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IMPROVED MATERIALS AND MANUFACTURING METHODS FOR GUN BARRELS

Charles F. Barth, et al

TRW, Incorporated
Cleveland, Ohio

June 1975

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IMPROVED MATERIALS AND MANUFACTURING METHODS FOR GUN BARRELS

FINAL REPORT

CHARLES F. BARTH
TRW Inc.
and
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A three-task effort was conducted to establish advanced fabrication procedures for 7.62mm gun barrels from materials more refractory in nature than the conventional Cr-Mo-V steels. Barrel configurations for the M134 and M219 weapon systems were selected for process evaluation in Task I. The process evaluation was centered about precision rotary forging to develop the rifling and chamber to finish dimension because fabrication costs for conventional methods would be prohibitive when the more difficult to machine alloys are considered. Preform

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20. design and fabrication methods, forging parameters, and machining studies were comprehensively evaluated in Task I to develop data for an optimum fabrication routing. H-11, IN 903, and U-700 materials were evaluated with the result that the first two alloys were found to be amenable to precision rotary forging and the U-700 was not due to high preform fabrication costs and an internal cracking problem encountered in the bore area. Task II was concerned with an actual demonstration of the fabrication sequence employing the technology developed in the first task. High quality M134 forgings were prepared in H-11 and IN 903 materials while fully contoured M219 forgings were prepared from H-11 steel. The M134 barrel forgings were finish machined according to an economical routing developed on this program. The entire process sequence was mathematically modeled in Task III to determine specific costs and fabrication parameters for each element in the routing. The importance of efficient material utilization through full O.D. contouring during rotary forging was emphasized by the cost model when barrels are forged from the more refractory alloys H-11 and IN 903. The overall program established the feasibility of precision rotary forging as a viable and cost-effective method of 7.62mm barrel fabrication.

FOREWORD

This final technical report was prepared by Dr. C. F. Barth of the Materials Technology Division, TRW, Inc., Cleveland, OH 44117, in compliance with Contract DAAF03-72-C-0170, and by Mr. J. D. DiBenedetto of the Research Directorate, GEN Thomas J. Rodman Laboratory, Rock Island Arsenal, Rock Island, IL 61201.

The principal investigators at TRW Inc. have been Dr. C. F. Barth and Dr. A. L. Hoffmanner*, Principal Engineers, with program management provided by Mr. F. N. Lake, Principal Engineer and Mr. C. R. Cook, Section Manager, Materials Development Department.

The work was authorized as part of the Manufacturing Methods and Technology Program of the U.S. Army Materiel Command and was administered by the U.S. Army Production Equipment Agency.

* Dr. A. L. Hoffmanner is currently with Battelle Memorial Institute, Columbus, Ohio.

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1.0 INTRODUCTION

Current trends in small caliber weapons designs for the U.S. Army emphasize rapid firing rates for saturation of a target area. The high ambient temperatures, thermal transients, and corrosive-erosive environment existing at the bore surface are serious factors limiting barrel life under rapid firing schedules. The field use of such weapons systems are thus restricted with conventional barrel materials. The most successful approaches to accommodate these problems with conventional methods have been realized through the chromium plating of gun barrel bores; or the use of short length cobalt alloy liners which are shrink fitted to the breech end of the gun barrel and chromium plating of the remaining steel muzzle end. However, the substrate (Cr-Mo-V steel) of the chromium plated bore does not have sufficient high temperature strength to withstand the erosive conditions imposed by high performance weapons; and the physical limitations of shrink fitting are such that only 6-8 inches of bore surface can be protected and failure of the gun barrel is usually initiated at areas in front of the liner. These problems can be averted by fabricating barrels from alloys with greater refractory properties than conventional barrel steels. However, it is a recognized fact that fabricability and refractory behavior of alloys are usually inversely related. Furthermore, such refractory materials are highly alloyed and are significantly more expensive than conventional barrel steels. In recognition of these problems, the U.S. Army Armament Command has pursued material and fabrication development programs to define the material conditions necessary to meet these intensive firing schedules and the fabrication methods to achieve cost effectiveness.

The most recent fabrication developments sponsored by the Armament Command have shown that 7.62mm barrels can be successfully produced either as homogeneous or lined barrels virtually from any refractory alloy. The lined barrels consist of a composite structure with a thin walled inner tube of the more refractory alloy acting as a bore liner. Precision swaging over a polished carbide mandrel has been employed to develop the rifling in these experimental barrels. This chipless fabrication method produces the rifling by forging the outer diameter under the reciprocating action of four hammers which nearly completely enclose the blank during the forging cycle. The high compressive working stresses imposed on the barrel blank greatly enhances the workability of the less tractable refractory barrel materials. Recently, the utility of this process involving compressive processing stresses was used to demonstrate the feasibility of forming M-134 barrels having both chamber and rifling in as-solution treated IN718 (R_c 36) fully hardened IN718 (R_c 45), and triple tempered Vasco M-A (R_c 36). Although no extensive study has been performed to evaluate the ultimate precision attainable by precision swaging, conservative estimates indicate that the process is at least as good as conventional broaching and button rifling. When combined with integral chambering, it is significantly more cost effective. Dimensional precision and concentricity of ±.0002 inch (±.00051cm) are readily attainable and the process significantly refines the surface finish and dimensional precision of the starting blank. Surface finishes of 8 microinches arithmetic average (AA) in the bore can be achieved with no special blank preparation. Typical process cycles are approximately 4-5 minutes per barrel while maintaining this finish quality level.

The superiority of the precision swage over conventional procedures of rifling and chambering has been established for CR-Mo-V barrel steels. Generation of full I.D. contours by precision swaging is an absolute necessity for the more refractory alloys because these alloys are virtually impossible to machine accurately and economically by traditional methods. Broaching and button rifling become very difficult for standard barrel steels at hardness levels above approximately R_c 32 while the more heat resistant alloys are significantly less machinable at R_c 32 than steels.

The need for applying precision rotary swaging to barrel fabrication of the more refractory alloys was dictated by their remarkably poor machineability yet the process is cost effective even for conventional alloys. Precision swaging has been demonstrated to be capable of generating high quality I.D. barrel configurations from a gun drilled tubular blank but is limited to a cylindrical O.D. geometry. As a result, the volume of material consumed in barrel fabrication is virtually the same for either conventional machining procedures or precision swaging. The material lost as chips in M-134 barrel fabrication is in excess of 1.5 times the net barrel weight for a cylindrical starting blank. This scrap loss is not particularly serious for low alloy steel barrels but will become significant for the more refractory iron and nickel base alloy systems which cost approximately 3 to 20 times more per pound. For example, U-700 would cost about $12 per pound in quantity purchases resulting in a material investment of $91 per barrel with a chip loss of $55. Therefore, efforts to reduce chip losses are cost effective when more highly alloyed materials are employed as gun tubes. The GFM Gesellschaft fur Fertigunstechnik und Maschinenbau) radial forging machines possess the compressive working behavior characteristic of the swage while providing both I.D. and O.D. contouring capabilities. The use of this type machine provides the potential for a significant advancement in the manufacturing technology for military gun barrels and represents a sophisticated approach to chipless machining.

The ability to achieve detailed I.D. and O.D. contouring by precision rotary forging will be limited primarily by the specific material performance capabilities and by costs originating from the manufacturing routing. As an example, an alloy of low workability may be subject to cracking during a one-pass forging operation, thus necessitating a multiple pass sequence with intermediate annealing. The added costs of a multiple close tolerance forging schedule may be of sufficient magnitude to offset the reductions in metal removal costs gained by the close contour forging. This tradeoff will become more significant as the cost of a candidate barrel material increases. Since material costs in general are approximately inversely proportional to workability, the need to forge closer to the finished configuration increases for the more refractory alloys of relatively low forgeability.

The current program requirement is to fabricate M-134 and M-219 barrels from an alloy steel and a superalloy. It is primarily designed to develop the manufacturing technology required to produce these barrels from the more refractory materials to demonstrate whether the performance gains can be made on a cost effective basis. Because of the high cost of material and metal removal processing required for candidate rapid fire weapons alloys, this program on advanced manufacturing methods considers the most advanced chipless machining and metal removal procedures to achieve the optimum level of cost effectiveness. It is felt that with these procedures the fabrication methods should become comparable to that for barrels of conventional steels. The materials cost penalty present for more sophisticated alloy systems can be greatly reduced by the contour forging capabilities offered by precision rotary forging. The extent to which these capabilities can be utilized depends however on bore surface quality and dimensional precision constraints on the amount of O.D. contouring that is practicable. Thus, a detailed examination of the entire process routing has been included in the program effort to define the performance limits of the overall program concepts.

2.0 BACKGROUND AND TECHNICAL DISCUSSION

The selection of a specific manufacturing process from scaled or pilot fabrication processes requires that precise economic evaluations be obtained for testing the many alternatives which the process sequence could follow. These considerations should include the following:

1. Material composition, cost, and condition, including hardness and microstructure before and after processing;
2. Capital investment requirements;
3. Machine cycling rate and parts produced per cycle;
4. Machine tooling and regrinding costs;
5. Machine maintenance:
6. Quality and dimensional constraints on final product;
7. Setup, tool change, and resharpen time; and,
8. Inspection.

The alternative to which these considerations might be applied were evaluated and reviewed during a previous program.(1) This work established that gun drilling was the most economical procedure for fabricating homogeneous gun barrel tubes if a blank could be through-drilled without resharpening the tool. Electrochemical drilling would be an alternative procedure in the event of extremely poor tool life. Feed rates with this procedure are very low and would necessitate a large capital investment to meet practical production schedules. Hot piercing and extrusion were found amenable to lined barrel fabrication and consolidation of powdered alloys respectively. Homogeneous tube fabrication costs by either of these two methods would be high because of secondary conditioning treatments and low product yields. Therefore, based on the results of the previous program, gun drilling was selected for this effort for fabrication of homogeneous barrel tubes. The gun drilling will be performed with special fixtures to reduce runout and hence facilitate subsequent processing operations.

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(1) A. L. Hoffmanner, "Improved Manufacturing Methods for Fabrication of 7.62 mm Superalloy Barrels (Part II)", Weapons Laboratory, USAWECOM, Report No. SWERR-TR-72-55, Sept. 1972

The full utility of GFM radial forging can be achieved if closely contoured barrel blanks are produced with good concentricity, straightness, bore dimensional precision within ±.0002 inch and bore surface finishes below about 20 microinch AA. Although the radial forging machine can produce O.D. contours, the basic action of the hammers or dies and, therefore, the dimensional reproduction possible are similar to precision rotary swaging. Variations of bore dimensions of ±.0001 inch or less are typical in both cases during cold working. However, the concentricity of the O.D. and I.D., straightness of the bore, and surface finish will depend on all of the following conditions: concentricity, straightness and surface finish of the drilled tube; reduction; and die design. The previous barrel fabrication program[(1)] demonstrated that rotary swaging would improve the concentricity level of the original tube, but the improvement became negligible for initial runouts below 0.010 inch (.025 cm) in 23 inches (.52 m) and a nominal 15 percent area reduction. This amount of runout was the upper limit of measurements made on centerless ground bars and supports the fact that the inherent gun drill design will produce forged tubes of minimum runout. This is an important consideration in that reduction of runout during forging occurs by an attempt to center the mandrel within the bar during plastic flow conditions by assymetric deformation. Depending on the magnitude of the reduction, this deformation mode can result in an assymetric residual stress pattern. This in turn will certainly lead to production of forgings of low straightness and will be a recurrent problem as the forging is finish machined. Once straightening is performed on a barrel, experience has shown that it must be repeatedly performed through the fabrication routing. Straightening also introduces additional high cost manual procedures and probably influences final barrel performance by adding further non-symmetrical residual stress patterns which can be relieved by service temperatures generated during rapid firing schedules.

The most severe limitation on the use of GFM forging for efficient barrel fabrication is the net part shape. Steep sided shoulders and lugs are nearly impossible to forge directly because constraints on die design contours are necessary to maintain workpiece alignment and achieve a reasonable feed, or production rate. Furthermore, quality and dimensional requirements, in general, place severe limitations on the variation of reduction which can be produced in a blank due to the effect of reduction on surface finish, residual stress, reproduction of the rifling and overall barrel dimensions. The internal surface finish of swaged parts improves as the surface finishes on the mandrel and initial prepared tube bore are improved and as the reduction increases. Therefore, requirements on minimum reduction and maximum surface finishes on the tube and mandrel are necessitated by

(1) A. L. Hoffmanner, "Improved Manufacturing Methods for Fabrication of 7.62 mm Superalloy Barrels (Part II)", Weapons Laboratory, USAWECOM, Report No. SWERR-TR-72-55, Sept. 1972.

the specified bore surface finish. An objectionable quality feature could still arise during O.D. contouring due to variations of surface finish along the bore surface below the maximum specified finish. This feature would appear as a variation of reflectivity throughout the bore which could be acceptable in terms of part print specifica tions. Typically, this variation might occur from a maximum of 20 micro-inches or less to 6 microinches. However, any subsequent electropolishing would have a larger effect on the highest values and, thereby would reduce the spread. This problem appears relatively minor because it is well understood and easily controlled. The following discussions will outline more severe limitations which, in general, are known to GFM barrel fabricators but are not well understood or publicized. Many of the following problems are also encountered with the precision swage.

During radial forging and swaging there is a minimum area reduction required to accurately generate rifling in the bore. This minimum is usually in the range of 15 to 22 percent reduction of area but also depends strongly on material characteristics and die design. There are also practical limits on the maximum reduction beyond which failures can occur by three basic mechanisms: a) the radii at the land-groove junction become distorted; b) shear strains under the lands become great enough to promote surface spalling; and c) the deformation capability of the material is exceeded and fracture occurs through the wall thickness. Contouring of the O.D. must therefore be achieved between these limiting constraints. The maximum reductions also depend on whether a tube is to be forged with rifling only or combined rifling and chambering. In the former case continued deformation following initial contact with the mandrel and development leads to shear failures and radii distortion after approximately 25-30 percent reduction. The difference between minimum and maximum deformation levels permits only a modest ± 4 percent variation in O.D. contours. As a consequence, a substantial amount of stock would remain to be machined from the barrel portion even if the breech end were forged very close to finish O.D. A much greater latitude exists for combined rifling and chambering, however because the total deformation capability of a typical barrel material is on the order of 50 to 60% reduction. The as-drilled blank must clear the larger diameter chambering mandrel and can thereby be reduced some 30 percent along the barrel portion before the I.D. contacts the rifling area on the mandrel. An additional 15 to 22 percent reduction can then be achieved to generate the rifling without encountering fracture through the wall thickness. Reductions at the breech end need only be 15 to 22 percent to properly form the larger body portion of the chamber. A potential contouring capability of ± 15 percent can be realized thus substantially reducing the volume of excess material along the barrel portion of the as-forged tube. The combined operation then represents a more economically attractive alternative, particularly when it is recognized that mechanical chambering operations are also eliminated along with reduced metal removal requirements on the O.D. surfaces.

The maximum and minimum reductions are processing limits imposed directly by the material. Other limits are imposed indirectly by the material through raw material costs, machining rates and other fabrication costs. These other fabrication costs involve machining or forging a preform. A machined preform would result in additional costs arising from loss of material and the cost of machining, whereas a forged preform would avert significant loss of material, but probably would necessitate subsequent heat treatment and bore conditioning before final forging. Preforming could also be performed up to 1600°F. However, the dimensional requirements and required lack of surface contamination of the final product would necessitate final cold forging. This deduction is based on the following data published by GFM for dimensional precision attainable with radial forging:

1. Cold Forging:
   a) Rifling tolerance ±0.0001 inch (±.25 μm)
   b) Chamber Tolerance ±0.0006 inch (±1.52 μm)
2. Hot Forging:
   a) O.D. Tolerances ±0.006 inch (±15.2 μm)
   b) I.D. Tolerances ±0.002 inch (±5.08 μm)

Material costs for barrels fabricated from alloys such as U-700 would be over $90 per blank, which is anticipated to be significantly greater than the fabrication costs. The inverse would be true for H-11 or Cr-Mo-V steels. Therefore, an effort to achieve a reduction in the material consumed per barrel becomes an important goal in the case of the more refractory alloys because this cost can seriously influence the overall process economics. For this reason the degree of I.D. and O.D. contouring produced in a given barrel cannot be approached arbitrarily but must be designed as part of an overall analysis of the entire fabrication sequence.

Metal removal costs are directly related to the amount and distribution of the stock envelope on the forged blank because feed rates and hence cycle times in either plunge grinding or turning must be determined approximately from the point of initial tool-workpiece contact. Plunge form grinding becomes economically attractive over turning as the machineability of the work decreases and appears to be the most economical method for finishing barrels of U-700 material while either grinding or turning may be suitable for the H-11 material. Increased form complexity also favors plunge grinding because follower rests cannot be efficiently used to achieve the rigidity necessary to sustain high stock removal rates during turning operations. The form complexity of the M-134 barrel is more amenable to economical plunge grinding than the M-219 contours. For these reasons plunge grinding appears to be suitable for the M-134 barrels of U-700 and H-11 materials while the relatively simple tapered M-219 barrel forged of H-11 can be NC turned utilizing a hydraulic follower rest.

Chamber finishing can be performed either by direct forging or by conventional procedures from a rifled only forging. ECM can be used to rough machine the chamber but cannot hold the required corner radii in the chamber neck area to be used as a finishing method. Tool life and forging evaluation must be utilized to establish the most reliable and cost effective procedural sequence.

The general fabrication scheme for M-134 barrels planned for investigation on this program is flow charted in Figure 1 and consists of the following major steps: tube preparation; radial forging, form grinding, chambering, and chromium plating. The two most critical steps in the sequence are radial forging and electroplating. The questions involving material response to attempts at O.D. and I.D. contouring represent more serious obstacles than identification of optimum metal removal procedures while the electroplating operations are dependent upon the overall quality of the rifled bore. Many of the process development efforts in each fabrication step must evolve with the program to define their relative impacts on barrel quality and cost.

The primary objectives of this program are threefold:

1) to examine and define the impact each of the many process variables exert on effective use of precision radial forging to produce M-134 and M-219 gun tubes;

2) to successfully fabricate a quantity of M-134 and M-219 barrels to demonstrate that precision rotary forging is a viable advanced fabrication method; and

3) to develop an optimum routing for O.D. finishing of the forged tubes.

Drawings of the M-134 and M-219 barrel configurations are presented in Figures 2 and 3 respectively for purposes of illustration.

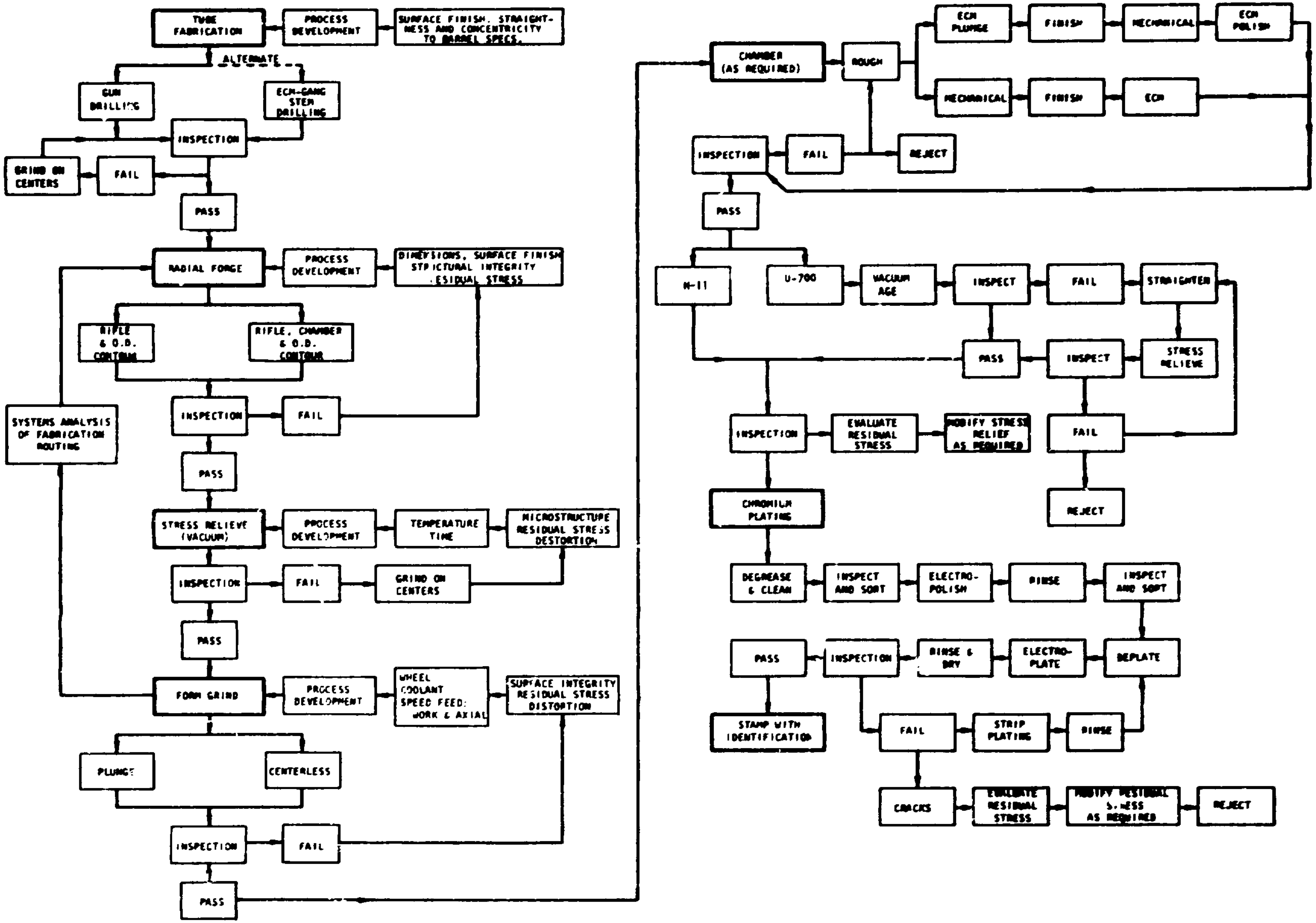

Figure 1. Flow Chart for Advanced Fabrication Sequence for the M-134 Barrel.

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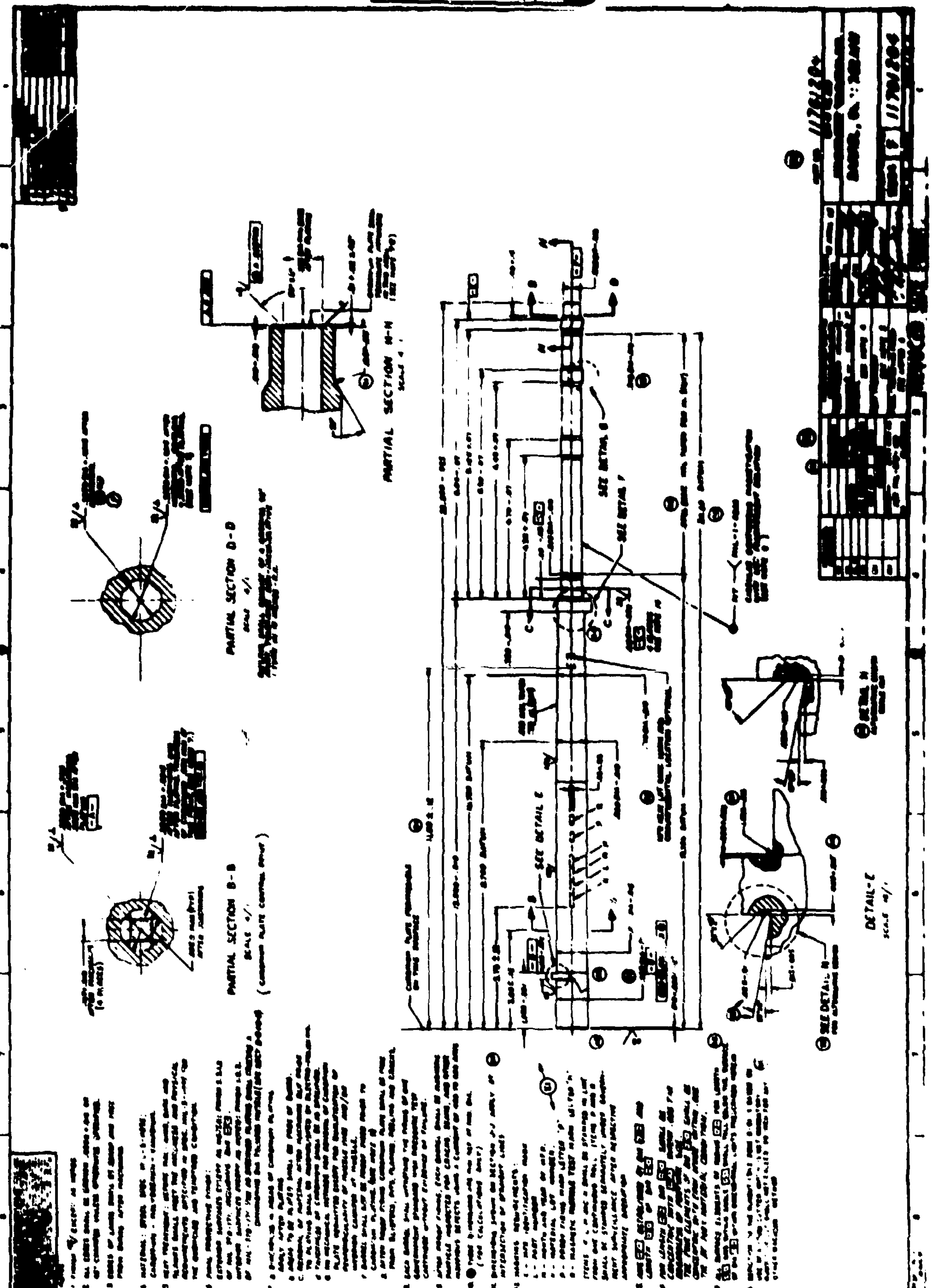


Figure 2. Barrel Configuration for M-134 Gun Tube.

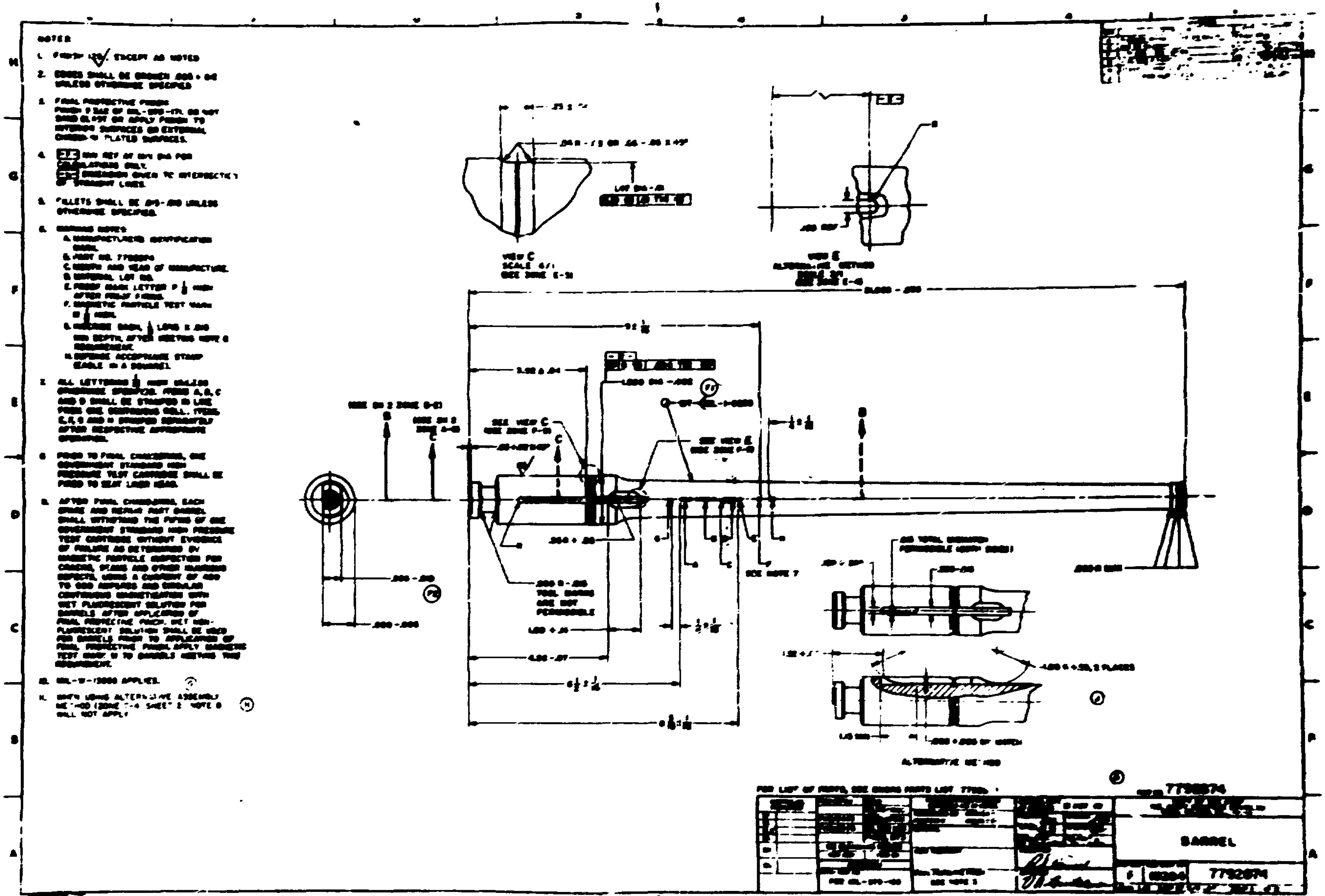


Figure 3. Barrel Configuration for M-219 Tube.

3.0 RESULTS AND DISCUSSIONS

The establishment of advanced procedures for fabrication of erosion resistant 7.62mm barrels has proceeded as an evolutionary-type program. Much of the supportive technology necessary to sustain this effort was developed as an integral part of the overall program activity. For purposes of organization, the results will be treated in a three part discussion. The process development activity will comprise Task I while the fabrication of barrels for actual test evaluation will be reviewed in Task II. The economic analysis and manufacturing routing development will be presented in Task III. Flow charts illustrating the sequence followed for each of the three tasks are presented in Figure 4.

3.1 TASK I - Process Development

3.1.1 Material

The process development phase was subjected to a sequential investigation according to the outline illustrated in Figure 4. Two materials were initially selected for evaluation on this program; U-700, a nickel-base superalloy and H-11, a 5% chromium hot work die steel. During the course of this investigation, Incoloy 903 was also included in the program. This alloy was selected on the basis of high strength, good formability, and unlike other alloys in this case is chromium-free. This latter point is important in that high chromium alloys are difficult to plate and is a reason why an alloy like IN718 was not selected. The compositions of the three materials are presented in Table I.

Stock sizes were determined through extensive discussions with GFM Machines Inc. (USA) and GFM at Steyr, Austria. The dimensions selected were designed to provide stock for subsequent forging of M-134 gun tubes having both rifling and chambering with O.D. contouring and rifled M-219 tubes with O.D. contouring. Stock allowance of .025 inch (.064 cm) were allowed to clean up the heat treated surfaces and permit bringing the T.I.R.* of the O.D. to within the desired ±.005 inch (±.013 cm) runout limit on the gun drilled hole during preform preparation. A summary of the sizes procured is presented in Table II.

Heat treating experiments were conducted on slugs of the U-700 material to establish baseline data on grain size, hardness, cracking, and banding of second phase constitutents as influenced by solutioning

*T.I.R. refers to the Total Indicator Reading of a dial gage mounted at bar center as the bar is rotated while supported on rollers located at the bar ends.

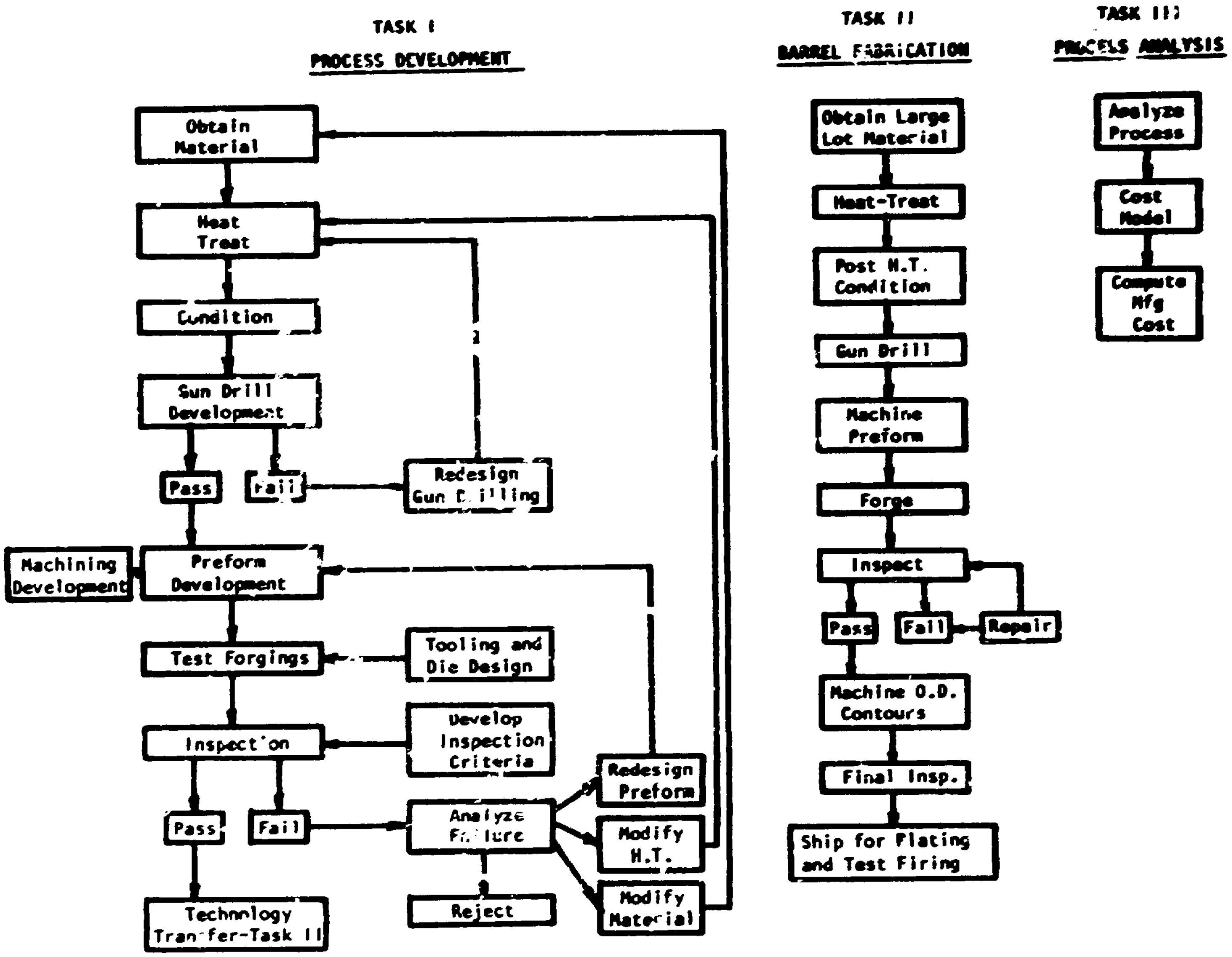


Figure 4. Flow Chart Illustrating Program Organization.

