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COMPOSITE BARREL MATERIALS RESEARCH AND DEVELOPMENT

PHILCO-FORD CORPORATION

TECHNICAL REPORT AFATL-TR-72-3

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70

Composite Barrel Materials
Research And Development

Richard A. Harlow
Richard C. Kimball

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FOREWORD

This report was prepared by Philco-Ford Corporation, Aeronutronic Division, Newport Beach, California, under Contract No. F08635-70-C-0116 with the Air Force Armament Laboratory, Eglin Air Force Base, Florida. The report covers work performed during July 1970 through November 1971. Mr. Ralph Blair (DLDG) was program monitor for the Armament Laboratory.

This technical report has been reviewed and is approved.

Lemuel D. Horton

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ABSTRACT

A 17-month program was conducted to advance high performance gun barrel technology by fabricating, testing, and evaluating small caliber insulated composite barrels which consist of lined barrels with an insulator at the liner/jacket interface. Fabrication process development included conventional barrel-making methods as well as development of a hot swaging process for rifling. Materials investigated included iron/nickel base superalloys, cobalt base superalloys, tantalum, columbium, and tungsten refractory alloys and high temperature ceramics.

Test firings conducted on nine 7.62mm composite barrels proved the effectiveness of the insulator which lowered the mass average temperatures of the jackets by several hundred degrees during extended bursts without a sacrifice in erosion life. A computer extrapolation of the data to 30mm showed similar predicted results which provide potential for very high performance lightweight barrel designs.

The final effort on the program consisted of fabricating eight .220 Swift/M-60 tes [illegible] ls for delivery to the Air Force.

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SECTION I

INTRODUCTION

During recent years, the necessity for improved gun barrel designs has become increasingly apparent with the inception of new high performance cased and caseless weapon systems. The requirements for high muzzle velocities, higher firing rates, and extended burst firing schedules have isolated barrels as perhaps the most critical of performance-limiting gun components. The more severe service requirements not only drastically increase barrel erosion rates and shorten barrel lives, but also present a more serious problem of barrel overheating and resulting structural failure.

In 1969, under Air Force Contract No. F08635-69-C-0156 entitled "Equilibrium Temperature Gun Concepts," Philco-Ford Corporation, Aeronutronic Division conducted a study in search of concepts to alleviate the problems associated with very high performance weapons. The study included advanced composite barrel materials, cooling techniques, ammunition modifications, and/or combinations of each. The insulated composite barrel evolved from this study as one of the most promising approaches to high performance barrel designs. The insulated composite barrel concept consists of a high temperature erosion-resistant (refractory alloy or superalloy) liner surrounded by a thin layer of ceramic insulation and encased within a high strength, lower temperature (steel or superalloy) outer jacket. The high temperature liner provides improved erosion resistance even under extreme firing schedules; the insulator reduces the heat loads to the outer jacket, thereby providing a capability for more severe firing schedules without structural failure or a significant increase in barrel weight.

Under internal funding, Philco-Ford conducted a small preliminary program to develop a design, an insulator, and an assembly process for 7.62mm barrels with partial length insulated inserts. A limited amount of test data indicated that the concept appeared feasible and that further development and testing were desirable.

In 1970, Contract No. F08635-70-C-0116, Composite Barrel Materials Research and Development, was initiated which is the subject of this report. This contract consisted of a 17-month three-phase effort which included materials selection, fabrication process development, 7.62mm insulated composite barrel design, testing and analysis, and fabrication and delivery of .220 Swift insulated composite test barrels to the Air Force. A summary of the program and resulting conclusions and recommendations are presented in Section II. Sections III, IV and V present detailed procedures and results of the research and development effort conducted in Phases I, II, and III, respectively.

SECTION II

SUMMARY

2.1 TECHNICAL APPROACH

The objective of this program was to advance gun barrel technology by developing a relatively new concept, designated as insulated composite gun barrels, which consists of a high temperature erosion resistant (superalloy or refractory metal) liner, externally insulated by a thin layer of ceramic and encased within a high strength, lower temperature (steel or superalloy) outer jacket. This concept offers a potential improvement in erosion life and also increases performance capabilities to withstand higher firing rates, longer bursts, and higher propellant flame temperatures.

The approach to the program was to conduct materials selection, fabrication development, barrel erosion testing, and analysis on small caliber 7.62mm or .220 Swift barrels, such that the results would also be applicable to larger caliber developmental cased and caseless high cyclic rate, high performance guns. A three-phase, 17-month effort was conducted.

Phase I consisted of materials selection and fabrication process development to isolate those materials and methods capable of producing economical and reliable insulated composite gun barrels. During this phase, nine 7.62mm test barrels compatible with a MG-3 machine gun were fabricated. Each barrel incorporated an erosion-resistant insert either insulated or non-insulated approximately 5 inches long, shrink fitted into the breech end. The insert materials included WC-3015, Ta-10W, L-605, VM-103, W-2.5 (Fe + Ni + Cu), and ZrB_2-VIII. The insulators were ZrO_2 base and represented two types (H-200 and H-300) previously developed by Philco-Ford, and the outer jacket materials included L-605, CG-27, Pyromet 860, and Haynes 188. The fabrication methods consisted of conventional gun drilling and O.D. machining, rifling by a single point hook cutter, and rifling by swaging. The various insert and jacket materials presented differing fabrication problems, and some required a considerable amount of fabrication process development. All nine barrels were successfully fabricated. Further Phase I details are presented in Section III.

Phase II involved testing and analysis of the nine Phase I barrels. Testing was accomplished on a MG-3 (recoil-operated single barrel) machine gun capable of firing 1100-1200 rpm. Comparative firing schedules of increasing severity were selected, and continuous bursts of lengths up to 700 rounds were utilized. The temperature of each barrel was measured at five locations on the O.D. during the burst firings. Muzzle velocity and accuracy were also monitored. The criteria for barrel failure were a muzzle velocity decrease of 10 percent from its original value and/or when ≥ 20 percent of the projectiles exhibited $\geq 15°$ yaw. M61 armor-piercing (AP) ammunition with WC-846 propellant was utilized for all tests.

The erosion data are summarized in Table I. Based on these results, it appeared that WC-3015, VM-103, and L-605 were the most promising barrel liner candidates. All the jacket materials performed well with little or no evidence of erosion. The insulators showed no deterioration or breakup and remained completely intact after longitudinal sectioning of the barrels during post-test evaluation.

Analysis of the thermal data showed considerably lower O.D. temperatures for insulated barrels compared to non-insulated barrels fabricated from the same materials. For example, barrels MGB-3 and MGB-4 (Table I) showed maximum O.D. temperatures of ~1200°F and ~800°F, respectively, near their breech ends after a 400-round continuous burst. Temperature profiles were calculated by computer for various cases, and these data were extrapolated by means of a computer to a typical high performance 30mm barrel.

The third phase of the program consisted of fabricating eight insulated composite barrels for delivery to the Air Force. The barrels were fabricated to a M-60 configuration modified to be compatible with .220 Swift ammunition. The barrels consisted of WC-3015, VM-103, and L-605 inserts, CG-27 and Haynes 188 jackets, and H-203 and H-304 insulators. Machining techniques developed under Phase I were utilized for all components except the WC-3015 inserts. A warm swaging process was successfully developed for rifling these components by means of a subcontract to Battelle Northwest Laboratories. All eight barrels were successfully fabricated and delivered to the Air Force, which concluded the technical effort.

2.2 CONCLUSIONS AND RECOMMENDATIONS

Based on the effort summarized above and detailed in Sections III, IV, and V, the following conclusions and recommendations were made:

1. The insulated composite barrel concept was proven feasible, attractive, and producible for high performance barrels. Compared to conventional homogeneous barrels, this concept offers a potential capability for:

    - Higher performance
    - Improved erosion life
    - Minimum weight.

2. Based on computer extrapolations of 7.62mm data to 30mm, insulated composite barrels may have potential for larger caliber high performance developmental guns.

TABLE I. SUMMARY OF BARREL EROSION TEST DATA

Serial No.	Insert	Jacket	Insulation	Number of Bursts*							Total Rounds	Total Erosion Rate (Mils/1000 Rounds)	Remarks
				≤199	200-299	300-399	400-499	500-599	600-699	700-799			
MGB-1	WC-3015	L-605	None	4	2	0	5	0	2	0	4212	0.7	Tests terminated prior to failure
MGB-2	WC-3015	L-605	H-203	4	0	0	8	0	3	0	5575	0.2	Tests terminated prior to failure
MGB-3	Ta-10W	L-605	None	0	1	0	3	0	0	0	1440	4.6	Tests terminated prior to failure
MGB-4	Ta-10W	L-605	H-203	0	3	1	2	0	0	0	1818	3.9	Failure ~20% yaw
MGB-5	L-605	CG-27	None	3	3	1	6	1	3	1	6813	0.2	Tests terminated prior to failure
MGB-6	VM-103	CG-27	None	4	1	3	8	1	3	1	9084	1.1	Tests terminated prior to failure
MGB-7	W Alloy	Pyromet 860	H-203	0	1	0	1	0	0	0	657	2.3	Severe erosion
MGB-8	W Alloy	Pyromet 86	H-304	3	0	0	0	0	0	0	334	5.1	Severe erosion
MGB-9	ZrB_2	Haynes 188	H-203	5	0	0	0	0	0	0	361	**	Insert fractured during checkout bursts of 200 rounds

* Bursts <400 rounds due to gun malfunction or preliminary checkout.
**Not measurable.

3. Further effort should be devoted toward developing full length insulated composite barrel fabrication processes applicable to larger calibers.

4. More process development effort should be devoted to machining, gun drilling, and rifling of superalloy and refractory metal liners.

5. The search for improved liner materials and/or coatings should be continued.

SECTION III

PHASE I: FABRICATION DEVELOPMENT

The goal for Phase I was to develop reliable fabrication processes for producing insulated composite barrels. The potential fabrication methods were selected such that the technology, developed for 7.62mm barrels, would also be applicable to larger calibers. A sketch of the basic 7.62mm barrel design, which was of a MG-3 configuration, is shown in Figure 1. The breech end of the barrel was redesigned to accept an insulated insert backed up by a chamber insert, as shown in Figure 2. This design was later changed to that shown in Figure 3 to prevent longitudinal movement of the forward inserts as discussed in Section IV. The dimensions were selected to provide a 0.001-inch interference fit between the inserts and barrel jackets. The barrels were assembled by shrink fitting.

The combinations of materials selected for the nine 7.62mm MG-3 test barrels are shown in Table II along with the nominal compositions of each. The L-605 was solution treated and then cold worked 25 percent for increased strength prior to machining since the alloy is known to retain some of the strengthening effects of cold work for short times at elevated temperatures. Haynes 188, a similar alloy, was also solution treated and 20 percent cold worked. The CG-27 and Pyromet 860 alloys were solution treated and fully aged prior to all gun drilling and machining operations. The VM-103 was fabricated in the solution heat-treated condition. The Ta-10W and WC-3015 were in annealed conditions.

Conventional gun drilling, turning, and single point hook cutter rifling operations were attempted on all materials with varying results summarized in Table III. The qualitative ratings shown in Table III are based on a comparison with Aeronutronic's experience on typical Cr-Mo-V gun steels, which would be assessed an "A" rating.

The intermediate temperature iron/nickel base superalloys, Pyromet 860 and CG-27, could be fabricated with little or no difficulty but took considerably more time than conventional steels. The three cobalt base superalloys, L-605, Haynes 188, and VM-103, created some problems involving tool breakage on gun drilling and were generally more time consuming than the Pyromet 860 or CG-27 alloys, although good surface finishes and high quality components were achieved. The Ta-10W and WC-3015 created many problems due to their high tendency for galling during each operation, particularly rifling. Good surface finishes could not be achieved on either alloy by conventional rifling techniques, which required that the Phase III WC-3015 inserts be rifled by swaging as discussed in Section V. Carbide cutting tools proved to be more satisfactory than tool steels for all operations except rifling of the iron/nickel base superalloys.

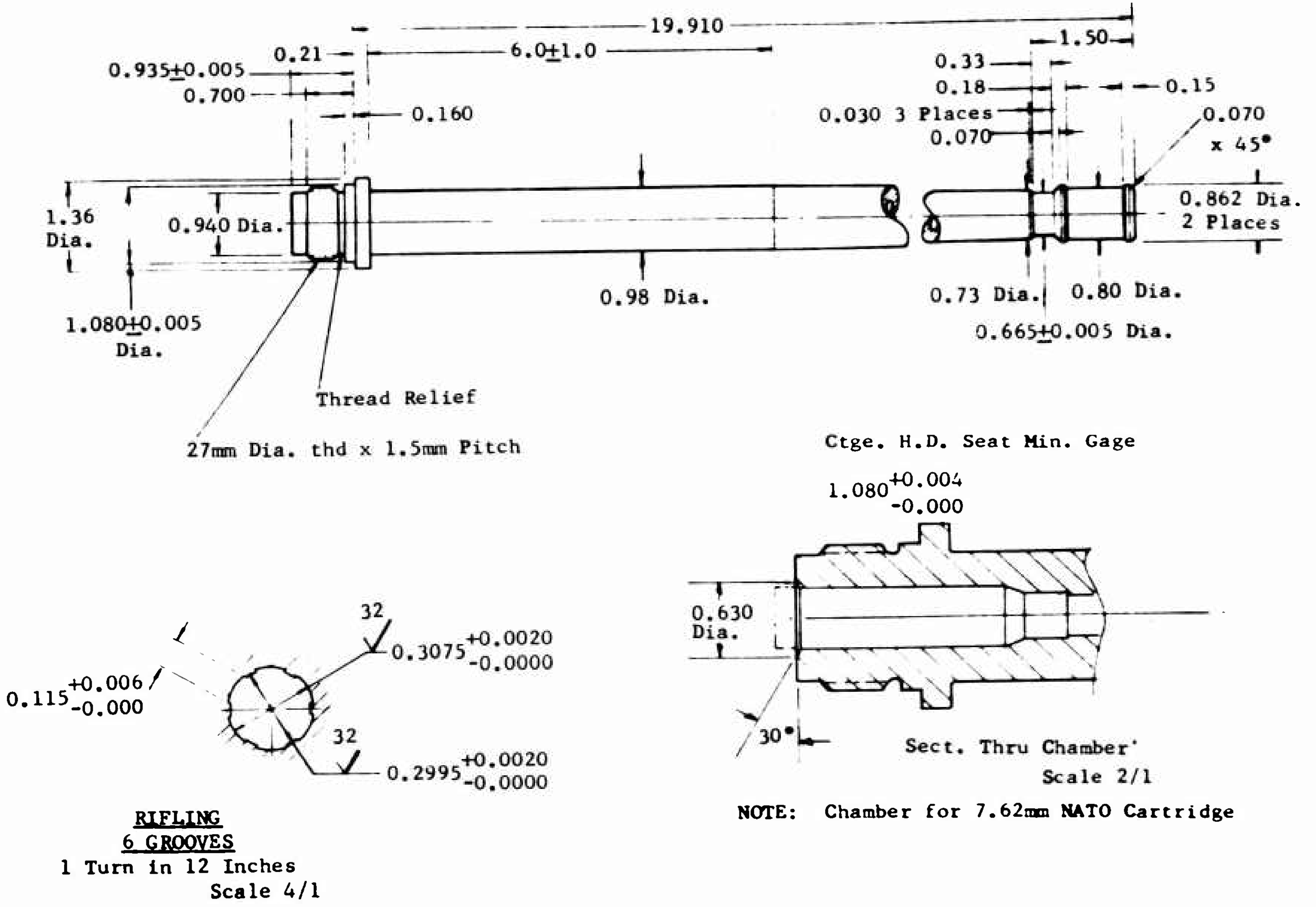


Figure 1. MG-3 Test Barrel

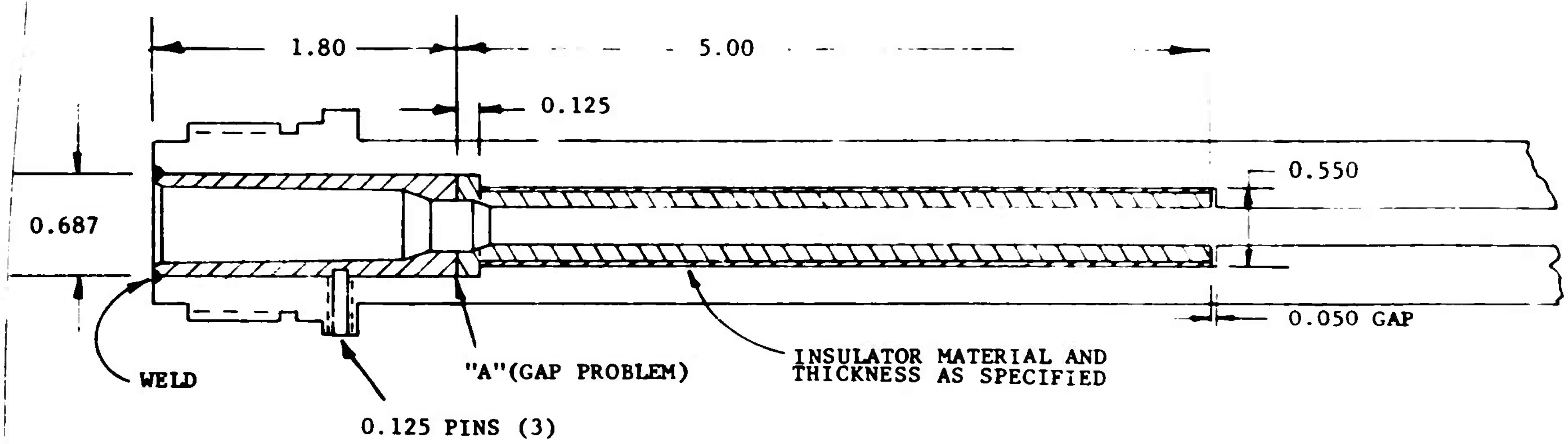


Figure 2. Insulated Composite Barrel for MG-3

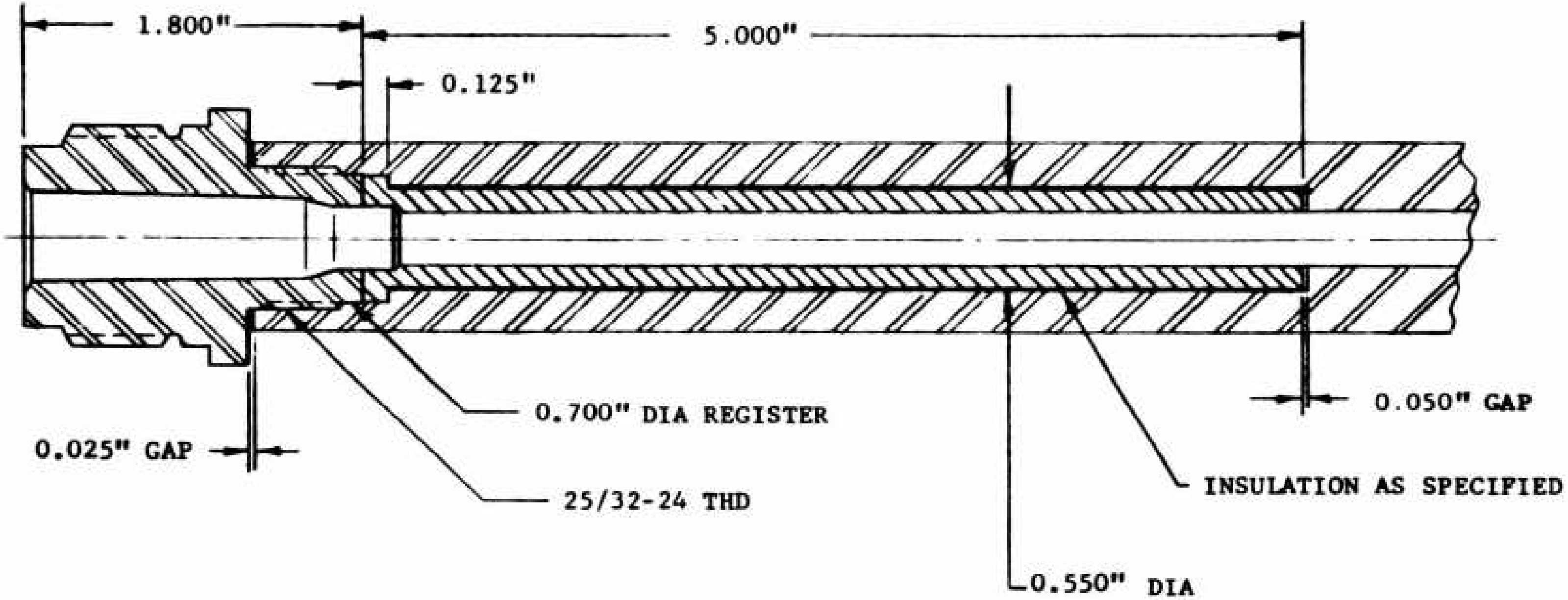


Figure 3. Insulated Composite Barrel for MG-3 (Revision A)

