PWA 1056E specification for IN-100 extruded billet.

2.1.2 When specified, forging stock shall be procured only from sources approved by P&WA.

2.2 Process Control Parameters

2.2.1 Preform Forging Operation

2.2.1.1 The billet shall be grit blasted with No. 60 to 90 grit and lubricated with boron nitride coating, Type "S."

2.2.1.2 The preform may be forged in an inert atmosphere or vacuum at a cross head speed of 1.5 in./min at a temperature of $1900 \pm 25\text{F}$ while maintaining an isothermal condition throughout the die assembly.

2.2.1.3 After removing the preform from the press, it may be allowed to air cool.

2.2.1.4 The preform shall be thoroughly sonic inspected to the sonic inspection standard, SIM-1.

2.2.1.5 The preform shall be grit blasted with No. 60 to 90 grit and lubricated with boron nitride coating, Type "S."

2.2.1.6 A locating dimple shall be machined in the center of the preform.

2.2.2 Final Forging Operation

2.2.2.1 The final forging may be done in an inert atmosphere or vacuum at strain rates of 0.1 min^{-1} at temperature of $1950 \pm 25\text{F}$ while maintaining an isothermal condition throughout the die assembly.

2.2.2.2 After removing the final forging from the press, it may be allowed to air cool.

2.2.2.3 Should a restrike be necessary, the forging shall be relubricated with boron nitride coating, Type "S" and reforged at same conditions as 2.2.2.1.

2.3 Isothermal Forging Dies for Near Net Shapes

2.3.1 Die material shall be TZM molybdenum or equivalent material for isothermal forging applications.

2.3.2 The punch-die engagement tolerance shall be 0.008- to 0.010-inch on the diameter.

2.3.3 The punch shall engage the die prior to contacting the forging material.

2.3.4 The dies and associated tooling shall be grit blasted with No. 60 to 90 grit and lubricated with boron nitride coating, Type "S" prior to first forging.

2.4 Forging Configuration

2.4.1 The near net shape forging configuration for a given part shall incorporate a minimum 0.050-inch envelope about the actual part, where possible.

2.4.1.1 The sonic inspectability of the configuration shall be determined by PWA NDT Group.

2.4.2 The configuration shall incorporate minimum draft angles, 1 to 2 deg in most situations is sufficient.