TABLE I

Composition of Candidate Barrel Alloys

Alloy	Heat Code	C	Cr	Mo	V	Si	Co	Ti	Al	S	P	Mn	Cu	B	Ni	Fe	Cb+Ta
U-700 (PWA 1013)	Spec.Metals HT 8-3564A	.06	14.9	4.70	-	.10	17.4	3.28	4.03	.003	.01	.10	.10	.29	Bal.	-	2.85
H-11 (AMS6485B)	Braeburn HT 996P	.39	5.05	1.30	.57	.90	-	-	-	.004	.019	.38	-	-	-	Bal.	
INCOLOY 903	Huntington HH 17 A1UY	.02	-	-	-	.07	14.84	1.33	.66	.07	-	.20	.02	-	38.53	41.53	2.97
	HH 20 A6UY	.01	-	-	-	.13	14.89	1.43	.48	.04	-	.16	-	-	37.96	42.07	2.85

TABLE II

Raw Material Stock Dimensions

Material	M-134 Rifling and Chambering	M-219 Rifling Only
U-700	1.41 in. dia. x 17.5 in. (3.58 x 44.5 cm)	-
IN 903	1.40 in. dia. x 17.5 in. (3.55 x 44.5 cm)	-
H-11	1.410 in. dia. x 17.5 in. (3.58 x 44.5 cm)	1.75 in. dia. x 19.0 in. (4.44 x 48.3 cm)

temperature, quench methods, and aging effects. The results of the heat treat evaluation are presented in Figure 5 and involved four variations on solutioning temperatures and quenching methods. A solutioning temperature of 2110°F (1154°C) was selected as a compromise between grain size and banding considerations. It represents the low temperature end of the range for maximum elevated temperature stress rupture properties and the extreme high temperature range for good toughness and low-cycle thermal fatigue performance. As a result of the study, the U-700 was heat treated for evaluation at two conditions: fully aged at maximum hardness; and at the softest condition, after aging at 1975°F (1079°C). The fully aged condition represents the most economically desirable state in that no further thermal treatment is needed after forging while the partially aged condition offers improved workability at the expense of requiring some further low temperature post-forge heat treatment. The IN903 material was prepared for evaluation in the fully heat treated condition as the solution treatment and aging process has been designed as a single, continuous operation. No evaluation was required for the H-11 material because it was an objective of the program to fabricate barrels at a hardness level of 36-38 R_C, ideally by a combination of an appropriate quench and temper operation prior to forging. A summary of the heat treating schedule is presented in Table III for the three candidate alloys.

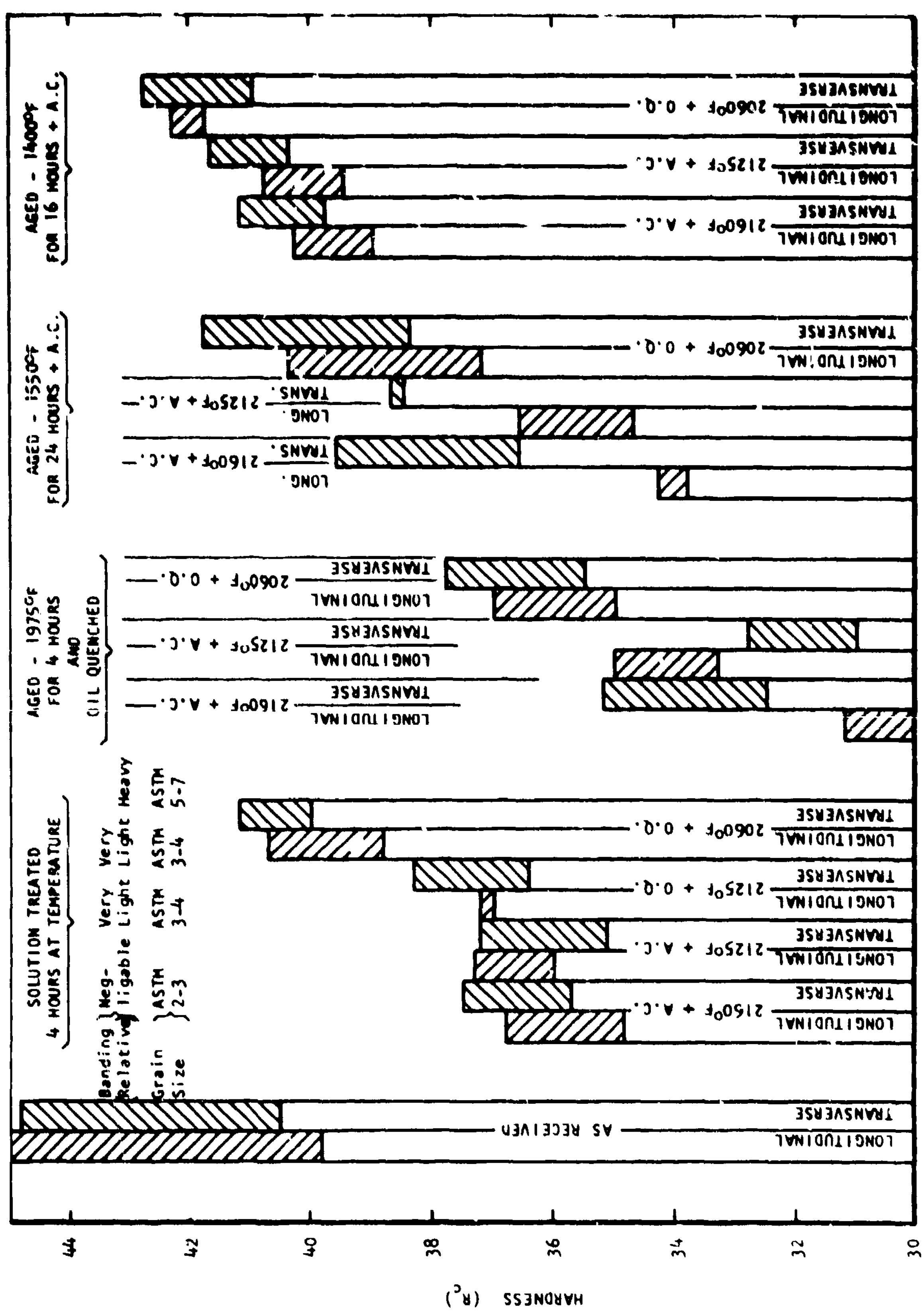


Figure 5. Heat Treatment Evaluations of U-700.

3.1.2 Bar Conditioning

The adherent salt on U-700 and the light oxide films present on the IN903 and H-11 resulting from the heat treating operation were removed by rotary table grit blasting preparatory to gun drilling. As a cost reduction effort, it was planned to eliminate an O.D. machining operation prior to hole drilling. Two requirements must be satisfied to meet this objective; first, it must be possible to remove sufficient stock on the O.D. to eliminate any potential surface cracking or compositional effects remaining from the heat treating process; and second, restore concentricity between the O.D. and the gun drilled hole.

Runout measurements were made before and after heat treatment to evaluate changes in T.I.R. and the variance associated with each group of determinations were computed to provide a 95% confidence interval statement. The significance of the confidence interval is that a 95% probability exists that all parts measured will fall below the maximum calculated limit. This upper limit defines an optimum stock allowance to assure that bars clean-up and the concentricity between bore and O.D. is restored to within the required ±.005 inch (.013 cm) tolerance. Recall that high concentricity is necessary to avoid residual stress effects due to assymetric deformation during the subsequent forging procedure. A summary of the observed data is presented in Table IV which shows that the maximum 95% limit on heat treatment distortion ranged between .0079 inches (.0201 cm) and .0024 inches (.0061 cm) for the larger diameter M-219 preform stock and ranged between .024 and .025 inches (.016 and .069 cm) for the H-11 and U-700 stock. The IN903 was apparently subject to slightly greater distortion, .031 inches (.078 cm), a fact which led to difficulties encountered later in the program.

TABLE III

Summary of Heat Treatment Parameters

Alloy	Time	Temperature	Cooling Mode	Hardness
U-700	4 Hr.	2110°F (1154°C)	A.C.	
	4 Hr.	1975°F (1079°C)	A.C.	
	24 Hr.	1550°F (843°C)	A.C.	
	16 Hr.	1400°F (760°C)	A.C.	R_c 40-41
H-11	Preheat	1500°F (815°C)	-	
	.5 Hr.	1800°F (982°C)	A.C.	
	2 Hr.	1180°F (638°C)	A.C.	
	2 Hr.	1180°F (638°C)	A.C.	R_c 35-36
IN 903	8 Hr.	1325°F (718°C)	Furnace Cool	100°/Hr to 1150°F (38°C, 621°C)
	8 Hr.	1150°C (621°C)	A.C.	R_c 38-40

TABLE IV

Dimensional Runout of H-11 and U-700 After Various Stages of Tube Preparation

	T.I.R. Runout, Inches (Centimeters)					
	As Centerless Ground		As Heat Treated		As Gun Drilled T.I.R. of I.D. from O.D.	
	Average	95%	Average	95%	Average	95%
H-11 (R_c 36/38)						
1.400"x17.5" (3.56x44.5)	.0065 (.0165	.0087 (.0221)	.0177 (.0450)	.0239 (.0607)	.0147 (.0373)	.0183 (.0465)
1.875"x14.5" (4.76x36.8)	.0024 (.0061)	.0068 (.0173)	.0025 (.0064)	.0079 (.0201)	.0064 (.0.63)	.0083 (.0211)
U-700 (Fully Aged)						
1.455"x17.5" (3.70x44.5)	.0072 (.0183)	.0091 (.0231)	.0139 (.0353)	.0210 (.0533)		
(Partially Aged)						
1.250"x17.5" (3.18x44.5)	.0072 (.0183)	.0094 (.0239)	.0165 (.0419)	.0271 (.0688)		
1.455"x17.5"(3.70x44.5)			.0130 (.0330)	.0267 (.0678)		
IN-903 (Fully Aged)						
1.410x17.5 (3.58x44.5)			.0238 (.0606)	.0308 (.0782)		

Studies of the runout deviations encountered established that a stock allowance of .030 inches (.076cm) would be adequate to permit simplification of the blank preparation sequence to the following steps:

1. Obtain bar stock to .030 inch (.076 cm) over preform O.D.;
2. Heat treat in salt or protective atmosphere;
3. Gun drill; and,
4. Machine O.D. concentric to gun drilled I.D. bore.

3.1.3. Gun Drilling Development

A series of experiments were conducted to define reasonably economical gun drilling parameters, particularly for the difficult-to-machine U-700 alloy. An initial series of tests established that Eldorado N-133 drills operated with less chatter than the N73E point geometry and gave slightly greater tool life as well. Further, comparative tests were conducted which established that a twofold difference in tool life existed between 36 inch (.91 m) and 22 inch (.56 m) drills. The shorter drills would not extend through the driver and machine guide bushings to drill the preforms completely through however. This difficulty was averted by welding a rigid extension to the drill base .75 inch (1.9 cm) diameter and 6 inches (15.2 cm) long to retain the better tool life advantage offered by the shorter and presumably more rigid drill.

Tests were conducted using the modified 22 inch (.56 m) N-133 gun drills and an oil pressure in the drill of 1000 psi (6.89 MPa) to investigate the influence of feed and speed on tool life and part quality. The data obtained are summarized in the first seven rows of Table V. These data show that a maximum tool life of approximately 1 inch (2.54 cm) was achieved with U-700 alloy for feed rates below .4 inches-min^{-1} (.019 cm-sec^{-1}). Drill breakage was considered severe in all cases in that a blank was also lost each time a drill was broken. A further complication was that the automatic torque sensor lacked the sensitivity to respond to drill shaft windup prior to failure for speeds above the .4 ipm (.019 cm-sec^{-1}) infeed rate. Most of the drill tests were therefore terminated manually at the first incidence of audible chatter, which usually began during the final 25 percent of tool life for a drill run until failure. There appeared to be no detectable difference in tool life between partially aged (min. hardness) and fully aged (max. properties) U-700 material. The major influence of running at slower speeds was that the torque cutoff would function and avert catastrophic drill breakage. Attempts to get incremental hole depths in excess of .8 inch (2 cm) resulted in a high probability of drill breakage.

TABLE V

Summary of U-700 Gun Drilling Tests

Material Condition	Cutting Oil	Drilling Parameters Speed SFM ($cm\text{-}sec^{-1}$)	Drilling Parameters Feed IPM ($cm\text{-}sec^{-1}$)	Tool Life, Min. Max.	Tool Life, Min. Min.	Tool Life, Min. Avg.	No. Tests	Wear Land In(cm)	Remarks
Partial Age	Peerless	47(23.9)	.63(.027)	1.50	.60	1.05	2	-	Both Drills Broken.
Partial Age	Peerless	47(23.9)	.51(.022)	.80	.70	.75	3	-	Two Drills Broken.
Fully Aged	Peerless	47(23.9)	.51(.022)	.75	.67	.73	6	.0008 (.0020)	One Drill Broken.
Fully Aged	Peerless	47(23.9)	.40(.017)	1.25	1.10	1.2	8	.007/.014 (.018/.036)	Two Drills Broken
Fully Aged	Peerless	33(16.8)	.36(.015)	1.0	.75	.95	8	.010/.012 (.025/.030)	Two Drills Broken.
Fully Aged	Peerless	33(16.8)	.28(.012)	1.0	.80	.95	4	.010/.012 (.025/.030)	One Drill Broken.
Fully Aged	Peerless	80(40.6)	.68(.029)	.63	-	-	1	-	Drill Broken.
Fully Aged	White & Bagley	33(16.8)	.36(.015)	4.0	3.0	3.6	7	.008/.010 (.020/.025)	No Drills Broken.

A change in the cutting fluid was then made because feed rate reductions failed to significantly extend tool life beyond approximately a one-inch (2.5 cm) maximum. A more heavily compounded cutting fluid, White and Bagl‹‹ No. 2480, was substituted for the Franklin Peerless Oil. The compositions for the two oils are compared in Table VI.

TABLE VI

Gun Drilling Oils Evaluated

Mfr and Grade Designation	Sulfur %	Chlorine %	Fatty Acids And Wax, %
Franklin Peerless Oil Lot No. 71571	3.3	2.7	21
White and Bagley No. 2480	3.75	14.5	>10

A dramatic fourfold improvement in tool life was observed; Table V, Row 8, and an approximate fivefold reduction in drill wear land development rates. Drills were repointed after 3.5 inches (9 cm) of drilling at 33 SFM (16.8 cm-sec^{-1}) and a .36 ipm (.015 cm-sec^{-1}) feed rate. No drill breakage was observed during preparation of 25 fully aged U-700 blanks which represents 437.5 inches (11.1 m) of total hole length. These parameters permitted a U-700 blank to be drilled in approximately one hour with five tool changes. Measurements of the surface finish revealed the 40 to 60 microinch AA (Arithmetric Average) (1.03 to 1.27 μm AA) which was adequate for the subsequent forging process without further hold conditioning. Although the performance improvements offered by the heavier duty cutting fluid represents a significant advance in the state-of-the-art for drilling U-700 alloys, the process economics still leave much to be desired as a potential production operation.

A fully hardened H-11 steel was successfully drilled at 0.9 ipm (.038 cm-sec^{-1}) at a speed of 200 SFM (102 cm-sec^{-1}) using the N133 drill geometry and an oil pressure of 1000 psi (6.89 MPA). Drill life with the improved cutting fluid was 5-10 blanks before a .010-.015 inch (.025 50 .038 cm) wear land developed. As with the U-700, no further finishing was required prior to forging for the I.D. surface. The IN 903 was intermediate between these extremes, with parameters of 100 SFM (50 cm-sec^{-1}) and .36 ipm (.015 cm-sec^{-1}) selected for drilling the fully aged blanks for forging evaluations. Tool life was adequate in that two blanks could be drilled before repointing was necessary.

A wear limit of approximately .010 inches (.025 cm) was established to avoid risk of drill breakage and to extend the useful life of a drill significantly. Incidence of edge chipping was considered undesirable as repointing required removal of a relatively large amount of stock to restore the original tip geometry, thus limiting the total number of regrinds available from a given tool. Gun drills 3 ft (.91 m) long were also tried to permit through drilling of preforms up to a length of 20 inches (.5 meters).

A summary of the optimum drilling parameters for each alloy identified as a result of this study is presented in Table VII. These parameters were adopted for all subsequent gun drilling operations.

TABLE VII

Optimum Drilling Parameters

Alloy	Speed SFM (cm-sec^{-1})	Feed Rate ipm (cm-sec^{-1})	Oil Pressure psi (MPa)
U-700	33(16.8)	.36(.015)	1000 (6.89 MPa)
Incoloy 903	100 (50.8)	.36(.015)	1000 (6.89 MPa)
H-11	200 (101.6)	1.2(3.05)	1000 (6.89 MPa)

An additional benefit from the gun drilling process was also exploited. The drill guide bushing and chuck assembly provided a concentricity error not exceeding $\pm$.005 inch ($\pm$.013 cm) T.I.R. between the I.D. and O.D. of the drilled blank for approximately 4 inches (10 cm). Concentricity errors on the exit end can reach $\pm$.015 inch ($\pm$.038 cm). A steel stamp was used to retain identity of the entrance end of a drilled blank such that the inherently high concentricity can be utilized in reducing the number of locations and machining operations required in preform preparation.

3.1.4. Machining Parameter Development

Metal removal studies were conducted concurrently with the gun drilling operations to identify the most practical and economical finishing procedure for the three candidate barrel materials. The study included development activity for forging preform generation as well as final machining of the O.D. configuration for the M-134 and M-219 barrels. The procedures evaluated included single point turning operations for tracer and NC lathes and plunge form grinding.

Initial turning tests were conducted on a 14 x 58 inch Hendey engine lathe employing a series of indexable carbide throwaway tools. The Metcut Machining Handbook was consulted as a point of departure to identify recommended tool geometries for the H-11 and superalloy materials. These data are summarized in Table VIII.

TABLE VIII

Tool Geometries for Machining

Tool Geometry	H-11 Steel	High Temperature Superalloys
Back Rake, °	-5	5
Side Rake, °	-5	0
End Relief Angle, °	5	5
Side Relief Angle,°	5	5
Side and End Cutting Edge Angles,°	15	45

Carboloy 883 (C-2 grade) inserts were employed in a series of turning experiments involving the H-11 material at a hardness level of 34-36 R_C. Heat treated H-11 bar stock approximating the dimensions of as-forged barrel blanks, 1.12 inches in diameter and 20 inches long (2.84 x 51 cm), was used for test samples. Tool lives were observed over metal removal rates (MRR) ranging between .7 and 3 cubic inches per minute (.19 to .82 cm^3-sec^{-1}). The most pertinent data observed are summarized in Table IX. Although the tool life was excellent for a work speed of approximately 150 SFM, a heavy built-up-edge (BUE) condition existed on the cutting tool nose. Surface finishes generated under this BUE condition were not regarded as adequate and further, the metal removal rates were unduly low. Increasing the spindle speed from 320 to approximately 550 rpm successfully alleviated the BUE condition and raised the MRR 55%. The observed tool lives were adequate to finish two or more barrels per insert before development of a .014 in. (.036 cm) flank wear land. Further increases in the MRR were achieved by increasing either the depth of cut or the feed rate without significantly reducing the tool life. Attempts to raise the part speed led to rapid tool consumption rates. The test data established that a MRR of approximately 3 in^3-min^{-1} (.82 cm^3-sec^{-1}) represented a practical maximum for this material while providing surface finishes less than 80 μin AA) and distortion levels well within the .005 inch (.013 cm) T.I.R. requirement of the finished barrels. Tests conducted on the IN 903 material employing the same cutting parameters indicated that an MRR of approximately 3 in^3-min^{-1} (.82 cm^3-sec^{-1}) was also suitable for this material as

'BLE IX

Tc Life Data Observed For H-11 Steel, R_c 34-36

Workspeed, SFM	Feed, ipr	Depth of Cut, In.	Metal Removal Rate In^3-min^{-1}	Life: Cut Length, In	Life: In^3	Wear Land, In.
147	.010	.050	.9			
147	.010	.050	.9	.67.5	19.1	.010
147	.010	.050	.9			
155	.010	.050	.9			
230	.010	.050	1.4	Chipped	-	-
230	.010	.050	1.4	26	7.4	.015
240	.020	.050	2.9	32	9.1	-
240	.010	.100	2.9	24	13.6	<.015

well. In fact, the surface finishes were better (50-60 μin.AA), (1.3 to 1.5 μmAA) and the tool life was approximately 10% greater. Attempts to increase the MRR beyond the 3 in^3-min^{-1} (.82 cm^3-sec^{-1}) level was precluded by the higher apparent cutting forces encountered with this alloy. Turning U-700 was found to be essentially uneconomical; tool lives were extremely short; and the maximum metal removal rates that could be sustained at all were less than 1/4 that observed for H-11.

Plunge grinding experiments were conducted on U-700 and H-11 bar stock samples using a Sheffield Cylindrical Crush Grinder, Model No. 187B. A grinding wheel 9 inches wide and 24 inches in diameter (23 x 61 cm) was used for all tests. Data obtained from an internal TRW superalloy grinding optimization program were employed to select an appropriate range of machine parameters for this study. The machine conditions are summarized in Table X. Tests with the A240M6V wheel developed severe

TABLE X

Superalloy Grinding Parameters

Wheel Speed	7000 SFM (35.6 m-sec^{-1})
Part Speed	300 RPM
H-11	98 SFM (.50 m-sec^{-1})
IN-903	39 SFM (.20 m-sec^{-1})
Infeed Rate	.038 - .075 in-min^{-1} (.0016 to .0032 cm-sec^{-1})
Contact Length	9 inch (22.9 cm)
Wheel Grade	A240M6V A46N10V
Coolant	Water Soluble Oil

chatter and wheel loading for both H-11 and U-700 materials and further testing with this wheel was terminated. Good results were obtained for the A60N10V wheels at the lower feed rates in the sense that wheel loading, wheel wear, part deflection, surface finish, and MRR were acceptable for both materials. Some chatter and wheel loading were observed at the higher feed rates. The data obtained are listed in Table XI and show that an MRR close to that obtained by turning could be maintained if wheel loading and chatter could be eliminated at the .075 inch-min^{-1} (.0032 cm-sec^{-1})

TABLE XI

Grinding Test Results

Material	Feed Rate $in\text{-}min^{-1}$ ($cm\text{-}sec^{-1}$)	G-Ratio	MRR for 9" Wheel $in^3\text{-}min^{-1}$ ($cm^3\text{-}sec^{-1}$)	Surface Finish μin.AA (μmAA)
H-11	.071 (.0032)	3.2	2.84 (.78)	< 40 (1.02)
H-11	.038 (.0016)	2.4	1.20 (.33)	< 40 (1.02)
U-700	.075 (.0032)	.83	.85 (.23)	< 40 (1.02)
U-700	.038 (.0016)	.83	.42 (.12)	< 40 (1.02)

feed rate. However, use of a softer wheel to reduce loading would further reduce the G-ratio (defined as $\frac{\text{Volume metal removed}}{\text{Volume wheel worn}}$) which in turn would require several dresses per grind to hold part tolerances within limits. Wheel breakdown at sharp corners is several times as rapid as that experienced by a flat wheel surface. Therefore, to minimize dresses and hence wear on the dresser rolls, an MRR of approximately .045 $in^3\text{-}min^{-1}$ per inch of wheel width represents the practical maximum for o.d. grinding of U-700 barrel forgings. Wheel breakdown calculations made with a TRW-developed parametric equation relating wear to wheel and part speeds and form geometry revealed that a .02 inch (.051 cm) inside radius on a barrel to lug corner would require 8 to 9 wheel dressings of .010 inch (.025 cm) to maintain the form within tolerance. A typical roll dresser has a useful life of 25,000 dresses, thus approximately 3,000 barrels could be produced before the dresser would require replacement. The calculated wheel wear data are summarized in Table XII and show that significant wheel wear would be experienced at the corner radii at either lug location.

TABLE XII

Wheel Form Loss Data For U-700 Grinding

Operation	Grinder Performance: Flat Area	Grinder Performance: .030 inch (.076 cm) Radius
G-Ratio	.83	.33
Actual Wheel Wear	.0343 in (.087 cm)	.0863 in (.219 cm)
Dresser Req'd to Maintain ±.005 inch (.0127 cm) Tolerance	4	9

Wheel breakdown at corner radii has always been a limiting factor for form grinding and imposed a severe limit on utilization of form grinding. Comparison of wheel wear data for flat (no form) plunge grinding (Table XI) with that for a .03 inch (.076 cm) corner radius (Table XII) on U-700 showed that the G ratio has been reduced approximately threefold. The most economical solution to application of precision form grinding to U-700 would be to add a secondary finishing operation to generate the desired corner radii at the two barrel lugs within the design tolerances.

3.1.5 Forging Tooling

An investigation was conducted to concurrently develop the correct preform design and forging parameters for the M-134 and M-219 barrel configurations. The tooling employed to forge the blanks and impart the I.D. configurations were the same for both barrels.

Forging dies, mandrels for rifling and rifling plus chambering, and forging templates were designed for use on the SHK10 GFM machine located at the Rock Island Arsenal. A set of four dies were fabricated from M-2 high speed steel hardened and drawn to R_c 62-64 to GFM Print No. Se 1254.04 with a modification to provide a basic hammer dimension of .70 inches (1.78 cm). This dimension is a basic setup parameter because it defines the various cam and template position to produce a given forging diameter from a particular template. This dimension also represents the minimum diameter that can be forged without hammer interference. The dies were designed for both hot and cold work with a stock allowance for rework if required.

Die contours are identical for all four quarters in the case of forging with rifling only while inclusion of a chambering operation requires that a slight change in the lead angle on two opposing die quarters be provided, Figures 6 and 7, respectively. This difference in lead angle introduces a small ovality in the forging immediately ahead of the minimum die opening, thus aiding in release of entrapped air during forging of the chamber. The chambering dies were used for all trials because it was observed that the small ovality maintained ahead of the final forging position reduced the forging loads.

Mandrels were designed for rifling only and combined rifling and chambering as shown in Figures 8 and 9, respectively. These mandrels have been scaled .004 inch (.010 cm) oversize to eliminate most of the electropolishing normally required to prepare military barrels for chromium plating. The electropolishing was not regarded as necessary because the forging process imparts the fine finish on the mandrels to the bore I.D. surfaces. The rifling sections of both mandrels were

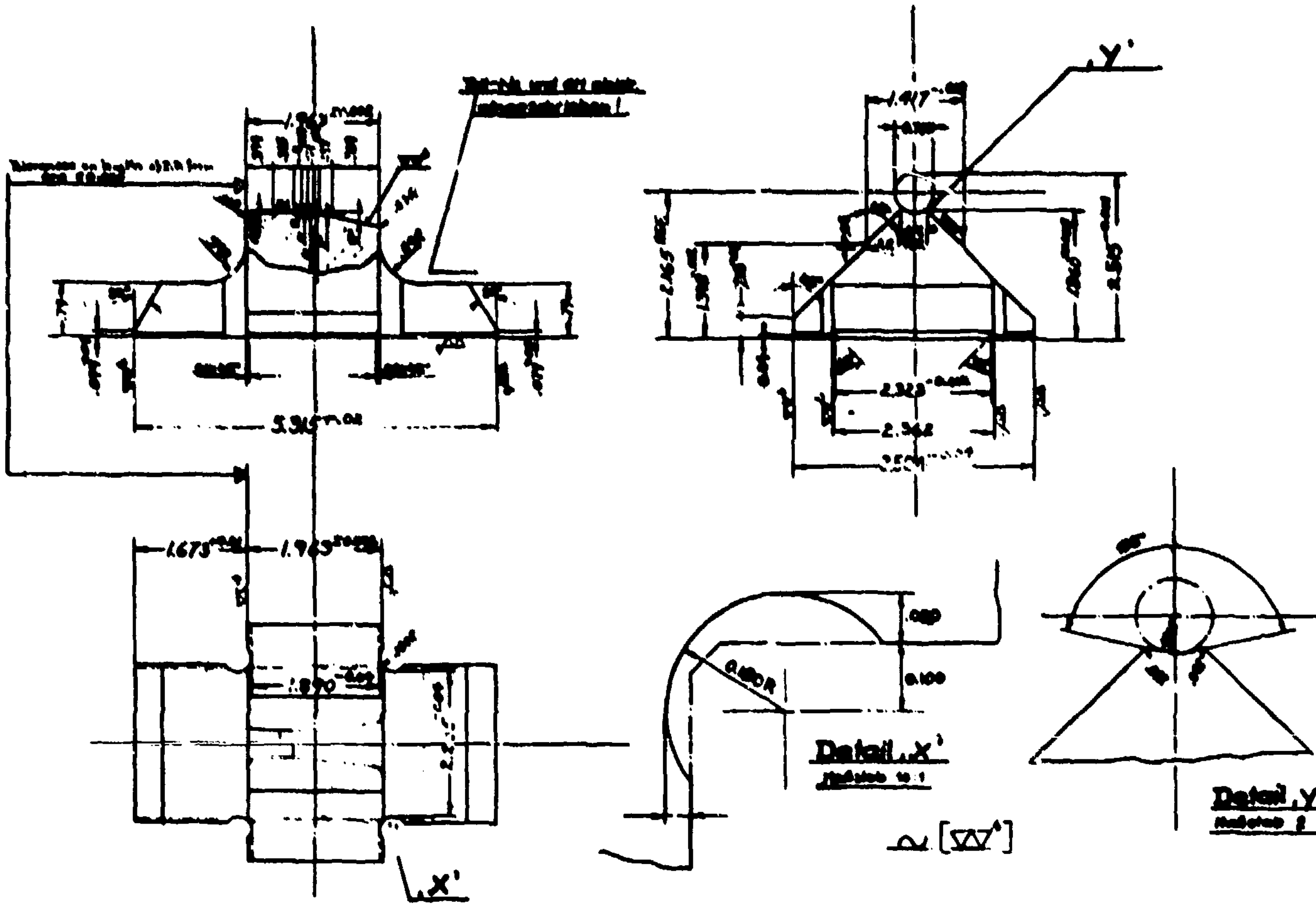


Figure 6. Forging Die for Rifling.