TABLE II. MATERIALS FOR PHASE I BARRELS

Materials Combinations			
Barrel Serial No.	Jacket Material	Insulator	Insert Material
MGB-1	L-605	None	WC-3015
MGB-2	L-605	H-203	WC-3015
MGB-3	L-605	None	Ta-10W
MGB-4	L-605	H-203	Ta-10W
MGB-5	CG-27	None	L-605
MGB-6	CG-27	None	VM-103
MGB-7	Pyromet 860	H-203	W Alloy
MGB-8	Pyromet 860	H-304	W Alloy
MGB-9	Haynes 188	H-203	ZrB$_2$-VIII

Nominal Materials Compositions (Weight Percent)	
L-605	Co + 10Ni + 20Cr + 15W + 3Fe* + 1Si* + 1.5Mn + 0.1C
CG-27	Fe + 38Ni + 13Cr + 5.75Mo + 2.5Ti + 1.6Al + 0.7Cb + 0.01B to 0.05C
VM-103	Co + 25W + 3Cr + 1Ti + 0.5Zr + 0.5C
Pyromet 860	Fe + 42Ni + 14Cr + 6Mo + 4Co + 3.3Ti + 1.2Al + 1.0Si* + 1Mn* + 0.01B + 0.1C*
Haynes 188	Co + 22Ni + 22Cr + 14W + 1.5Fe + 0.08C + 0.2Si + 0.08La
WC-3015	Cb + 29Hf + 1.5Zr + 14.5W + 2Ta + 2.5Ti + 0.2C
Ta-10W	Ta + 10W
W Alloy	W + 2.5(Fe + Cu + Ni)
ZrB$_2$-VIII	ZrB$_2$ + 11SiC + 34C
H-203	Yttria stabilized ZrO$_2$
H-304	Yttria stabilized ZrO$_2$

* Maximums

TABLE III. QUALITATIVE COMPARISON OF MACHINABILITY RATINGS OF CANDIDATE BARREL MATERIALS*

	Gun Drilling and Honing	Rifling	Turning	Overall Rating
Pyromet 860	B	B	B	B
CG-27	B	B	B	B
20% Cold Worked L-605	C	B	B	B-
20% Cold Worked Haynes 188	C	B	B	B-
VM-103	C	B	C	C+
WC-3015	D	E	D	D-
Ta-10W	D	E	D	D-
ZrB_2-VIII	D	D	**	D

*Explanation of Comparative Machinability Ratings:

	Difficulty Encountered	Machining Time Required	Surface Finish Achieved
A (Excellent)	None	Low	Good
B (Good)	Low	Medium	Good
C (Fair)	Medium	Medium	Good
D (Poor)	High	High	Good
E (Very Poor)	High	High	Poor

** Grinding was utilized

In addition to consideration of the basic materials' machinability characteristics, questions regarding optimum fabrication and assembly sequences were investigated. The initial approach was to shrink fit the inserts into the unrifled barrel jacket, hone the bore of the entire assembly to achieve maximum concentricity and alignment, and then attempt to rifle the assembled composite in one operation. The shrink fitting operation was successfully accomplished by heating the jacket in an air furnace to approximately 1000°F, then inserting the forward and aft inserts. [As indicated previously, the design incorporated a 0.001-inch diametrical interference fit between the inserts and jackets (Figure 2).] This procedure proved successful, but application of longitudinal pressure to the rear insert in a hydraulic press during cooling was necessary to prevent the two inserts from backing out of the jacket. The rear insert was subsequently TIG-welded in place, as shown in Figure 2. Later, upon adopting the redesign in Figure 3 a mandrel was used to hold the forward insert in place on the press during cool-down. No difficulty was achieved in honing the bore of the shrink-fitted assembly to within the desired tolerances. Approximately 0.002-inch was left on the bore I.D. for the honing operation.

Attempts to simultaneously rifle the shrink-fitted insert and barrel jacket assemblies (barrels MGB-1 - 4) met with considerable difficulty due to the wide variation in machining characteristics of the various materials combinations. It was necessary to make additional rifling machining passes on the jacket portion after the inserts were rifled to size. Based on this experience, the remaining barrels were processed differently with fewer problems, i.e., the inserts were rifled prior to shrink fitting, and the jackets were rifled to match the inserts after shrink fitting. The processing flow diagram for the remaining Phase I barrels is shown in Figure 4.

As mentioned previously, the H-200 and H-300 series insulators were developed by Philco-Ford prior to the award of this contract. These two proprietary series respectively consist of plasma spraying or tape wrapping yttria-stabilized zirconia with various compositional additives for adherence, then grinding to the desired size and concentricity. No difficulty or additional development effort was encountered during fabrication of the Phase I insulated barrels, and it appears that either type of insulation could be utilized on a production basis.

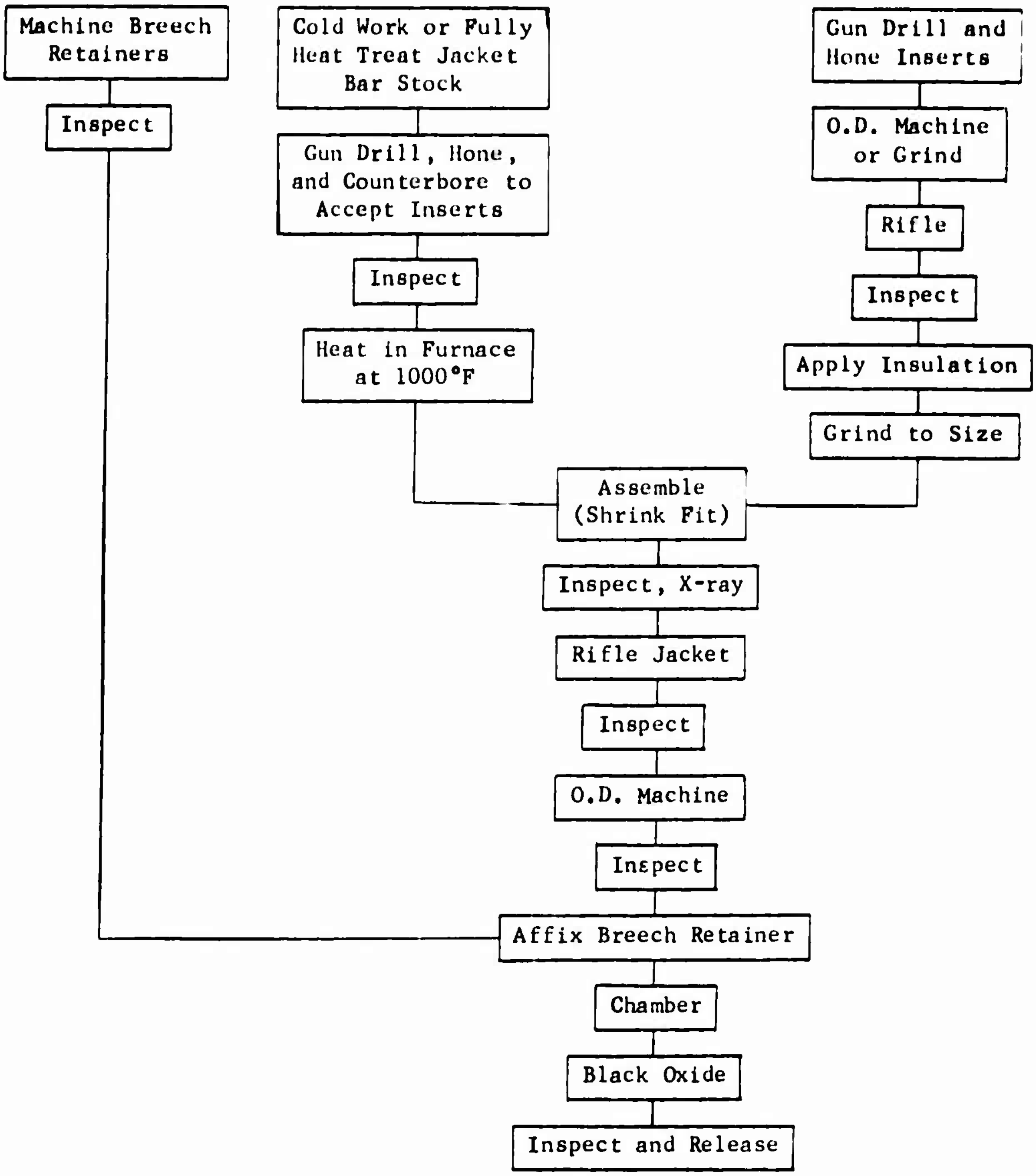


Figure 4. Insulated Composite Barrel Fabrication Sequence

SECTION IV

PHASE II: 7.62MM BARREL TESTING AND ANALYSIS

4.1 TESTING PROCEDURE

The MG-3 test weapon was set up at the Capistrano Test Facility. The gun, which was fired remotely, is capable of firing 1100-1200 rpm and has previously been fired in burst lengths of 800 rounds at Aeronutronic. The weapon was located approximately 50 feet from a cardboard target used to detect projectile yaw and/or drift resulting from barrel warpage. A Lumiline/recorder system was used to measure the muzzle velocity of each round. The gun with an instrumented barrel removed is shown in Figure 5.

The ammunition supplied by the Air Force was 7.62mm M-61 armor piercing with WC-846 propellant. The rounds were linked with M-13 disintegrating links which are completely compatible with the MG-3 gun.

Temperature measurements were made at five locations by means of thermocouples attached to the barrels and monitored by a multipoint recorder. The locations, hereafter designated as stations 1-5, were selected such that station 1 was located on the O.D. radially opposite the mouth of the cartridge, and stations 2, 3, 4, and 5 were spaced 2, 4, 10, and 16 inches, respectively, from station 1 toward the muzzle.

Erosion measurements were made by means of RTV-30 silicone rubber replicas and/or star gage after each burst.

The test schedule selected was very severe in order to simulate calculated thermal environments of developmental larger caliber weapons. The schedule then increased in severity to determine the possible ultimate performance of each barrel. Attempts to test all barrels identically were made such that comparative erosion and thermal performance data could be generated. The schedule selected follows:

No. of Bursts	Burst Length (rounds)
5	400
5	600
2	700
2	800
2	900
N to failure	1000

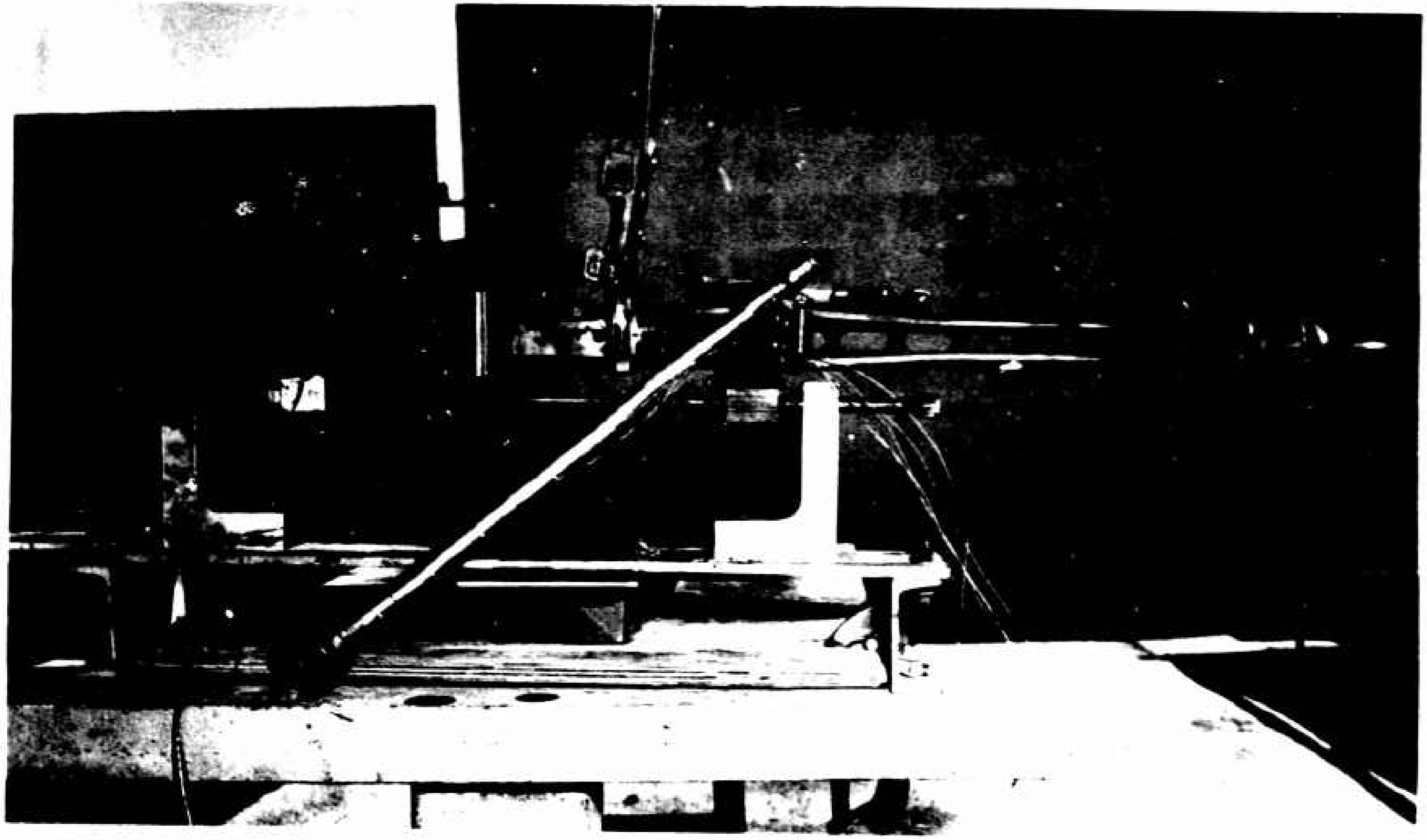


Figure 5. MG-3 Test Weapon with Instrumented Barrel Removed

The barrels were cooled to ambient temperature prior to each burst. As with any test program, variations occurred due to gun stoppages, etc., but reasonably comparable data were acquired, as discussed in paragraph 4.2.

4.2 TEST RESULTS

4.2.1 OVERALL BARREL PERFORMANCE

The initial question during the test program was whether the insulated composite barrel concept would involve any inherent design or structural performance limitations as a result of the brittle ceramic insulators, differential thermal expansions of the various materials, etc. As noted in Figure 2, an expansion gap was designed at the forward end of the insulated insert to accommodate the higher temperatures anticipated for those components. The chamber insert was pinned and welded (Figure 2) to prevent longitudinal movement or backing out. After many 400- and 600-round bursts on several of the initial barrels, sufficient movement of the two inserts occurred, in spite of these precautions, to create a small gap between the chamber insert and the insulated insert, which created a fire-forming problem with the steel cartridge cases and resulted in gun stoppages. To alleviate this problem, the barrels were modified to eliminate the rear insert, as shown in Figure 3, to allow a positive, longitudinal pressure to be exerted upon the breech end of the insulated insert. This modification proved very satisfactory and was adopted for the .220 Swift/ M-60 Phase III barrels.

No other mechanical or structural difficulties were encountered in testing the barrels. The gun-firing rate varied from 900-1150 rpm; however, the majority of bursts were between 1000 and 1050 rpm. The insulators remained completely intact and crack-free, even after post-test sectioning of the barrels and removal of the inserts.

4.2.2 EROSION DATA

A summary of the erosion data generated on the nine 7.62mm test barrels is included in Table I. This table documents the complete firing history of each barrel and includes an accounting of the shorter-than-planned burst firings resulting from gun stoppages and checkouts. The total erosion rates (Table I) of the various insert materials which were calculated to serve as a basis for comparison are somewhat useful but can be very misleading unless the firing schedules and total rounds fired are concurrently considered. The rates indicate that WC-3015, L-605, and VM-103 were the most promising liner materials of those tested. The most significant data generated on burst lengths near 400 rounds or greater are recorded in Tables IV - XII for barrels MGB-1 through MGB-9, respectively. Shorter burst data are included for MGB-7, 8, and 9 due to their poor performance which precluded much extensive testing. No measurable erosion

TABLE IV. SUMMARY OF TEST DATA FOR MGB-1*

Run No.	Burst	Maximum O.D. Temperature (°F)	Velocity (ft/sec)		Maximum Erosion (in.)		Accuracy (Yaw)
			Initial	Final	Insert	Jacket	
14	400	**	2717	2712	<0.0005	<0.0006	None
15	400	**	2727	2669	<0.0005	<0.0005	None
16	400	**	2705	2691	0.0005	<0.0005	None
22	400	989	2723	2713	0.001	<0.0005	None
25	400	1044	2714	2703	0.001	<0.0005	None
47	600	1355	2720	2667	0.002	<0.0005	None
58	600	1338	2711	2623	0.003	<0.0005	None

* Jacket: 20% Cold Worked L-605
Insert: WC-3015
Insulator: None

**Instrumentation Malfunctioned

TABLE V. SUMMARY OF TEST DATA FOR MGB-2*

Run No.	Burst	Maximum O.D. Temperature (°F)	Velocity (ft/sec)		Maximum Erosion (in.)		Accuracy (Yaw)
			Initial	Final	Insert	Jacket	
29	400	8[illegible]2	2716	2729	<0.0005	<0.0005	None
30	400	803	2697	2735	<0.0005	<0.0005	None
31	400	786	2717	2735	<0.0005	<0.0005	None
33	400	820	2722	2735	<0.0005	<0.0005	None
34	400	829	2722	2728	<0.0005	<0.0005	None
48	600	1103	2674	2717	<0.0005	<0.0005	None
59	600	1082	2695	2657	<0.0005	<0.0005	None
65	489	905	2703	2717	<0.0005	<0.0005	None
70	473	892	2735	2738	0.001	0.0005	None
87	600	1052	2700	2615	0.001	<0.0005	None
90	423	833	2690	2620	0.0012	<0.0005	None

* Jacket: 20% Cold Worked L-605
Insert: WC-3015
Insulator: 0.025" H-203

TABLE VI. SUMMARY OF TEST DATA FOR MGB-3*

Run No.	Burst	Maximum O.D. Temperature (°F)	Velocity (ft/sec)		Maximum Erosion (in.)		Accuracy (Yaw)
			Initial	Final	Insert	Jacket	
75	400	1222	2687	2555	0.004	<0.0005	None
81	400	1201	2623	2529	0.005	<0.0005	None
84	400	1201	2577	2478	0.007	<0.0005	None

* Jacket: 20% Cold Worked L-605
Insert: Ta-10W
Insulator: None

TABLE VII. SUMMARY OF TEST DATA FOR MGB-4*

Run No.	Burst	Maximum O.D. Temperature (°F)	Velocity (ft/sec)		Maximum Erosion (in.)		Accuracy (Yaw)
			Initial	Final	Insert	Jacket	
80	400	862	2672	2655	0.003	<0.0005	None
85	319	649	2653	2643	0.006	<0.0005	<<1%
99	400	926	2685	2660	0.007	<0.0005	>20%

* Jacket: 20% Cold Worked L-605
Insert: Ta-10W
Insulator: 0.025" H-203

TABLE VIII. SUMMARY OF TEST DATA FOR MGB-5*

Run No.	Burst	Maximum O.D. Temperature (°F)	Velocity (ft/sec)		Maximum Erosion (in.)		Accuracy (Yaw)
			Initial	Final	Insert	Jacket	
36	400	947	2795	2790	<0.0005	<0.0005	None
37	400	905	2787	2778	<0.0005	<0.0005	None
39	400	913	2795	2759	<0.0005	<0.0005	None
43	400	968	2801	2734	<0.0005	<0.0005	None
50	400	862	2778	2786	<0.0005	<0.0005	None
51	423	939	2775	2826	<0.0005	<0.0005	None
61	600	1243	2781	2728	<0.0005	<0.0005	None
64	600	1286	2750	2710	<0.0005	<0.0005	None
68	600	1295	**	**	0.001	0.0006	None
107	532	1146	2775	2740	0.001	0.0007	None
108	700	1395	2750	2710	0.0015	0.0013	None

* Jacket: CG-27
Insert: L-605
Insulator: None

**Instrumentation Malfunctioned

TABLE IX. SUMMARY OF TEST DATA FOR MGB-6*

Run No.	Burst	Maximum O.D. Temperature (°F)	Velocity (ft/sec)		Maximum Erosion (in.)		Accuracy (Yaw)
			Initial	Final	Insert	Jacket	
38	400	1031	2723	2750	<0.0005	<0.0005	None
40	400	968	2758	2762	<0.0005	<0.0005	None
42	400	989	2752	2743	<0.0005	<0.0005	None
45	400	989	2731	2735	<0.0005	<0.0005	None
49	400	972	2706	2693	0.001	<0.0005	None
52	469	1124	2716	2701	0.001	<0.0005	None
54	359	939	**	**	0.001	<0.0005	None
60	600	1372	2698	2648	0.003	<0.0005	None
62	476	1137	2664	2653	0.003	<0.0005	None
76	550	**	2672	2632	0.005	<0.0005	None
86	600	**	**	**	0.006	<0.0005	None
88	491	**	**	2610	0.006	<0.0005	None
89	600	**	2625	2610	0.007	<0.0005	<10%
93	700	1538	**	**	0.008	0.0005	<10%
94	614	**	2620	2550	0.010	0.0009	<10%

* Jacket: CG-27
Insert: VM-103
Insulator: None
**Instrumentation Malfunctioned

TABLE X. SUMMARY OF TEST DATA FOR MGB-7*

Run No.	Burst	Maximum O.D. Temperature (°F)	Velocity (ft/sec)		Maximum Erosion (in.)		Accuracy (Yaw)
			Initial	Final	Insert	Jacket	
82	400	1023	2697	2465	0.0015	<0.0005	None

* Jacket: Pyromet 860
Insert: W-2.5(Fe + Ni + Cu)
Insulator: 0.025" H-203

TABLE XI. SUMMARY OF TEST DATA FOR MGB-8*

Run No.	Burst	Maximum O.D. Temperature (°F)	Velocity (ft/sec)		Maximum Erosion (in.)		Accuracy (Yaw)
			Initial	Final	Insert	Jacket	
95	116	296	2725	2730	<0.001	<0.0005	None
97	162	408	2720	2735	0.0017	<0.0005	None

* Jacket: Pyromet 860
Insert: W-2.5(Fe + Ni + Cu)
Insulator: 0.017" H-304

TABLE XII. SUMMARY OF TEST DATA FOR MGB-9*

Run No.	Burst	Maximum O.D. Temperature (°F)	Velocity (ft/sec)		Maximum Erosion (in.)		Accuracy (Yaw)
			Initial	Final	Insert	Jacket	
101	10	**	**	**	<0.0005	<0.0005	None
102	25	**	**	**	<0.0005	<0.0005	None
103	50	**	**	**	<0.0005	<0.0005	None
104	94	**	**	**	<0.0005	<0.0005	None
105	192	484	2620	2685	***	<0.0005	None

* Jacket: Haynes 188
Insert: ZrB_2
Insulator: 0.025" H-203
**Not instrumented during initial checkout bursts
***Insert fractured

occurred on the jackets of any of the nine barrels, except for localized erosion of the bore at the expansion gap between the insert and jacket. Since all jacket materials performed so well, no conclusions regarding relative erosion rates of these materials could be drawn. Discussions of each insert material based on test data and post-test metallographic examinations are included in the following paragraphs.

The WC-3015 inserts in barrels MGB-1 and MGB-2 performed well, withstanding 4200 and 5600 rounds, respectively. Testing was terminated prior to failure on these barrels due to the insert gap problem discussed in paragraph 4.2.1. The insert portion of MGB-2 is shown in Figure 6. Considerable erosion and some galling can be seen. Also, the expansion gap which was loaded with copper appears considerably wider than designed which must have resulted from a machining error. Note that the insulator appears unharmed. Figure 7 shows a photomicrograph of the worst area detectable in the maximum erosion area. As can be seen, considerable cracking occurred at the bore surface. A thin oxide layer was also apparent on the bore surface. This characteristic of the alloy may be beneficial and afford some degree of protection. As mentioned previously, the initial surface finishes of the WC-3015 inserts were poor due to machining difficulties which could have somewhat adversely affected their erosion performance.

The Ta-10W inserts showed poor erosion resistance, and the MGB-4 failed after only 1800 rounds (including three 400-round bursts). Galling was predominant, as shown in Figure 8, and severe intergranular cracking was prevalent throughout the eroded areas, as evidenced in Figure 9. These data may also have been somewhat adversely affected by the poor initial surface of the insert resulting from machining problems.

The cobalt base superalloys, L-605 and VM-103, showed excellent erosion resistance and much less galling than the refractory metals (Figures 10 and 12). Both alloys endured extreme firing schedules, even including a 700-round burst. Although the VM-103 showed a higher total erosion rate, it endured considerably more burst firings than L-605, such that a conclusion regarding which alloy is better cannot be made based on these two barrels. Also, both alloys showed similar slight cracking at the bore as shown in Figures 11 and 13. VM-103 showed slightly more oxidation as expected, since L-605 has better oxidation resistance.

The W-2.5 (Fe + Ni + Cu) alloy demonstrated extremely poor erosion resistance. Figure 14 shows the very severe erosion after only one 400-round burst on barrel MGB-7. A photomicrograph of the eroded area of this barrel is shown in Figure 15. As can be seen, the powder metallurgy product consists of spherical particles with a metallic binder. The binder apparently had insufficient strength to hold up during firing, so that any beneficial effects of tungsten were not realized. No additional testing was considered worthwhile on these two barrels.

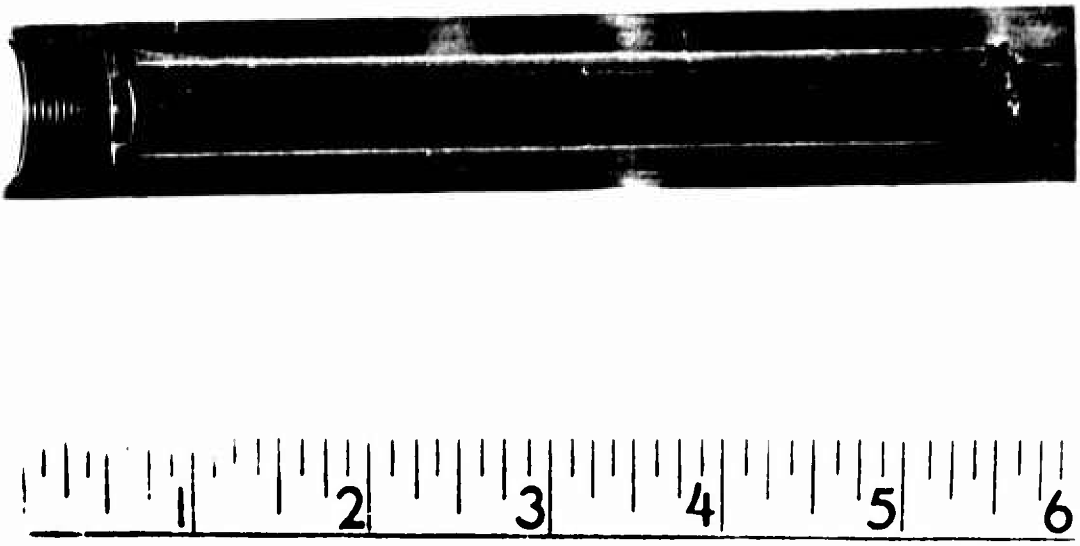


Figure 6. Sectioned Barrel MGB-2 After Firing 5600 Rounds

Etchant: Equal parts 50X
Lactic Acid, HNO_3, Hf, H_2O_2

Figure 7. Photomicrograph of Eroded WC-3015 from MGB-2

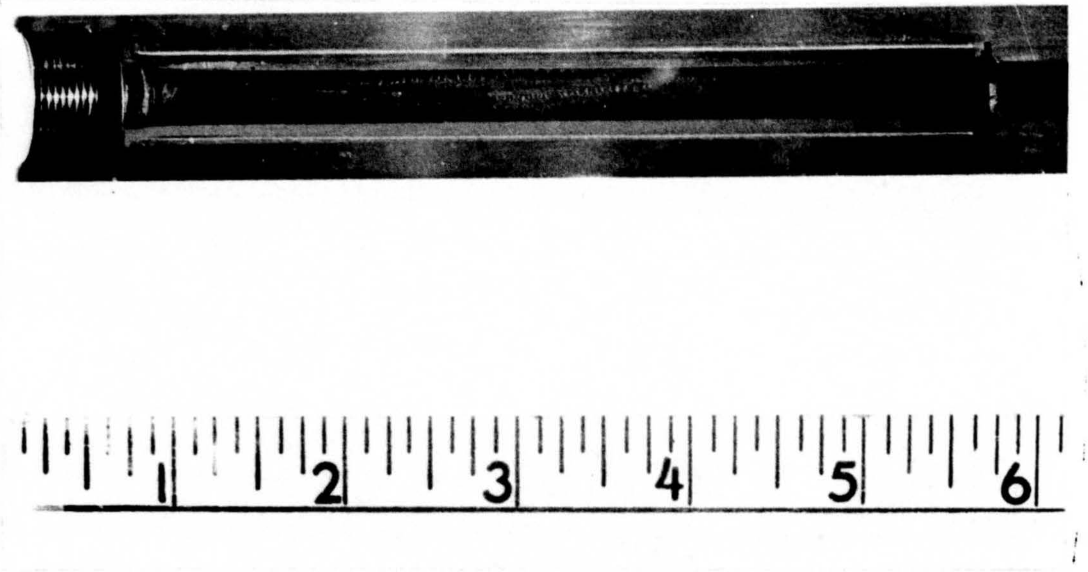
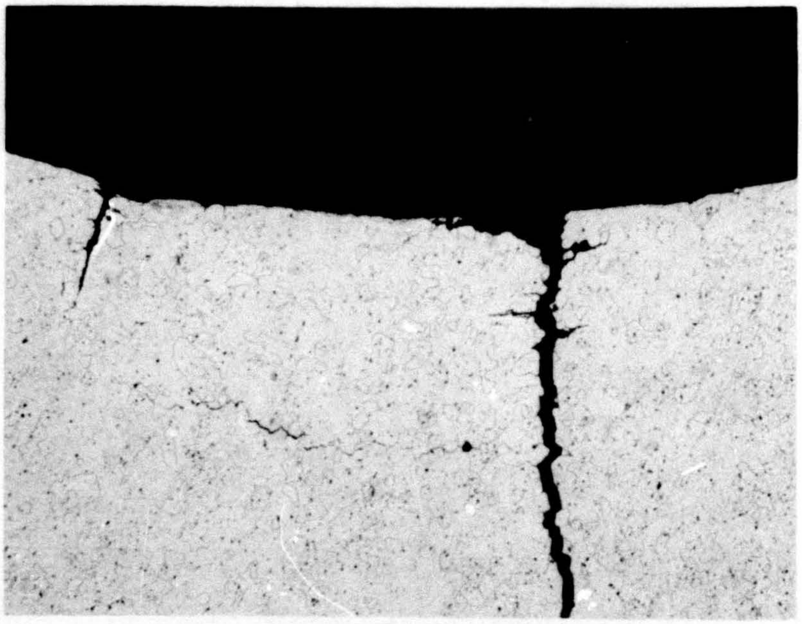


Figure 8. Sectioned Barrel MGB-4 After Firing ~1800 Rounds



Etchant: Equal parts
Lactic Acid, HNO_3, Hf, H_2O_2

50X

Figure 9. Photomicrograph of Eroded Ta-10W from MGB-4

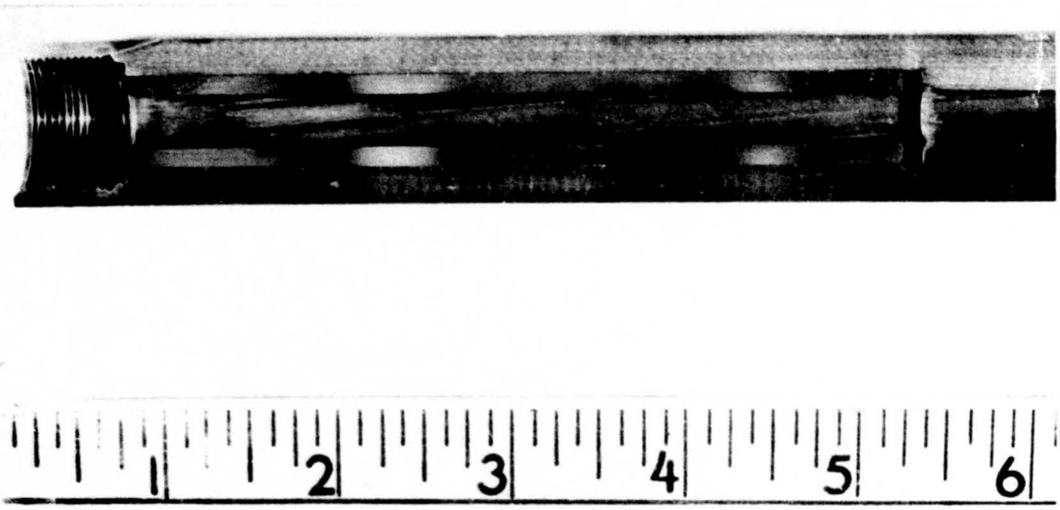
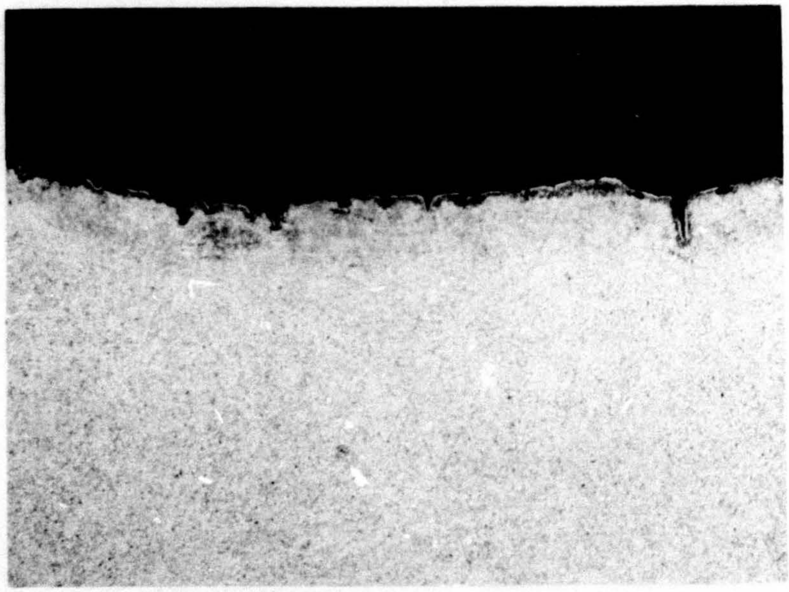


Figure 10. Sectioned Barrel MGB-5 After Firing ~6800 Rounds



Etchant: 5g $FeCl_3$,
100 ml HCl

50X

Figure 11. Photomicrograph of Eroded L-605 from MGB-5

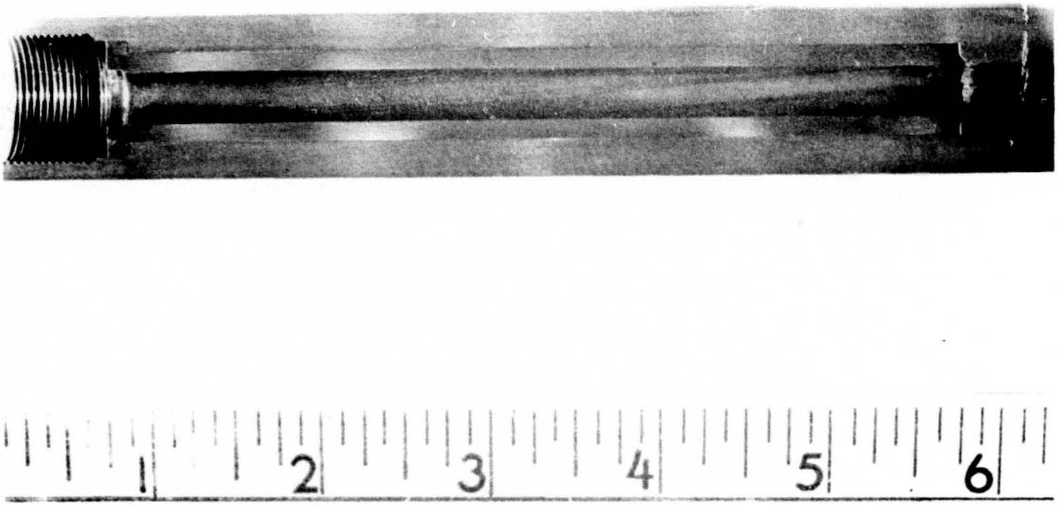
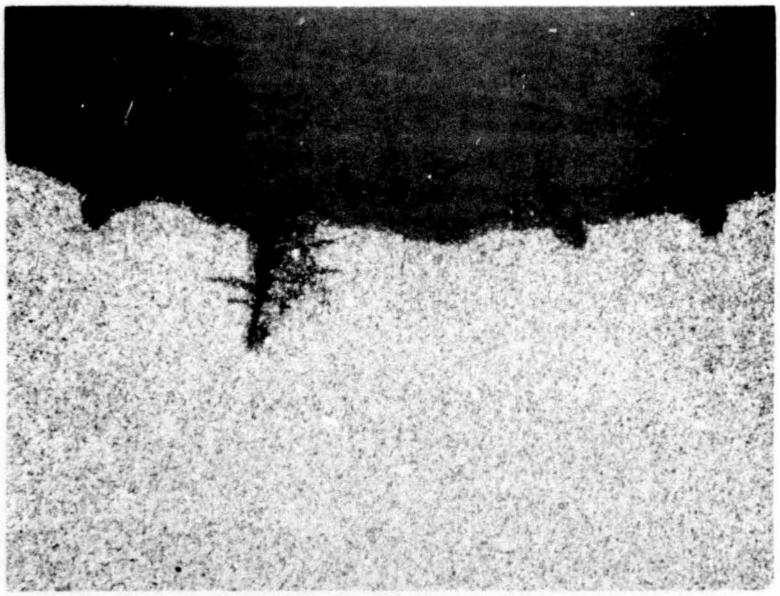