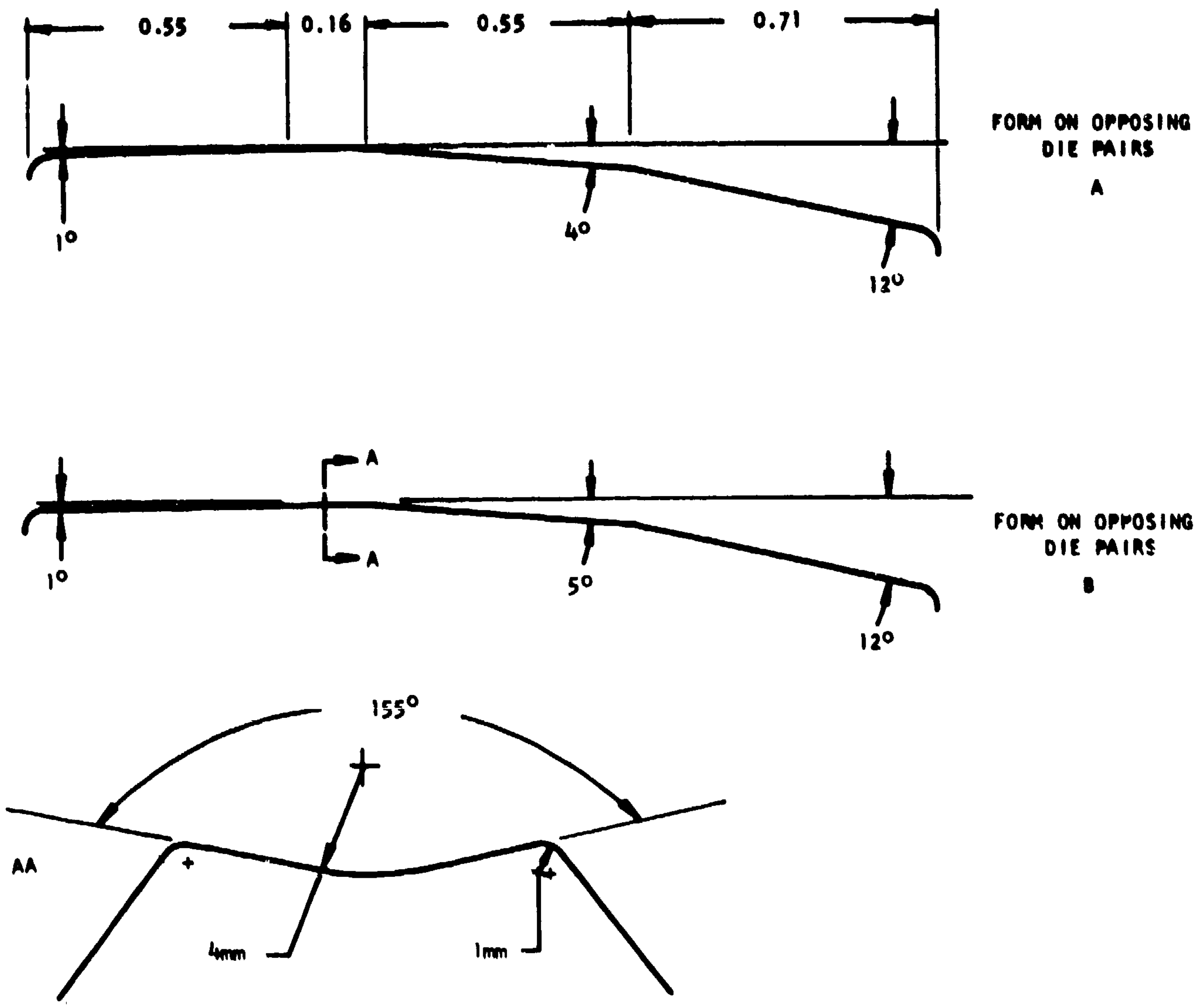
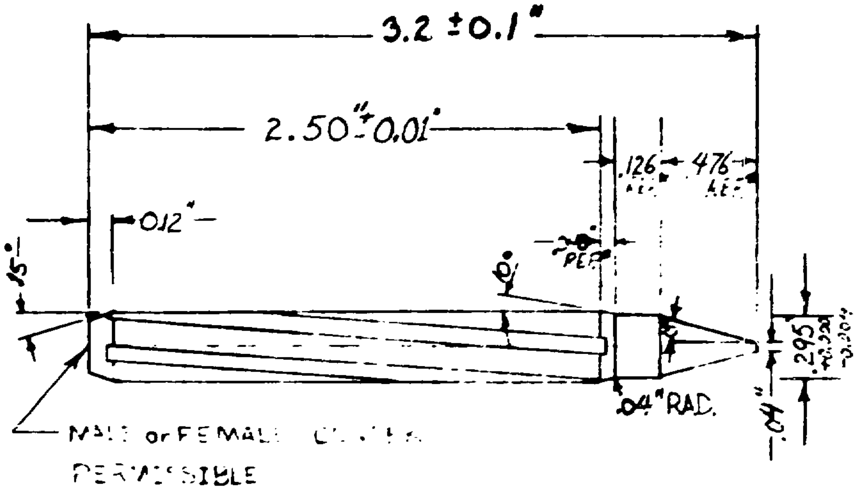
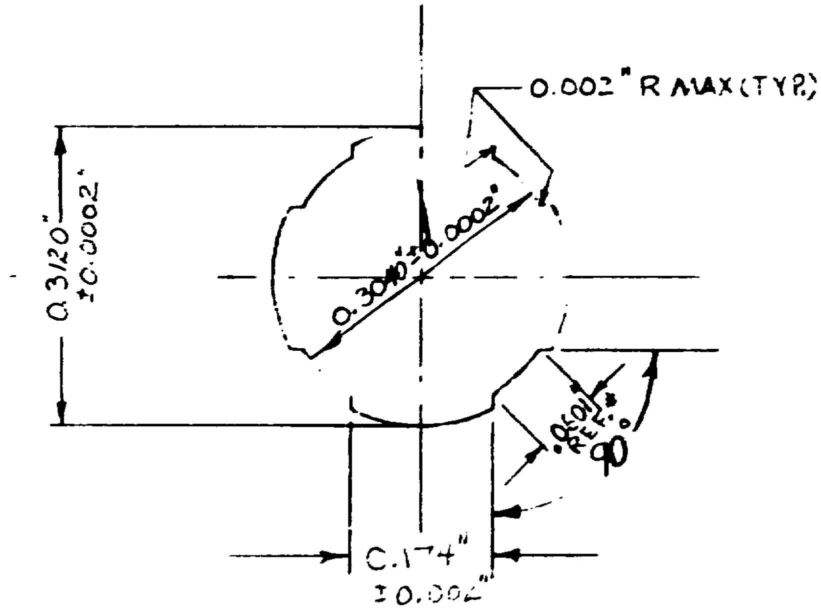


Figure 7. Die Contour Modification for Combined Rifling and Chambering Operations.



Surface finish: 8 microinch AA on rifled portion of mandrel and 32 microinch elsewhere unless specified otherwise.



RIFLING SHALL CONSIST OF 4 GROOVES 90° APART, TOLERANCE NON-ACCUMULATIVE.
1 TURN IN 10 INCHES - R.H.: TRW-19-4A
1 TURN IN 12 INCHES - R.H.: TRW-19-4B

*For reference only

Figure 8. Rifling Mandrel Configuration.

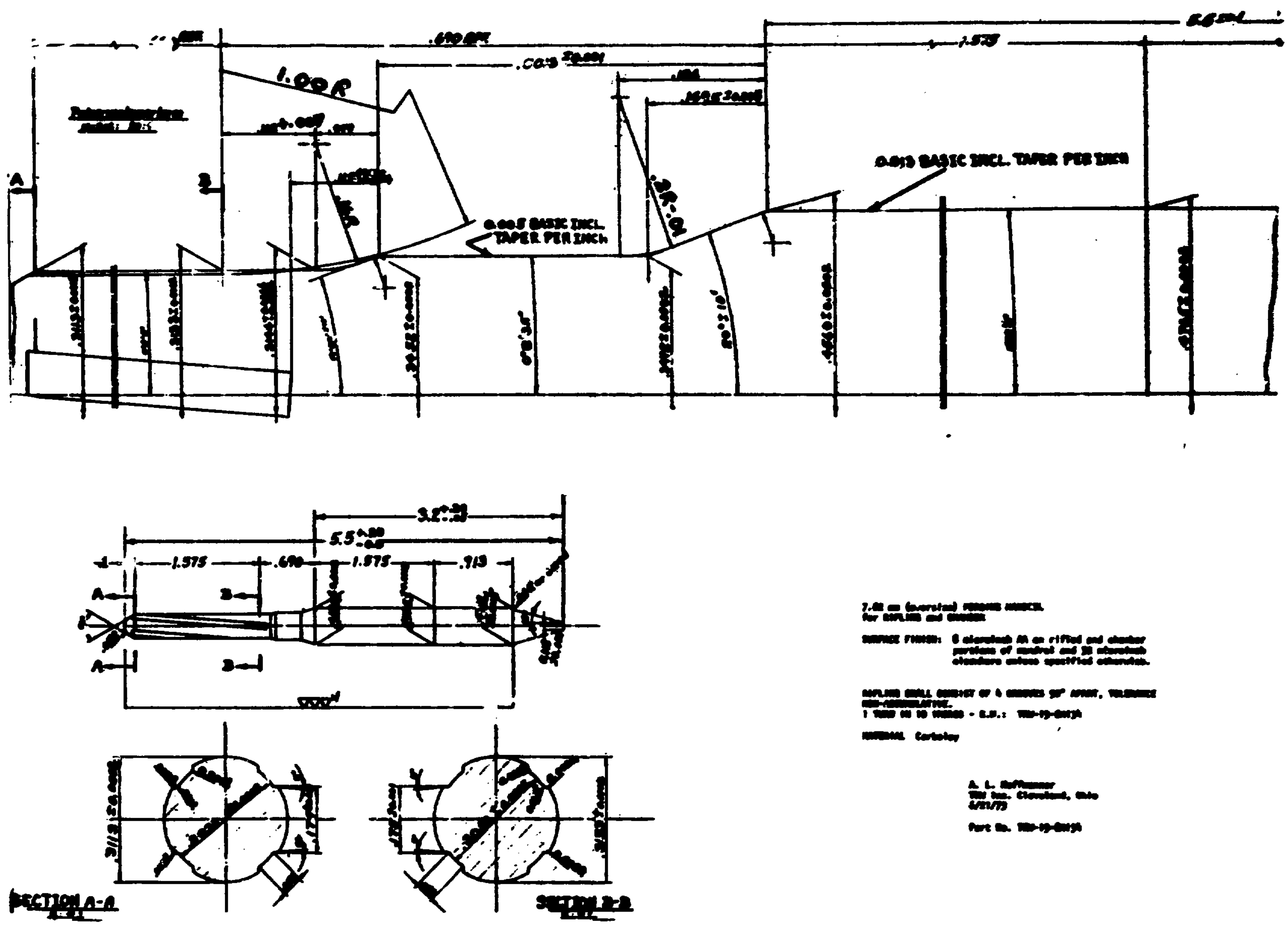


Figure 9. Rifling Plus Chambering Mandrel Configuration.

designed with a slight taper to permit adjustment of bore diameter through changes in the axial location of the mandrel between the forging dies. Corner and blend radii at the rifling lands were selected on the basis of prior GFM experience with metal flow and mandrel durability and review with Rock Island Arsenal personnel involved with barrel design indicated no objections existed to these minor departures from standard barrel print specifications.

Four templates were designed and constructed to produce the following configurations:

1. Template T-1, a two step tapered template with decreasing tapers toward the muzzle for fabrication of M-134 and approximate M-219 forgings with and without chambers, Figure 10.

2. Template T-2, a positive and negative tapered design for contour forging of M-134 barrels with and without chambering, Figure 11.

3. Template T-3, a single taper design for the M-134 barrel.

4. Template T-4, a single taper template for the M-219 barrel.

The templates determine the local die separation during the feed portion of the forging cycle. It is necessary that the template design be computed from the constraints imposed by the forging envelop configuration, the preform shape, and the die design. The preceding parameters are significant in determining the final barrel segmented lengths and the forging contours. The width of the template at a given location is defined by the relation.

Width - Forging Diameter - Basic Hammer Dimension + 1.574 inch.

Other factors for consideration in template and preform design are the radius on the template follower stylus (.5 inch, 1.27 cm) which limits the minimum template radius and the machine's capability to follow the template at feed rates of 100 $min\text{-}min^{-1}$. This latter constraint limits the maximum angular change to approximately 13°.

3.1.6. Preform Design

Two analytical procedures have been developed for use in this program to design preforms for subsequent forging operations. The first procedure involves use of a digital computer and is useful in producing precise, close tolerance forgings containing bi-directional tapers and many short geometric elements. However, the template follower systems,

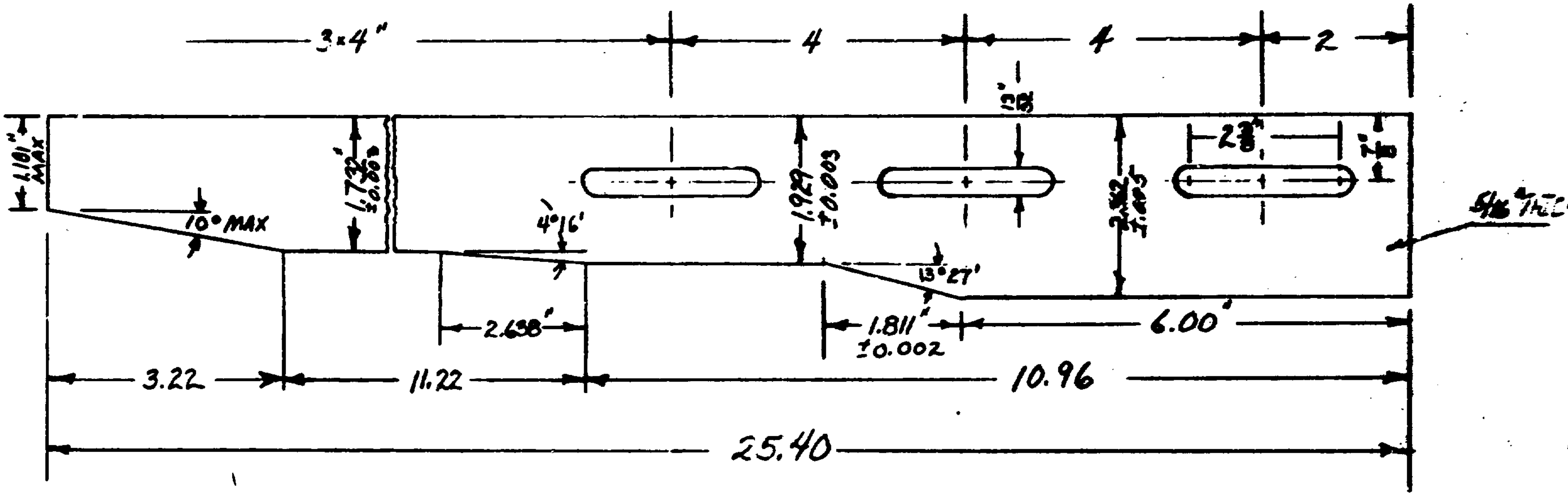


Figure 10. Template T-1 Design for M-134 and Approximate M-219 Barrel Forgings.

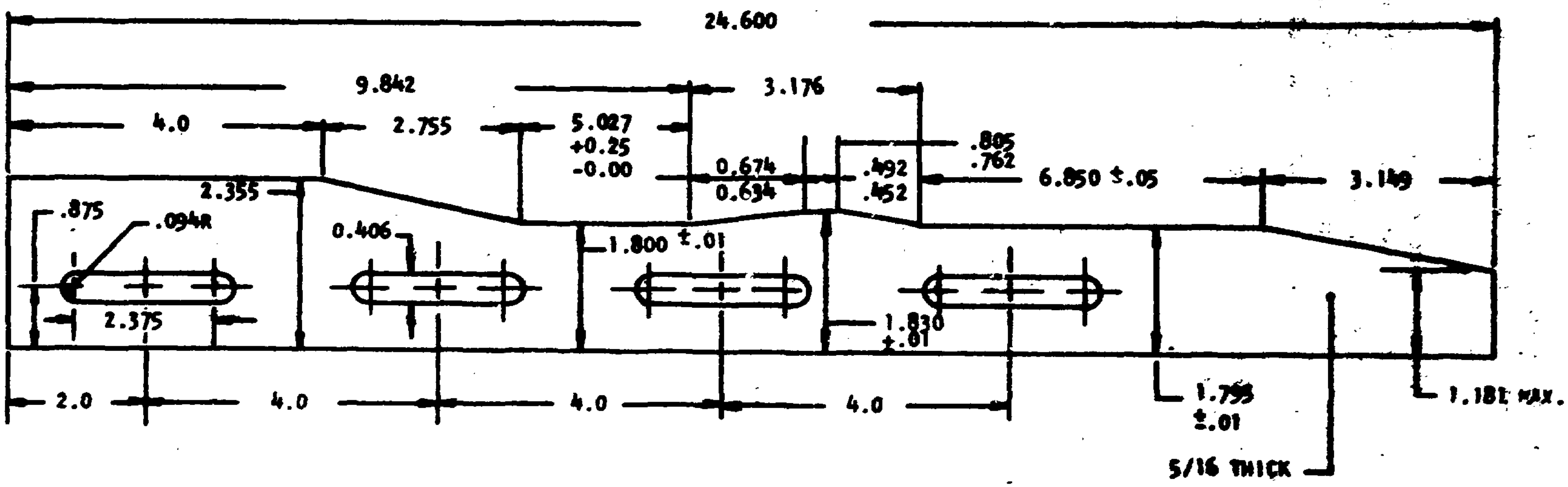


Figure 11. Template T-2 for Contour Forging of M-134 Barrels.

template machining tolerances, and its actual positioning on the forging machine are such as not to warrant use of this precise and complex procedures.

The second, or approximate, procedure which has been developed ignores the difference in volume of material beneath the dies at initiation and termination of successive geometric elements along the blank as the forging process proceeds. This assumption seldom will result in errors in excess of .04 inches (1 mm) in a total barrel length of 21-24 inches (53-61 cm) or an error of less than 2%. Errors of this nature can be readily corrected by either template modification or repositioning on the machine. Since the contemplated changes in barrel cross-sectional areas and tapers are not large, this approximation was not considered a serious source of error.

The approximate procedure will now be outlined for design of an M-219 preform containing rifling but without a chamber. The first step requires that an envelope forging be amperically selected which approximates the minimum stock allowances over the finished GFM machine and yielding good rifling. The constraint improved by the rifling quality will in general not permit contour changes greater than the entrance die angle of 13° to avoid contact between the dies and the work except at the minimum opening diameter or working faces. Further, the reductions must also remain between a maximum to avert material failure and a minimum deformation to impart full rifling. These conditions required application of experience gained in earlier experimental programs [2] to establish the appropriate boundary conditions. A conservative M-219 barrel blank is illustrated in Figure 12 with the breech end gripping stub and muzzle-end discard removed.

The reduction used to achieve any geometric element must remain within the boundary conditions established for adequate rifling development. This range has been established by a series of preliminary forging tests for H-11 steel (R_c 36-38) to be within 22.4 to 29.2% areal reduction. A discussion of the forging activity relating to these data will be reviewed at the conclusion of the preform design procedure outline.

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(2) A. L. Hoffmanner, J. D. DiBenedetto, K. R. Iyer, "Improved Materials and Manufacturing Methods for Gun Barrels (Part II)", Weapons Laboratory, USAWECOM, Report No. SWERR-TR-72-55, Sept. 1972.

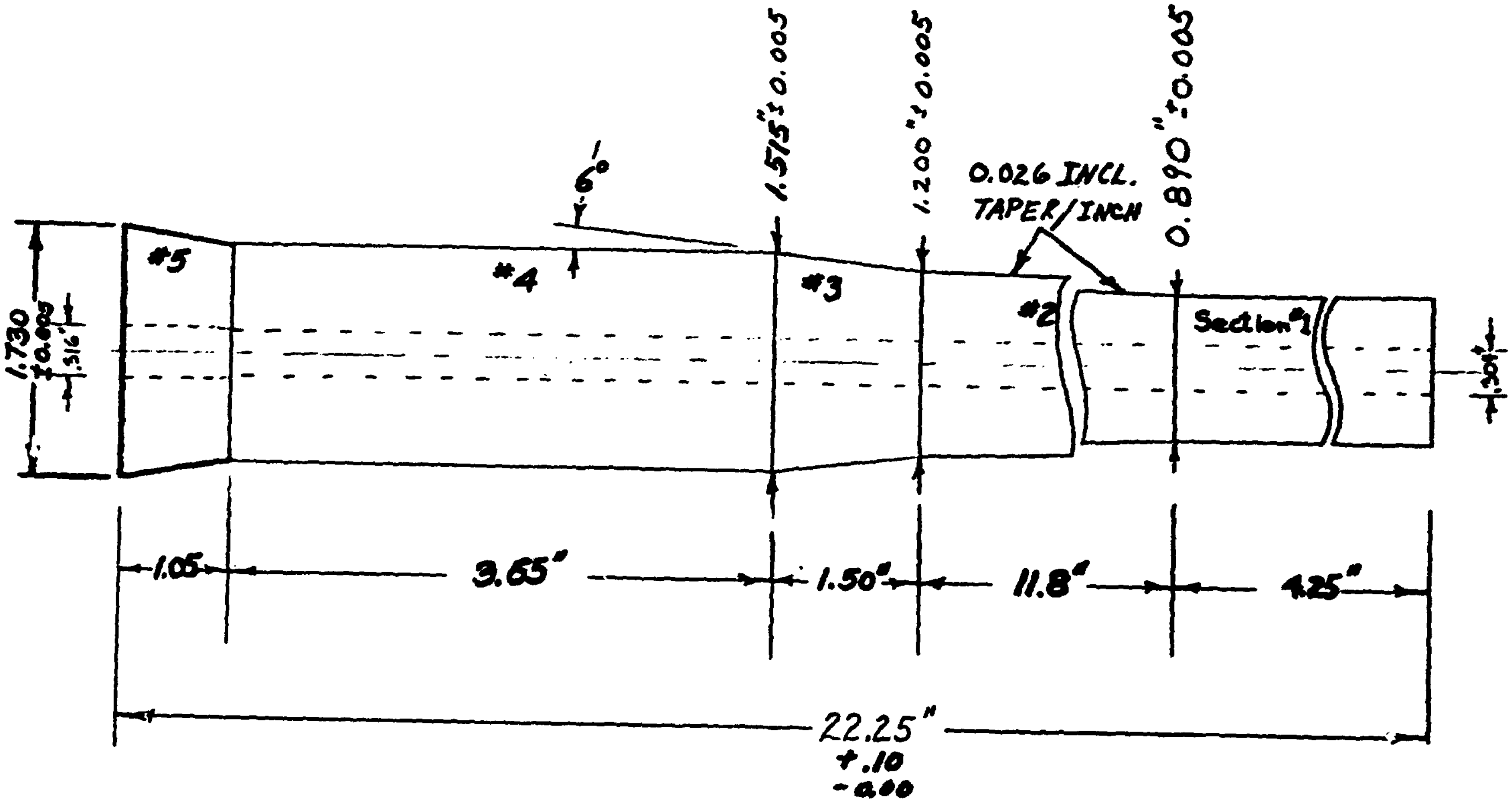


Figure 12. Forged Preform for M-219 Barrel Containing Rifling.

The actual preform design is computed in stepwise fashion from the first to last geometric element. The following symbols are used to describe the j^{th} element of the preform:

	Preform	Forging
Length	L_{oj}	L_{1j}
Initial Diameter of Element	D_{oj}	D_{1j}
Final Diameter of Element	D_{oj+1}	D_{1j+1}
Average I.D.	d_{oj}	d_{1j}
Basic Included Taper	T_{oj}	T_{1j}
Area	A_{oj}	A_{1j}
Fractional Reduction	R_j	R_j

The following calculations will be performed to develop a preform design for the barrel forging illustrated in Figure 6:

1. Segment 1

a) Barrel Blank Dimensions

$R_1 = 25\%.$

$L_{11} = 4.25$ inches.

$D_{11} = D_{12} = .890$ inch.

$d_{11} = \frac{.304 + .312}{2} = .308$ inch.

b) Preform Dimensions

$d_{01} = .315$ inch.

Straight Segment in General Form

$A_{1j} L_{1j} = A_{oj} L_{oj}$

$\frac{A_{1j}}{A_{oj}} L_{1j} = L_{oj} = (1 - R_j) \, L_{1j}$

$L_{oj} = (1 - R_j) \, L_{1j}$ or $L_{oj} = (.75) \, (4.25)$

c) <u>**Preform Diameter**</u>

$$R_j = 1 - \frac{(D_{ij}^2 - d_{ij}^2)}{(D_{oj}^2 - d_{oj}^2)}$$

$$D_{oj} = \left[\frac{D_{ij}^2 - d_{ij}^2}{(1-R_j)} + d_{oj}^2\right]^{1/2}$$

$L_{01} = 3.19$ inch

$D_{01} = D_{02} = 1.014$ inch

2. <u>**Segment No. 2**</u>

a) <u>**Barrel Blank Dimensions**</u>

$R_1 = R_2 = 25\%$.

$L_{11} = 11.8$ inch.

$D_{12} = 0.890$ inch.

D [illegible] 1.200 inch.

Included Taper $T_{12} = .0263$ in-in^{-1}.

b) <u>**Preform Dimensions**</u>

$d_{02} = .315$ inch

i) Tapered Segment, General Form for Constant Reduction.

T[illegible], $T_{ij} = \frac{D_{ij} + 1 - D_{ij}}{L_{ij}}$

ii) For Constant Reduction

$$\frac{D_{ij}^2 - [illegible]}{D_{oj}^2 - d_{oj}^2} = 1 - R = \frac{D^2_{ij+1} - d^2_{ij+1}}{D^2_{oj+1} - d^2_{oj+1}}$$

and

$$L_{oj} = (1 - R)L_{ij}$$

iii) Substituting in Taper Equation

$$T_{ij} = \frac{[(1-R_j)\, D^2_{oj+1} - R_j d_{oj+1}{}^2]^{1/2} - [(1-R_j) D_{oj}{}^2 - R_j d_{oj}{}^2]^{1/2}}{L_{oj}/(1-R_j)}$$

Rearranging

$$T_{ij} = \frac{(1-R_j)^{3/2}(D_{oj+1} - D_{oj})}{L_{oj}}$$

iv) The Preform Taper Becomes

$$T_{oj} = \frac{D_{oj+1} - D_{oj}}{L_{oj}} = \frac{T_{ij}}{(1-R_j)^{3/2}}$$

3. <u>Segment 3</u>

d_{02} = .315 inch

L_{02} = $(1-R_3)L_{12}$ = 8.85 inch

T_{02} = .04049 in-in^{-1}

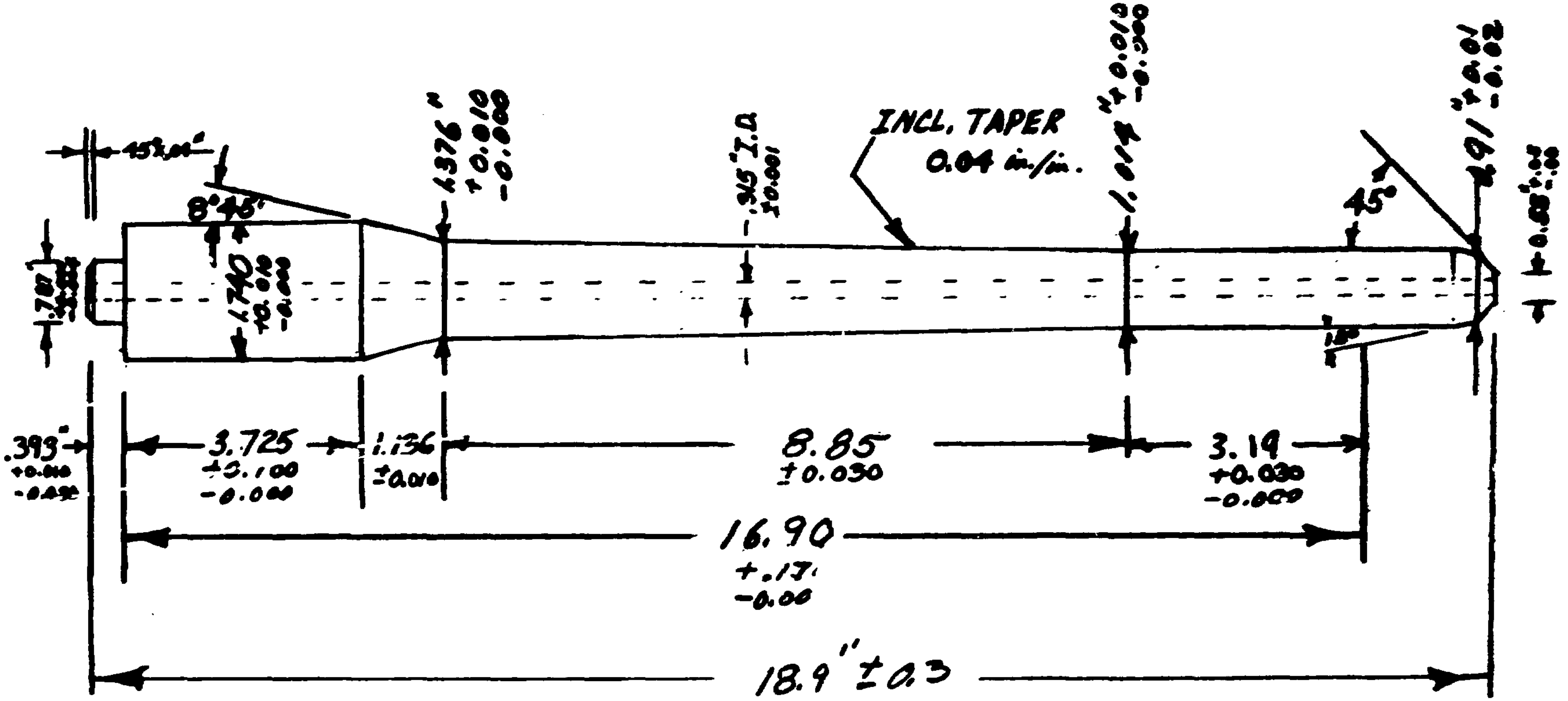
D_{02} = 1.014 inch

D_{03} = $D_{02} + (T_{02})(L_{02})$ = 1.373 inch.

also

$$D_{03} = \left[\frac{D_{13}{}^2 - d_{13}{}^2}{.75} + d_{03}{}^2\right]^{1/2} = 1.376 \text{ inch.}$$

The equations developed in general form in the preceding discussion can be used to generate the preform shape, shown in Figure 13 in its entirety. Since the template contour is directly related to the preform, the length dimensions on both the template and preform are identical but their forms are inversely related. The template design procedures, using the forging diameters D_{ij} to establish the template width and the preform segmental lengths L_{oj} for length definitions, is illustrated below and this process is sequentially repeated for each geometric element in the preform.



O.D. must be concentric with I.D. to within 0.005" T.I.R.
Surface Finish: 200 microinch (Max.) on O.D.

Figure 13. Preform Design for M-219.

Template Dimensions

1) **General Relations**

a) The Template Width at Diameter $D_{oj} = W_j$

and

$$W_j = D_{ij} - \text{Basic Dimension, } B + 1.574 \text{ inch}$$
$$= D_{ij} - B + 1.574.$$

b) Template Length Over the j^{th} Section

$$L_j = L_{oj}$$

2) **Template Segment Dimensions** ($B = .70$ inch) *

a) **Section 1**

$W_1 = D_{11} - B + 1.574 = 1.764$ inch

$L_1 = 3.19$ inch

b) **Section 2**

$W_2 = W_1$

$W_3 = 1.200 + .874 = 2.074$ inch

$L_2 = 8.85$ inch

A taper of 10° or less is designed into the template nose so the dies will gradually come down to the initial forging diameter, D_{11}, without impacting the leading edge of the die on the workpiece. An initial length of approximately 1 inch (2.5 cm) must be discarded from the muzzle end of the forging as the rifling is not fully developed at the immediate leading end of the forged barrel and 1.5 inches (3.8 cm) at the breech end in the case of chambering to permit hammer clearance over the counterholder support. Provision of these allowances must be made in both the preform and template designs. A final taper is also provided on the template to raise the hammer off the workpiece at the conclusion of the processing for part retraction.

* The minimum diameter that can be forged and is controlled by the die design.

3.1.7 Forging Development

The forging development activity was conducted concurrently with preform design and design modification studies. The basic preform design employed for the forging evaluations is presented in Figure 14 with variations in the O.D. and I.D. dimensions as required for rifling only or rifling plus chambering evaluations. Table XIII summarizes these variations and identifies the material conditions and the corresponding specimen codes.

The forging trials were conducted at the Rock Island Arsenal and the results obtained from the first round of trials are summarized in Table XIV. The mandrels described in the preceding section were employed to impart the I.D. configuration while templates T-1 and T-2 were utilized for O.D. contour control. All hot forging experiments were conducted without a mandrel because the primary objective was to measure forging loads and it was considered an unnecessary risk to also expose a carbide mandrel to the high temperature environment. A feed rate of 100 $mm\text{-}min^{-1}$ and a workpiece rotation rate of 48 rpm were used for all tests. The listed counterholder and chuckhead plunger pressures are basic setup parameters and have also been included for full documentation (1 atm ∿ 114 lbs of force). The counterholder pressure determines the magnitude of the axial compressive loading on the barrel as it is being forged and thus controls the relative rates of I.D. and O.D. reduction. Increasing the counterholder pressure accelerates the bore diameter reduction rate. The two plungers are hydraulically actuated and can develop a maximum pressure difference of 110 atmospheres or approximately 5 tons. During rifling this pressure is adjusted to the maximum and the barrel blank fed between the dies at the desired rate of chuck head travel, approximately 100 $mm\text{-}min^{-1}$. This provides a processing cycle of about 4-5 minutes for a 17-inch (43 cm) preform. During chambering the normal forward flow of metal must be reversed to properly form the chamber near the end of the forging cycle. This flow reversal is achieved by a machine cam setting which drops the plunger pressure and reduces the feed load which in turn causes the desired metal flow reversal over the chambering portion of the mandrel. When this flow reversal occurs, the mandrel is engaged by the chuck head and moves forward with it at a controlled rate while the plunger slowly retracts. The exact positions of the dies, mandrel, and workpiece are critical in producing a good chamber as is the control of the plunger pressure level and timing of the pressure changes.