Figure 12. Sectioned Barrel MGB-6 After Firing ~9100 Rounds



Etchant: 5 g $FeCl_3$, 100 ml HCl 50X

Figure 13. Photomicrograph of Eroded VM-103 from MGB-6

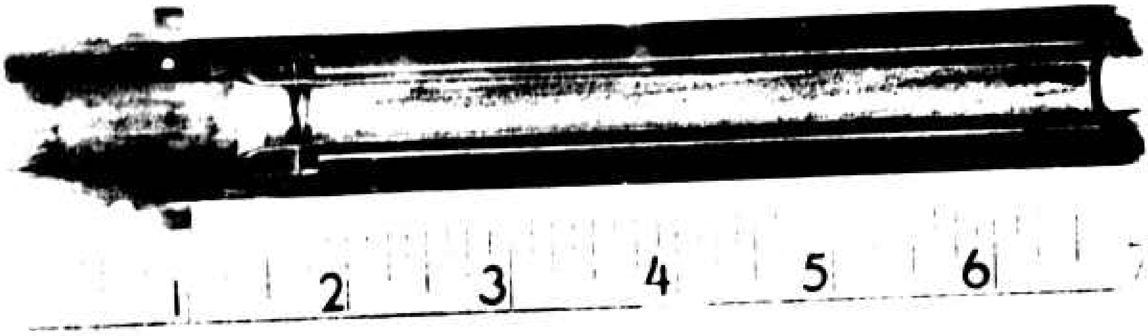
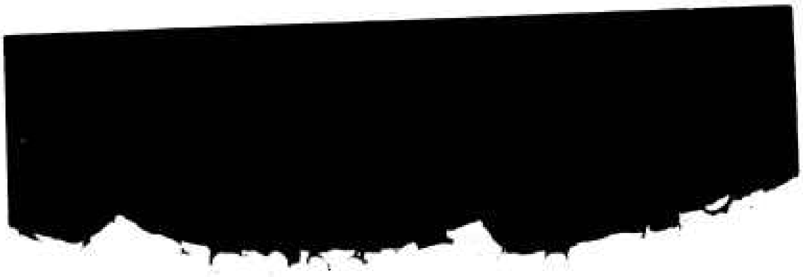


Figure 14. Sectioned Barrel MGB-7 After Firing 400 Rounds



Etchant: None

50X

Figure 15. Photomicrograph of Eroded W Alloy from MGB-7

The ZrB_2-VIII material showed little or no erosion, but lacked the mechanical shock resistance necessary for this barrel design. Even though it withstood a 100-round burst in perfect condition, attempts at longer bursts resulted in complete breakup after 193 continuous rounds. Although the ZrB_2 could be machined to a good surface finish and demonstrated its expected good erosion resistance, considerably more effort would be required to generate a barrel design (if possible) that would provide adequate structural support to compensate for the materials' low mechanical shock resistance.

A comparison of the erosion behavior of all barrels is shown in Figure 16. The graph shows comparative erosion data as generated sequentially for each barrel. It should be noted that the graph should be considered only semi-quantitative since the barrels were not tested identically but, in general, were tested under the same progressively severe test schedule. As indicated, barrels MGB-1, 2, 5, and 6 showed the lowest erosion rates, and their insert materials, WC-3015, L-605, and VM-103, were selected for further testing by means of Phase III deliverable barrels.

4.2.3 THERMAL DATA

As mentioned in paragraph 4.1, the temperature was monitored at five locations on the barrels during burst firing. Tables IV - XII show the maximum temperatures reached by station 2, located on the O.D. of the barrel 2 inches forward from the mouth of the cartridge. Earlier temperature measurements and computer calculations of bore temperatures at Aeronutronic indicated that the bore reaches a maximum temperature at this approximate location. As can be seen from inspection of the data for non-insulated versus insulated barrels of the same materials (i.e., MGB-1 versus MGB-2 and MGB-3 versus MGB-4), the maximum temperatures of the insulated barrels were several hundred degrees cooler. This is shown graphically in Figure 17 which plots typical temperature versus rounds fired for these four barrels. The maximum O.D. temperatures of the insulated barrels (MGB-2 and MGB-4) were 220° and 390°F cooler than the non-insulated barrels (MGB-1 and MGB-3, respectively). The curves continue to diverge for 600-round bursts, indicating increased insulator effectiveness at higher temperatures. The higher temperatures on the Ta-10W inserted barrels compared to the WC-3015 can be explained, at least in part, by the higher thermal conductivity of the Ta-10W.

The implications of the O.D. temperature decrease are very significant with respect to lightweight, high performance barrel designs. For example, a high strength steel such as 300 grade maraging (280 ksi yield strength) could be considered as a jacket material for use with an insulated liner under extended burst firings, even though this alloy lacks good strength above 800°F. With no insulator, a much thicker barrel wall, and/or selection of a superalloy with improved elevated temperature strength, but inherently higher density and lower ambient temperature strength would be required (such as CG-27, 130 ksi yield strength).

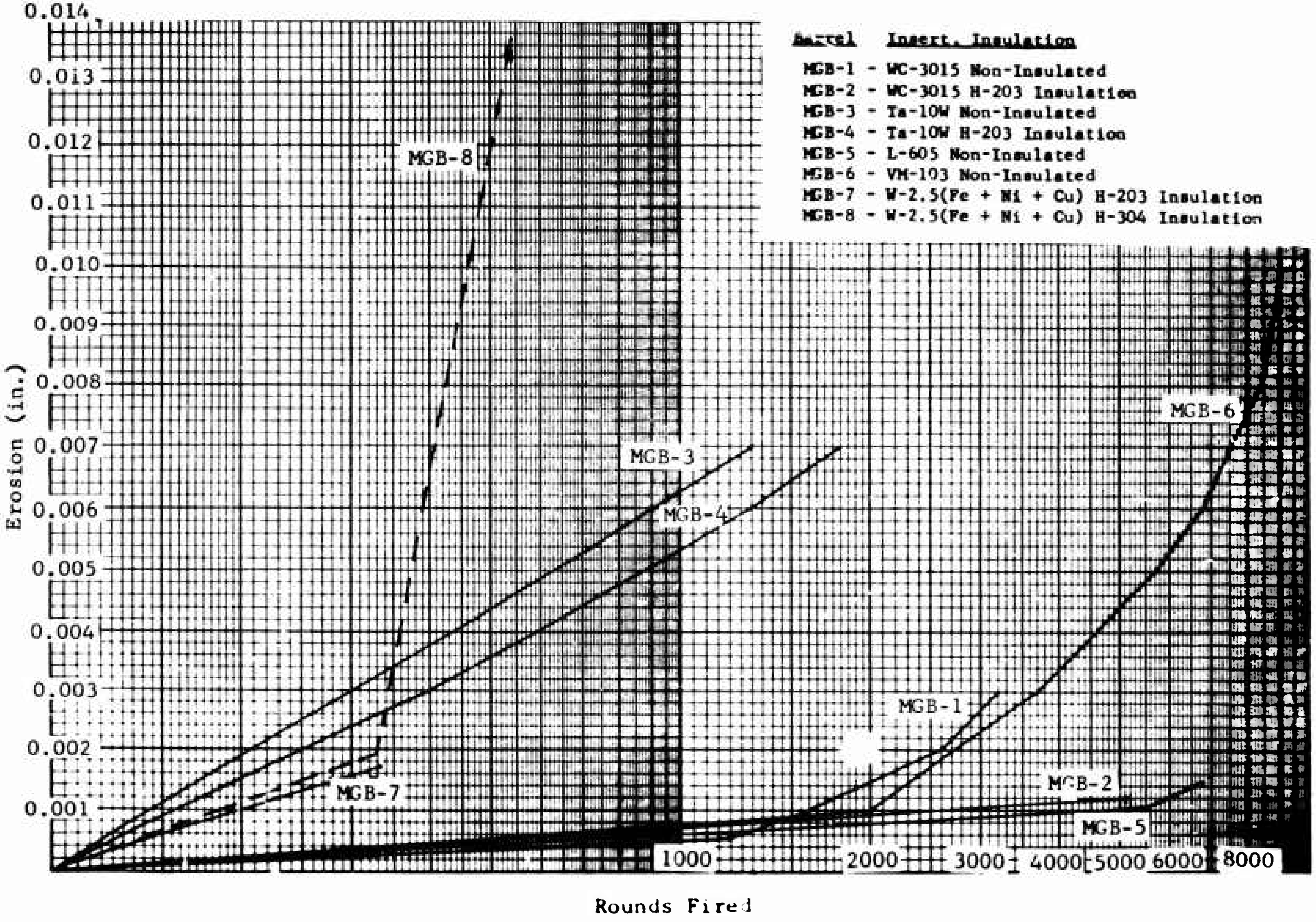


Figure 16. Summary of Erosion Data

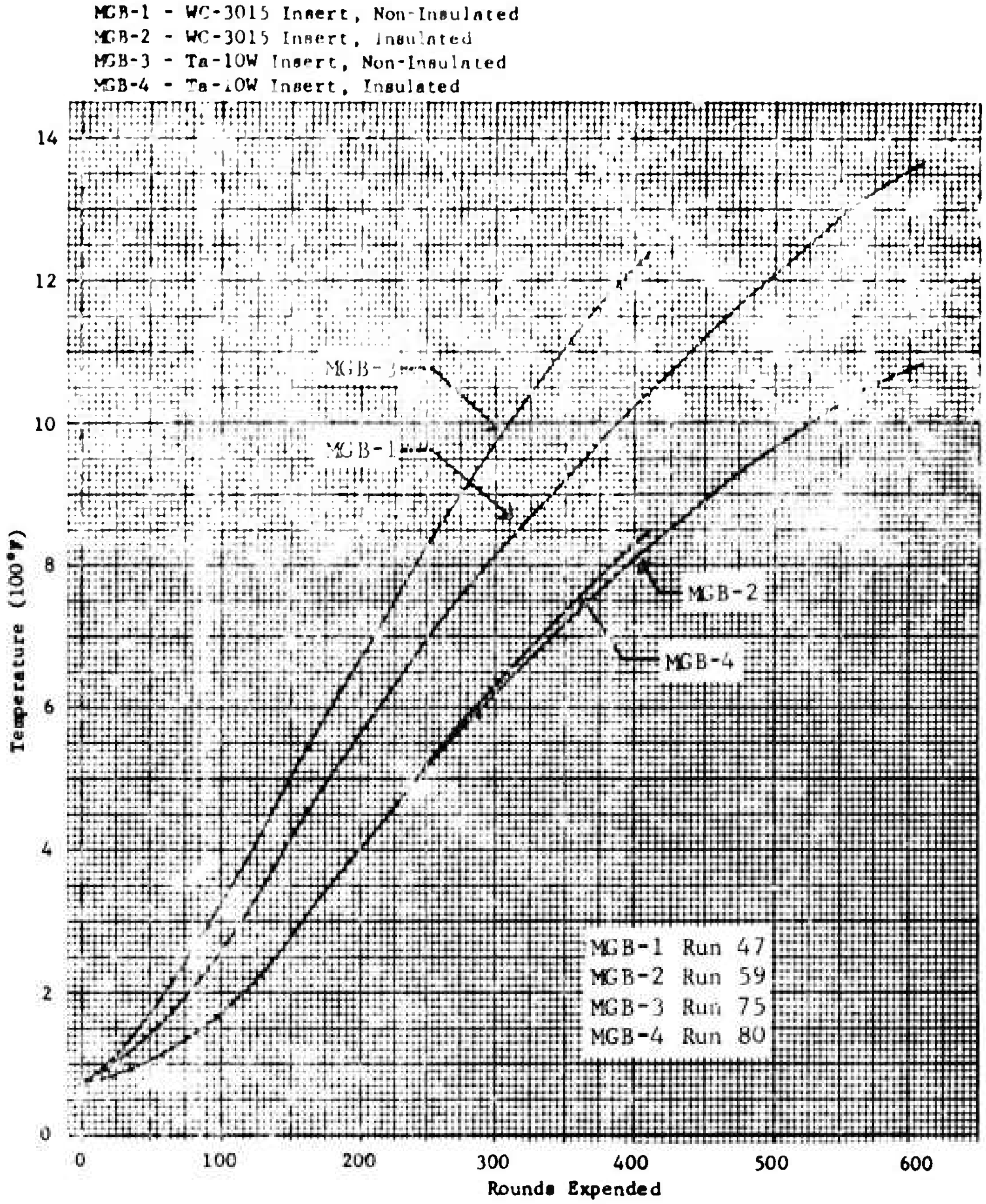


Figure 17. Typical Station 2 - O.D. Temperature Versus Rounds Fired for MGB-1 Through 4

The temperature profiles of MGB-1 through 7 are shown graphically in Figures 18 through 24, respectively, for the longest burst achieved on each barrel. The various stations are described in paragraph 4.1. Because the stations near the muzzle characteristically run hotter due to the thinner wall, the possibility of utilizing a full length liner for lightweight barrel designs appears worthy of consideration. Development of fabrication technology for full length insulated liners would be required.

4.3 THERMAL ANALYSIS AND EXTRAPOLATION TO 30MM

This portion presents the results of an analysis to correlate non-insulated and insulated 7.62mm barrel temperature data with analytical predictions and extrapolates the results to a 30mm barrel configuration.

The temperature response of the barrel wall was computed using an Aeronutronic-developed one-dimensional (radial heat flow), variable material property, conduction time share computer program named GUNHT. The program utilizes a forward difference computational scheme and is capable of handling composite barrels. The interior surface boundary condition consists of a periodic heat transfer coefficient and gas temperature, while the outer surface boundary condition consists of a free convection heat transfer coefficient, a radiation factor, and a constant ambient air temperature.

The first requirement of the study was to empirically determine the inner surface heat transfer coefficient history of the 7.62mm weapon. This was accomplished by assuming a heat transfer coefficient history, computing the temperature response of a non-insulated barrel using this heating profile and then comparing the predicted outer surface temperature history with actual test data. The first cut at the heat transfer coefficient history was obtained from Cornell Aeronautical Laboratory data on 7.62mm weapons. The heat transfer coefficient history was adjusted until a good comparison between computed and measured surface temperature response was obtained. Once a good correlation was obtained, the 7.62mm heating parameters were assumed to be correct and the barrel wall temperatures were computed for the insulated and non-insulated Ta-10W inserted barrels, MGB-3 and 4.

Figures 25 and 26 present the final comparisons between predicted and measured outer surface temperature response at station 2. The cross-hatched curves represent all the 400-round bursts for each barrel. As can be seen, the match between predicted and measured surface temperature response was quite good.

The predicted residual bore, interface, and outer surface temperature histories are presented in Figures 27 and 28 for the non-insulated and insulated barrel, respectively. From these figures it is readily apparent that the mass average temperature of the supporting jacket is significantly lower for the insulated barrel (approximately 1250°F versus 900°F). As expected, the bore temperatures are somewhat higher.

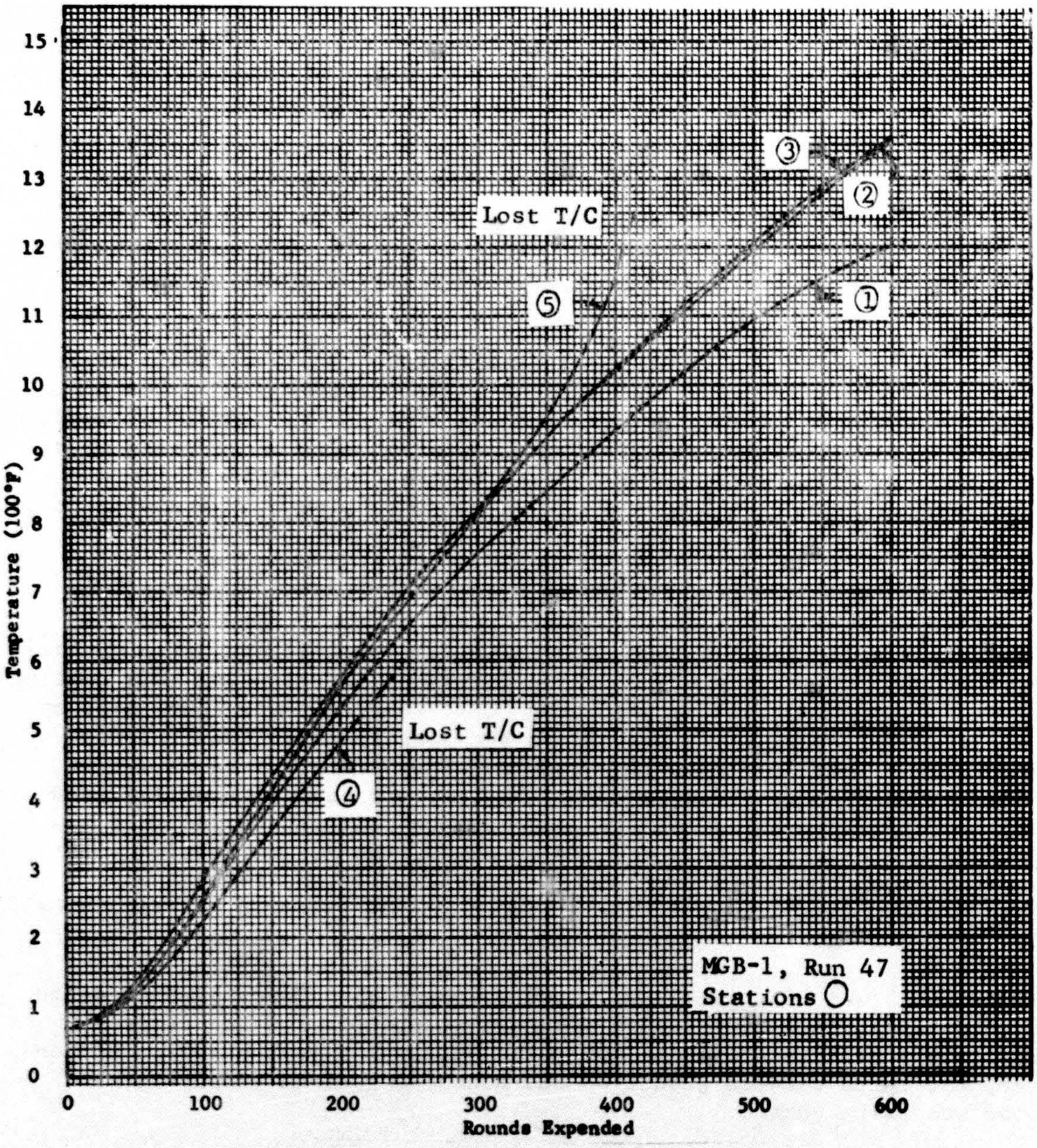


Figure 18. O.D. Temperature Versus Rounds Fired, MGB-1

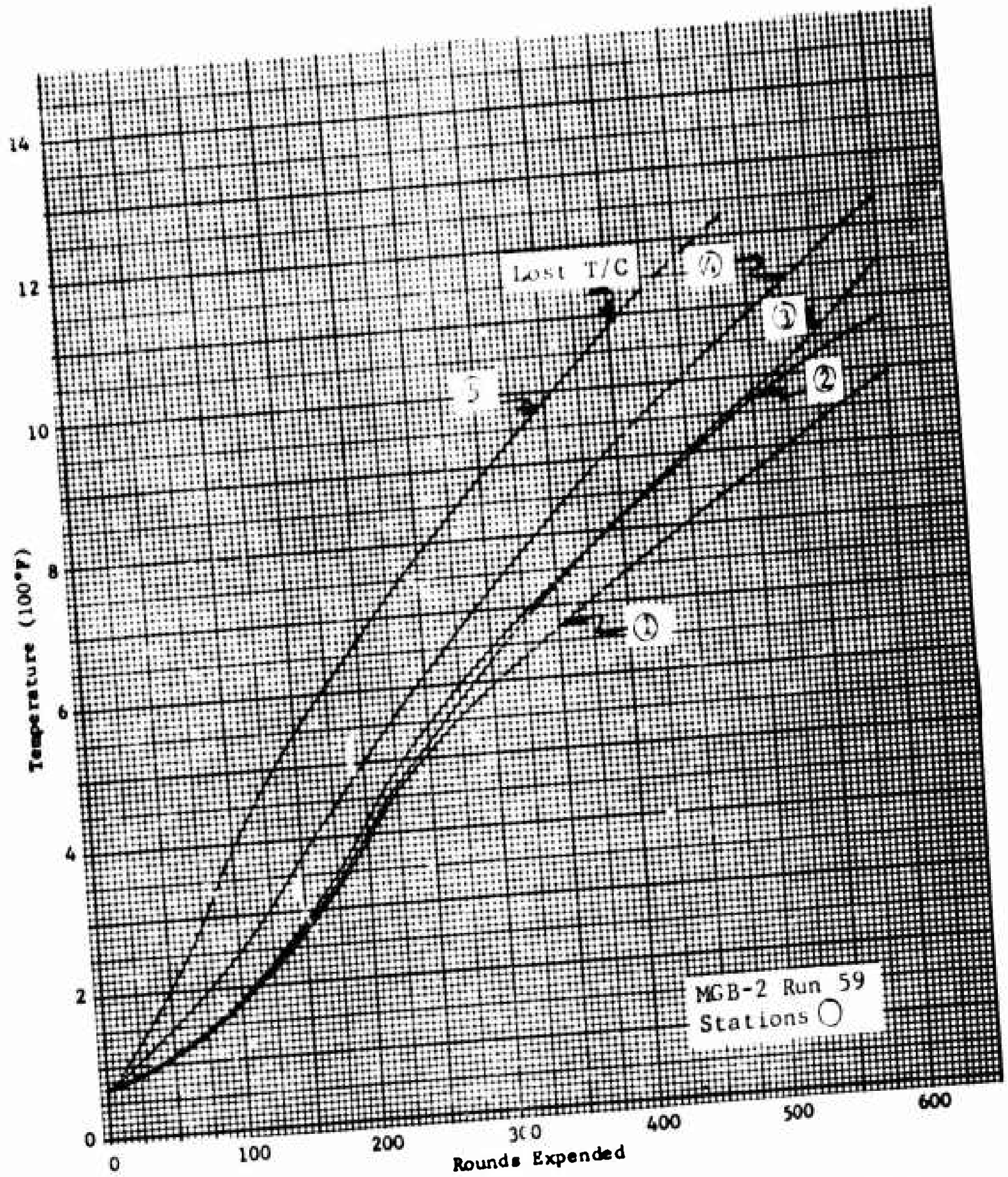


Figure 19. O.D. Temperature Versus Rounds Fired, MGB-2

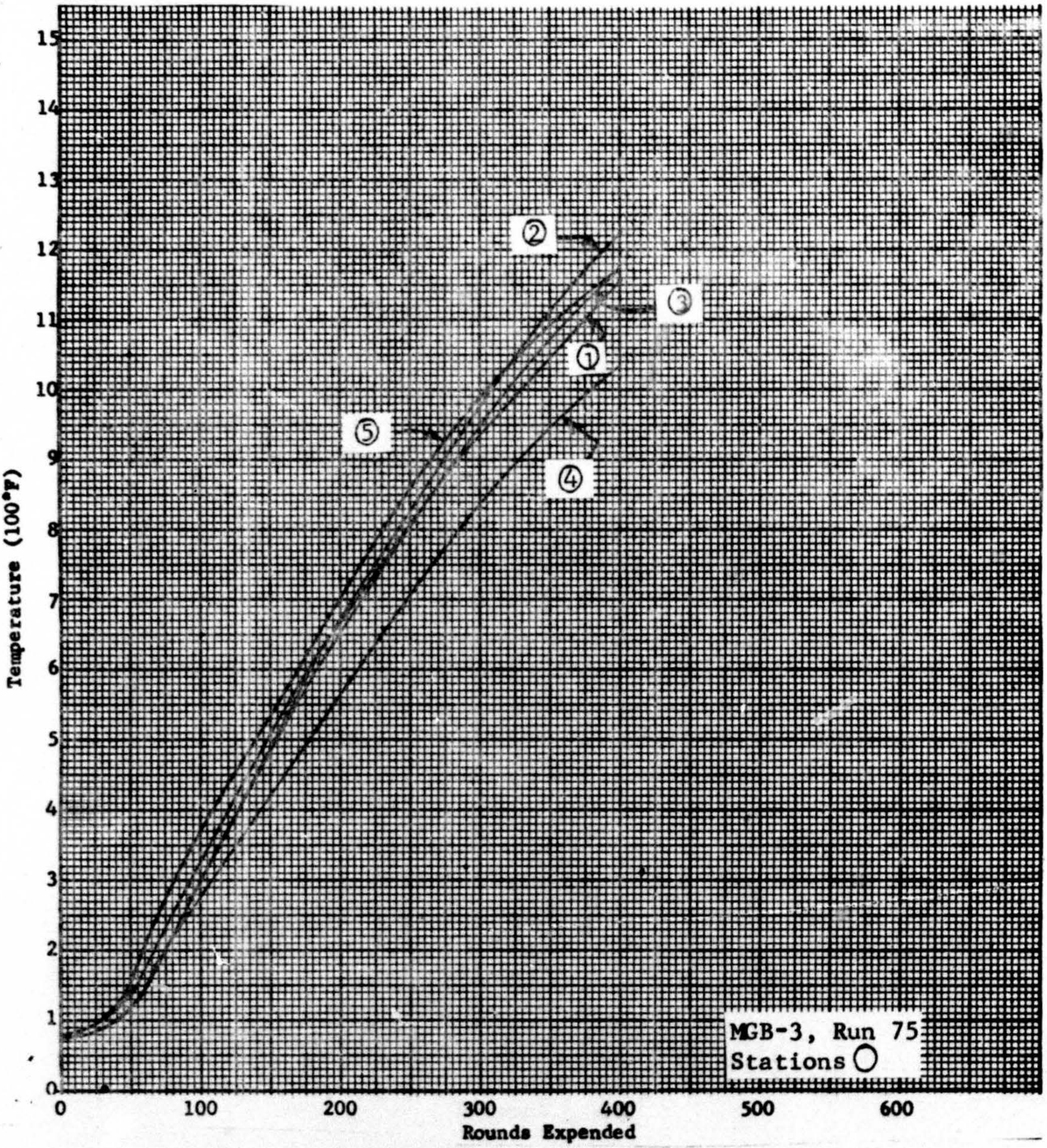


Figure 20. O.D. Temperature Versus Rounds Fired, MGB-3

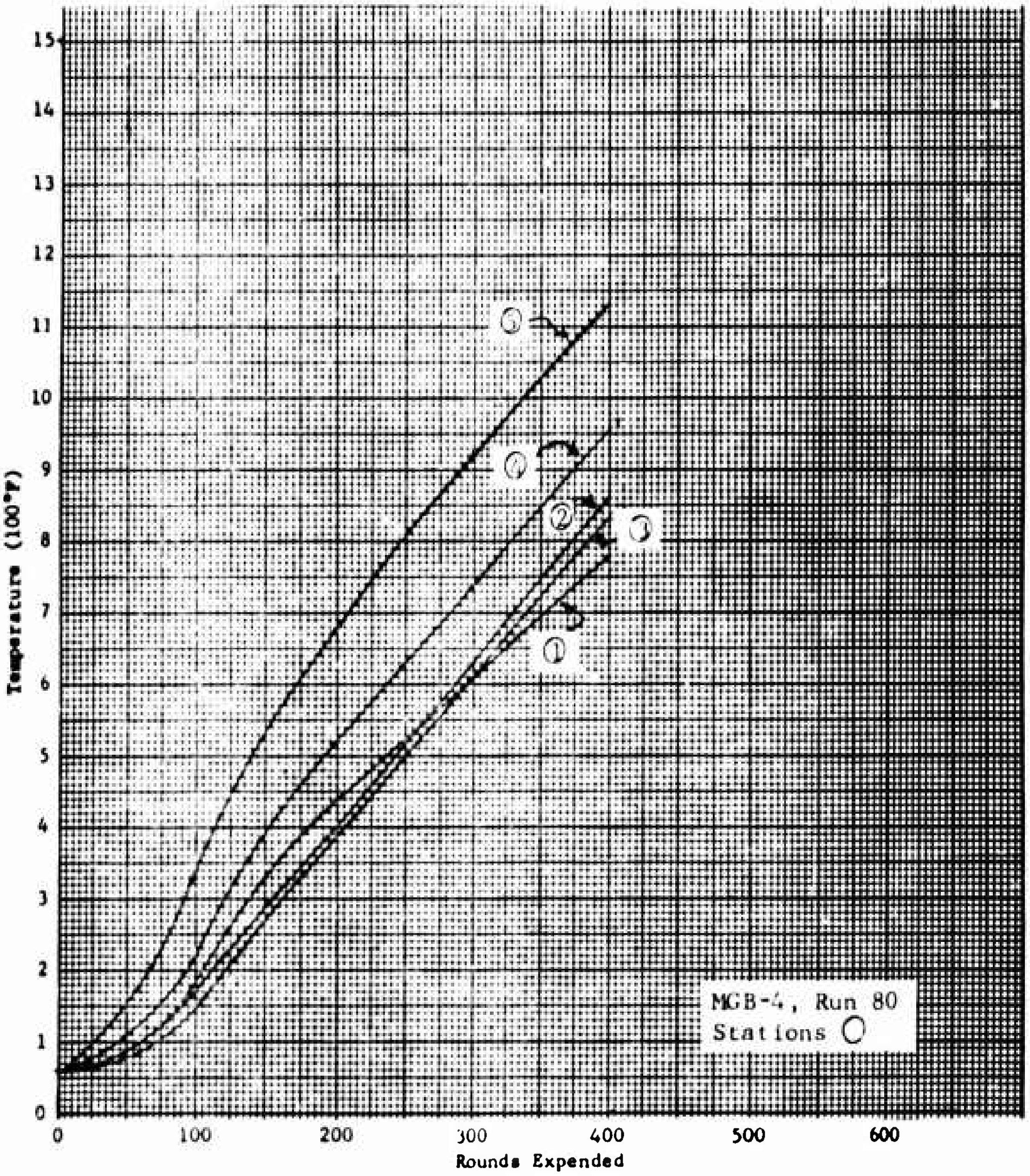


Figure 21. O.D. Temperature Versus Rounds Fired, MGB-4

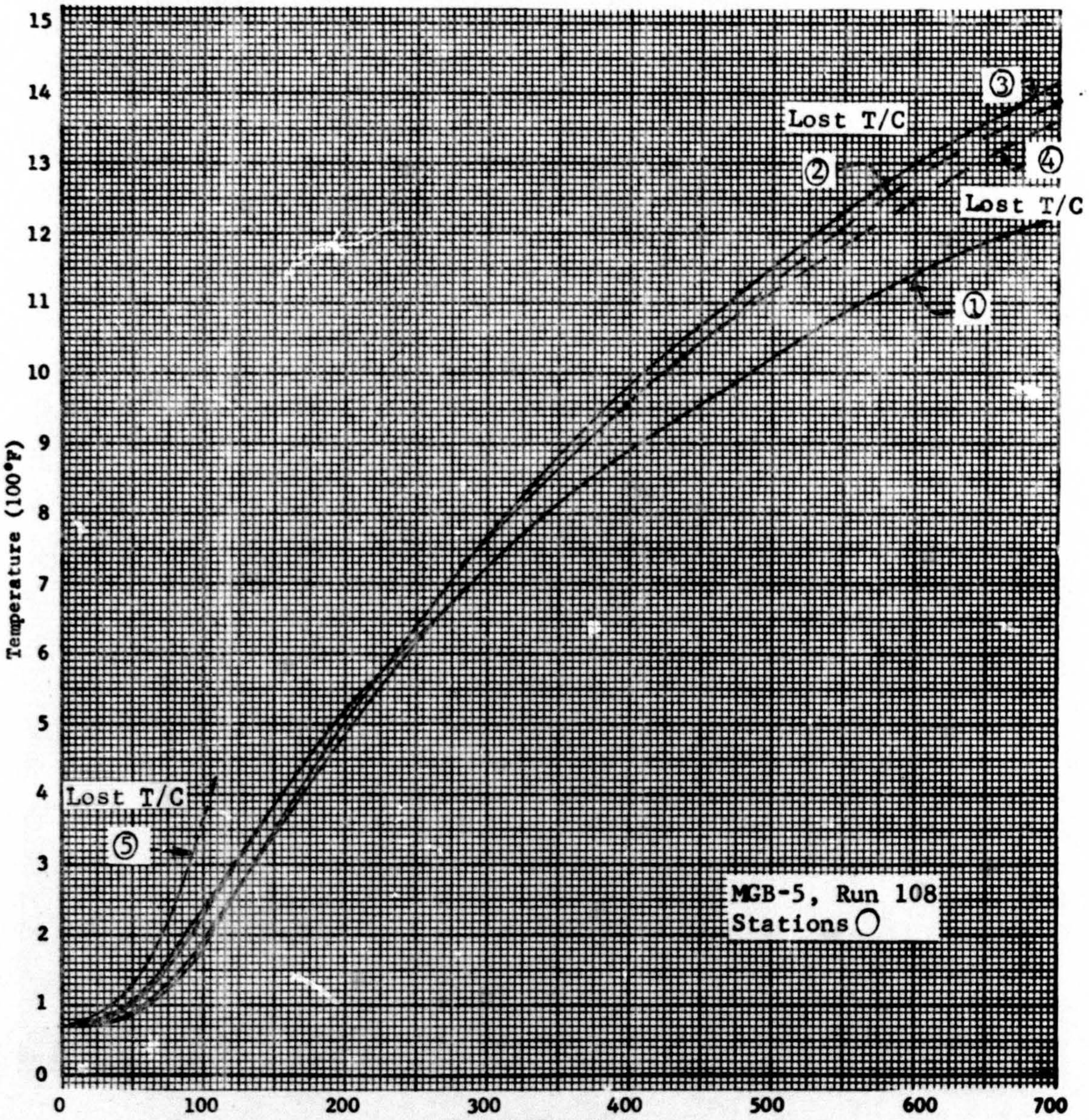


Figure 22. O.D. Temperature Versus Rounds Fired, MGB-5

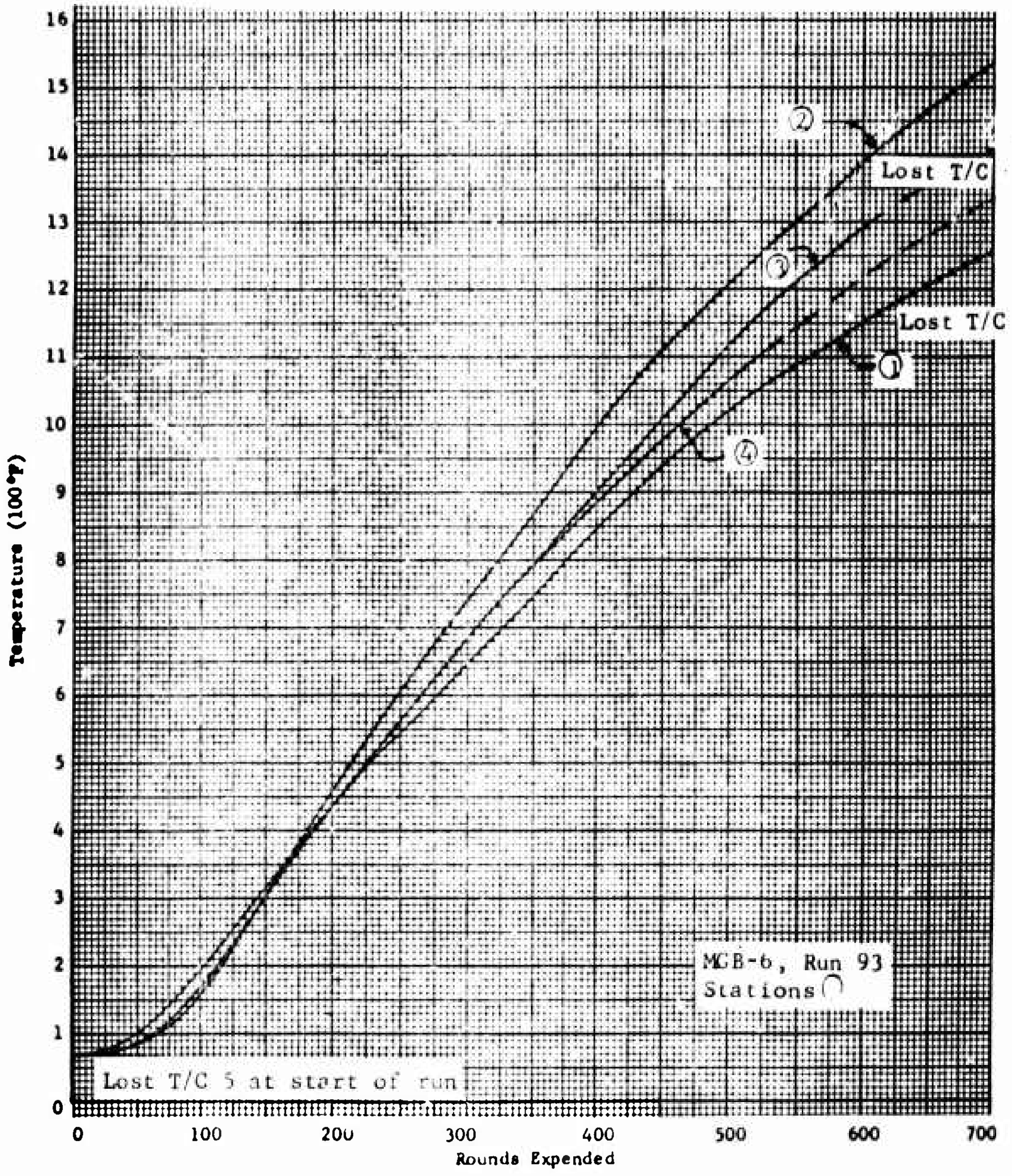


Figure 23. O.D. Temperature Versus Rounds Fired, MGB-6

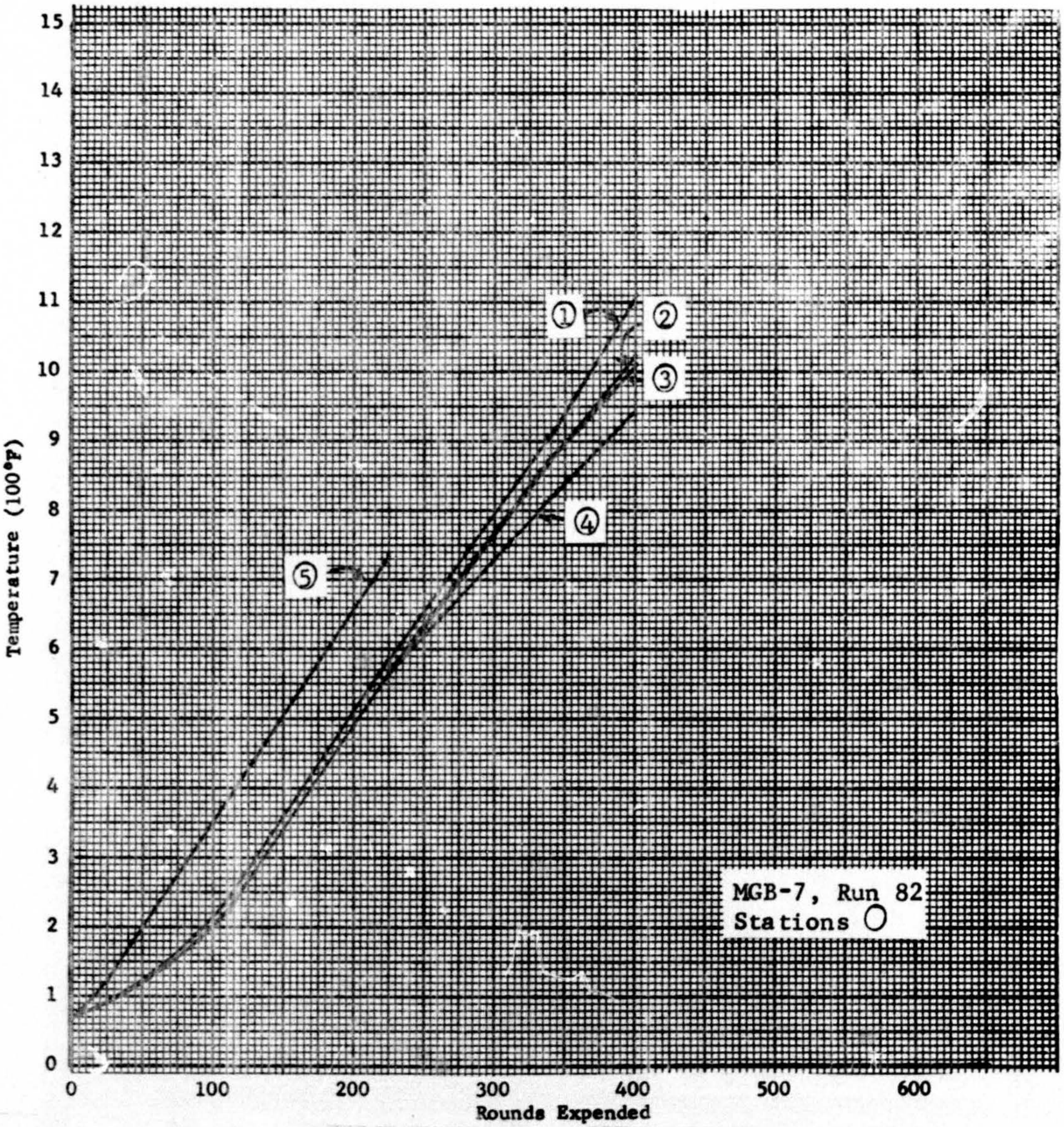


Figure 24. O.D. Temperature Versus Rounds Fired, MGB-7

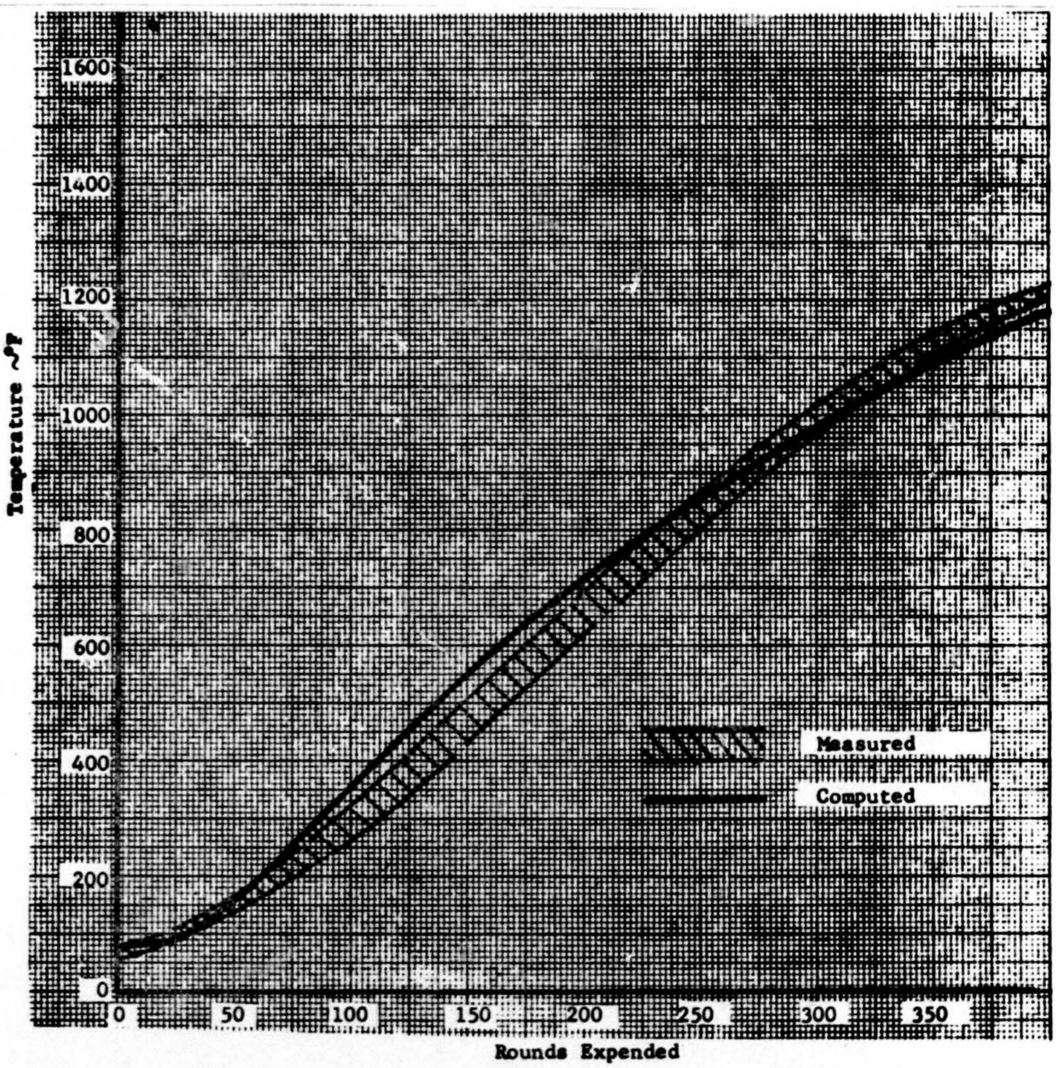


Figure 25. MGB-3 (Non-Insulated) O.D. Barrel Temperatures

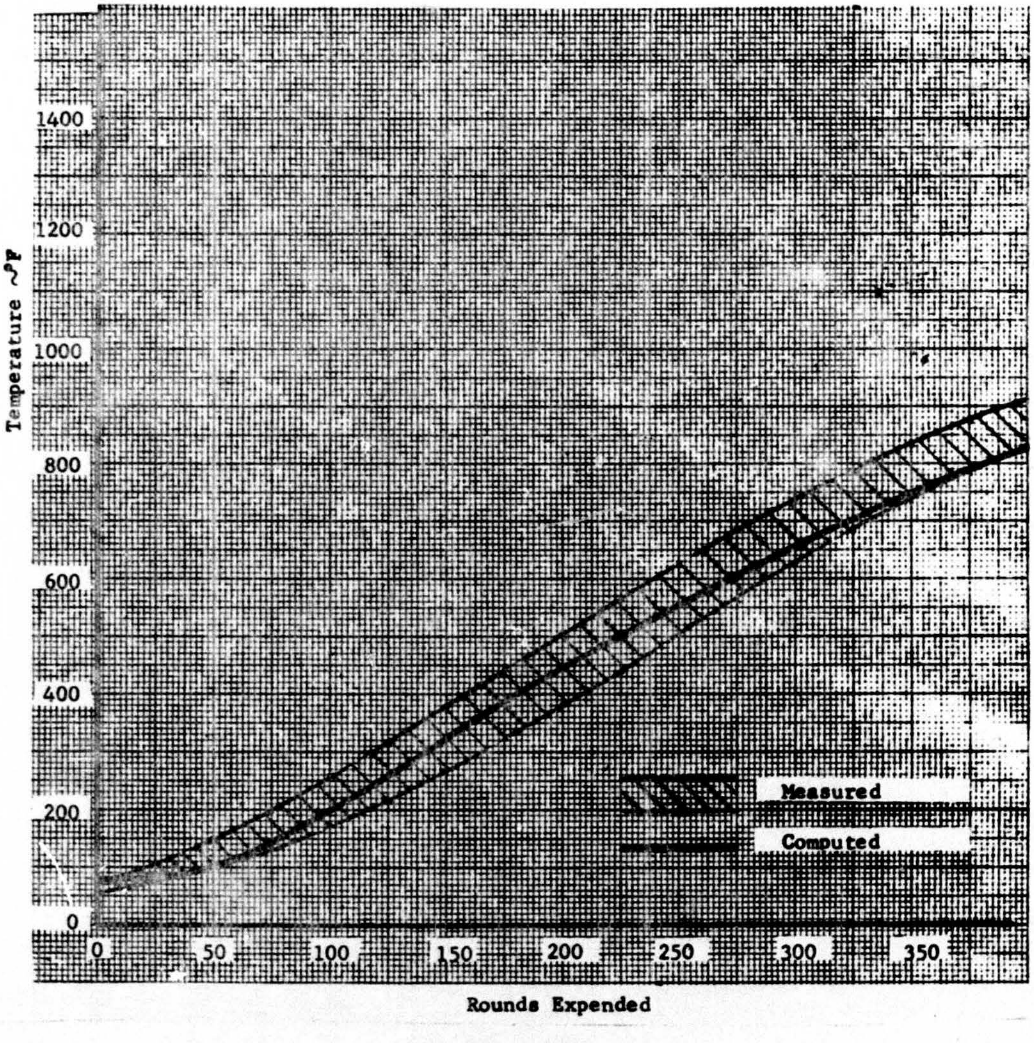


Figure 26. MGB-4 (Insulated) O.D. Barrel Temperatures

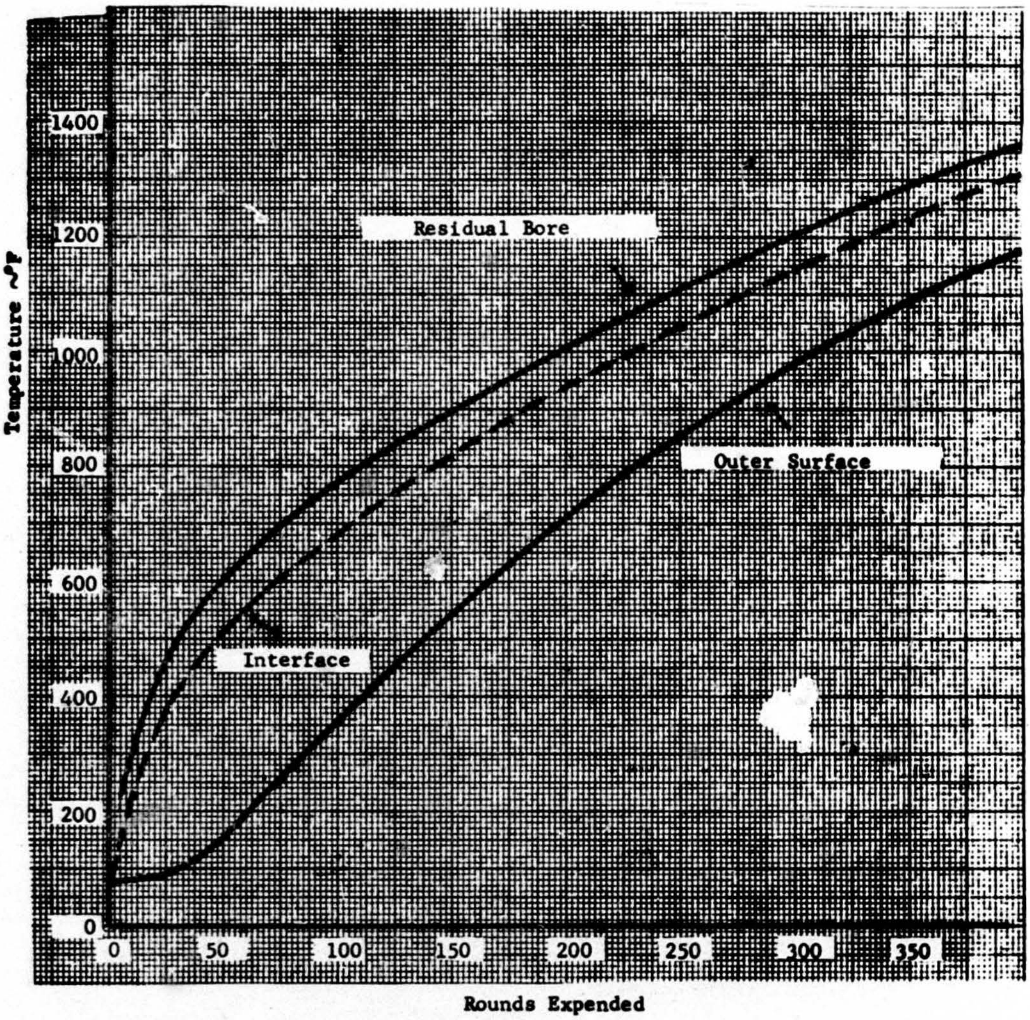


Figure 27. MGB-3 (Non-Insulated) Barrel Thermal Profile