The remaining columns in Table XIV list the reduction, the preform and forged blank diameters, and remarks concerning bore quality. The latter determinations were made with direct borescope examinations and air gaging measurements. Straightness of the as-forged

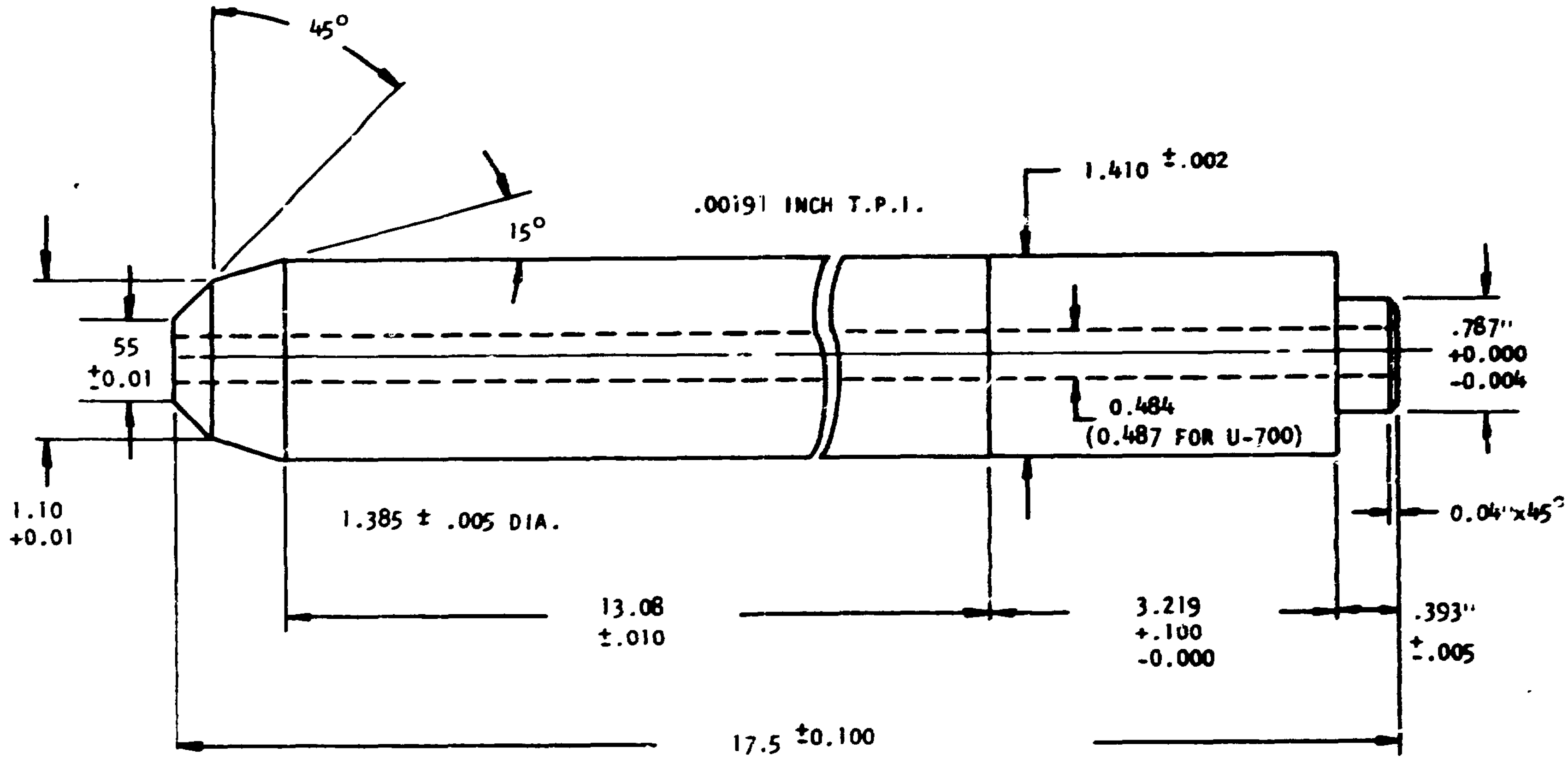


Figure 14. Preform Design (See Table XIII for Diameter and Length Dimensions.)

TABLE XIII

Preform Design: Dimensions and Material Conditions

Material	Condition	O.D. (Inch)	I.D. (Inch)	Overall Length (Inch)	Code
H-11	As Hot Worked	1.315	0.315	17.5	ASA1 thru ASA10
H-11	Tempered R_c 36/38	1.375	0.315	17.5	HST1 thru HST12
H-11	Tempered R_c 36/38	1.375	0.500	17.5	HST13 thru HST23
H-11	Tempered R_c 36/38	1.574	0.500	14.5	HLT1 thru HLT8
H-11	Tempered R_c 36/38	1.850	0.500	14.5	HLT9 thru HLT13
U-700	Sol. Treated & Aged 4 Hrs. 1975°F	1.230	0.315	17.5	UA1 thru UA5
U-700	Sol. Treated & Aged 4 Hrs. 1975°F	1.230	0.3185 (Reamed)	17.5	UA6 and UA7
U-700	Sol. Treated & Aged 4 Hrs. 1975°F	1.375	0.500	17.5	UA8
U-700	Sol. Treated & Aged 4 Hrs. 1975°F	1.375	0.315	17.5	UA8 thru UA11
U-700	Sol. Treated & Fully Aged	1.375	0.315	17.5	UT1 thru UT14

TABLE XIV

Forging Results From Process Evaluation

Speci-men No.	Forging Conditions	Pressure (Atms) Counter-Holder	Plunger	Reduction %	Initial/Final Dia. (In/In)	Remark
ASA1	Rifling	45	110	22.4	1.376/1.219	Good.
ASA2	Rifling	45	110	19.0	1.376/1.244	Slight Underfill.
ASA3	Rifling	45	110	34.0	1.376/1.130	Cver Reduced.
ASA4	Countour T-1*	25	110	28.3/714/33.7	1.376/1.174, 1.324,1.132	Good/Under/Overfill.
ASA5	Contour T-1*	25	110	28.3/7.4/33.7	" "	Good/Under/Overfill.
ASA6	Contour T-1*	25	110	28.3/7.4/33.7	" "	Good/Under/Overfill.
ASA7	Contour T-1* (continuous)	35	110	36.7/17.6/42.4	1.376/1.108, 1.253,1.061	Over/Under/Overfill.
ASA8	Contour Taper	45	110	22.6	1.376/1.195	Underfill/Overfill.
ASA9	Hot Forge 1500°F/1560°F	35 45	110 110	32.0/17.5/37.3 22.6	1.376/1.146, 1.376/1.195	Forged w/o Mandrel.
ASA10	Contour T-1	35	110	32.0/17.5/37.3	1.376/1.146, 1.254,1.103	Over/Under/Overfill.
HST1	Rifling	45	110	20.4	1.376/1.233	Slight Underfill.
HST2	Rifling	45	110	24.4	1.376/1.204	Good.
HST3	Rifling	45	110	32.5	1.376/1.142	Over Reduced.
HST4	Rifling	30	110	35.0	1.376/1.122	Over Reduced, Cam Settings Same As HST3.
HST5	Rifling	45	110	30.9	1.376/1.154	Sight.Over Reduction.
HST6	Rifling	45	110	27.1	1.376/1.184	Good.
HST7	Rifling	25	110	22.4	1.376/1.219	Slight Underfill.
HST8	Rifling	25	110	24.4	1.376/1.204	Good, Same Cam Set-ing as HST2.
HST9	Rifling	25	110	29.2	1.376/1.168	Sight.Over Reduction.
HST10	Rifling	25	110	23.7	1.376/1.209	Good.
HST11	Contour T-1**	35	110	35.1/21.5/40.7	1.376/1.121, 1.225,1.075	Over/Good/Overfill.
HST12	Hot Forge 1400°/1500°F	45	110	33.1	1.376/1.114	Forged w/o Mandrel***
HST13	Chamber	45	110/32	22.8/36.7	1.376/1.232 1.064	C-Good,R-sl.Overfill.
HST14	Chamber	45	110/34	22.8/33.9	1.376/1.232, 1.086	C & R - Good.

* Changed template by machining 0.048 inch off mid-lug height.
** Same setting as UT12 and UT13
***C = chamber form and R = rifling form

TABLE XIV (CONTINUED

Speci-men No.	Forging Conditions	Pressure (Atms) Counter-Holder	Plunger	Reduction %	Initial/Final Dia. (In/In)	Remarks
HST16	Chamber	45	110/28	22.8/28.7	1.376/1.232, 1.125	C-good R-incomplete fill
HST17	Chamber	45	110/32	22.8/31.5	1.376/1.232, 1.104	C-good R-just filled
HST18	Chamber	45	110/32	22.8/33.0	1.376/1.232, 1.093	C-good R-good
HST19	Chamber	45	110/32	22.8/33.9	1.376/1.232, 1.086	C-good, R-good
HST20	Chamber	45	110/32	22.8/33.9	1.376/1.232, 1.086	Repeat of HST19 C-good
HST21	Chamber	45	110/32	22.8/35.0	1.376/1.232, 1.078	R-good, C-good
HST22	Chamber	45	110/32	22.8/35.1	1.376/1.232, 1.077	R-good
HST23	Chamber	45	110/32	22.8/37.2	1.376/1.232, 1.061	C-overfill R-near max. fill
UA1	Rifling	45	110	22.2	1.235/1.097	Good*
UA2	Rifling	45/25	110	19.1/19.2	1.235/(1.117/1.116)	Very slight underfill*
UA3	Rifling	25	110	33.5	1.235/1.021	Overfill*+
UA4	Rifling (partially honed)	25	110	21.5	1.235/1.102	*Improved surface
UA5	Rifling (partially honed)	25	110	30.0	1.235/1.045	*Improved surface Good form
UA6	Rifling (reamed)	25	110	21.4	1.235/1.102	*Improved surface Good form
UA7	Rifling (reamed)	25	110	30.0	1.235/1.045	*+Improved surface Good form
UA8	Chamber (reamed)	45	110/32	22.8/35.9	1.376/1.232, 1.071	Chamber-overfilled Rifling-near max.
UA9	Hot forge 1150°/1200°F	45	110	34.4	1.376/1.103	Forged w/o mandrel
UA10	Hot forge 800°/1150°F	45	110	27.7	1.376/1.156	Forged w/o mandrel
UA11	Contour T-1 same as ASA10	35	110	30.4/16.1/35.6	1.376/1.158, 1.264/1.115	Over/under/overfill

* Continuous surface texture
\+ Very fine cracks
** Reset machine for .016 in. smaller diameter from settings for UA11.

TABLE XIV (CONTINUED)

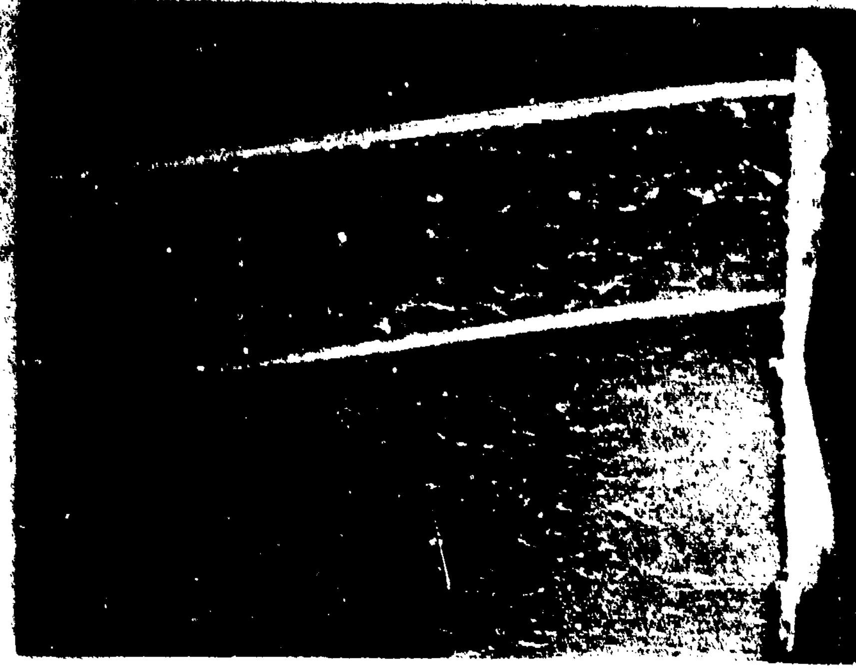
Speci-men No.	Forging Conditions	Pressure (Atms) Counter-Holder	Plunger	Reduction %	Initial/Final Dia. (in/in)	Remarks
UT1	Rifling	25	110	19.1	1.376/1.243	Almost no rifling
UT2	Rifling	25	110	29.8	1.376/1.163	Sl. overfill*+
UT3	Rifling	25	110	34.1	1.376/1.129	Overfilled*+
UT4	Rifling	25	110	22.5	1.376/1.218	Good form*
UT5	Rifling	25	110	29.3	1.376/1.167	*Good form Near max. red.
UT6	Hot forge 740°/750°F	45	110	25.8	1.376/1.171	Forged w/o mandrel
UT7	Hot forge 740°/770°F	45	110	36.0	1.376/1.090	Forged w/o mandrel
UT8						Not forged
UT9						Not forged
UT10						Not forged
UT11						Not forged
UT12	Contour T-1**	35	110	32.0/17.6/ 37.6	1.376/1.146, 1.253, 1.101	Slightly over/ slightly under/ overfill
UT13	Contour T-1**	35	110	33.3/19.9/ 38.7	1.376/1.135, 1.237, 1.092	Slightly over/ good/overfill
UT14						Not forged
HLT1	Chamber	31	110/32	22.8/31.7	1.574/1.270	Chamber-good Rifling-oversize
HLT2	Hot forge, 850°/900°F	45	110	51.9	1.574/1.054	Forged w/o mandrel
HLT3	Hot forge 830°/880°F	45	110	42.1	1.574/1.153	Forged w/o mandrel

* Continuous surface texture
\+ Very fine cracks
** Reset machine for .016 in. smaller diameter from settings for UA11.

barrel O.D.'s were within .007 inch (.0178 cm) T.I.R. error maximum and the precision of the bore I.D. was ±.0001 inch (.00075 cm). A major objective of this comprehensive evaluation sequence was to establish the minimum reduction required to produce fully developed rifling and the maximum reduction limits before shear or overfill conditions were encountered. These data were obtained for both rifling only and for combined rifling and chambering. These limits were also intended to establish the maximum variation in reduction that can be sustained during O.D. contouring and the accuracy necessary in the preform and template fabrication. The results of these determinations are summarized as follows

Material	Initial Preform O.D., in (cm)	Reduction Minimum	Reduction Maximum
H-11			
Rifling Only	1.376 (3.50)	23.0%	29.2%
Rifling Plus Chamber	1.376 (3.50)	31.5	37.2
U-700			
Rifling Only	1.235 (3.14)	21.4	30.0
Rifling Plus Chamber	1.376 (3.50)	22.4	29.3

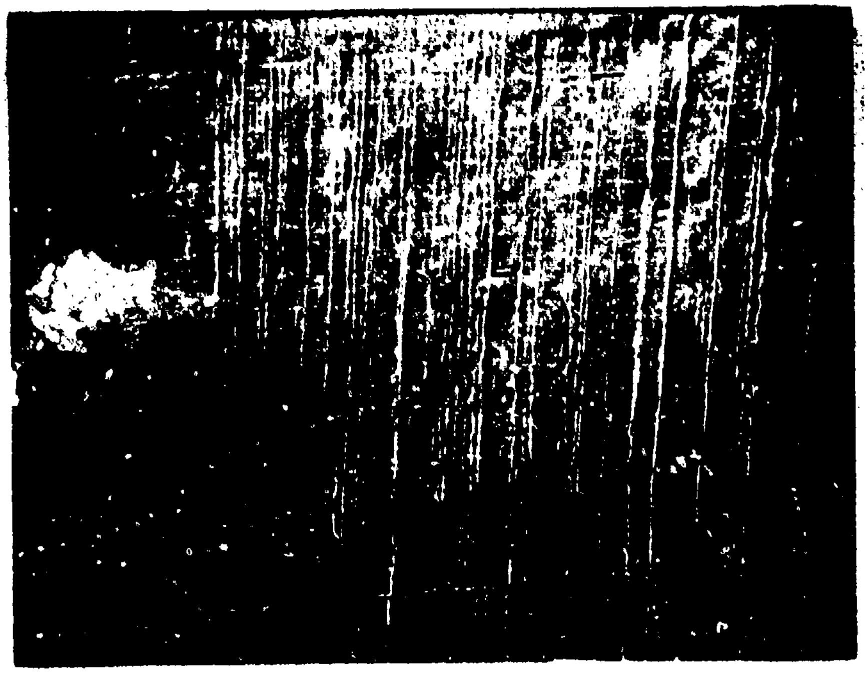
Although the bore was dimensionally excellent and the gross I.D. surface finish was less than 6 µinches AA(.15 µmAA), a serious material problem was encountered with the U-700 alloy. A network of fine surface cracking was observed along grain boundaries and second phase particles throughout the bore. These features were subjected to an exhaustive examination employing light microscopy of metallographic sections and the scanning electron microscope (SEM) was used to directly examine the bore surface. Sections were removed from U-700 barrels UA-8 and UT-13 for study. The former blank was in the partially aged condition while the latter represented the fully aged material at maximum hardness. The surface cracking appeared to be quite extensive in the partially aged material (UA-8) but the individual cracks were deeper in the fully aged alloy (UT-13). A series of SEM photomicrographs were prepared to illustrate the appearance of the cracks in the as-forged condition (Figures 15 and 16) and after electropolishing .003 inches (.008 cm) from the bore surface (Figure 17). The cause of the surface texture and cracking is probably associated with the very intense deformation at the bore surface extending to depths usually less than .001 inch (.0025 cm) which appears to be characteristic of swaged and



UA-8 20X

UA-8 500X

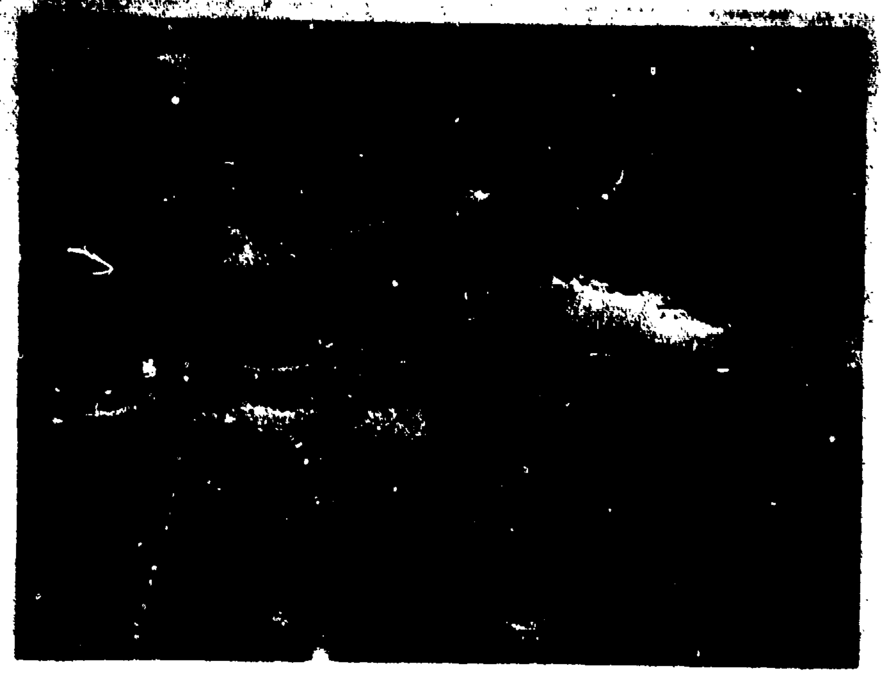
Figure 15. SEM Photomicrographs Illustrating Cracking on Bore I.D. Experienced for Partially Aged U-700 Material.



UT-13 50X

UT-13 1000X

Figure 16. SEM Photomicrographs Illustrating Cracking on Bore I.D. Experienced for Fully Aged U-700 Material.



a) UA-8 500X

b) UA-13 500X

Figure 17. SEM Photomicrographs Prepared After Electropolishing .003 inches (.008 cm), Illustrating Relative Crack Depths Remaining in a) Partially Aged, and b) Fully Aged U-700.

forged nickel-base superalloy barrels[2,3]. This problem remains as a serious impediment to the utilization of this alloy as a barrel material. This development is in addition to the low rates observed for gun drilling and O.D. finishing operations.

Attempts to forge the M-219 barrels directly from a cylindrical preform were unsuccessful. Severe impacting along the leading edges of the forging dies was encountered as the workpiece engaged the tooling. Figure 18 illustrates the appearance of an H-11 bar, the as-machined preform, the forged blank, and the profiled template used in the forging procedure. Although the SHK10 machine has a rated capacity in excess of 2 inches (5 cm), this limit was probably established for the conventional Cr-Mo-V low alloy steels and the higher strength levels of the H-11 steel represented a more difficult situation. It was planned to conduct further forging evaluations on the M-219 barrels to explore alternative methods for producing this configuration. These alternatives included the following:

1. hardness reduction to R_c 34 to 36,
2. warm working,
3. use of a tapered preform, and
4. die redesign.

A second series of forging trials was conducted to identify solutions for the M-219 problem as well as to develop the technology for the IN 903 material. Further information relative to minimization of material utilization for the M-134 barrel by means of full contour forging was also required.

The cylindrical preform for the M-219 forging was redesigned to avert the severe impacting experienced during the initial forging trials. The modified preform and template designs are illustrated in Figures 19 and 20 respectively. This design allows for a gradual taper leading up to the chamber area.

One of the major problems associated with contour forging M-134 barrels was that variations in the reduction schedule aimed at development of good rifling had the effect of moving the center lug

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(2) A. L. Hoffmanner, J. D. DiBenedetto, and K. R. Iyer, "Improved Materials and Manufacturing Methods for Gun Barrels (Part II)", Weapons Laboratory, SWERR-TR-72-55, September 1972.

(3) D. C. Drennen, C. M. Jackson, R. B. Miclot, and K. R. Iyer, "Rotary Swaged Rapid Fire Barrels", SWERR-TR-72-56, August 1972.

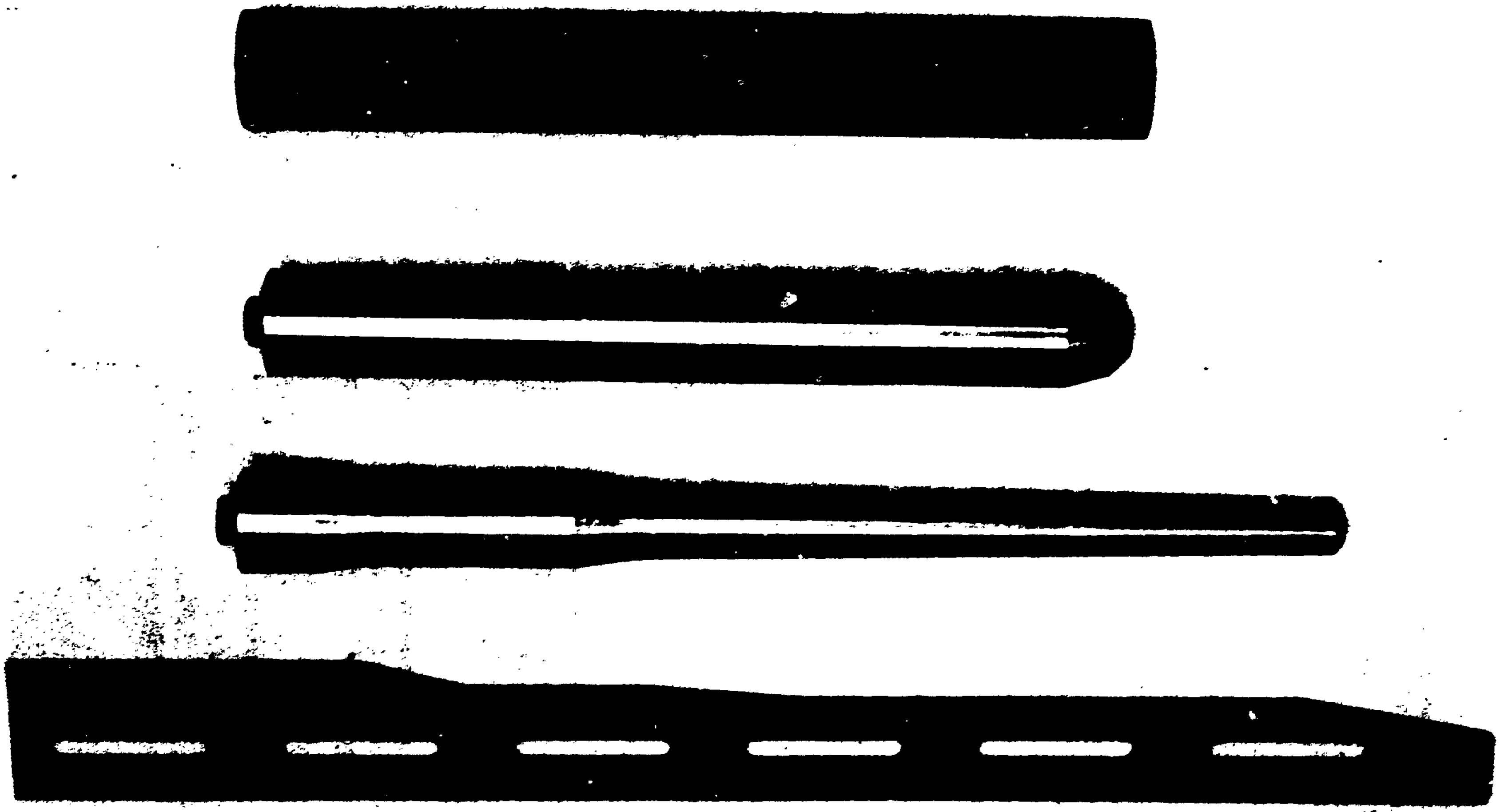
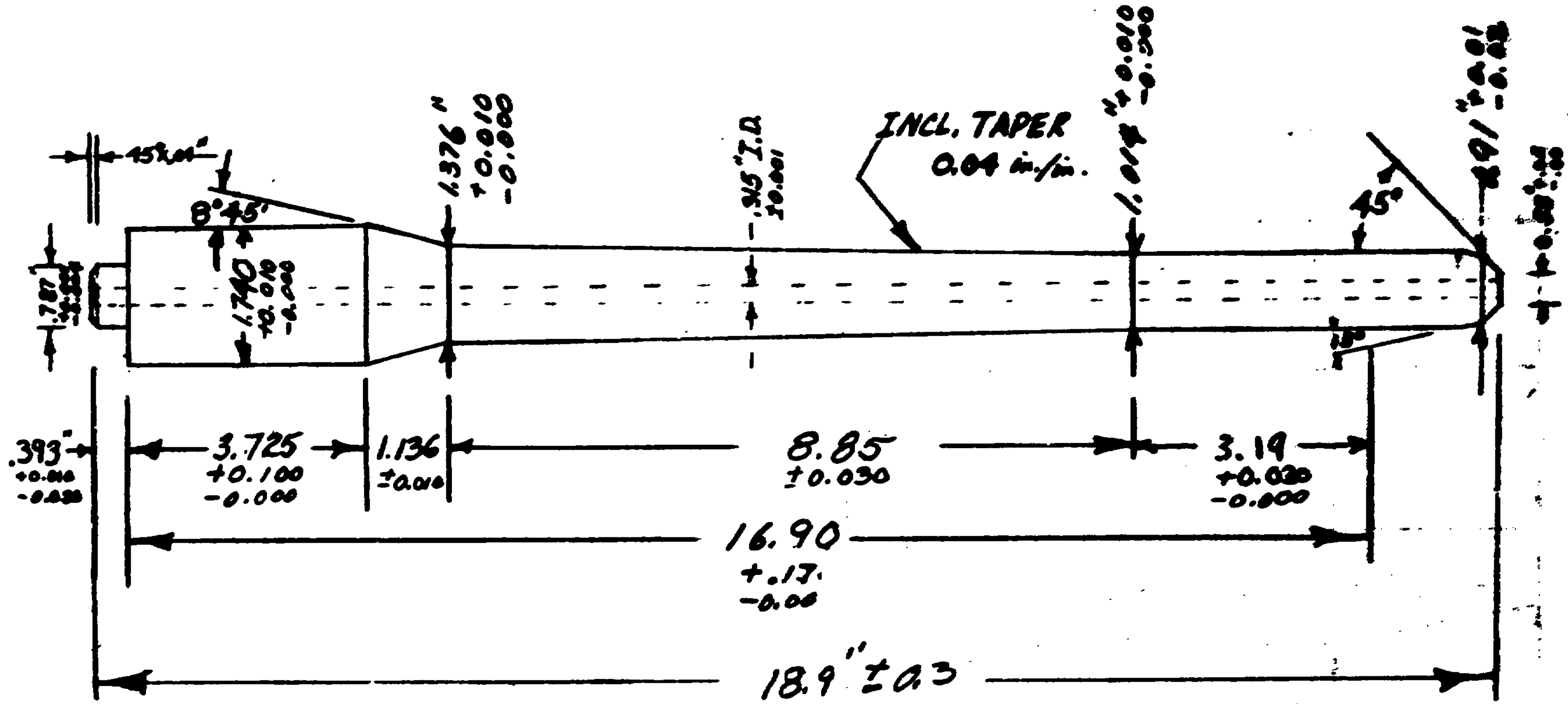


Figure 18. Illustration of the Blank, Preform, Forging, and Template Used For the First Processing Evaluation for the M-219 Barrel.



O.D. must be concentric with I.D. to within 0.005" T.I.R.
Surface Finish: 200 microinch (Max.) on O.D.

Figure 19. Preform Design for M-219.

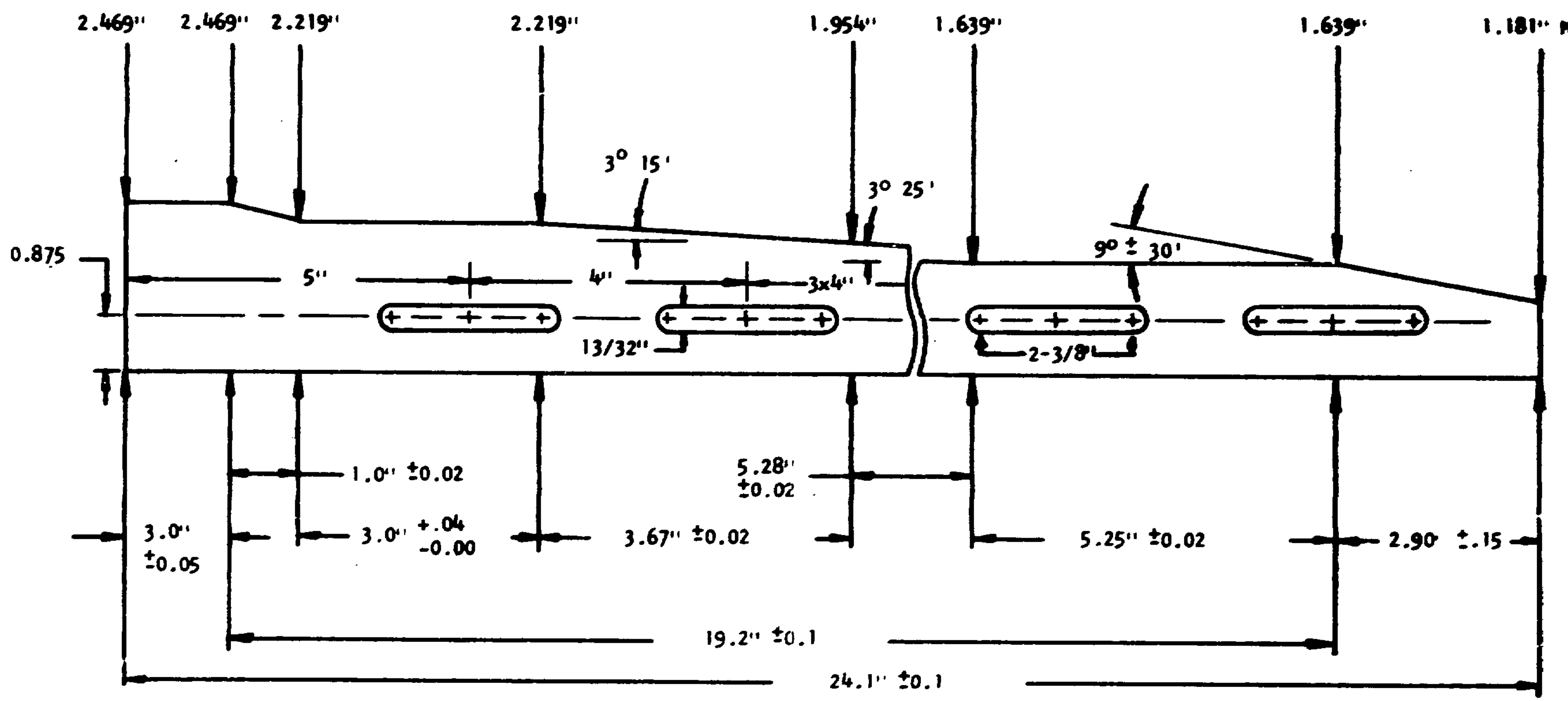


Figure 20. Template Design for Forging the M-219 Barrel.

projection in an axial direction along the barrel forging. Rather than provide a multiplicity of templates or design an adjustable template, the simple expedient of transferring machine control from the template to the cam panel after development of the center lug was employed. Adjustments in correctly positioning the lug along the barrel could then be readily made. Alterations made to the preform design and forging envelope are illustrated in Figures 21 and 22.

The second series of process evaluations were conducted and the results are summarized in Table XV for IN 903 and H-11 materials used to forge M-134 blanks. Both solution treated IN 903 and fully aged forgings were prepared with either rifling only and combined rifling and chambering. The 1.380 inch O.D. (3.51 cm) M-134 preforms were gun drilled to produce a .315 inch (.800 cm) inner diameter for rifling only and a .500 inch (1.27 cm) bore for chambering and O.D. contouring experiments. A fully contoured preform at a hardness level of R_c 34 to 36 was used for the M-219 barrel to avert the severe impacting experienced during forging at the breech end.

Inspection of the forged blanks showed that both solution treated and fully aged IN 903 material could be successfully forged with either rifling only or combined rifling and chambering. Some minor rippling was noted at the chamber shoulder when the IN 903 barrels were forged with integral chambers. The exact conditions of cam position for chamber forging, mandrel position, the magnitude of the low plunger pressure, and its sequence position could not be fully established to avert this waviness due to the relatively few number of trial forgings prepared. This waviness was regarded as only a minor problem which can be overcome by a brief trial and error procedure involving no more than six additional setup pieces during future forging operations. Two more serious problems were encountered with attempts to contour forge the M-134 barrel configuration. The first involved maintaining adequate O.D. stock for the breech lug while providing good chamber quality. Solution of this problem requires that the preform O.D. be increased from 1.385 inches to 1.410 inches (3.518 to 3.581 cm) at the breech end. This problem can be reviewed by observing Figure 23 which shows a cross-section of the breech end of an M-134 blank with the lug configuration superimposed. The O.D. of the forging must provide an absolute minimum dimension of 1.194 inches (3.033 cm) about the location of the rear breech lug. Control of this situation is established by the following requirements:

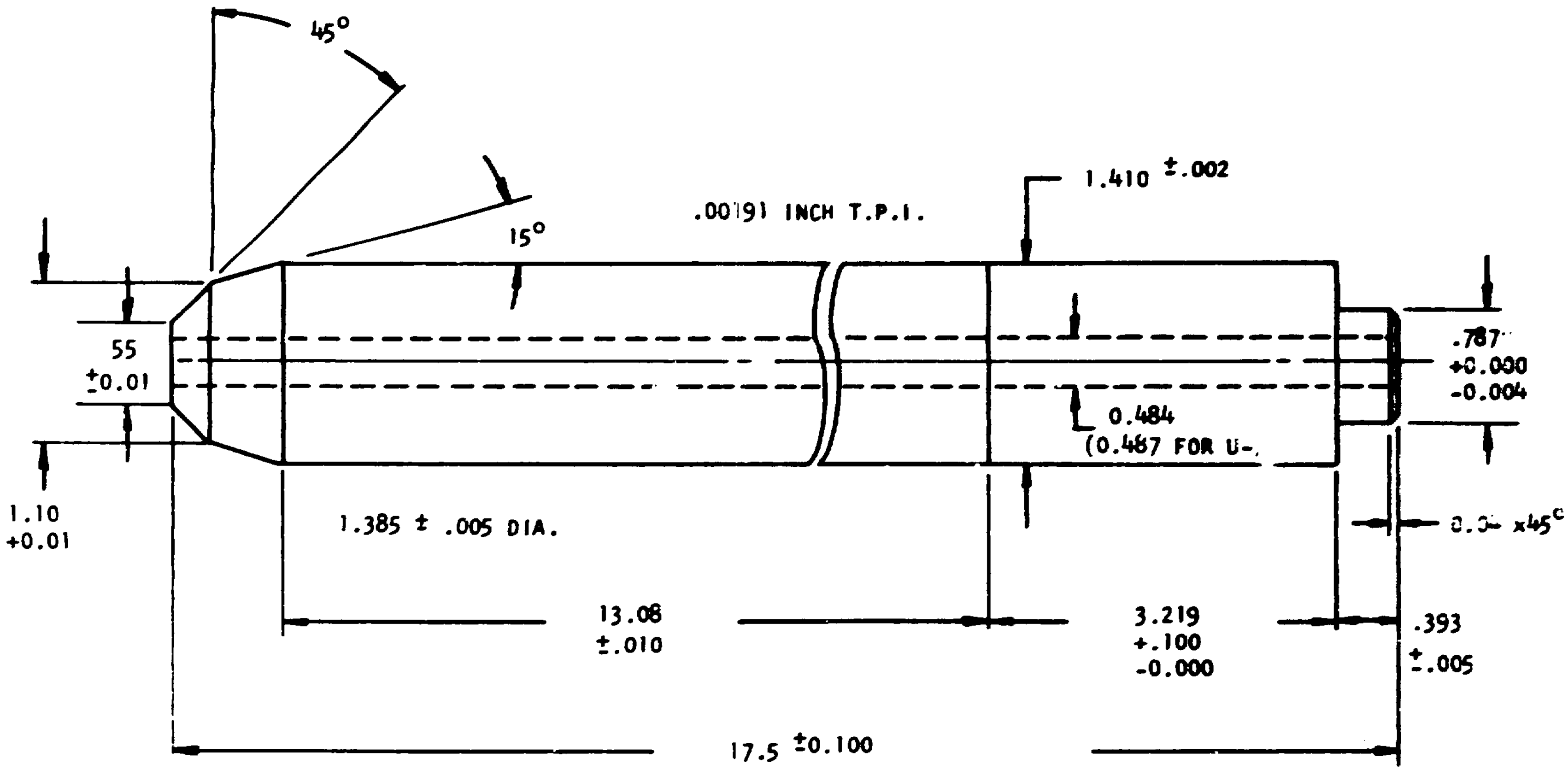


Figure 21. Preform Design for the M-134 Barrel.

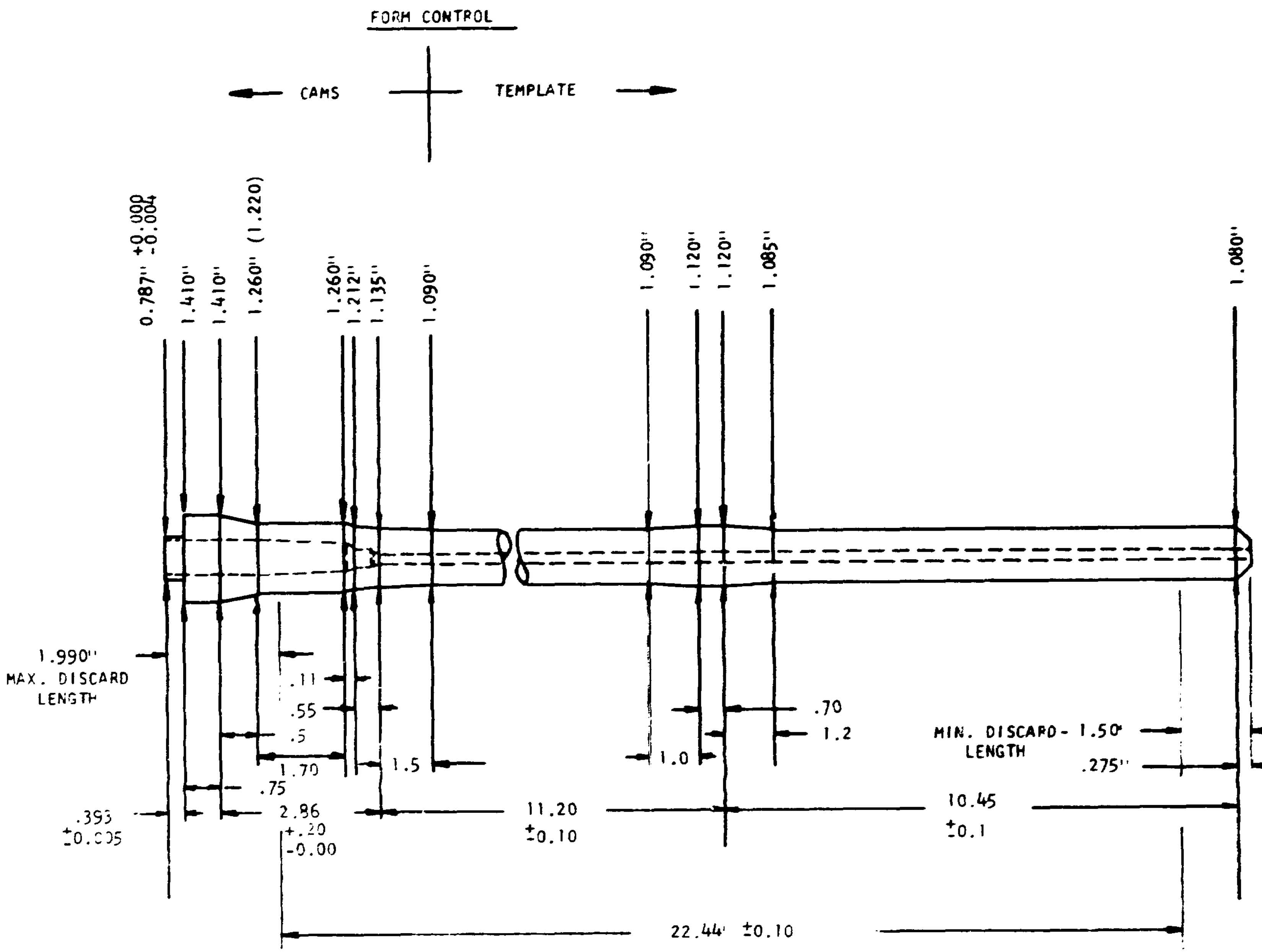


Figure 22. M-134 Forged Blank Design.

TABLE XV

Forging Results From Process Evaluation - Phase II

Specimen No.	Forging Conditions	Pressure (Atms.) Counter-holder	Pressure (Atms.) Plunger	Reduction (%)	Initial/Final Diameters (Inch)	Bore Quality	Remarks
M-134 Blanks (IN 903)							
S3	Rifling	45	105	32.2	1.380/1.147	Good	.308 Mandrel
S4	Rifling	45	105	24.5	1.380/1.208	Good	.308 Mandrel
H1	Rifling	45	105	22.6	1.380/1.220	Slight Underfill	.308 Mandrel
H2	Rifling	45	105	31.6	1.380/1.153	Slight Overfill	.312 Mandrel
T6	Chambering	45	105/32	20.6	1.395/1.113	-	Setup Piece of H-11
S1	Chambering	48	105/32	35.9/35.9/24.4*	1.380/1.083/1.214**	Rifling-Good Chamber-Rippled	
H3	Chambering	48	105/32	32.2/32.2/19.5	1.380/1.112/1.247	Rifling-Good Chamber-Ripplied	
H4	Chambering	48	105/45	34.5/34.5/22.2	1.380/1.094/1.229	Rifling-Good Chamber-Fair	
S2	Chambering	48	105/45	35.9/35.9/2414	1.380/1.083/1.214	Rifling-Good Chamber-Fair	Forging Chamber .14 Inch Sooner.
H5	Chambering-Contour	48	105/45	41.0/28.3/20.9	1.380/1.043/1.141/1.238	Good Except at Lug Front	
H6	Chambering-Contour	48	105/45	41.7/29.1/21.3	1.380/1.037/1.135/1.235	Good Except at Lug Front	
H7	Chambering-Contour	48	105/45	-	1.380 Follower Slipped Off Template at Start	No Rifling	Mandrel Not Properly Positioned.
M-134 Blanks (H-11)							
6 8-74-1	Chambering-Contour	48	105/45	34/7/24	1.385/1.123/1.334/1.308	Setup-No Mandrel	
-2	Chambering-Contour	48	105/45	34/21/25	1.385/1.128/1.233/1.200	Setup-No Mandrel	Contour Reduced.
-3	Chambering-Contour	48	105/45	38/26/24	1.385/1.090/1.191/1.205	Setup-No Mandrel	
-4	Chambering Contour	48	105/45	39/26/24	1.385/1.060/1.190/1.205	Poor Rifling At Lug	
-5	Chambering-Contour	48	105/45	40/31/24	1.385/1.070/1.153/1.205	Poor Rifling At Lug	
-6	Chambering-Contour	48	105/45	40/34/24	1.385/1.075/1.125/1.208	Improved	Contour on Center Lug.
-7	Chambering-Contour	48	105/45	43/36/24	1.385/1.049/1.108/1.208	Overfill	Reduced 20%
-8	Chambering-Contour	48	105/45	40/33/24	1.385/1.072/1.130/1.209	Good Rifling At Lug	Bore I.D. Variations
-9	Chambering-No Contour	48	105/45	39/ -.	1.385/1.078/ - /1.208	Good Rifling	Bore .3045 to .3048
-10	Chambering-No Contour	48	105/45	39/ -/24	1.385/1.078/ - /1.208	Good Rifling	Bore .3045 to .3048
-11	Chambering-No Contour	48	105/45	39/ -/24	1.385/1.078/ - /1.208	Good Rifling	Bore .3045 to .3048
-12	Chambering-No Contour	48	105/45	39/ -/24	1.385/1.078/ - /1.208	Good Rifling	Bore .3045 to .3048

* The percent reductions are given in the order = muzzle/center lug/chamber.

** The diameters are given in the order - initial preforms/muzzle/center lug/chamber.

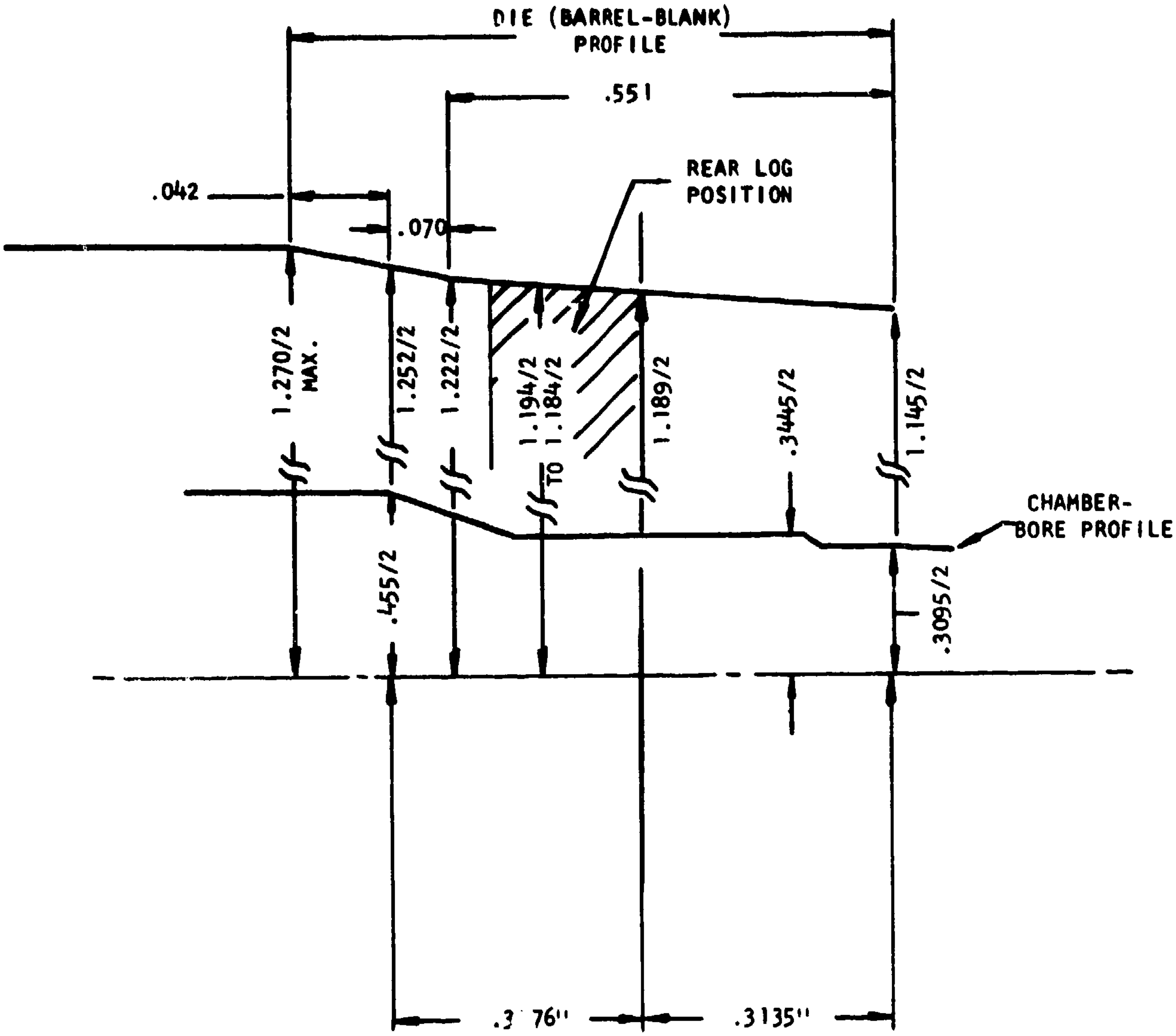


Figure 23. Chamber Cross Section for Forging M-134 Blanks from a 1.400 Inch Diameter Preform (Dimensions Controlled by Cam Settings When Forging with or without O.D. Contouring.

1. A minimum reduction for good rifling of 32% is required.

2. The low plunger pressure of 40±5 atm must be maintained.

3. The chambering dies must have the configuration illustrated in Figure 7.

4. The chamber shoulder must be formed under the smallest die entrance angle (4 or 5°) to achieve proper control over metal flow.

5. The reduction over the chamber body area must be 20 to 25% to produce a smooth 1.0 surface free of tool marks.

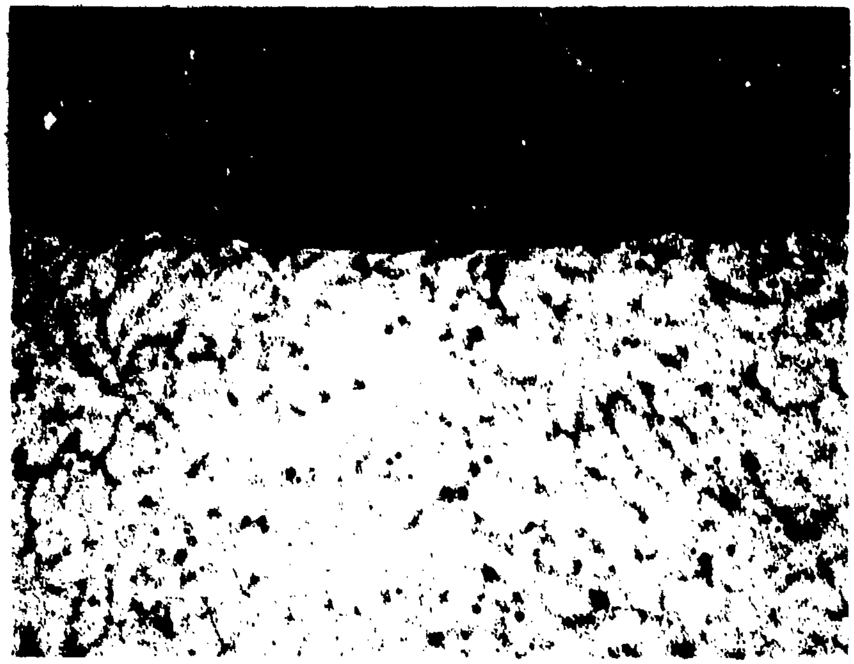
The adequacy of these requirements were confirmed during the second process evaluation series for a 1.410 inch (3.58 cm) preform O.D. Fabrication of barrels without O. D. contouring can be achieved with this diameter cylindrical preform to provide stock over the center lugs (1.100 inch/2.79 cm) at a reduction of approximately 38%.

Contour forging of the barrel was investigated to reduce the amount of material required by forging between the upper and lower reduction limits of 31 to 41%. Blanks were forged using a modified T-2 template to provide a lug diameter nominally .100 inch (.25 cm) greater than the muzzle diameter of the forging. This degree of contouring would save 2.71 cubic inches (44.4 cm^3) of material per barrel which in turn would save approximately 300 minutes of machining time for H-11 material and 600 minutes for IN 903 or U-700 alloys per 100 barrels manufactured. The material savings per 100 barrels would amount to $115.24, $208.71, and $673.35 for H-11, IN 903 and U-700 respectively.

The contour forgings were produced by sequencing to internal cam control after generation of the center lug to form the breech end configuration. This procedure is recommended to provide the necessary flexibility to control both the overall contours and their axial location on the barrel. The first group of contoured barrels (S1, S2, and H3 through H7 on Table XV) were found to have well developed rifling over the cylindrical portion of the barrel and immediately over the center lug, but the rifling was not complete for about 3/8 inch (1 cm) on the taper leading up to the center lug from the muzzle end. Analysis of the metal flow in this region indicated that the forging was accomplished in two stages. The leading end of the 4° die taper partially reduced the preform as the template follower engaged the lead taper on the template while the balance of the deformation was produced by the trailing edge of the die taper. Under these conditions, the maximum radial force over the contour was reduced resulting in a smaller inward displacement of metal over the rifling mandrel although the cumulative reduction at this point was theoretically adequate to form complete rifling. Apparently this problem is serious for contours generated by die opening sequences and not as critical for contours produced by die closures, i.e., the breech side taper on the center lug.

The T-2 template was further modified to provide a taper leading up to the center lug slightly less than 4° to relieve the previously observed bridging effect during the die opening mode. A series of eight barrels were forged with increasing reductions (specimens 618-74-1 through 8, Table XV) in an effort to produce properly developed rifling throughout the bore. The entire range of reductions were explored up to a maximum of 36% at the lug and 43% along the muzzle during this effort. Sectioning of these barrels showed that good quality rifling was developed at an optimum reduction of 40% at the muzzle, 33% at the center lug, and 24% over the chamber body. Illustrations of underfill, overfill, and properly developed rifling are presented in Figures 24 through 26 respectively for transverse sections removed from the H-11 barrels. A contour forged M-134 H-11 barrel is shown in Figure 27 along with the starting bar, the preform, and the modified template.

Although borescope inspection revealed that good rifling had been developed throughout the 618-74-8 forging, air gaging established that a non-uniform bore diameter condition existed. The region under the center lug was found to be .3055 to 3.060 inch (7.760 to 7.772 cm) in diameter while the remainder of the bore was at the desired.3045 to .3046 inch (7.734 to 7.742 cm) oversize for direct chromium electroplating. Data were gathered which suggested that the bore variation was directly related to the amount of reduction, implying that a constant reduction preform design is required for successful contour forging of M-134 barrels. These data are presented in Table XVI to document the observed apparent springback effect. Based on this unexpected development, a further modification to the preform design must be considered. A design for a contoured preform design has been developed to provide a constant reduction throughout the rifled bore believed necessary to alleviate the non-uniform springback condition encountered during forging of cylindrical preforms. Although the material had already been received for the final series of forgings and further modifications could not be evaluated, Figure 28 illustrates a proposed preform design to achieve a constant reduction forging. Rather than machine such a preform with a serious attendant material loss, a preliminary forging operation could be performed to generate this preform design.



a) 50X

b) 250X

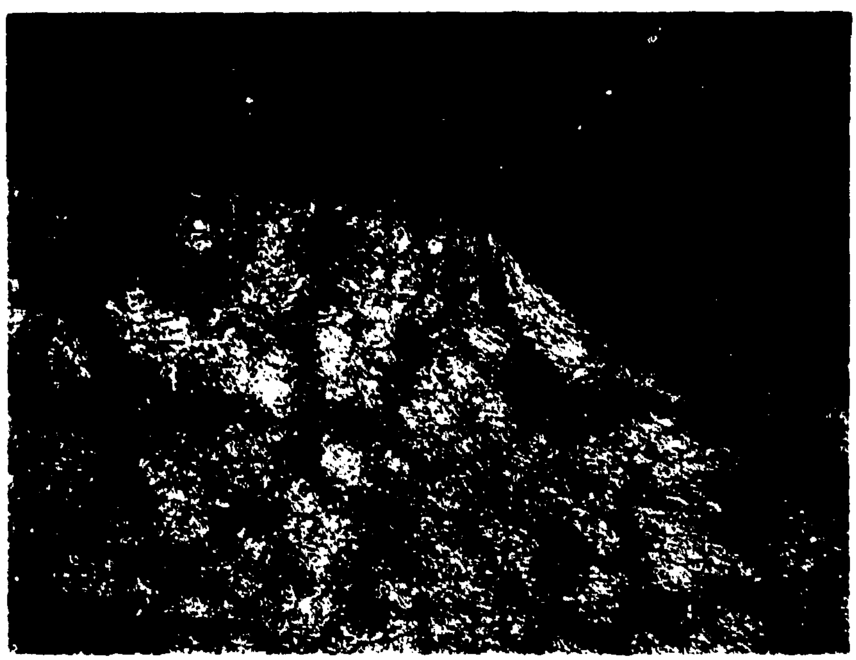
Figure 24. Underfill Condition for Contour Forged M-134 H-11 Preform at a Reduction of 31% Over the Center Lug, Specimen 618-74-5.

a) 50X

b) 250X

Figure 25. Overfill Conditions for Contour Forged M-134 H-11 Preform at a Reduction of 36% Over the Center Lug, Specimen 618-74-7.

a) 50X



b) 250X

Figure 26. Properly Developed Rifling for Contour Forged M-134 H-11 Preform at a Reduction of 33% Over the Center Lug, Specimen 618-74-8.

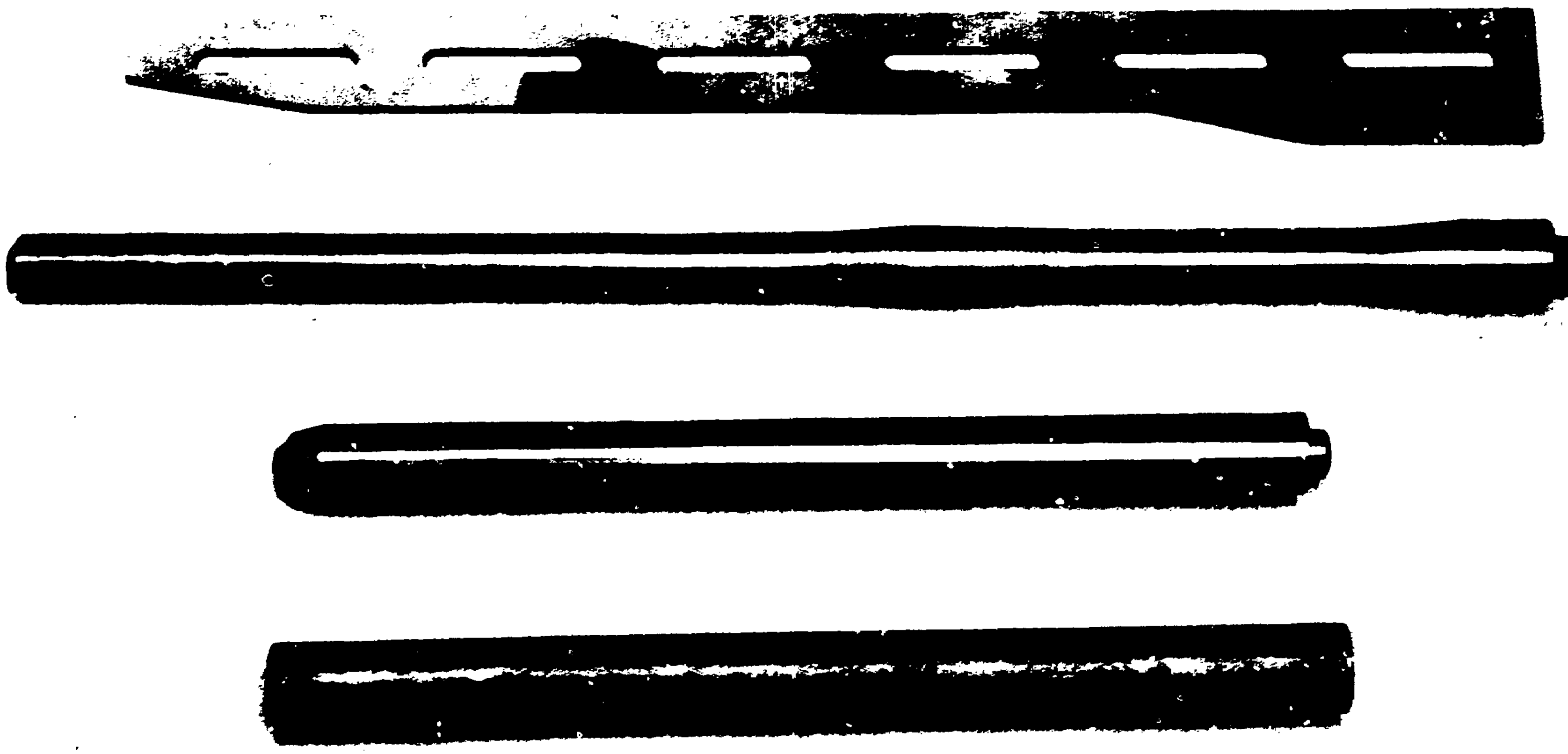


Figure 27. Illustration of the Initial Bar, Preform, Forged Barrel, and Template Used to Produce a Contoured M-134 Barrel.

TABLE XVI

Relation of Bore Springback to Reduction Ratio During GFM Forging

Mandrel Dia. In. (mm)	Final O.D. In. (mm)		Percent Reduction		Bore Size In. (mm)		Springback In. (mm)	
	Barrel	Lug	Barrel	Lug	Barrel	Lug	Barrel	Lug
0.300 (7.620)	1.070 (27.18)	1.120 (28.45)	36	41	0.3015 (7.658)	0.3035 (7.709)	0.0015 (0.0381)	0.0035 (0.0889)
0.3040 (7.722)	1.070 (27.18)	1.120 (28.45)	31	38	0.3048 (7.742)	0.3060 (7.772)	0.0008 (0.0203)	0.0020 (0.0508)

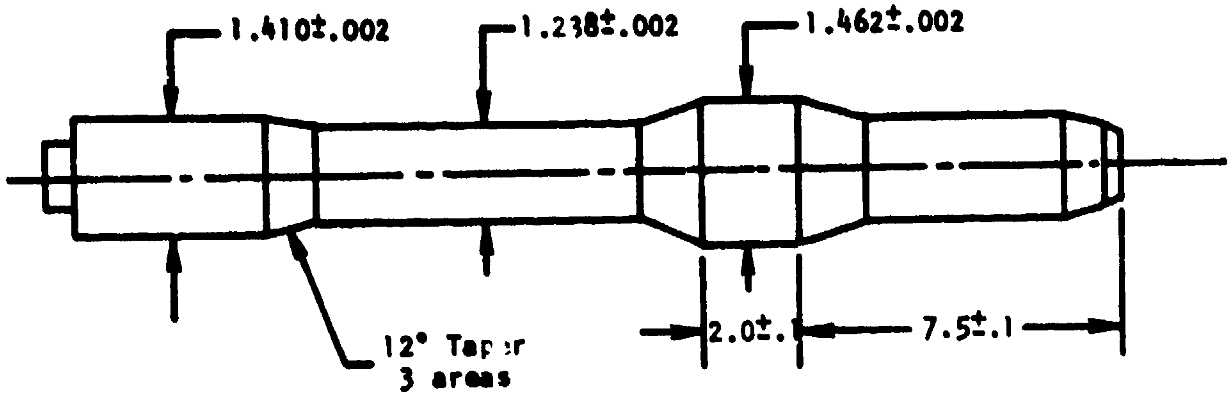


Figure 28. Proposed Preform Design for Contoured Constant Reduction M-134 Forging.

A cylindrical bar approximately 12 inches long (30.5 cm) having a 0.5 to 0.6 inch (1.27 to 1.52 cm) gun drilled hole would be forged into the configuration illustrated in Figure 28. Heat treatment to the desired 36-38 R_c level would then be performed prior to the final contour forging procedure.

A series of four non-contoured M-134 forgings were prepared from H-11 material to verify a reduction schedule suitable for use on the quantity production demonstration phase of the program (specimens 618-74-9 through 12, Table XV). It was necessary to revert to non-contoured forgings because the material had already been received for this phase and delivery schedules for new materials, preform preparation, and the subsequent two-stage forging operation precluded further program delays. Good quality rifling and chambering results were obtained although the 35% reduction schedule adopted for the barrel portion resulted in an undersize condition of .010 inch (.025 cm) at the center lug. It was decided through mutual consent of Rock Island Arsenal personnel that this condition would not seriously interfere with an evaluation of the barrel performance during subsequent firing tests. Borescope inspections revealed that good quality rifling was developed while the chambers were not completely filled at the cartridge neck despite the fact that the chamber O.D. was at the minimum required to produce the rear lug configuration. The preforms employed were 1.385 inches (3.518 cm) in diameter, thus the additional .025 inches (.064 cm) planned for the final production series was definitely required to correct this situation. This additional stock allowance on the preform would increase the reduction at the chamber from 29% to 27% and permit complete fill in the chamber area.