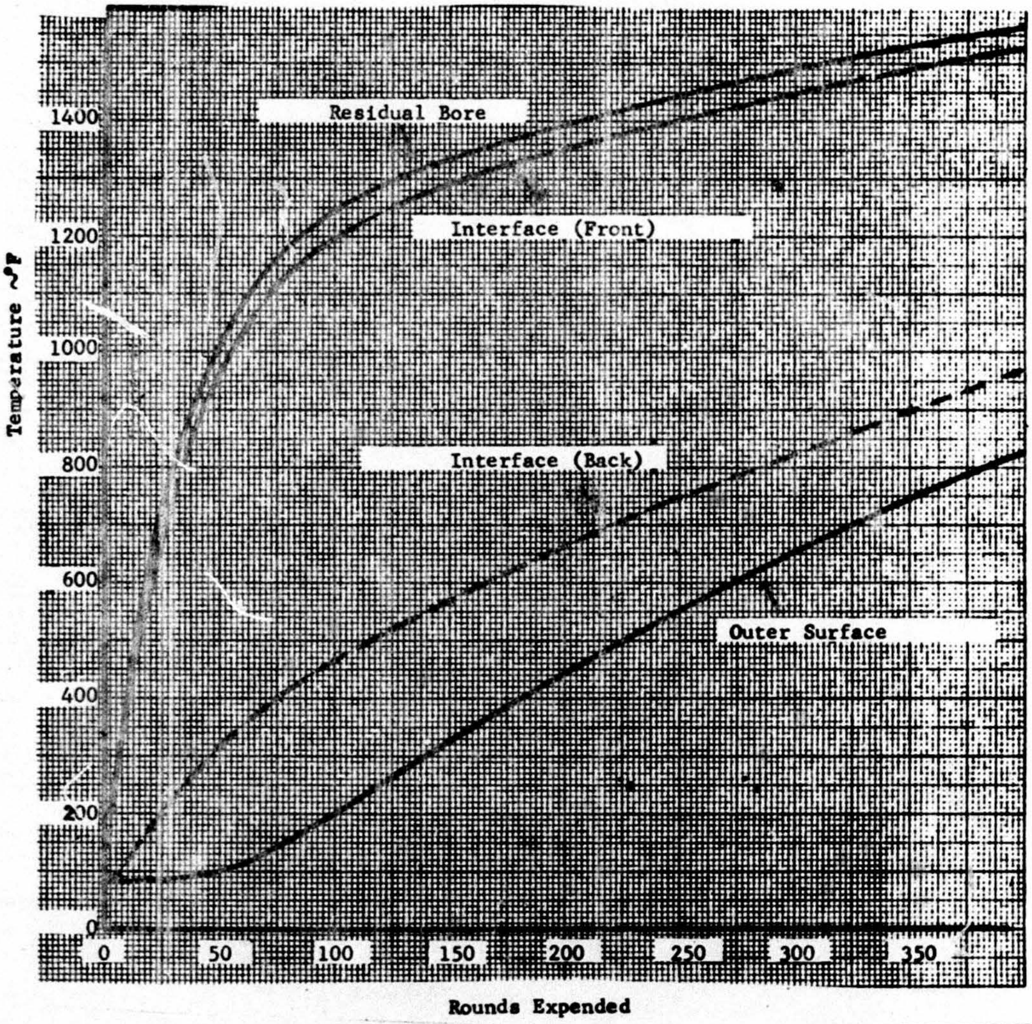


Figure 28. MGB-4 (Insulated) Barrel Thermal Profile

Utilizing the above correlation of computed versus actual O.D. temperatures as a background, attempts to extrapolate these data to a high performance 30mm barrel were made. Residual bore, interface, and outer surface temperature response predictions for the 1.5-inch station of a 30mm barrel are presented in Figures 29 and 30. The liner is Ta-10W, the insulator zirconia (~0.030-inch thick), and the jacket L-605. Again it is seen that a significant reduction in the mass average jacket temperature can be obtained by the addition of a small amount of insulation (approximately 1400°F versus 1000°F). Such a temperature drop is particularly significant where lightweight barrels are required. At 1000°F, steels or high strength stainless steels such as Pyromet X-15 can be used, but at 1400°F lower strength, higher density, more costly superalloys are required.

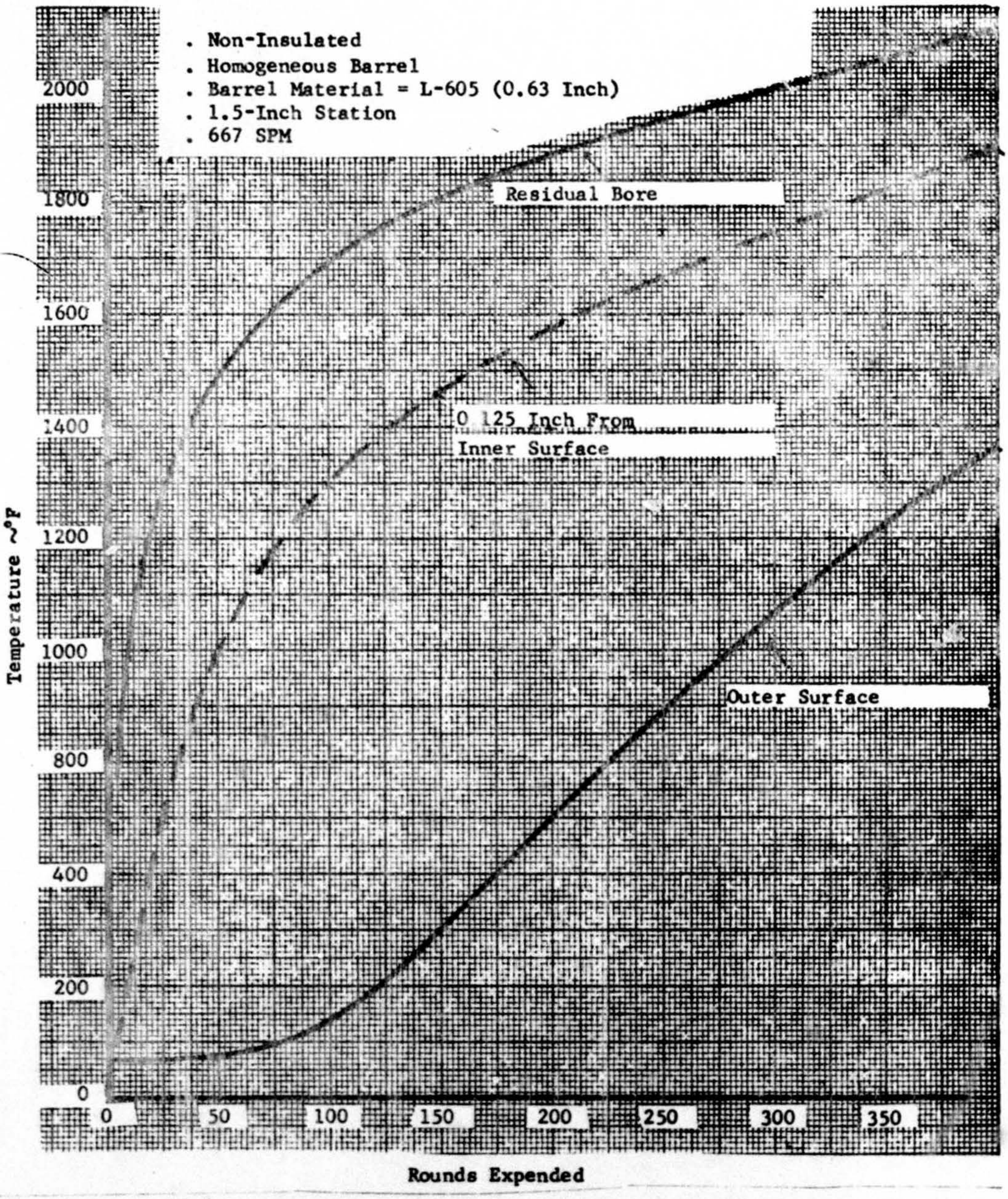


Figure 29. Typical 30mm Non-Insulated Barrel Thermal Profile Versus Rounds Fired

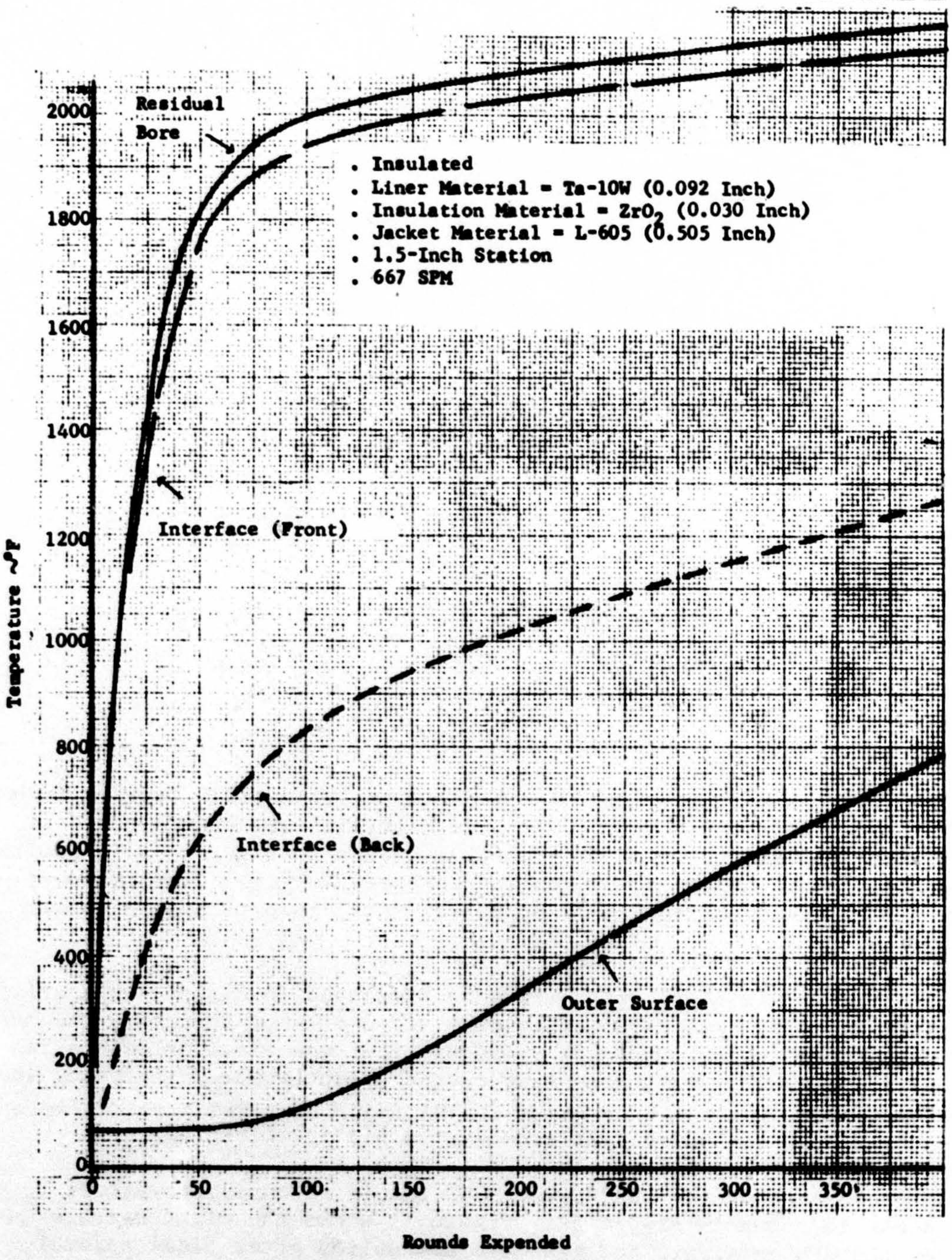


Figure 30. Typical 30mm Insulated Barrel Thermal Profile Versus Rounds Fired

SECTION V

PHASE III: .220 SWIFT BARREL FABRICATION

5.1 DELIVERABLE BARREL CONFIGURATIONS

Based on the Phase II test results presented in Section IV, the materials combinations selected jointly with the Air Force Technical Monitor for the eight deliverable .220 Swift/M-60 barrels were:

SN	Jacket	Insert	Insulator (0.025-Inch Thick)
A	CG-27	L-605	H-204
B	CG-27	L-605	H-305
C	CG-27	VM-103	H-204
D	CG-27	VM-103	H-305
E	Haynes 188	WC-3015	H-203
F	Haynes 188	WC-3015	H-203
G	Haynes 188	WC-3015	H-304
H	Haynes 188	WC-3015	H-304

The barrels were fabricated in conformance with AFATL Drawing Number X-69F6211, dated 18 March 1969. The breech section was counterbored to accept the .220 Swift insert configuration shown in Figure 31. A nominal 0.025-inch thick insulator was applied to the 0.400-inch diameter surface which made the nominal wall thicknesses of these inserts approximately 0.090 inch.

The same basic fabrication sequence presented in Figure 4 was utilized for these barrels, except for additional steps of heat shrinking the breech retainer and adding the M-60 gas cylinder after the black oxide coating step. In general, the .220 Swift bore size caused slightly more difficulty than the 7.62mm size fabricated in Phase I. No insurmountable problems were encountered, and all barrels were delivered within tolerance.

A photograph of the .220 Swift/M-60 insulated composite barrel components is shown in Figure 32. Figure 33 shows the eight barrels including the GFE retainers and gas tube assemblies after final assembly as delivered to Eglin Air Force Base.

Because of the difficulties encountered in rifling the 7.62mm WC-3015 inserts during Phase I, it was considered necessary to develop an improved

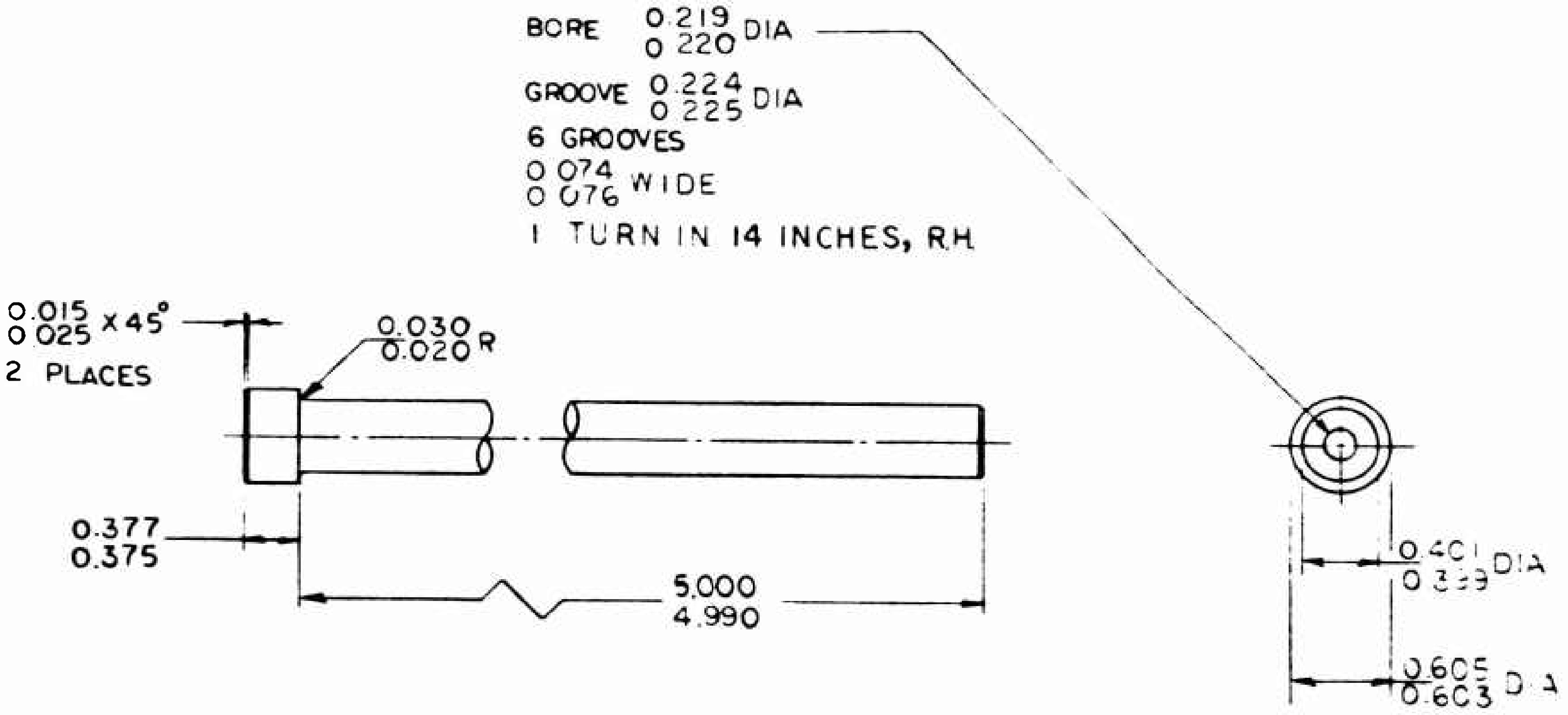


Figure 31. .220 Swift/M-60 Insert Configuration

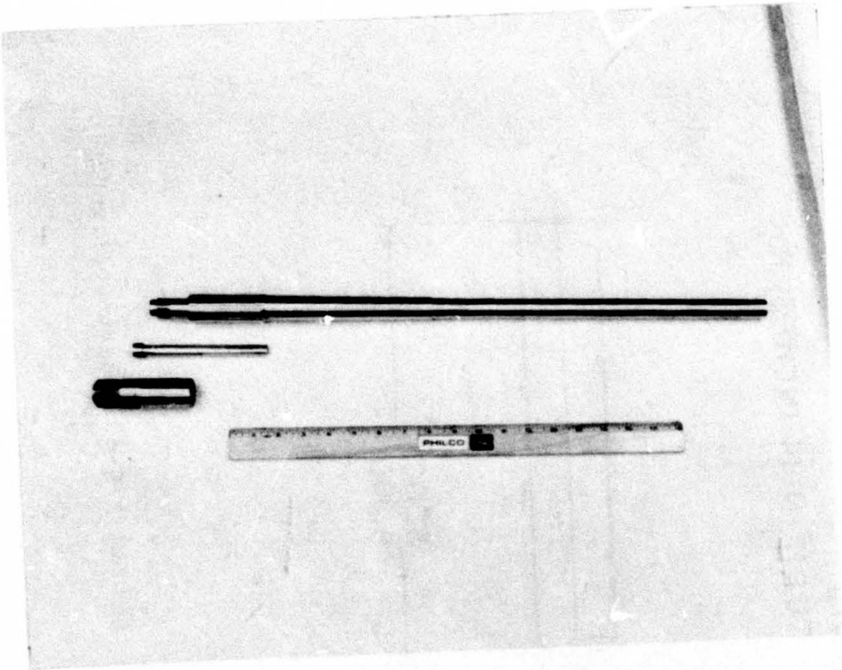


Figure 32. .220 Swift/M-60 Barrel Components Prior to Assembly by Shrink Fitting

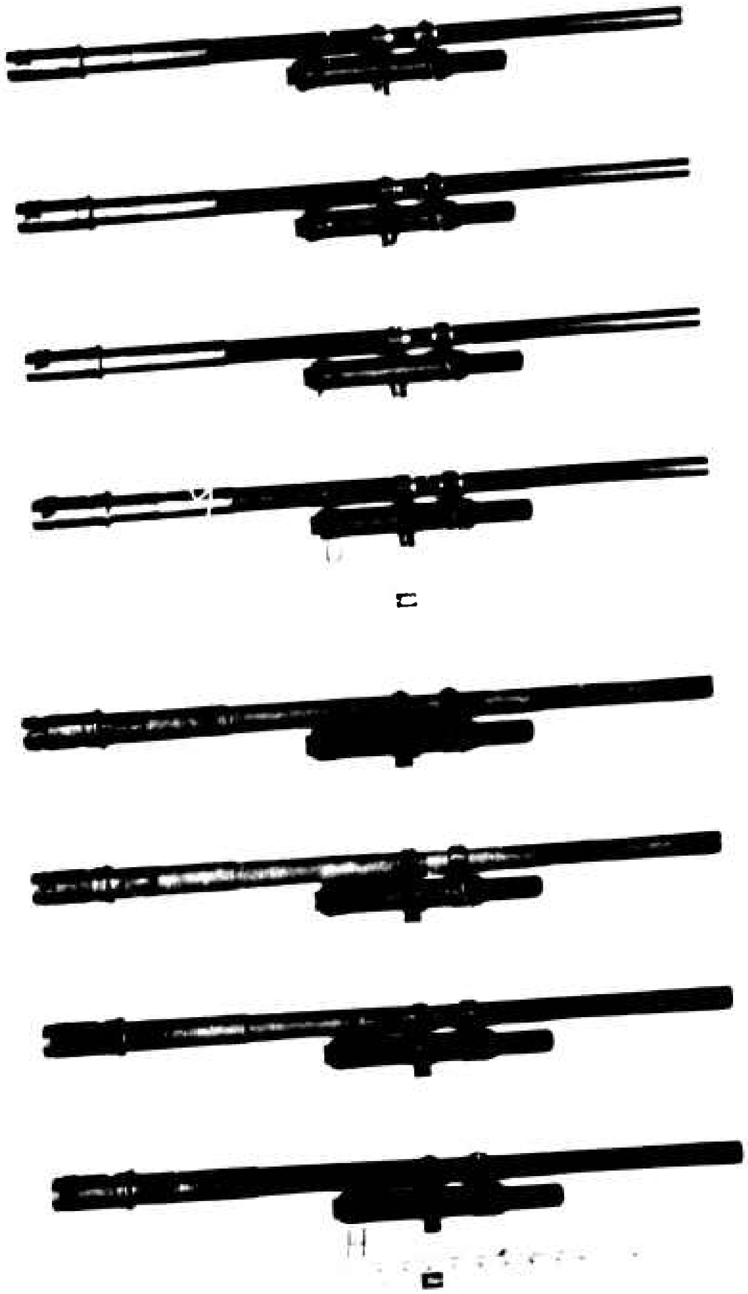


Figure 33. .220 Swift/M-60 Test Barrels As Delivered

method for rifling that material. A subcontract was issued to Battelle Northwest Laboratories, Richland, Washington, to adapt an existing rotary swaging rifling technique which had been developed for .220 Swift/M-60 gun barrels of other materials. Details of this work are presented in the following portion of the report.

5.2 ROTARY SWAGING RIFLING PROCESS DEVELOPMENT

The swaging parameters to be established for rifling the .220 Swift WC-3015 inserts were:

- Work preheat temperature
- Swage die configuration and size
- Mandrel size.

The primary piece of equipment utilized was the Fenn Number 5F, four-die rotary swage shown in Figure 34 which was equipped with a power feed and a mandrel positioning device. In the rifling operation a tungsten carbide mandrel which forms the rifling is held axially within the die throat by a long rod extending backward through the work and feed carriage to an anchor point on the bed. The work piece is fastened to a hollow handle, placed into the feed chuck, and fed simultaneously into the rotating four-die swage and over the mandrel. The radial motion of the four dies hammer the work radially onto the mandrel with sufficient pressure to form the rifling contour. The details of the die and mandrel arrangement are shown in Figure 35. The shims behind each die are used to control the inwardmost travel of the die for fine adjustment of the work piece diameter. The mandrel shown in Figures 36 and 37 is attached to the mild steel holder rod of slightly smaller diameter by brazing on the taper.