Concurrent with the second M-134 process evaluation series, M-219 H-11 forgings were also prepared employing the preform design presented in Figure 19. The use of a tapered preform alleviated the impacting and partial machine overloading conditions experienced during the initial evaluation sequence. Five forgings were prepared at increasing reduction schedules and the pertinent data are summarized in Table XVII, specimens T1 and M1 through M4. The rifling quality was found to be of good quality except at the preform shoulder and was improved somewhat as the reductions were increased. This problem was similar to that obtained at the lugs on the M-134 preforms but the absence of lugs simplified the solution. The preform and forging templates were modified to provide a continuous taper up to the breech diameter of 1.750 inches (4.445 cm). An additional six forgings were prepared over a range of reductions from 19 to 33%, specimens 618-74-1 through [illegible], Table XVII. The modified preform design, net forging, and template geometries employed are illustrated in Figures 29, 30, and 31 respectively. The modified preform design resulted in such an improvement in metal flow about the breech area that the mandrel became trapped in the bore near the breech. The metal contracted about the slight taper between the mandrel and its steel retainer stub, thus

TABLE XVII

Forging Evaluations for M-219 Barrels

Specimen No.	Forging Conditions	Pressure (Atms.) Counter-holder	Pressure (Atms.) Plunger	Reduction %	Diameters, In. Initial/Final (Breech)	Bore Quality	Remarks
T1	Rifling-Contour	48	105	23.3/ -	1.750/1.438/ -		Setup Piece.
M1	Rifling-Contour	48	105	24.6/ -	1.750/1.525/ -	Excellent Except at Shoulder.	
M2	Rifling-Contour	48	105	24.6/ -	1.750/1.525/ -	"	Moved Template Back To Improve Rifling at Shoulder.
M3	Rifling-Contour	48	105	26.9/ -	1.750/1.503/ -	"	
M4	Rifling-Contour	48	105	26.9/ -	1.750/1.503/ -	" Improved	
618-76-1	Rifling-Contour	48	105	27.5/27.9	1.750/1.490/.900		Mandrel Struck at Breech.
-2	Rifling-Contour	48	105	28.0/30.2	1.750/1.485/.896		
-3	Rifling-Contour	48	105	32.7/33.3	1.750/1.435/.866	Overfilled	
-4	Rifling-Contour	48	105	27.5/28.1	1.750/1.490/.899		Breech I.D. Increased to 11/32"
-5	Rifling-Contour	48	105	19.7/20.3	1.750/1.568/.946	Rifling Good to Counter Bore.	
-6	Rifling-Contour	48	105	19.3/19.8	1.750/1.572/.944		

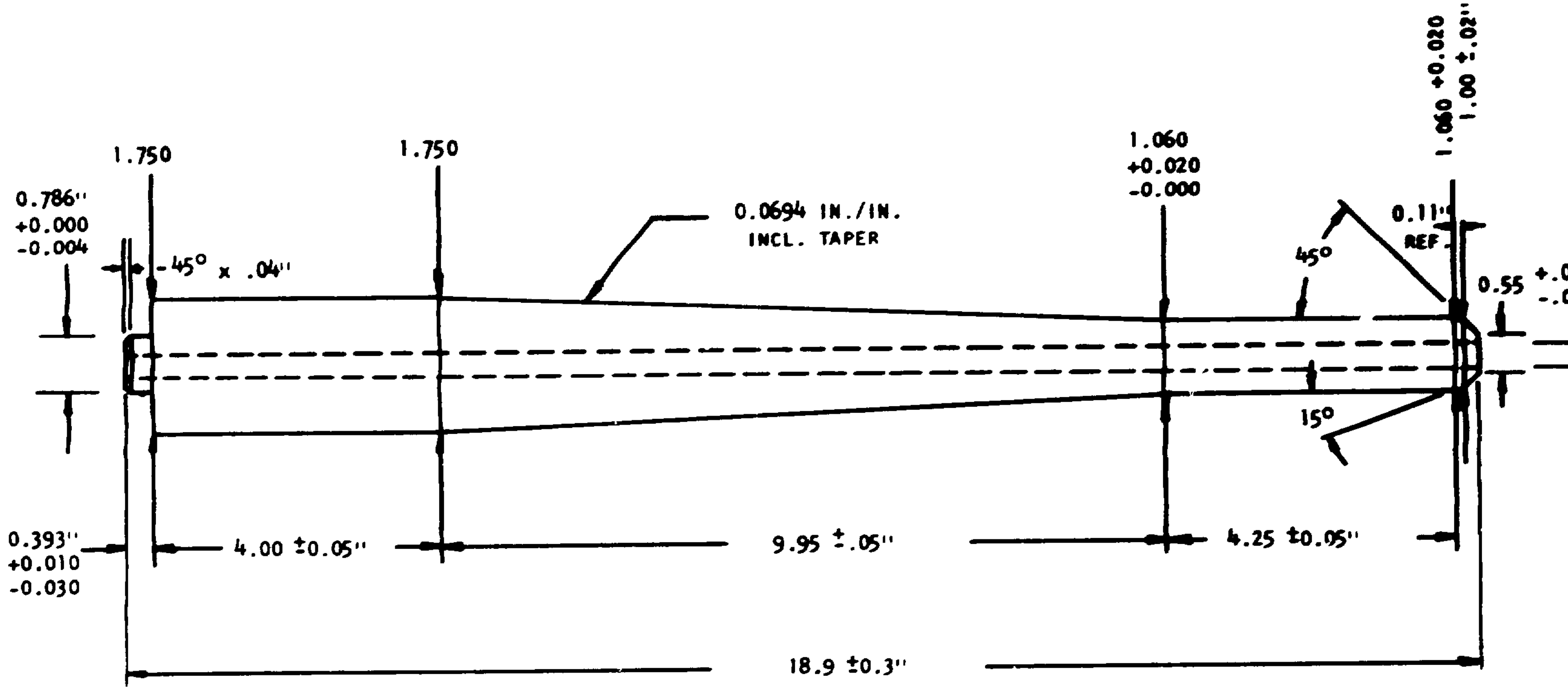


Figure 29. Modified M-219 Preform Design

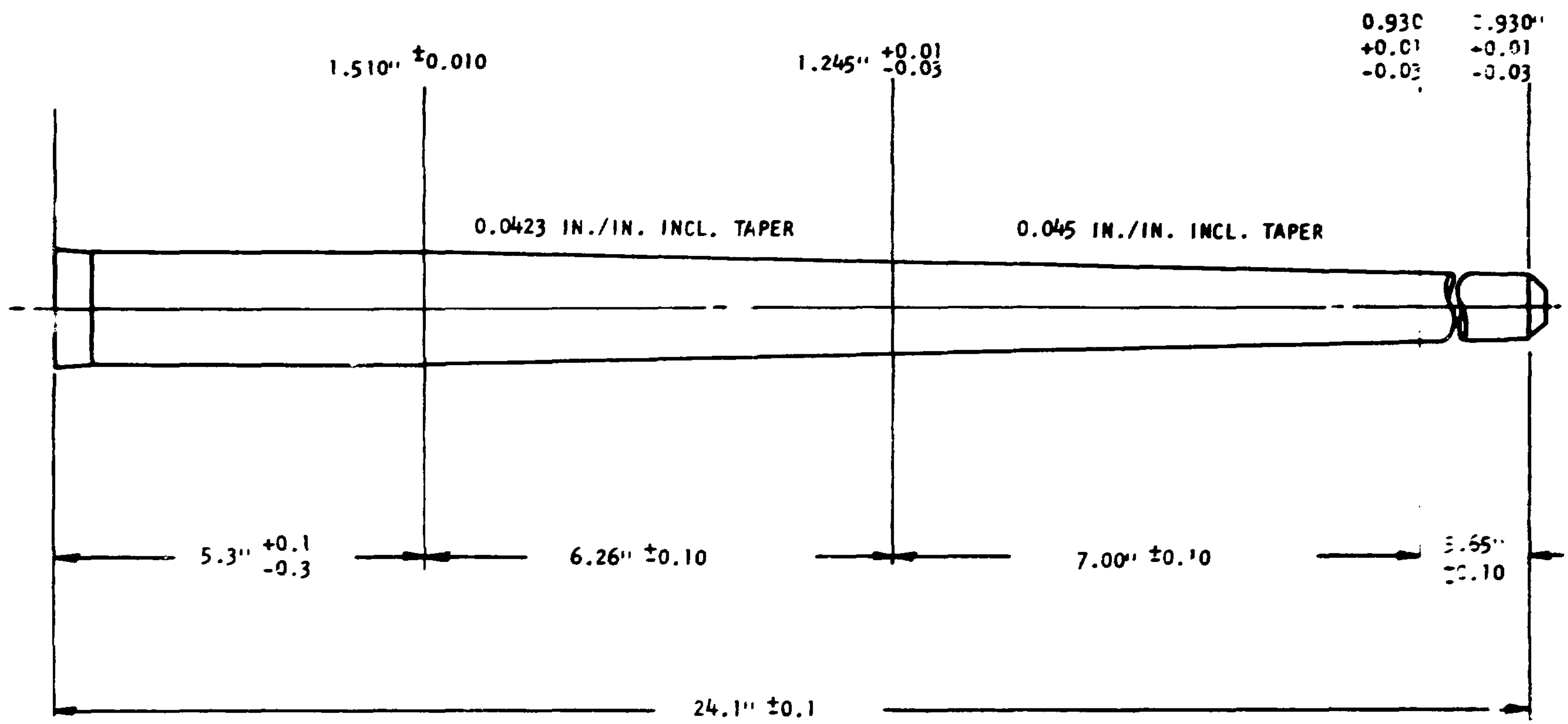


Figure 30. M-219 Barrel - Blank Design After Forging.

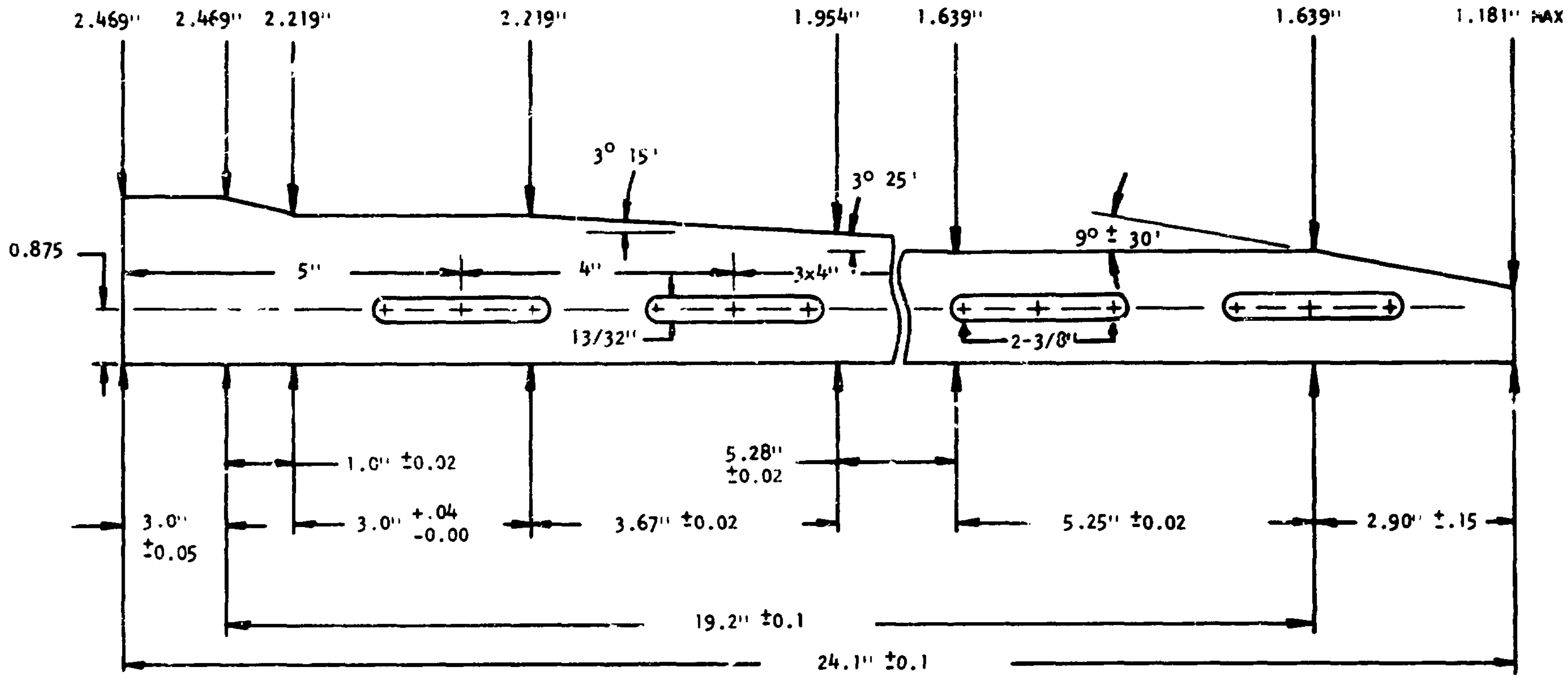


Figure 31. Final M-219 Template Modification.

holding it firmly in the bore and causing the mandrel extension rod to break at the screw attachment point. A mandrel longer than the 2.5 inch (6.35 cm) design (Figure 8) was not available to alleviate this problem but the rear portion of the preform counterbored to 11/32 inch (.87 cm) diameter for a distance of 6 inches (15.2 cm) solely to relieve the mandrel overlap condition such that the full contouring concept for the M-219 barrel configuration could be validated. To this end, the final preform design was fully satisfactory in producing a fully contoured forging without overloading the machine or encountering severe die impacting. Further, the rifling developed in the counterbored region was of reasonable quality which was taken as evidence that a normal preform having a .318 inch (.808 cm) bore throughout and forged with a rifling mandrel at least 3 inches (7.62 cm) long would contain full rifling even in the previously troublesome shoulder area. The appearance of the as-forged M-219 barrel is illustrated in Figure 32.

Barrel O.D. finishing operations were evaluated employing a template-controlled tracer lathe located at a subcontractor, General American Industrial Corporation, Blairsville, Penna. (GAICO). This machine tool had the capability of turning the O.D. to size in one pass with secondary finishing operations of end facing, lug milling, and corner radii required. The existing tooling required, however, that the barrel blank have a cylindrical O.D. As an expedient to avoid development time and purchase costs for a hydraulic follower rest, the forgings were encapsulated in matrix to provide a cylindrical form 1.250 inches (3.175 cm) in diameter. Cerrocast, an aluminum oxide filled wax, an aluminum filled wax, and glass powder filled epoxy were evaluated as support materials. Some preliminary turning tests quickly established that CIBA Araldite 502 epoxy filled with 50% by weight of powdered 60 mesh glass provided excellent support for the machining operations. Figure 33 illustrates the appearance of a) alumina filled wax, b) epoxy-glass encapsulation after trial machining, c) a fully encapsulated M-134 forging, and d) a finished H-11 M-134 barrel. A series of six M-134 barrels were subsequently machined, two IN 903 and four H-11, to finished dimensions to demonstrate the process and develop a machining routing for cost analysis. An additional group of four M-134 barrels were also prepared employing an HES tracer lathe to further refine the routing for O.D. finishing procedures. These data were obtained in support of the Task III Process Analysis phase of the program and will be treated in detail in discussion of the Task III results.

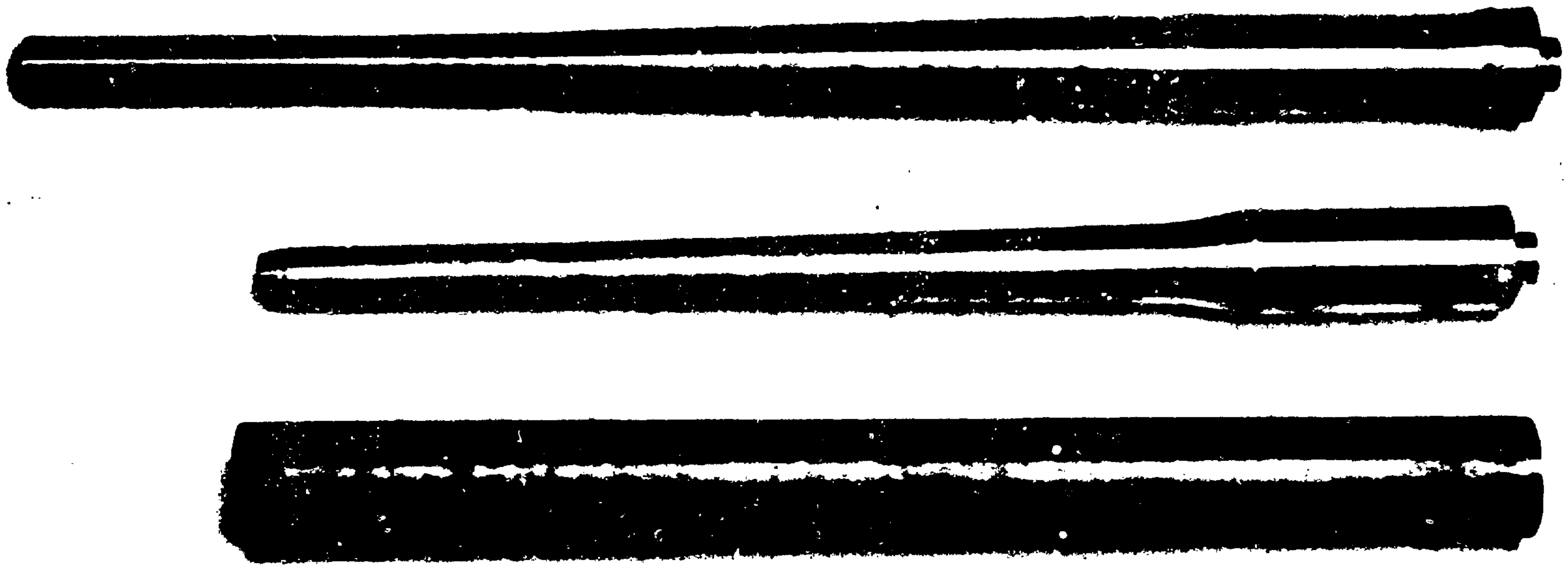


Figure 32. A Forged M-219 Barrel Illustrating Achievement of Full O.D. Contouring.

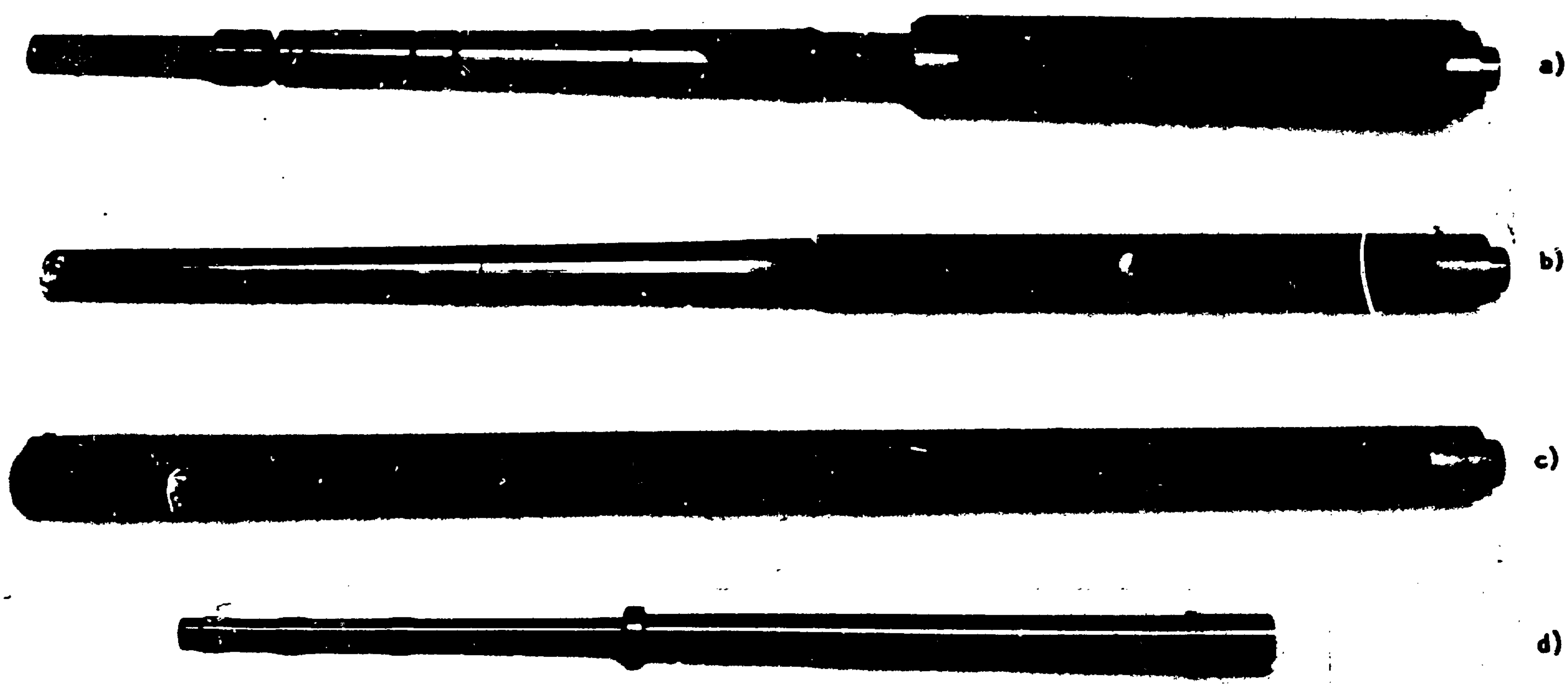


Figure 33. M-134 Barrels Encapsulated with Various Support Media: a) Alumina-Wax After Test Cut, b) Epoxy-Glass After Test Cut, c) Fully Encapsulated M-134 Forging Prior to Machining, d) Finish Machined Barrel.

3.2 TASK II - Barrel Fabrication Demonstration

The fabrication parameters developed as a result of the extensive Task I effort were employed in the preparation of 23 M-134 barrels of H-11 material, R_C hardness 36-38, and 32 M-134 barrels of IN 903 alloy aged to R_C 38-40. These barrels were shipped to Rock Island Arsenal for bore electroplating and subsequent evaluation.

3.2.1 Preform Preparation

Fully heat treated bar stock was obtained from Huntington Alloys (IN 903) and Braeburn Alloy Steel (H-11) for preform fabrication. The IN 903 and H-11 bars were $1.410^{+.005}_{-.000}$ inches ($3.581^{+.0127}_{-.000}$ cm) in diameter and $17.5^{+.10}_{-.00}$ inches ($44.45^{+.25}_{-.00}$ cm) long and were grit blasted prior to receipt to remove any heat treat scale. The entrance end of the bars were faced square prior to gun drilling to aid in initiation of the gun drilled hole and to identify the drill entrance hole. Although a concentricity loss of .001 inch (.0025 cm) T.I.R. per inch (2.54 cm) is experienced during gun drilling, a .4844 inch (1.230 cm) drill guide bushing controlled the runout within the desired .005 T.I.R. (.0127 cm) for the first 4 to 5 inches (10 to 13 cm) of the drilled bar. The N13 Eldorado gun drills (.484 inch, 1.229 cm) and White and Bagley No. 2480 oil were used to bore the bars at the parameters listed in Table XVIII. The surface finish was within 40 to 60 microinch AA (1.0 to 1.5 μm AA) requirement for finish prior to GFM forging.

TABLE XVIII

Gun Drilling Parameters

	H-11	IN 903
Speed, SFM ($cm\text{-}sec^{-1}$)	200 (102)	36 (18.4)
Feed, $in\text{-}min^{-1}$ ($cm\text{-}sec^{-1}$)	1.2 (.051)	.36 (.015)
Tool Life, in (cm)	>17.5 in (44.4)	3 (7.62)
Drilling Time, min	14.6	48.6

The drilled bars were machined to the finalized preform design configuration illustrated in Figure 21. Concentricity was established with the bore by turning between centers located on the gun drilled holes. The bar ends were oriented such that the gun drill entrance hole was at the breech end of the preform. A serious problem was encountered during the O.D. machining operation when it was recognized that a combined out of round and straightness error existed for the as received bar stock which precluded maintaining concentricity requirements at the breech end at the desired diameter of 1.410 inches (3.581 cm). The geometry of the bars was analyzed after turning them to a constant diameter of 1.405 inches (3.569 cm) and the amount of material required to be removed to restore concentricity determined. These data are presented in Table XIX. Thus, the maximum achievable preform diameter to achieve cleanup within the .005 inch (.0127 cm) T.I.R. requirement for overall concentricity was 1.390 inches (3.531 cm).

TABLE XIX

Bar Geometry Analysis

Measurement	Value, in (cm)
Bar Diameter	1.405 (3.569)
Average Runout	.0038 (.0097)
Standard Error, S	.0025 (.0064)
Minimum Cleanup (97.5 Tolerance Interval)	1.390 (3.531)

The inordinately long lead times associated with reordering bar stock having additional specifications on out of round and straightness tolerances not included in the original specification precluded replacement and dictated the use of 1.390 inch (3.531 cm) preforms for the final fabrication sequence. This unfortunate development dictated that extreme care be exercised in setting up the subsequent forging operation to assure optimum chamber formation while providing adequate stock for the O.D. breech lug.

3.2.2 Forging

A total of 77 H-11 and 40 IN 903 M-134 preforms were shipped to Rock Island Arsenal for rotary forging. It was established during the Task II evaluation that a cylindrical or non-contoured barrel forging would be necessary to produce a gun tube having a uniform bore dimension. The technology required to prepare the necessary contoured preforms for a contoured forging was regarded as being outside the present scope of the program and would have required substantial further forging evaluation.

The final processing parameters were established employing a number of trial forgings in both the H-11 and IN 903 materials. Hammer settings established for a particular diameter in H-11 steel required a 3% decrease to achieve the same result in the IN 903 alloy. Establishment of hammer control settings were readily achieved to produce the net 1.208 inch (3.068 cm) chamber and 1.080 inch (2.74 cm) M-134 barrel diameters. The major problem encountered was the location of the step in diameters in relation to the chamber neck such that the chamber was fully developed while providing adequate stock for the rear barrel lug. The final cam settings on the axial, or length, control panel provided a new forging with the leading edge of the 1.208 inch (3.068 cm) breech diameter located .3 inch (.762 cm) ahead of the body taper of the chamber. This location represents the closest approach the forging envelop can make to the rear lug and assure clean-up during finish machining. This configuration is illustrated in Figure 30. The settings on the diameter and length cam panels are listed in Table XV for purposes of documentation. The main control panel settings are also listed in Table XXI to complete the documentation and permit future re-establishment of the forging conditions with a minimum of trial-and-error.

TABLE XX

GFM Machine Cam Panel Control Settings for M-134 Forgings

Cam Panel No.	Diameter Panel	Length Panel Left	Length Panel Right
1	-	1200 -	80
2	-	1200 -	204
3	8.5 mm	1200 -	71
4	15.5 mm	1200 -	16
5	26.5 mm	1200 -	655
6	-	-	-
7	-	-	-
8	-	-	-
9	-	-	-
10	-	-	-
11	26.5 mm	-	-

TABLE XXI

GFM Machine Main Control Panel Settings for M-134 Barrel Forgings

	Cycle Number					
	3	6	7	8	9	10
Selector Switch Settings	1	0	4	0	4	0
	3	1	4	1	5	1
	0	2	0	2	0	4
	1	3	1	4	1	5

The bores were air gaged at .3045-.3048 inches (7.734 to 7.742 mm) across the lands and .3125+0 .3128 (7.938 to 7.945 mm) across the grooves. These dimensions are appropriate for direct electroplating of the bore to finish bore specifications without electropolishing. Borescope inspection revealed fully developed rifling had been produced without visible tool marks remaining from the gun drilling operation. Some roughness was detected at the chamber neck but further margin for adjustments in the O.D. contour or reductions to improve the finish was not possible.

The quantity forging operations were initiated with M-134 H-11 barrels using the oversize rifling and chambering mandrel. A total of 18 blanks were forged when the mandrel fractured at an internal discontinuity midway in the rifling portion. The back-up oversize mandrel was substituted and forging resumed. However, since it was the last remaining oversize mandrel, operations were transferred to the IN 903 material because it was desirable to avoid the need to electropolish barrels of this material should the second mandrel fail. The decision was justified, for chipping of the mandrel lead edge on the rifling lands occurred after nine IN 903 M-134 barrels were forged. The chipped edge resulted in some damage to the rifling lands and the mandrel was replaced with a standard size rifling and chambering mandrel. The remaining 59 H-11 and 31 IN 903 barrel forgings were produced with this tooling.

The barrels forged with the standard tooling were air gaged at .3015 to .3018 inches (7.658 to 7.666 mm) across the lands. The slight oversize condition was regarded as beneficial in that the amount of electropolishing required to size the bore prior to electroplating with chromium was minimized.

The forging evaluation program conducted in Task I was considered an adequate demonstration of the feasibility of producing fully contoured M-219 barrels of H-11 material. The appearance of an as-forged M-219 blank was presented in Figure 32. Since this preform was forged entirely under template control, machine cam panel controls were limited to hammer closure and retraction commands at the initiation and completion of the cycle.

All forgings were returned to TRW for cleaning, machining, and final inspection.

3.2.3 Post-Forge Inspection

The as-forged barrels were returned to TRW for cleaning and inspection. Examination of longitudinally sectioned M-134 barrels in both H-11 and IN 903 alloys reinforced the earlier borescope inspections showing that the rifling quality and surface finish were excellent. The previously noted roughness at the chamber neck was found to be of a more serious nature than revealed by simple borescope inspection procedures. A definite lack of fill existed on all forgings at the chamber neck immediately below the rear barrel lug. A typical example of this condition is illustrated in Figure 34 for an M-134 H-11 sectioned barrel. A direct cause of this underfill condition was the loss of the planned 1.410 inch (3.581 cm) O.D. dimension on the preform due to the out of round and straightness errors encountered on the incoming bar stock materials and the inability to move the chamber step illustrated in Figure 35 further to the rear of the forging. The remaining critical areas on the forgings were within desired tolerances for subsequent machining operations. These areas included the following:

1) the rifled length exceeded the 20 inches (51 cm) required,

2) the breach and barrel O.D. meet the barrel envelope requirements, and

3) the chamber was properly forged back into the 1.5 inch (3.81 cm) discard length.

An H-11 M-134 barrel forging was prepared in which the chamber step was moved back .5 inch (1.270 cm) towards the breech end. The appearance of the fully developed chamber is illustrated in Figure 36 along with an inset of this section after macroetching to develop the metal flow pattern.

Discussions were conducted between Rock Island Arsenal and TRW personnel to adopt an acceptable repair sequence. Three possible solutions were proposed:

2.5X

8X

Figure 34. Sectioned M-134 H-11 Forging Illustrating Underfill Conditions Experienced at the Chamber Neck Beneath the Rear Barrel Lug Location.

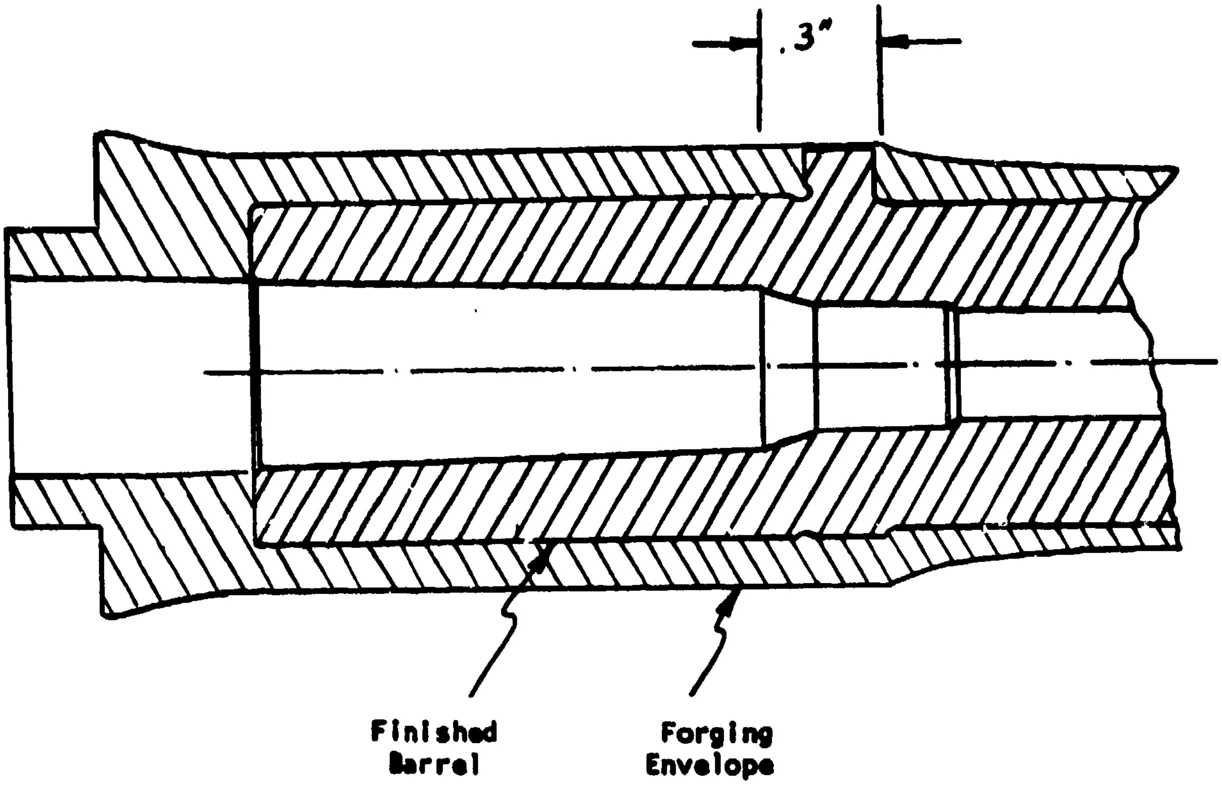


Figure 35. Illustration of Relationship Between M-134 Chamber Geometry, Rear Barrel Lug, and the Step on the Forging Envelope.

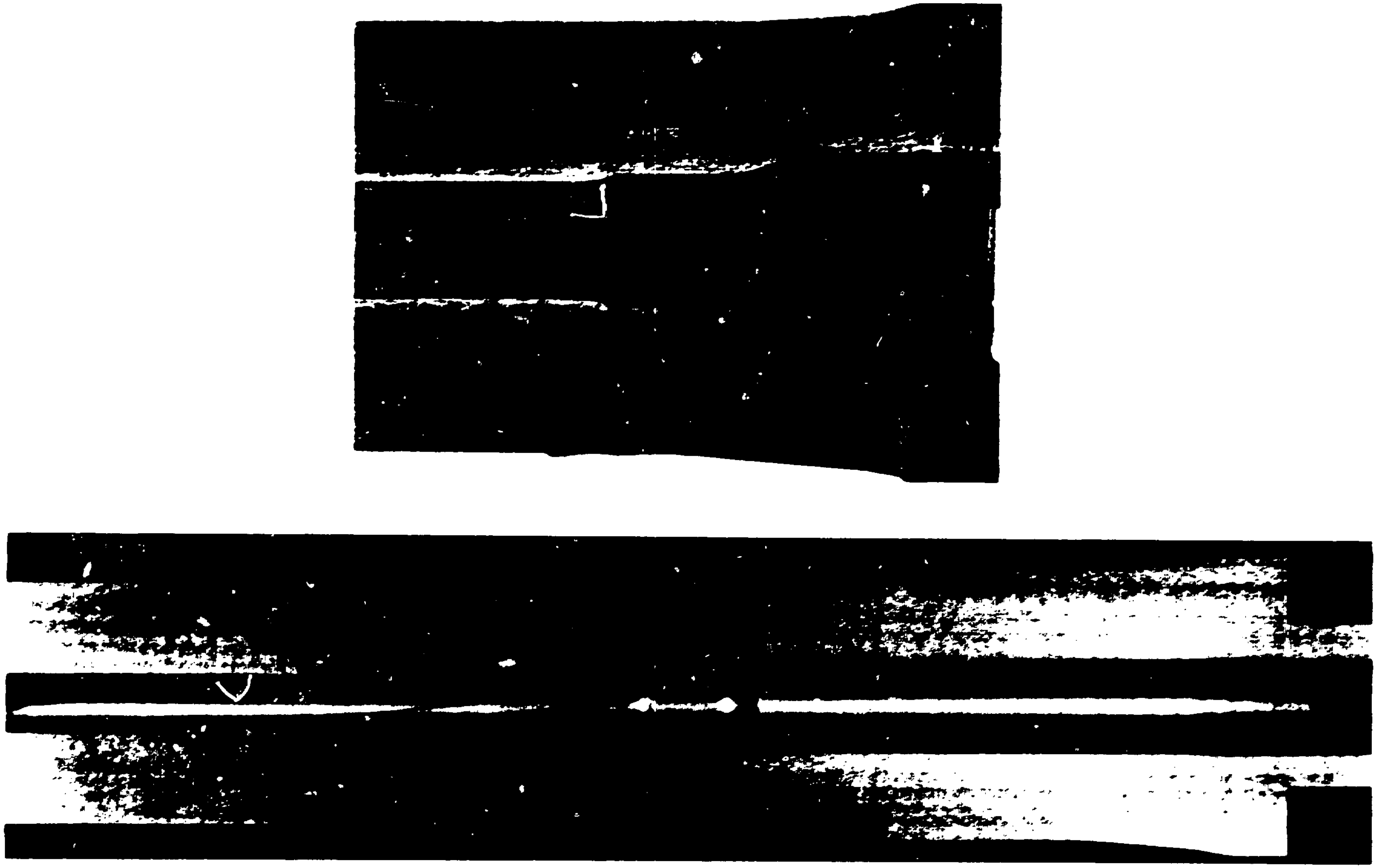


Figure 36. Illustration of As-Forged M-134 Barrel with Fully Developed Rifling and Chambering and an Inset of a Macroetched Section Showing the Metal Flow Lines.

1) deposit weld metal ahead of step for rear lug and rechamber,

2) nickel plate neck area and re-establish contours, and

3) bore neck area oversize and insert premachined collar.

The first alternative was adopted by unanimous agreement. Two weld wire alloys to effect the repair were selected as being highly compatible with the IN 903 and H-11 barrel materials. These alloys are identified in Table XXII with respect to trade name and composition. The repair sequence

TABLE XXII

Identification of Weld Repair Alloys

IN 92 for IN 903 Barrels

Element	Wt %
Ni	67 min
Cr	20
Mn	3.0
Cb+Ta	2.5
Fe	3.0 max
Co	.10 max
Si	.5 max
Ta	.3 max
Cu	.5 max
Ti	.75 max
C	.10 max
S	.015 max

Eureka 72A for H-11 Barrels

Element	Wt %
Fe	Bal
Cr	5.00
W	1.36
Mo	1.39
Si	.84
C	.36
Mn	.28
V	.44

involved a seven step operation:

1) locate weld zone 0.3 inches (.762 cm) ahead of present lug location,

2) grind reference diameter or barrel O.D. concentric with rifling to permit post weld evaluation of possible distortion effects,

3) preheat barrel at weld zone to 1000°F (538°C) on rotating fixture with argon flowing through bore,

4) deposit weld to 1.22 inch (3.10 cm) diameter in five passes,

5) force cool with air blast,

6) inspect for chamber runout with respect to reference diameter on barrel O.D., and

7) rechamber and polish.

Inspection of the welded barrels revealed that the maximum T.I.R. error was less than 0.0015 inches (0.0038 cm) in all cases. The multipass technique produced a tempering effect on the initial weld deposits and effectively stress relieved the underlying base metal, thus producing minimal effects on material properties in this area. No hardness changes were detected in the IN 903 material while a slight hardness increase was noted immediately adjacent to the weld deposit in the case of H-11. This effect was limited to a depth of .1 inch (.254 cm) and was not regarded as detrimental to the barrel performance capabilities. No oxidation or heat effects could be detected in the bore region beneath the weld location. The chambers were extended .3 inches (.762 cm) employing Clymer reamers having a pilot extension and spiral teeth. Felt bobs impregnated with 1 micron alumina abrasive were used to refine the chamber finish to a degree equivalent to that produced within the bore by GFM forging.

This experience provided an additional advance in technology for inspection of rotary forged small arms barrels. Borescope examinations do not provide the capacity for precise definition of contours or elevations. A definite need has been established to either section a test forging for direct evaluation of chamber quality or to pour a cerroalloy chamber casting to indirectly characterize the degree of fill achieved. The latter procedure can be readily done at the forge machine by dropping a steel plug into the breech end which has a body diameter slightly less than the bore diameter across the lands and a small sharp flange on one end to seat at the rifling throat. A cerroalloy chamber casting can be readily prepared and removed for evaluation without damage to either the bore or the casting.

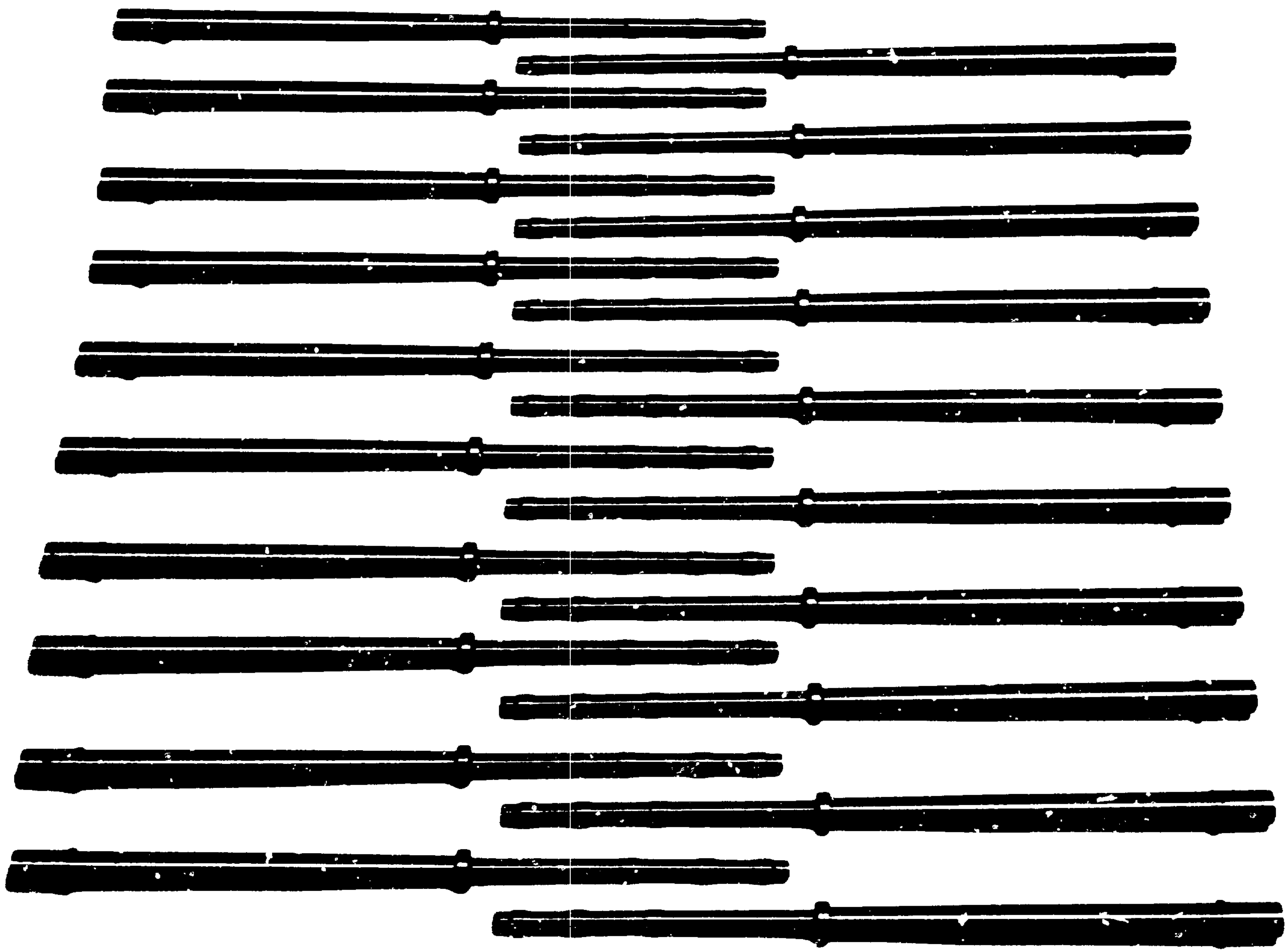


Figure 38. Photograph of 20 Finished M-134 Barrels of H-11 Steel Prepared by Cold Rotary Forging with Combined Rifling and Chambering.

3.2.4 Finish Machining

The IN 903 and H-11 barrel forgings were finish machined following the rechambering operation which corrected the underfill condition at the chamber neck. Four basic machine tools were employed in the finishing operations: a Hendy 14 x 58 Engine Lathe, an HES Tracer Lathe, a Brown and Sharpe Cylindrical Grinder, and a Bridgeport Milling Machine. Photographs of 30 completed IN 903 M-134 barrels and 20 H-11 M-134 barrels are presented in Figures 37 and 38, respectively.

A machining routing was established for the finishing operations taking as-forged and chambered blanks to the finished barrel. The routing is summarized in Table XXIII. Specific analysis of the routing and its optimization for quantity production will be treated in Task III. However, some of the more important aspects of finishing these barrels will be reviewed within the context of the routing described in Table XXIII.

The bore and chamber of gun tubes prepared by rotary forging are essentially finished after forging and all O.D. machining must be located with respect to the position of the chamber. The first operation must be to cut the breech end to length and thus establish headspace control. As a practical consideration a stock allowance for the female center should also be provided in addition to the headspace allowance. Establishment of the breech face then provides a reference surface for all subsequent gaging operations. See Figure 2 for dimensional organization for the M-134 barrel which shows the breech face to be the primary reference surface. Operations 1 through 5 thus provide accurate location points for the remaining procedures and essentially finish the breech end. The roughing operations (6 and 7) allow rapid stock removal and act to reduce cycle times for any given operation to facilitate queing problems associated with volume production schedules if one operation becomes significantly longer than the average individual procedures. Operations 8 and 9 represent the limiting links in the process chain. With two roughing passes and a finishing pass for each case, the net machining time for Operation 8 is 6.75 minutes and 9.75 minutes for Operation 9. The plunge grinding operation was also employed to dress the front face of the center barrel lug to finish dimensions as the four .619 inch (1.572 cm) bosses were ground, thus saving one corner radiusing step in Operation 11. Both lugs were milled using one setup in Operation 12. The center lug flat was milled first, the barrel rotated 117° about its axis, and then a one-pass milling cut was continued for 126° rotation to complete the rear lug configuration. Final inspection after trimming the barrel ends to remove the centers was conducted employing conventional gaging equipment although special gage fixtures would be constructed for volume production to qualify the dimensions as they were generated during the routing.

3) preheat barrel at weld zone to 1000°F (538°C) on rotating fixture with argon flowing through bore,

4) deposit weld to 1.22 inch (3.10 cm) diameter in five passes,

5) force cool with air blast,

6) inspect for chamber runout with respect to reference diameter on barrel O.D., and

7) rechamber and polish.

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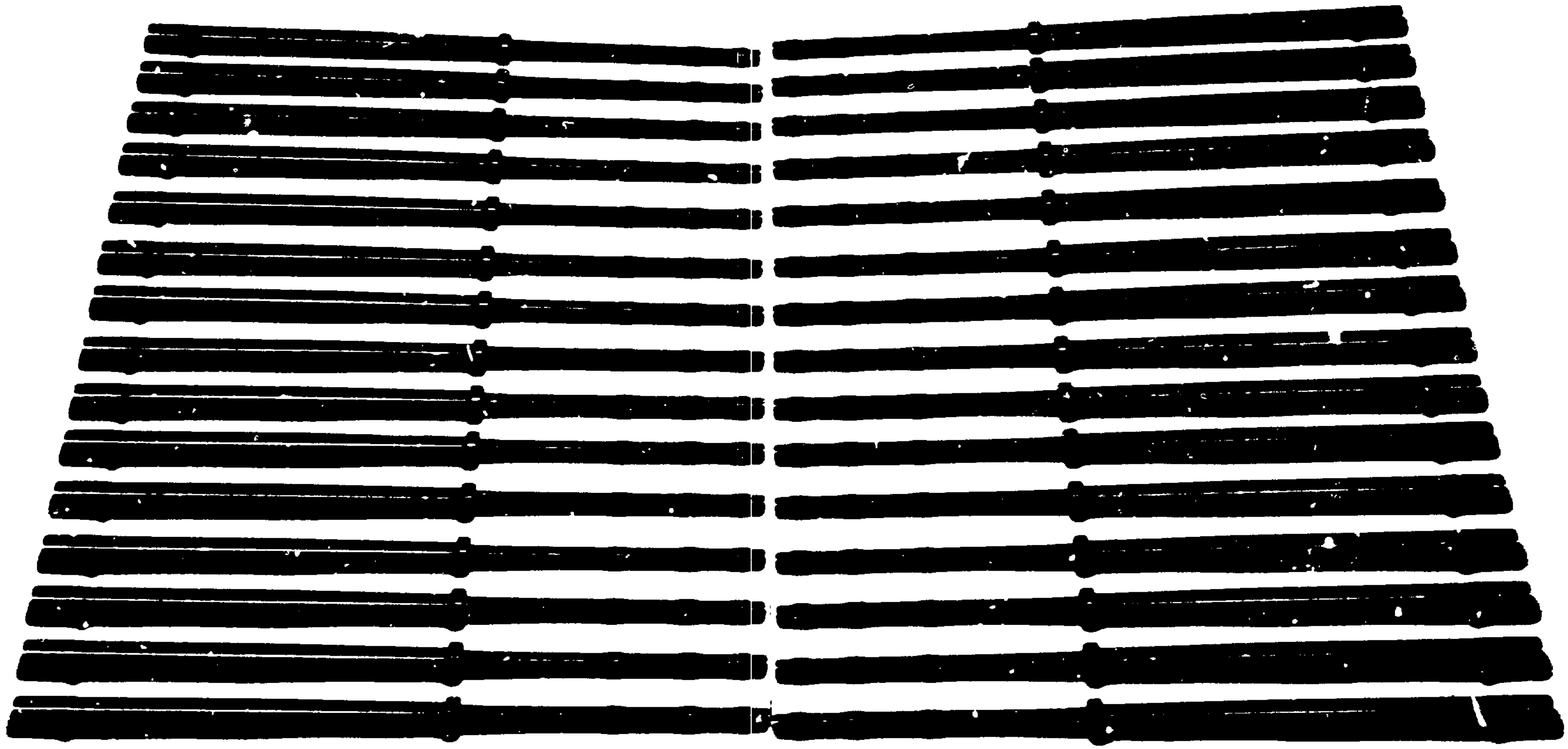

Figure 37. Photograph of 30 Finished M-134 Barrels of IN 903 Alloy Prepared by Cold Rotary Forging with Combined Rifling and Chambering.

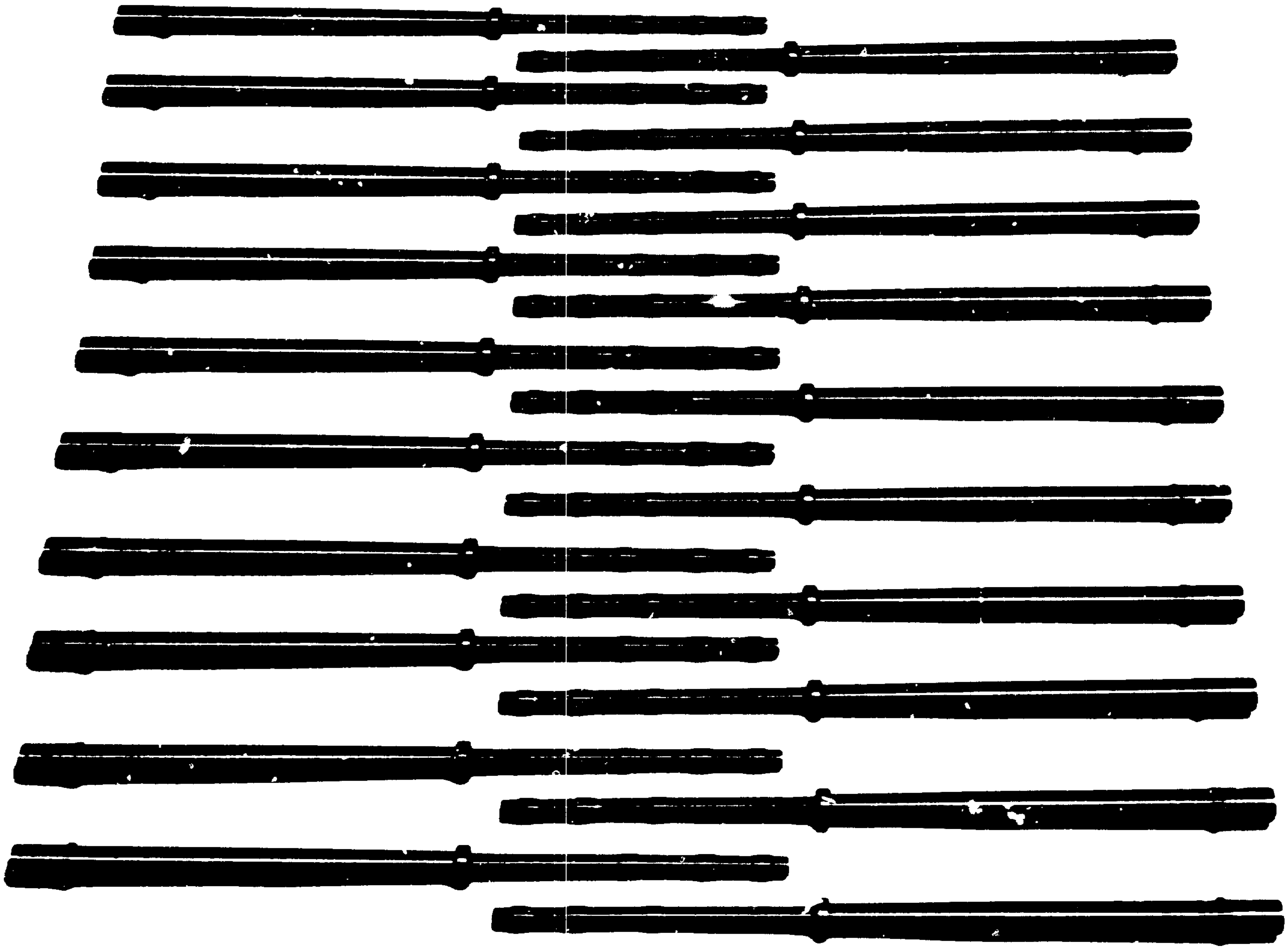

Figure 38. Photograph of 20 Finished M-134 Barrels of H-11 Steel Prepared by Cold Rotary Forging with Combined Rifling and Chambering.

TABLE XXIII

Routing for Finish Machining of M-134 Barrel Forgings

No.	Machine	Operation	Tooling Requirements and Comments
1.	-	Locate Chamber	Ball and Depth Micrometer
2.	Hendey Lathe	Cut Breech End	Parting Tool-Stock Allowance for Center
3.	Hendey Lathe	Cut Muzzle End	Parting Tool - Stock Allowance for Center
4.	Hendey Lathe	Turn Breech O.D. Concentric with Bore	Triangular C-2 Carbide Inserts
5.	B&S Grinder	Grind Center Lug	Concentric Reference Dia. and Steady Rest Support
6.	Hendey	Rough Turn Front Barrel Segment	Triangular C-2 Carbide Inserts
7.	Hendey	Rough Turn Rear Barrel Segment	Triangular C-2 Carbide Inserts
8.	HES Lathe	Finish Turn Front Barrel Segment	Template, VNMG 432E Coated U225 Inserts
9.	HES Lathe	Finish Turn Rear Barrel Segment	Template, VNMG 432E Coated U225 Inserts
10.	B&S Grinder	Plunge Grind 4 Bosses at Barrel Front	Inspection Micrometer
11.	Hendey	Finish 3 Corner Radii at Barrel Lugs	VNMG 432E Coated U225 Inserts
12.	Bridgeport Mill	Mill Lugs	Dividing Head, Support Jack, Carbide End Mill
13.	Hendey	Face Barrel Ends to Remove Centers and Chamber	Triangular C-2 Inserts
14.	-	Final Inspection	Misc. Gaging

3.3 TASK III - Process Analysis

The three basic barrel fabrication procedures; preform machining, rotary forging, and finish machining, were analyzed and reduced to a series of elemental operations. A complete flow chart generated as a result of technology developed on this program is presented in Figure 39.

3.3.1 - Cost Model

An equation was written for each of these operations which defined the incremental part cost in terms of machine parameters, part geometry, and indirect costs such as tooling and gaging requirements. The combined series of equations represents a comprehensive cost model for the entire manufacturing process as:

$$\frac{\text{COST}}{\text{BARREL}} = \begin{matrix}\text{RAW MATERIAL}\\ \text{COSTS}\end{matrix} + \begin{matrix}\text{PREFORM}\\ \text{MACHINING}\end{matrix} + \begin{matrix}\text{GFM}\\ \text{FORGING}\end{matrix} + \begin{matrix}\text{FINISH}\\ \text{MACHINING}\end{matrix}$$

The model was constructed to allow for operator inefficiency and yield for each operation. The latter term was expressed as the fraction of useable parts produced per operation divided by the total number of parts machined. Thus, dividing the elemantal cost by the appropriate yield factor will account for scrap losses incurred as a result of a particular operation.

The first operation involves raw material and it can be expressed as a product of the cost per pound, the volume, and the material density, as;

$$\begin{matrix}\text{RAW MATERIAL}\\ \text{PER PART}\end{matrix} = C_{RM}\,(\rho)\,\left(\frac{\pi}{4}\,D^2_{IPF}\right)\,(L_{PF}) \qquad (1)^3$$

On receipt of the material, one end of the bar is faced to provide a square surface for gun drilling and to identify the highly concentric entrance hole. The facing operation involves a straightforward chucking operation, as:

$$\begin{matrix}\text{FACING COST}\\ \text{PER BLANK}\end{matrix} = \frac{AC_M}{Y_{M2}}\left(t_{LU} + \frac{D_{IPF}}{2F_{CD}}\right) + \frac{C_{IT}}{N_{CT}}\,(N_{CPF}) \qquad (2)$$

[3] A complete glossary of terms in the cost model equation appears at the conclusion of this section for ready reference.

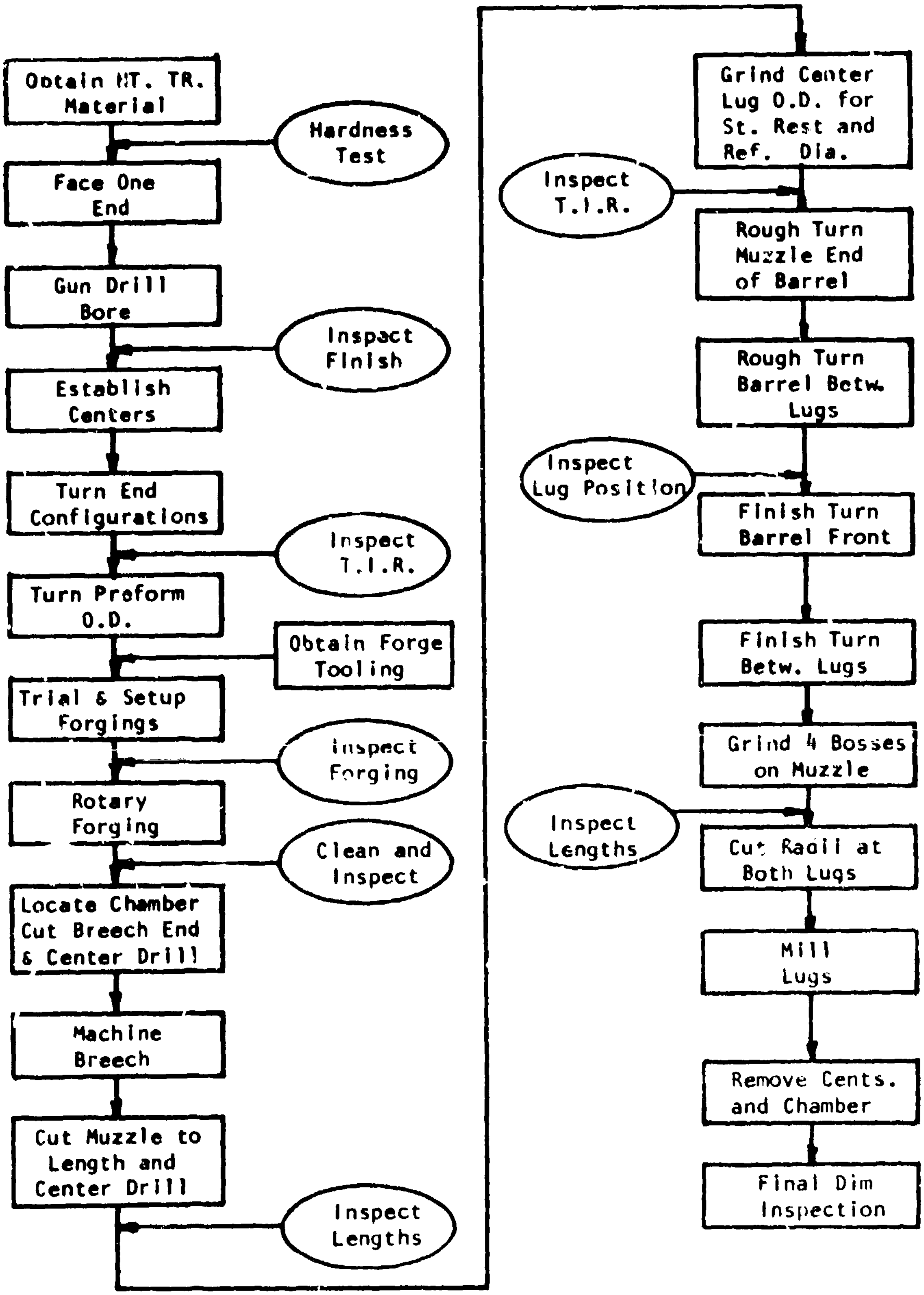

Figure 39. Flow Chart for M-134 Barrel Manufacturing Sequence.

The term t_{LU} is the load-unload time while the second term represents the facing time for one cut, in symbols $\frac{RADIUS}{FEED\ RATE}$. The last term expresses the tool costs on a per part basis. The gun drilling costs involve a machine cost element and a tooling consumption cost. The equation has the form;

$$\text{GUN DRILLING PER BLANK} = \frac{AC_{CGD}\ (L_{PF})}{Y_{GD3}f_{GD}} + \frac{C_{GD}L_{PF}}{T_{IDS}N_S} + C_{GDS}N_{SPF}A \qquad (3)$$

Actual drilling time is the quotient of blank length, L_P, and the feed rate, f_{GD}. Subsequent multiplication by the labor plus overhead rate, C_{CGD}, and the yield factor terms results in the actual costs. The last two terms represent the tooling and resharpening costs, respectively, on a per barrel basis.

The preform preparation following gun drilling was accomplished in three operations: center drilling time, t_{CC}, end shaping time, t_{PM} and t_{GS}, and O.D. cleanup time, t_{OD}. The drive end stub cutting time was expressed as the volume of stock removed divided by the metal removal rate, MRR_{PF}, as;

$$t_{GS} = \frac{V_{PFS}}{MRR_{PF}} \qquad (4)$$

The O.D. turning time was defined as the preform length, L_{PF}, divided by the feed rate, f_{PF}, and the part speed, RPM_{PF}. The full equation then becomes;

$$\text{PREFORM O.D. MACHINING COSTS} = \frac{AC_{PF}}{Y_{PF}} \left(2t_{CC} + t_{PM} + \frac{t_{SU}}{N_P} + \frac{V_{PFS}}{MRR_{PP}} + \frac{L_{PF}}{f_{PF}RPM_{PF}}\right)$$

$$+ \frac{2C_{CD}}{N_{CD}} + \frac{C_{IT}}{N_{ET}}\ (N_{CPF}) \qquad (5)$$

The completed preforms were then GFM forged which involved machine time costs, C_{GFM}, multiplied by the preform length, L_{PF} and the feed rate, f_{GFM}, plus the die and mandrel tooling costs expressed on a per part basis. The equation has the form;

$$\text{GFM FORGING COSTS PER BARREL} = \frac{A(C_{GFM})(L_{PF})}{(f_{GFM})Y_{GFM}} + \frac{C_{FM}}{N_F} + \frac{C}{N_{PD}} \quad (6)$$

The subsequent finishing process sequence for the M-134 barrels was reduced to twelve operations. The first operation involved location of the chamber with respect to the breech end of the barrel, cutting off the rear stub, and center drilling the breech end. The costs involved the gage time, t_G; the setup time, t_{SU}, divided by the number of parts in the manufacturing lot, N_P; cut-off time, t_{CO}; and the center drilling time, t_{CC}. The center drill, C_D; and cut-off tool insert, C_{COT}; costs represented the tooling costs for this operation. The equation was written as;

OPERATION 1
CHAMBER LOCATE
BREECH CUTOFF
AND CENTER DRILL

$$\frac{\text{COST}}{\text{PART}} = \frac{AC_M}{Y_M}\left(t_G + \frac{t_{SU}}{N_P} + \frac{D_{IB}}{2f_{CO}} + t_{CC}\right) + \frac{C_{CD}}{N_{CD}} + \frac{C_{COT}}{N_{ET}\,(N_{COT})} \quad (7)$$

With the breech end remaining in the chuckhead, the breech configuration was finish turned over the rear barrel lug. Basically, this operation involved turning the breech O.D. and the rear lug O.D. to finish size. The equation was formulated in terms of initial and final diameters and lengths for each section divided by the feedrates, depths of cut, and part RPM. Tooling costs were limited to the indexable triangular carbide inserts. The equation has the form after much algebraic simplifying;

OPERATION 2

BREECH MACHINE

$$\frac{\text{COST}}{\text{PART}} = \frac{AC_M}{2f_B RPM_B Y_M}\left(\frac{L_B(D_{IB}-D_{FB})}{d_B} + L_{RL}\right) + \frac{C_{IT}N_{CB}}{N_{ET}} \quad (8)$$

After the breech geometry was established, the muzzle end was cut to length and center drilled to provide concentricity control between the bore axis and the O.D. Five operations were conducted on the machine tool:

1) t_G = gage length time,

2) t_{CO} = cut-off time, = $D_{IM}/2f_{CO}$

3) t_S = setup time,

4) t_{LU} = load-unload time, and

5) t_{CD} = center drill time

Two tools were required, a cutoff and a center drill. The full equation was written as:

OPERATION 3

CUT MUZZLE AND CENTER DRILL

$$\frac{COST}{PART} = \frac{AC_M}{Y_M}\left(t_a + \frac{D_{IM} - .308}{2f_{CO}} + \frac{t_{SU}}{N_P} + t_{LU} + t_{CD}\right) + \frac{C_{CD}}{N_{CD}} + \frac{C_{COT}}{(N_{COT})N_{ET}} \quad (9)$$

Preservation of the T.I.R. at the center lug and provision for steady rest surface was accomplished in Operation 4. The center lug was ground to size in time, $t_G = \frac{D_{IM} - D_{CL}}{2f_G}$ and a load-unload time t_{LU} was required for each barrel. Wheel consumption and the cost of dresser wear was included in the tooling costs. The equation was formulated as:

OPERATION 4

GRIND O.D AT CENTER LUG

$$\frac{COST}{PART} = \frac{AC_M}{Y_M}\left(t_{LU} + \frac{D_{IM} - D_{CL}}{2f_G}\right) + \frac{C_W}{N_{PW}} + \frac{C_D N_D}{N_{UD}} \quad (10)$$

Two roughing operations were provided to remove excess stock to within .010 inch (.0762 cm) of finish size at an economically high MRR but without serious loss of T.I.R. Subsequent finishing operations were designed to restore any lost T.I.R. accuracy at minimum machine time requirements. The muzzle end was rough turned to a .629 inch (1.598 cm) cylindrical diameter. The metal removal costs were defined as a load-unload time, t_{LU}, and a machining time, t_M. The latter was defined as the quotient of the stock volume removed, $V = \frac{\pi L_M (D_{IM}^2 - D_{RTM}^2)}{4}$ and the $MRR = \frac{1}{2}\pi (D_{IM} + D_{RTM})(RPM_R)(d_R)(f_R)$. Combining and simplifying these terms yielded the following expression:

OPERATION 5

ROUGH TURN MUZZLE END

$$\frac{COST}{PART} = \frac{AC_M}{Y_M}\left(t_{LU} + \frac{L_M(D_{IM} - D_{RTM})}{2\, d_R f_R RPM_R}\right) + \frac{C_{IT}N_{CRT}}{N_{ET}} \qquad (11)$$

A similar development was made for rough turning the area between the two barrel lugs. With the exception of the diameters involved, this expression has the same form as equation (11) previously discussed. Thus, this relation was written as:

OPERATION 6

ROUGH TURN BETWEEN LUGS

$$\frac{COST}{PART} = \frac{AC_M}{Y_M}\left(t_{LU} + \frac{L'_M(D_{IM} - D_{RTB})}{2 d_R f_R RPM_R}\right) + \frac{C_{IT}N_{CRT}}{N_{ET}} \qquad (12)$$

The rough turned blanks were finish machined in two setups on a tracer lathe. Each of these operations were modeled individually. Turning of the portion between the center lug and the muzzle, L_M, was conducted between the rough turned diameter, D_{RTM}, and the final size, D_{FM}. The major tool costs were the diamond shaped carbide inserts, C_{ID}, and that for tracer template fabrication, C_T, divided by the total number of parts it can produce within specification, N_{PT}. The final equation becomes:

OPERATION 7

FINISH TURN FRONT BARREL

$$\frac{COST}{PART} = \frac{AC_M}{Y_M}\left(t_{LU} + \frac{L_M(D_{RTM} - D_{FM})}{2 d_f f_f RPM_f}\right) + \frac{C_{ID}(N_{CFD})}{N_{ED}} + \frac{C_{TF}}{N_{PT}} \qquad (13)$$

As with the roughing operations on the barrel segments, the similarity also exists for the other finishing procedure. The equation for describing the cost of finish machining the barrel area between the lugs differs from Equation (18) only by the actual values of length and diameter involved. This equation was written as:

OPERATION 8

FINISH TURN BETWEEN LUGS

$$\frac{COST}{PART} = \frac{AC_M}{Y_M}\left(t_{LU} + \frac{L'_B(D_{RTB} - D_{FB})}{2d_f f_f RPM_f}\right) + \frac{C_{ID}N'_{CRD}}{N_{ED}} + \frac{C_{TF}}{N_{PT}} \qquad (14)$$

A grinding operation was required to size the four bosses within the specified tolerance envelope of $.619^{+.000}_{-.002}$ inches ($1.573^{+.000}_{-.005}$ cm), B_{TE}. Each boss was plunge ground with a flat wheel at an infeed rate of f_G from the finish turned diameter D_{FT} to the finish boss diameter B_{TE}. In addition wheel and dresser costs were included on a per part basis, C_W and C_D. The former was determined on the basis of the stock volumes removed, the amount of available wheel volume, the grinds between dresses, and a dressing allowance of .001 inch (.0025 cm) per dress. The combined dressing equation then had the form:

$$\frac{\text{Wheel Costs}}{\text{Part}} = \frac{2C_W\,(10^{-4})}{D_{IW} - D_{SW}} \qquad (15)$$

The grinding costs per part was then expressed as:

OPERATION 9

BOSS GRINDING

$$\frac{COST}{PART} = \frac{AC_M}{Y_G}\left(\frac{2(D_{FT} - B_{TE})}{f_G} + t_{LU} + \frac{4t_D}{N_B}\right) + \frac{2C_W(10^{-4})}{D_{IW} - D_{SW}} + \frac{C_D(N_D)}{N_{DD}} \qquad (16)$$

Included in Operation 9 is the finishing of the front face of the center lug and the generation of the corner radius between the lug and the boss diameter. Thus, only three remaining radii required cleanup at the two barrel lugs. The operation involves setting up a form tool to plunge into the corner to a preset distance, thus the cycle time becomes a summation of a setup time, t_{SU}, and a cutting time t_M. The setup is made once for N_P parts machined so the cycle time is a sum of t_M and the load-unload time t_{LU}. The complete cost equation including tool consumption costs becomes:

OPERATION 10

CUT RADII

$$\frac{COST}{PART} = \frac{AC_M}{Y_M}\left(3t_M + 2t_{LU}\right) + \frac{C_{ID}N_{CRAD}}{N_{ED}} + \frac{t_{SU}AC_M}{N_P} \qquad (17)$$

The reliefs on the center and breech lug are milled on a single setup to assure proper registry of the contoured surfaces. The milling time becomes the sum of the paths transversed by the mill divided by the feedrate, f_M. For the front lug this is 1.1 L_W and the rear lug is the partial circumference represented by the 126° segment around the lug of diameter D_{RL}. This path becomes $\frac{126}{360}(\pi D_{RL})$ plus an allowance factor of 10% for slight overtravel. The overall equation also considered load-unload time t_{LU}, the setup time per part $\frac{t_{SU}}{N_P}$, and the tool consumption cost per part $\frac{C_M}{N_M}$ and was written as:

OPERATION 11

LUG MILLING

$$\frac{COST}{PART} = \frac{AC_M}{Y_M}\left\{\frac{t_{SU}}{N_P} + t_{LU} + 1.1\left(\frac{L_W + .35\pi D_{RL}}{f_M}\right)\right\} + \frac{C_{ML}}{N_M} \qquad (18)$$

The final operation involved removal of the excess stock at each end of the barrels containing the centers and chamfering the cut edges to print specifications. This involved a gage time T_G plus the plunge cuts and chamfering times. The cutting times were defined as the depth of cut in terms of the barrel thickness divided by the feed rate f_C. For the breech end this was $\frac{D_{FB} - D_C}{2f_C}$ and $\frac{D_M - .308}{2f_C}$ at the muzzle. The complete equation was expressed therefore as:

OPERATION 12

REMOVE CENTERS
CHAMFER ENDS

$$\frac{COST}{PART} = \frac{AC_M}{Y_M}\left(2T_G + \frac{D_{FB} - D_C}{2f_C} + \frac{D_M - .308}{2f_C} + t_C\right) + \frac{2C_{IT}\,N_f}{N_{ET}} \quad (19)$$

The total barrel fabrication cost then becomes a sum of Equations (1) through (19) with the exception of Equations (4) and (15) which merely define specific aspects of time elements within a cost equation. All terms in the equation are in units of dollars, inches, and minutes and a complete glossary of these terms in alphabetic order is presented at the conclusion of this report.