Auxiliary equipment such as the preheat furnace, hone, and machine tools were of standard design and set-up. The finished pieces were inspected by air gaging the bores and visual examination for surface quality at Battelle. Metallographic examination and additional air gage measurements were taken at Aeronutronic.

The WC-3015 material was procured from Wah Chang, Albany, Oregon, in accordance with Figure 38. It was requested to be in optimum condition for swaging to 20 percent reduction at 900°-1200°F. The material which represented three heats was either forged or extruded from the ingot, cold worked 20-50 percent by swaging, machined to final configuration, and vacuum annealed. Hardness ranged between 25-32 R_c.

The swaging data are included in Table XIII. All pieces were attached to the swage handle, preheated in air, lubricated with "Oil Dag," placed in the swage, swaged, cleaned, and inspected. The first piece was swaged at

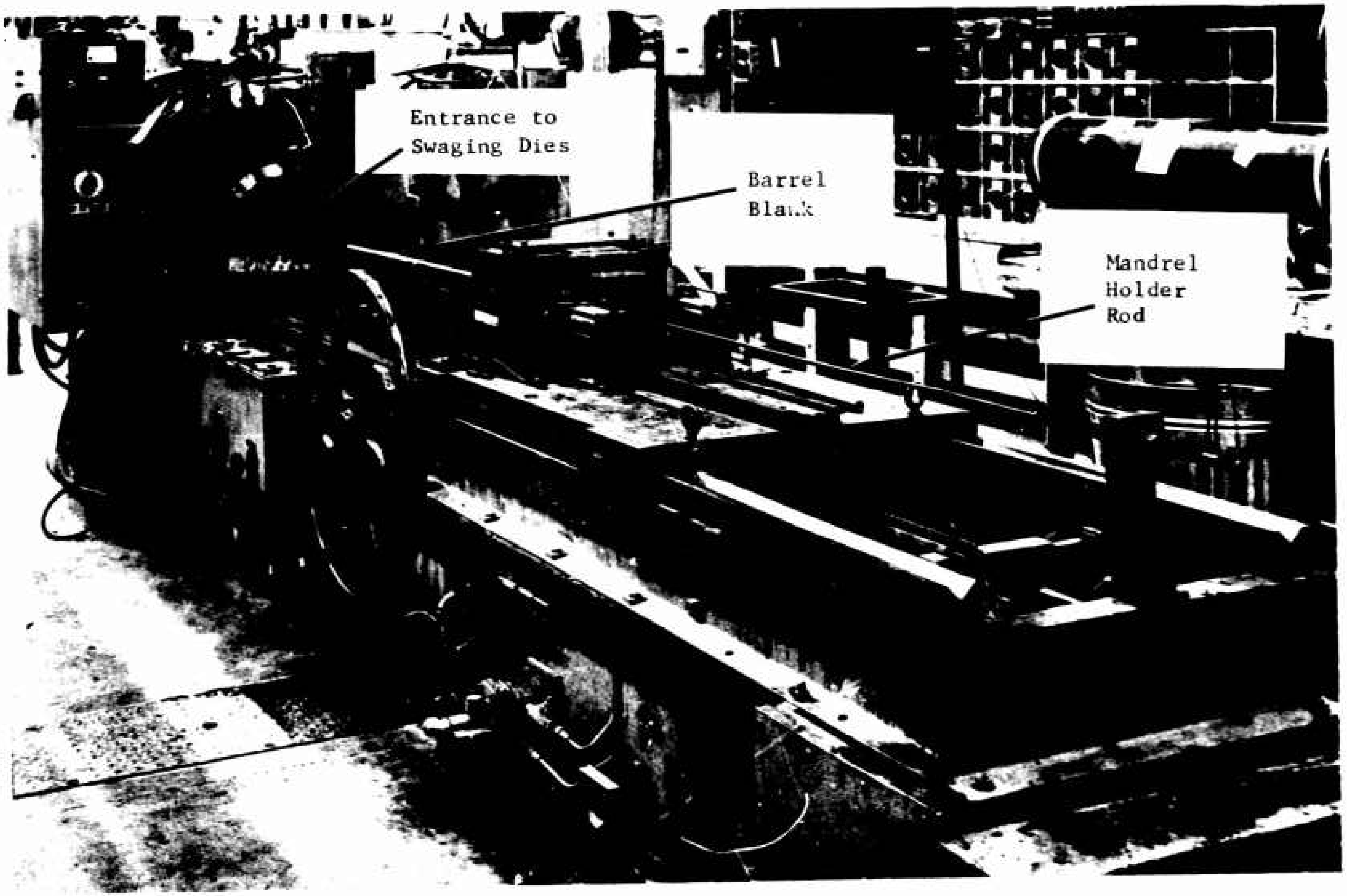


Figure 34. Four-Die Rotary Swage Setup for Rifling

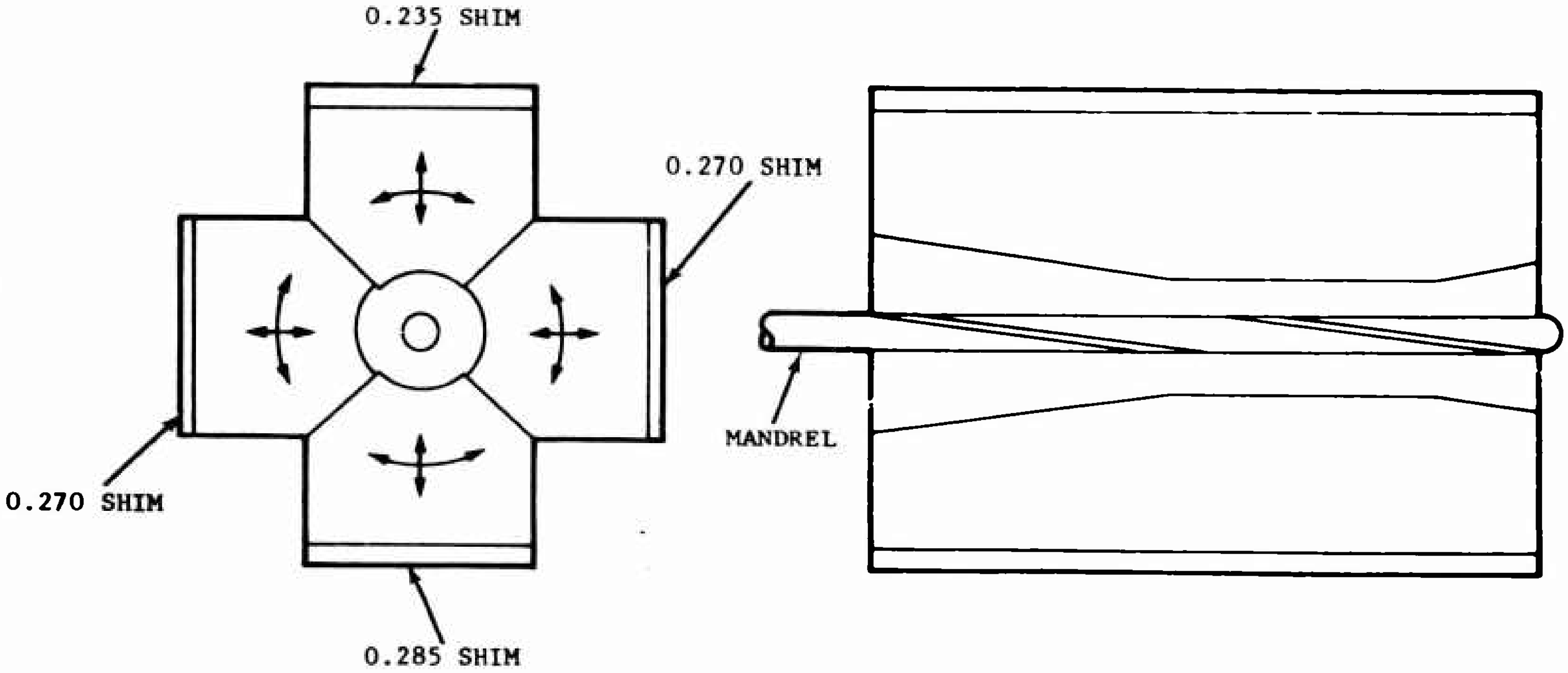
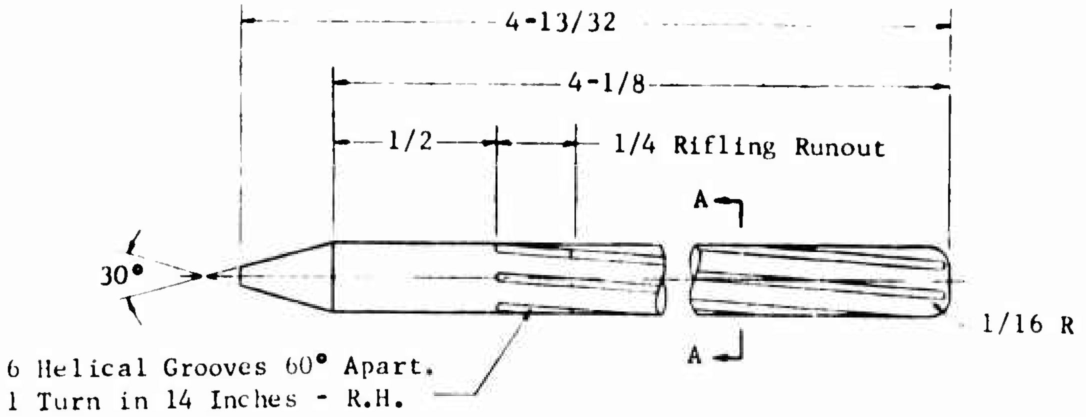
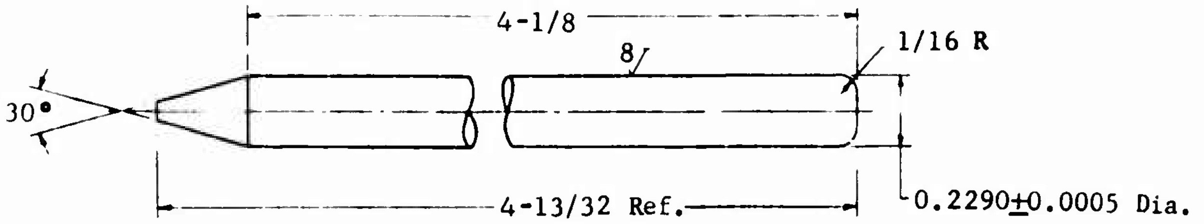


Figure 35. Swage Die and Mandrel Arrangement

Figure 36. Tungsten Carbide Rifling Mandrels



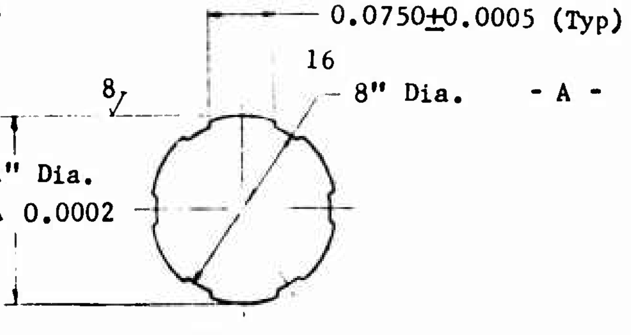
Part	"A" Dia.	"B" Dia.	Material
1	$0.2240^{+0.0000}_{-0.0005}$	$0.2190^{+0.0000}_{-0.0005}$	Carboloy 55 B
2	$0.2230^{+0.0000}_{-0.0005}$	$0.2180^{+0.0000}_{-0.0005}$	Carboloy 55 B
3	$0.2235^{+0.0000}_{-0.0005}$	$0.2185^{+0.0000}_{-0.0005}$	Carboloy 55 B
4	$0.2245^{+0.0000}_{-0.0005}$	$0.2195^{+0.0000}_{-0.0005}$	Carboloy 55 B
5	$0.2250^{+0.0000}_{-0.0005}$	$0.2200^{+0.0000}_{-0.0005}$	Carboloy 55 B



6 **SMOOTH MANDREL**
CARBOLOY 55 B

GENERAL NOTES
(Unless Otherwise Specified)

1. Tolerances: Fractional ±1/64, Decimal ±0.005, Angular ±0°30'.
2. All Material to be As Specified.



SECTION A-A

Figure 37. .220 Swift Swaging Mandrel

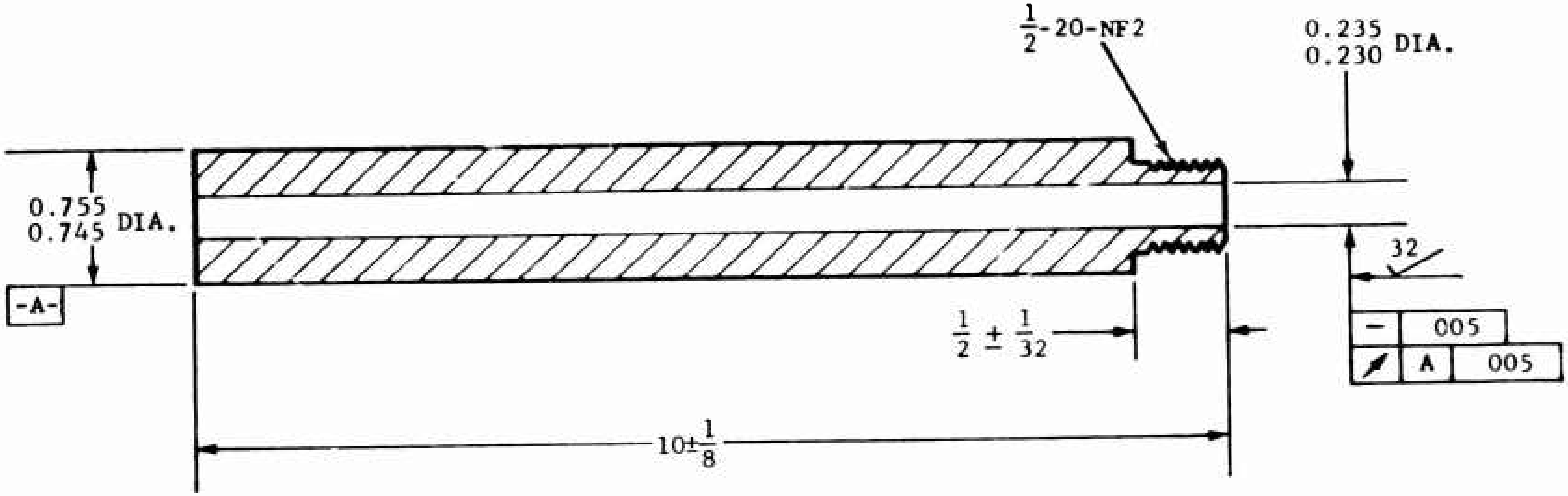


Figure 38. Sketch of Barrel Insert Blank

TABLE XIII. SWAGING DATA LOG

Tube Serial No.	Tube Condition					Swage Data						Swaged Tube				Comments
	O.D. (in.)	I.D. (in.)	Length (in.)		O.D. Hardness (R_c)	Die Size (in.)	Shim Size (in.)	Mandrel Size (in.)	Pre-Heat (°F)	Swage Setting	Brake Setting	O.D. (in.)	Bore (in.)	Groove Diameter (in.)	O.D. Hardness (R_c)	
			Before Swaging	After Swaging												
590259	0.751	0.232	4		25	0.650	0.290/0.275	0.223	75	38	35	0.701			34	Mandrel broke.
590259	0.750	0.234	3-9/16		32	0.650	0.290/0.275	0.223	900	35	30	0.704		0.2237	35-39	Galled rifling.
590191	0.751	0.238	8-9/16	9-3/4	27	0.650	0.285/0.270	0.223	1075	40	35	0.703-4	0.2195	0.2245	32-33	
590191	0.751	0.240-0.247	9-9/16	11	27	0.650	0.285/0.270	0.223	1075	40	35	0.702	0.2197- 0.220	0.2247- 0.2250	32	
590284-1	0.750	0.238	9-3/4		28	0.650	0.285/0.270	0.223								Mandrel broke off.
590284-2	0.747	0.238-0.245	9-13/16		28	0.650	0.285/0.270	0.223								Mandrel broke off.
590284-3	0.750	0.241-0.243	9-9/16	10-15/16	28	0.650	0.285/0.270	0.223	1075	40	35	0.706	0.2203- 0.2202	0.2243- 0.2247	34	Thread 0.077 out of concentricity with outer diameter.
590284-4	0.750	0.238-0.245	9-5/8	7-1/8	28	0.650	0.285/0.270	0.223	1075	40	35	0.706		0.2247- 0.2242	33	Thread 0.078 out of concentricity with O.D. Handle broke. Mandrel stuck.
590284-2	0.747	0.238-0.245	6-7/8	7-5/8	28	0.650	0.285/0.270	0.223	1075	40	35	0.705		0.2242- 0.2247	34	OK

room temperature but broke at the base of the thread which, in turn, broke the mandrel. The second tube was swaged at 900°F. The rifling galled slightly, and the leading end sustained five more or less equally spaced radial cracks. In both cases the rifling dimensions were within specification. Consultation with the material supplier indicated that the remainder of the material would be more ductile (no cracking) and that temperature should be raised to 1000°F. Therefore, the remainder of the pieces were swaged successfully at 1075°F. The mandrel breaking and handle thread breaking were attributed to the eccentricity of the bore with respect to the outer diameter.

In the swage data the die size is the nominal size produced with 0.290 inch shims. In the "shim size" column two figures are entered. It was found that slightly different shim thickness between opposite pairs of dies reduces the tendency of the work to bind on the mandrel. The "mandrel size" refers to the mandrel outer diameter which forms the groove diameter in the bore. The "swage setting" and "brake setting" are air pressures which control the feed rate and braking moment of the work.

Figure 39 shows a finish rifled piece which was typical of six acceptable rifled insert blanks. The rifling dimensions were within specified tolerance, and the bore finish was excellent. The corners of the grooves in the mandrel did not fill 100 percent which resulted in a slight radius on the land corners in the barrels, as shown in Figure 40. This is not considered significant with respect to performance.

Figure 39. WC-3015 Insert Blank After Rifling

As Polished 10X

Figure 40. Cross Section of Swage Rifled WC-3015

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13. ABSTRACT

A 17-month program was conducted to advance high performance gun barrel technology by fabricating, testing, and evaluating small caliber insulated composite barrels which consist of lined barrels with an insulator at the liner/jacket interface. Fabrication process development included conventional barrel-making methods as well as development of a hot swaging process for rifling. Materials investigated included iron/nickel base superalloys, cobalt base superalloys, tantalum, columbium, and tungsten refractory alloys and high temperature ceramics. Test firings conducted on nine 7.62mm composite barrels proved the effectiveness of the insulator which lowered the mass average temperatures of the jackets by several hundred degrees during extended bursts without a sacrifice in erosion life. A computer extrapolation of the data to 30mm showed similar predicted results which provide potential for very high performance lightweight barrel designs. The final effort on the program consisted of fabricating eight .220 Swift/M-60 test barrels for delivery to the Air Force.

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Gun concepts						