The influence of any machining or forging variable on cost can be quantitatively defined through the cost model equation(s) for the appropriate element. Further, the high cost elements can be identified for consideration of process optimization studies. Operations 1 through 12 in the cost model represent the O.D. machining costs and are valid for any method of generating the internal barrel configuration whether it be conventional drilling and broaching or GFM combined rifling and chambering procedures.

3.3.2 Manufacturing Costs

Appropriate data derived from Tasks I and II were inserted in the routing and cost model to define the actual cost to manufacture an M-134 barrel from H-11 steel. The assumptions involved in this calculation are as follows:

1) the lot size is 3000 barrels,

2) all machine tools have adequate rigidity to sustain the cutting forces involved; a typical machine would be a W&S 1SC NC chucker, for example, and

3) appropriate chucking and gaging tooling is available.

The raw material costs were computed with Equation 1 where:

C_{RM} = 1.708 \$/lb

ρ = .249 lb/in^3

D_{IPF} = 1.420 in

L_{PF} = 17.5 in

thus;

$$C_1 = \rho C_{RM} \left\{ \frac{\pi D_{IPF}^{\,2}}{4} \right\} L_{PF}$$

and;

C_1 = \$11.79 per barrel.

Facing prior to gun drilling involved Equation 2 where;

A = 1.05

C_M = \$.42/min (\$25.00/hr for man-machine L+OH rate)

t_{LU} = .16 min

D_{IPF} = 1.420 in

f_{CD} = 1.4 in/min

C_{IT} = \$1.15

N_{ET} = 6

Y_{M2} = 1.00

N_{CPF} = 0.1

thus;

$$COST = \frac{AC_M}{Y_{M2}} \left\{ t_{LU} + \frac{D_{IPF}}{2f_{CD}} \right\} + \frac{C_{IT} N_{CPF}}{N_{ET}}$$

and;

$$C_2 = \frac{1.05\ (.42)}{1.00} \left\{ .16 + \frac{1.42}{2(1.4)} \right\} + \frac{1.15\ (0.1)}{6}$$

= \$.31 per barrel.

Gun drilling costs were computed with Equation (3) where:

$A = 1.05$

$C_{GD} = \$.42/\text{min}$

$f_{GD} = 1.2 \text{ in/min}$

$L_{PF} = 17.5 \text{ in}$

$Y_{GD3} = .995$

$C_{GD} = \$40$

$l_{IDS} = 35 \text{ in}$

$N_S = 50$

$C_{GDS} = \$2.00$

thus;

$$C_3 = \frac{AC_{GD}L_{PF}}{f_{GD}Y_{GD3}} + \frac{C_{GD}L_{PF}}{l_{IDS}N_S} + C_{GDS}N_{SPF}A,$$

and;

$$C_3 = \frac{(1.05)(.42)(17.5)}{(1.2)(.995)} + \frac{(40)(17.5)}{(36)(50)} + (3)(.50)(1.05),$$

$$C_3 = \$8.427 \text{ per barrel.}$$

Completion of the preform configuration for the M-134 barrel illustrated in Figure 21 but with a cylindrical O.D. $D_{IPF} = 1.420$ inches is described by Equation (5) of the cost model. The relevant terms are defined as follows:

$A = 1.05$

$C_{PF} = \$.42/\text{min}$

$Y_{PF} = .995$

$N_P = 3000$

t_{CC} = .083 min

t_{PM} = .50 min

t_{SU} = 60 min

V_{PFS} = PREFORM STUB VOL = $\frac{\pi}{4}(D_{IPF}{}^2 - .787^2)(.393) = .431\ in^3$

MRR_{PF} = (RPM)(FEED)(DEPTH OF CUT)(π)$\left(\frac{D_1 + D_2}{2}\right)$

= (400)(.02)(.05)(π)$\left(\frac{1.42+.787}{2}\right)$

= 5.55 in^3/min

L_{PF} = 17.5 in

C_{CD} = \$8.50

f_{PF} = .02 in

N_{CD} = 100

RPM_{PF} = 400

C_{IT} = \$1.15

N_{ET} = 6

Y_{PF} = 1.00

N_{CPF} = .5

thus;

$$C_5 = \frac{AC_{PF}}{Y_{PF}} \left\{ 2t_{CC} + t_{PM} + \frac{t_{SU}}{N_P} + \frac{V_{PFS}}{MRR_{PF}} + \frac{L_{PF}}{f_{PF} RPM_{PF}} \right\} + \frac{2C_{CD}}{N_{CD}} + \frac{C_{IT} N_{CPF}}{N_{ET}}$$

and;

$$C_5 = \frac{1.05(.42)}{1.00} \left\{ 2(.083) + .50 + \frac{60}{3000} + \frac{.431}{5.55} + \frac{17.5}{(.02)(400)} \right\} + \frac{2(8.50)}{100} + \frac{(1.15)(.5)}{6}$$

C_5 = \$1.567 per barrel.

The completed preforms are then rotary forged at a unit cost defined by Equation (6). The pertinent costs are identified as follows:

$A = 1.05$

$C_{GFM} =$ \$0.833/min (Estimated L+OH rate for GFM machine \$50/hr)

$L_{PF} = 17.5$ in

$f_{GFM} = 3.937$ in/min

$Y_{GFM} = .995$

$C_{FM} = \$420.00$

$N_F = 500$

$C_D = \$2000$

$N_{PD} = 10{,}000$

thus for Equation (6)

$$C_6 = \frac{A(C_{GFM})(L_{PF})}{f_{GFM}(Y_{GFM})} + \frac{C_{FM}}{N_F} + \frac{C_D}{N_{PD}},$$

and;

$$C_6 = \frac{(1.05)(.833)(17.5)}{(3.937)(.995)} + \frac{420}{500} + \frac{2000}{10000},$$

$C_6 =$ \$4.949 per barrel.

The twelve machining operations to finish the O.D. are treated individually. The first involves machining the breech end and requires definition of the following terms to solve Equation (7):

$A = 1.05$

$C_M =$ \$.42/min

$Y_M = .995$

$t_G = .16$ min

$t_{SU} = 60$ min

N_P = 3000

D_{IB} = 1.208 in

f_{CD} = 1.4 in/min

t_{CC} = .083 min

C_{CD} = \$8.50

N_{CD} = 100/

C_{COT} = \$1.15

N_{COT} = 20

N_{ET} = 6

thus for Equation (7);

$$C_7 = \frac{AC_M}{Y_{MT}} \left(t_G + \frac{t_{SU}}{N_P} + \frac{D_{IB}}{2f_{CD}} + t_{CC} \right) + \frac{C_{CD}}{N_{CD}} + \frac{(C_{COT})}{(N_{ET})(N_{COT})}$$

and;

$$C_7 = \frac{(1.05)(.42)}{.995} (.16 + \frac{60}{3000} + \frac{1.208}{2(1.4)} + .083) + \frac{8.50}{100} + \frac{(1.15)}{6(20)},$$

C_7 = \$.403 per barrel.

The breech machining costs are defined by Equation (8) with the following values assigned to the terms:

A = 1.05

C_M = \$.42/min

f_B = .01 in/rev

RPM_B = 400

Y_M = .995

L_B = 1.650 in

D_{IB} = 1.208 in

D_{FB} = .937 in

d_B = .02 in

L_{RL} = .188 in

D_{RL} = 1.194 in

C_{IT} = \$1.15

N_{CB} = .25

N_{ET} = 6

Y_{M8} = .995

thus;

$$C_8 = \frac{AC_M}{2f_B RPM_B Y_{M8}} \left\{ \frac{L_B(D_{IB} - D_{FB})}{d_B} + L_{RL} \right\} + \frac{C_{IT}N_{CB}}{N_{ET}}$$

$$C_8 = \frac{(1.05)(.42)}{(2)(.01)(400)(.995)} \left\{ \frac{1.55(1.208 - .937)}{.02} + .188 \right\} + \frac{(1.15)(.25)}{6}$$

C_8 = \$1.297 per barrel.

Cost for the next operation, cutting the muzzle and a center, is described by Equation (9) with the following values for the various terms:

A = 1.05

C_M = \$.42/min

Y_{M9} = .999

t_G = .083 min

D_{IM} = 1.080 in

f_{CO} 1.4 in/min

t_{SU} = 10 min

N_P = 3000

t_{LU} = .16 min

t_{CD} = .25 min

C_{CD} = \$8.50

N_{CD} = 100

C_{COT} = \$1.15

N_{COT} = 20

N_{ET} = 6

thus Equation (9) has the form:

$$C_9 = \frac{AC_M}{Y_{M9}} \left\{ t_G + \frac{D_{IM} - .308}{2f_{CO}} + \frac{t_{SU}}{N_P} + t_{LU} + t_{CD} \right\} + \frac{C_{CD}}{N_{CD}} + \frac{C_{COT}}{(N_{COT})(N_{ET})}$$

and;

$$C_9 = \frac{(1.05)(.42)}{.999} \left\{ .083 + \frac{(1.080-.308)}{(2)(1.4)} + \frac{10}{3000} + .16 + .25 \right\}$$

$$+ \frac{8.50}{100} + \frac{1.15}{20(6)},$$

C_9 = \$.436 per barrel.

Generation costs of the reference diameter at the center lug by grinding are defined by Equation (10) with the following terms defined:

$A = 1.05$

$C_M = \$.42/\text{min}$

$Y_{M10} = .999$

$t_{LU} = .16$

$D_{IM} = 1.080 \text{ in}/1.120 \text{ in at Lug}$

$D_{CL} = 1.100 \text{ in}$

$f_G = .036 \text{ in/min}$

$C_W = \$12.50$

$N_{PW} = 25000$ @ .001'' dress & 100 parts/dress

$C_D = \$25.$

$N_D = 10^{-2}$

$N_{DD} = 10^5$

thus for Equation (10);

$$C_{10} = \frac{AC_M}{Y_{M10}} \left\{ t_{LU} + \frac{D_{IM} - D_{CL}}{2f_G} \right\} + \frac{C_W}{N_{PW}} + \frac{C_D N_D}{N_{DD}}$$

$$C_{10} = \frac{(1.05)(.42)}{.999} \left\{ .16 + \frac{1.120-1.100}{(2)(.036)} \right\} + \frac{12.50}{25000} + \frac{(25)(10^{-2})}{10^5}$$

$C_{10} = \$.194/\text{barrel}.$

Rough turning costs for the barrel ahead of the center lug are described by Equation (11) with the terms identified as follows:

$A = 1.05$

$C_M = \$.42/min$

$Y_{M11} = 1.00$

$t_{LU} = .16$ min

$L_M = 9.0$ in

$D_{IM} = 1.120$ in

$D_{RTM} = .629$ in

$d_R = .05$ in

$f_R = .02$ in

$RPM_R = 400$

$C_{IT} = \$1.15$

$N_{ET} = 6$

$N_{CRT} = 2$

thus for the equation;

$$C_{11} = \frac{AC_M}{Y_{M11}} \left\{ t_{LU} + \frac{L_M(D_{IM} - D_{RTM})}{2d_R f_R RPM_R} \right\} + \frac{(C_{IT})(N_{CRT})}{N_{ET}}$$

and

$$C_{11} = \frac{(1.05)(.42)}{1.00} \left\{ .16 + \frac{(9)(1.120 - 0.629)}{(2)(.05)(.02)(400)} \right\} + \frac{(1.15)(2)}{6},$$

$$C_{11} = \$2.890 \text{ per barrel.}$$

Similarly, roughing the barrel between the lugs on a taper is defined by Equation (12) with the following terms identified:

$A = 1.05$

$C_M = \$.42/\text{min}$

$Y_{M12} = 1.00$

$t_{LU} = .16 \text{ min}$

$L'_B = 11.312 \text{ in}$

$D_{IM} = 1.120 \text{ in}$

$D_{RTB} = .880 \text{ in}$ avg

$d_R = .05 \text{ in}$

$f_R = .02 \text{ in}$

$RPM_R = 400$

$C_{IT} = \$1.15$

$N'_{CRT} = 2$

$N_{ET} = 6$

thus, Equation (12) has the form:

$$C_{12} = \frac{AC_M}{Y_{M12}} \left\{ t_{LU} + \frac{L'_B \, (D_{IM} - D_{RTB})}{2d_R f_R RPM_R} \right\} + \frac{C_{IT} N'_{CRT}}{N_{ET}}$$

$$C_{12} = \frac{(1.05)(.42)}{(1.00)} \left\{ .16 + \frac{11.312(1.120 - .880)}{(2)(.05)(.02)(400)} \right\} + \frac{(1.15)(2)}{6}$$

$C_{12} = \$1.950$ per barrel.

The next operations involved finishing the barrel ahead of the center lug, Equation (13), and betwaen the lugs, Equation (14). The terms for cost analysis of the former equation are listed as follows:

$A = 1.05$

$C_M = \$.42/\text{min}$

$Y_M = .995$

$t_{LU} = .16 \text{ min}$

$L_M = 9.0 \text{ in}$

$D_{RTM} = 0.629 \text{ in}$

$D_{FM} = .550 \text{ in avg}$

$d_f = .01 \text{ in}$

$f_f = .01 \text{ in/rev.}$

$RPM_f = 400$

$C_{ID} = \$1.85$

$N_{CFD} = 1$

$N_{ED} = 4$

$C_{FT} = \$150$

$N_{PT} = 10^4$

thus for Equation (13);

$$C_{13} = \frac{AC_M}{Y_{M13}} \left\{ t_{LU} + \frac{L_M(D_{RTM} - D_{FM})}{2d_f f_f RPM_f} \right\} + \frac{C_{ID}N_{CFD}}{N_{ED}} + \frac{C_{TF}}{N_{PT}}$$

$$C_{13} = \frac{(1.05)(.42)}{.995} \left\{ .16 + \frac{9.0(.629 - .550)}{(2)(.01)(.01)(400)} \right\} + \frac{(1.85)(1)}{4}$$

$$+ \frac{150}{10^4}$$

C_{13} = \$4.486 per barrel.

For the second finishing operation, the terms are defined as:

A = 1.05

C_M = \$.42/min

Y = .995

t_{LU} = .16 min

L'_B = 11.312 in

D_{RTB} = .880 in avg

D_{FB} = .860 in avg

d_f = .01 in

f_f = .01 in/rev

RPM_f = 400

C_{ID} = \$1.85

N'_{CRD} = 1

N_{ED} = 4

C_{TF} = \$150

N_{PT} = 10^4

thus for Equation (14);

$$C_{14} = \frac{AC_M}{Y_{M14}} \left\{ t_{LU} + \frac{L'_B(D_{RTB} - D_{FB})}{2d_f f_f RPM_f} \right\} + \frac{C_{ID}N'_{CRD}}{N_{ED}} + \frac{C_{TF}}{N_{PT}}$$

and;

$$C_{14} = \frac{(1.05)(.42)}{.995} \left\{ .16 + \frac{11.312(.880-.860)}{(2)(.01)(.01)(400)} \right\} + \frac{(1.85)(1)}{(4)} + \frac{150}{10^4},$$

C_{14} = \$1.802 per barrel.

Equation (16) describes grinding costs to finish the 4 bosses to size and dress the front lug radius. The pertinent terms are as follows:

A = 1.05

C_M = \$.42/min

Y_A = .999

D_{FT} = .629 in

B_{TE} = .619 in

f_G = .036 in/min

t_{LU} = .16 min

t_D = .4 min

N_B = 20

C_W = \$12.50

D_{IW} = 12 in

D_{SW} = 7 in

C_D = \$25.

N_D ≈ 5×10^{-2}

N_{PD} = 10^5

thus for Equation (16);

$$C_{16} = \frac{AC_M}{Y_{M16}} \left\{ \frac{2(D_{FT} - B_{TE})}{F_G} + T_{LU} + \frac{4t_D}{N_B} \right\} + \frac{(2C_W)(10^{-4})}{D_{IW} - D_{SW}} + \frac{C_D N_D}{N_{DD}},$$

and;

$$C_{16} = \frac{(1.05)(.42)}{.999} \left\{ \frac{2(.629 - .619)}{.036} + .16 + \frac{4(.4)}{20} \right\} + \frac{(2)(12.50)(10^{-4})}{12 - 7}$$

$$+ \frac{(25)(2 \times 10^{-2})}{10^5},$$

C_{16} = \$3.517 for grinding one barrel.

The costs to cut the remaining three radii involve the following terms:

$A = 1.05$

$C_M = \$.42/\text{min}$

$Y_M = .995$

$t_M = .25$ min

$t_{LU} = .16$ min

$C_{ID} = \$1.85$

$N_{CRAD} = .25$

$N_{ED} = 4$

$t_{SU} = 30$ min

$N_D = 3000$

The cost equation for radii finishing, Equation (17), has the form;

$$C_{17} = \frac{AC_M}{Y_{M17}} \left\{ 3t_M + 2t_{LU} \right\} + \frac{C_{ID}N_{CRAD}}{N_{ED}} + \frac{t_{SU}(A)(C_M)}{N_P}$$

$$C_{17} = \frac{(1.05)(.42)}{.995} \left\{ (3)(.25) + 2(1.6) \right\} + \frac{(1.85)(.25)}{4} + \frac{(30)(1.05)(.42)}{3000}$$

C_{17} = \$.594 per barrel.

Lug milling costs involve the following terms:

A = 1.05

C_M = \$.42/min

Y_M = .995

t_{SU} = 60 min

t_{LU} = .16 min

N_P = 3000

L_W = .726 in

D_{RL} = 1.042 in avg

f_M = .5 in/min

C_{ML} = \$15.00

N_M = 20

thus for cost calculation, Equation (18) has the form:

$$C_{18} = \frac{AC_M}{Y_M} \left\{ \frac{t_{SU}}{N_P} + t_{LU} + 1.1 \left(\frac{L_W + .35\pi \; D_{RL}}{f_M} \right) \right\} + \frac{C_{ML}}{N_M},$$

and;

$$C_{18} = \frac{(1.05)(.42)}{.995} \left\{ \frac{60}{3000} + .16 + 1.1 \left(\frac{.726 + .35\pi \; (1.042)}{.5} \right) \right\}$$

C_{18} = $2.503 per barrel.

The final operation, breech and muzzle end finishing, involves the following terms:

A = 1.05

C_M = $.42/min

Y_M = .999

t_U = .16 min

D_{FB} = .537 in

D_C = .488 in

f_C = 1.4 in/min

D_M = .540 in

t_C = .2 min

C_{IT} = $1.15

N_f = .05

N_{ET} = 6

Cost Equation (19) has the form:

$$C_{19} = \frac{AC_M}{Y_{M19}} \left\{ 2t_G + \frac{D_{FB} - D_C}{2f_C} + \frac{(D_M - .308)}{2f_C} + t_C \right\} + \frac{2C_{IT}N_f}{N_{ET}}$$

$$C_{19} = \frac{(1.05)(.42)}{.999} \left\{ (2)(.16) + \frac{.937 - .488}{(2)(1.4)} + \frac{.540 - .308}{(2)(1.4)} + .2 \right\}$$

$$+ \frac{2(1.15)(.05)}{(6)}$$

C_{19} = \$.355 per barrel.

The total manufacturing cost is represented by the sum of these incremental costs and amounts to \$35.723 per M-134 barrel in H-11 alloy plus a raw material cost of \$11.79 per starting blank or a total cost of \$47.513. Similar calculations for the IN 903 alloy resulted in a manufacturing cost of \$52.390, when combined with the \$29.525 raw material cost for a final total cost per barrel of \$81.915. These costs must be weighed against the performance increase of these materials over the conventional Cr-Mo-V steel barrels. The incremental costs are summarized in Table XXIV for comparison with the H-11 M-134 barrel. The data show that manufacturing costs for IN 903 barrels are 147% greater than H-11 and the material costs are 250% greater with the total cost differential reaching 172%. The importance of contour forging the M-134 barrel becomes apparent when it is recognized that while use of a more refractory alloy raises the metal removal costs significantly, the raw material costs remain the largest single cost factor. Thus, efforts to minimize material loss as chips can be cost effective. Comparison of GFM procedures to generate the rifled bore and chamber with conventional mechanical means in ordinary Cr-Mo-V steels established that this process is cost-effective. Complete rifling and chambering costs for GFM processing amounts to slightly less than \$5.00 per barrel including tooling while conventional methods would involve drilling, reaming, broaching, and chambering operations costing approximately \$10.00 for a 20-22 inch (51-56 cm) 7.62mm gun tube.

TABLE XXIV

Cost Comparison: H-11 vs IN 903

Cost Element	H-11	IN 903	Operation
C_1	$11.790	$29.525	Raw Material
C_2	.313	.313	Facing Bar
C_3	8.427	11.927	Gun Drilling
C_5	1.567	2.579	O.D. Preform Turning
C_6	4.949	4.949	GFM Forge
C_7	.403	.403	Breech Trim
C_8	1.297	2.546	Finish Breech O.D.
C_9	.436	.436	Cut Muzzle End
C_{10}	.194	.194	Ref. Dia.
C_{11}	2.890	5.326	Rough Turn
C_{12}	1.950	3.447	Rough Turn
C_{13}	4.486	8.423	Finish Turn
C_{14}	1.802	3.054	Finish Turn
C_{16}	3.517	3.517	Grind Bosses
C_{17}	.594	.594	Cut Radii
C_{18}	2.503	4.327	Mill Lugs
C_{19}	.355	.355	Trim Ends
C_T	$47.513	$81.915	Total Cost*
C_{MFG}	$35.723	$52.390	Cost w/o Material

*Since plating costs are comparable to standard gun barrels, these figures are not included.

4.0 CONCLUSIONS

1. Rotary forging offers a method to significantly reduce raw material requirements over conventional procedures that start from a larger initial bar size. Material savings become substantial as the alloy costs exceed $10 per pound in bar stock form.

2. Rotary forging can be employed to produce cold formed barrels to close tolerances both on the bore and the outer envelope.

3. The rotary forging process offers the only economical alternative to produce rifled and chambered gun tubes from the more refractory alloys. Conventional drilling and broaching methods would involve prohibitively high tool consumption rates to rifle and chamber the more refractory alloys at hardness levels up to R_c 36-40.

4. The first task of the program successfully defined systems of rotary forging parameters and preform design data to produce partially contoured M-134 barrel forgings of either H-11 steel or INCOLOY 903 alloy containing fully developed rifling and a high quality chamber.

5. Additional technological development is required to produce fully contoured M-134 barrel forgings.

6. Fabrication of M-134 barrels using U700 material is extremely difficult and highly costly in terms of a cost effectiveness comparison with IN 903.

7. Fully contoured M-219 barrels containing rifling only can be successfully forged on the SHK10 GFM machine.

8. Forging M-219 barrels of H-11 material with combined rifling and chambering is impossible on the SHK10 GFM machine because of limited machine capacity, however, they may be successfully forged on a larger GFM machine.

9. The cost model developed as a result of this program can serve as a basis for further process optimization and cost reduction.

10. The cost analysis established that IN 903 must outperform H-11 M-134 barrels by a factor greater than 1.7 to be cost-effective. Although even slightly greater performance levels in a weapon system may amount to the difference between non-survival and survival and hence the cost-benefit ratio must be carefully analyzed.

11. Cost modelling procedures have established that the GFM process is superior to conventional bore and chambering operations in Cr-Mo-V steels.

5.0 GLOSSARY OF TERMS IN COST MODEL

A = Operator Allowance of 5% = 1.05

B_{TE} = Boss Diameter, in.

C = Cost/Barrel, $

C_{CD} = Center Drill Cost, $/Drill

C_{CGD} = L+OH Costs Man-Machine for Gun Drill, $/Min

C_D = Gun Drill Cost, $/Drill

C_{GD} = Gun Drill Cost, $/Drill

C_{GFM} = L+OH Costs Man-Machine for GFM Machine, $/Min

C_{FM} = Mandrel Cost for GFM, $/Mandrel

C_{GDS} = Gun Drill Sharpening Costs, $/Event

C_{ID} = Carbide Insert Costs (Diamond), $/Insert

C_{IT} = Carbide Insert Costs (Triangular), $/Insert

C_M = L+OH Costs, Man-Machine Machining, $/Min

C_{ML} = Mill Cost, $/Tool

C_{COI} = Cutoff Tool Insert Cost, $/Insert

C_{PF} = L+OH Costs, Man-Machine Preform Machining, $/Min

C_{RM} = Raw Matrial Costs, $/lb

C_W = Grinding Wheel Cost, $/Wheel

C_{TF} = Cost Finish Turn Template, $

D_{CL} = Center Lug Dia., in.

D_{FM} = Final Muzzle Dia., in.

D_{IPF} = Initial Rough Preform O.D., in.

D_{FT} = As-Turned Dia. at Lugs, in.

D_{IM} = Initial Muzzle Dia., in.

D_{IW} = Initial Grinding Wheel Dia., in.

D_{IB} = Initial Breech Diameter, in.

D_{FB} = Final Breech Diameter, in.

D_{RL} = Rear Lug Diameter, in.

D_{RTB} = Rough Turned Dia. Between Lugs, in.

D_{SW} = Stub Diameter, Grinding Wheel, in.

D_{RTM} = Rough Turned Muzzle Dia., in.

D_{C} = Chamfer Dia., in.

D_{M} = Muzzle O.D., in.

d_{b} = Depth of Cut at Breech, in.

d_{PF} = Depth of Cut on Preform O.D., in.

d_{R} = Depth of Cut for Rough Turning Barrel, in.

d_{f} = Depth of Cut for Finish Turning Barrels, in.

f_{B} = Feed Rate on Breech, in/rev.

f_{CO} = Cutoff Feed Rate, in/min.

f_{f} = Finish Turning Feed Rate, in/rev.

f_{G} = Grinding Infeed Rate, in/min.

f_{GD} = Gun Drilling Feed Rate, in/min.

f_{GFM} = Forging Infeed Rate, in/min.

f_{PF} = OD Preform Turning Feed Rate, in/min.

f_R = Rough Turning Feed Rate, in/rev.

f_M = Milling Feed Rate, in/min.

L_B = Breech Length to Rear Lug, in.

L_{FL} = Center Lug Width, in.

L_{PFS} = Length Preform Stub, in.

L_M = Length, Center Lug to Muzzle, in.

L'_M = Length Between Lugs, in.

L_{PF} = Preform Length, in.

L_{GD} = Gun Drill Life (Inches Between Sharpenings) (N_S), inches

L_{RL} = Rear Lug Width, in.

L_W = Front Lug Flat Width, in.

MRR = Metal Removal Rate $in^3/min = \pi d_i \frac{D_i + D_F}{2} (f_i)(RPM_i)$

N_B = Number of Bosses Ground Between Dressings

N_{Ci} = Number of Edges Consumed/Part CPF = Preform, CF Forging, CB Breech

N_{CD} = Number of Centers Cut/Center Drill

N_{CFT} = Number of Tool Edges Consumed/Barrel, Finish Turning, Front, Primed, Rear

N_{CRAD} = No. Tool Edges Consumed Per Radius Cut

N_{CRT} = Number Tool Edges Consumed/Barrel, Rough Turning Front, Primed, Rear

N_D = Number of Dresses per part, Lug Grind

N_{DD} = Number of Dresses per Dresser, Lug Grind

N_{DW} = Number Dresses per Wheel = 500 $(D_{IW}-D_{SW})$

N_E = Number of Edges/Insert, ET = 6 on Triangular, ED = 4 on diamond

N_{CPF} = Number of Edges Consumed/Preform Turning

N_F = Number of Forgings/Mandrel

N_f = Number of Tool Edges Consumed/Chomfer Cut

N_M = Number Lugs Milled/Tool

N_P = Number of Barrels in Lot

N_{PD} = Number of Forgings/Die Set

N_{PT} = Number of Parts Made/Template (Finish, Tracer Lathe)

N_{PW} = Number of Parts Ground/Wheel

N_{COT} = Number of Barrel Ends Cut/Tool Edge

N_S = Number of Sharpenings/Gun Drill

N_{SPF} = Number Sharpenings/Preform Drilled

RPM_B = Breech Machining

RPM_{PF} = Preform Machining

RPM_R = Rough Turning

RPM_f = Finish Machining

t_{CC} = Cut Female Center, Min.

t_{CO} = Cut Off Time, min. = $DI/2f_{CO}$

t_D = Wheel Dress Time, min.

t_{DR} = Gun Drilling time, Minutes/Barrel = L_{PF}/f_{GD}

t_G = Avg Gage Time, min.

t_{GS} = Machine Gripper Stub on Preform = $\frac{V_{PFS}}{MRR_{PF}}$, min.

t_{LU} = Load-Unload Time, min.

t_M = Cut Radius, min.

t_{OD} = OD Turn Preform = $L_{PF}/f_{PF}(RPM)$

t_{PM} = Cut Muzzle Preform Tapers, min.

t_{SU} = Setup Time, min.

t_{CD} = Center Drill Time, min.

V = Volume Stock Removed = $\frac{\pi}{4}(D_I{}^2 - D_F{}^2)\ L_I$

V_{PFS} = Volume Drive Feed Stub, in^3

W_{RM} = Raw Material Weight/Bar, lb/Bar

Y_F = Forging Yield $0 < Y < 1.0$

Y_M = Machining Yield

Y_{PF} = Preform Yield

Y_G = Grinding Yield