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RESULTS OF ENGINEERING STUDY ON SPIW MUZZLE DEVICE

CONTRACT NO. DAAG25-69-C-0409

ER-6328

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I. INTRODUCTION

AAI Corporation is presently under contract with the U. S. Army Weapons Command, Rock Island Arsenal, to perform continued research and development activities on the XM19 Rifle. Modification DAAG25-69-C-0409-P00007 to the contract outlines the "Scope of Work for Phase III" dated 3 April 1970. Item d of this scope authorizes the performance of an engineering study on the muzzle device used on the XM19 Rifle. During the study the contractor was to

1. Investigate alternative materials which will ease fabrication and still offer characteristics suitable for use in the muzzle device.
2. Investigate design considerations such as stress analyses and configuration changes to reduce weight and ease fabrication.

Based on the above considerations the contractor was to submit specific technical recommendations with supporting rationale for reducing the weight and easing fabrication of the muzzle device without degradation of current performance.

The following sections of this report include a review of the development effort which culminated in the current design of the muzzle device. A description of the three primary areas for achieving the goals of the study - material study, fabrication techniques and weight reduction are presented. Appendices A, B and C contain an analytical study of the gas expansion phenomenon and stress analyses of the barrel extension and expansion chamber, respectively.

II. REVIEW OF MUZZLE DEVICE DEVELOPMENT

The muzzle device performs a multitude of functions, all of which contribute to the successful performance of the SPIW system. The muzzle device provides compensation, reduces impulse and suppresses noise and flash. Each of these functions is interrelated and proper overall muzzle device performance requires control of the parameters which influence these functions. For example, if compensation was not required to compromise muzzle climb when firing a three-round burst, then the noise and flash problems would be greatly reduced. This would allow the entire muzzle device to be replaced by a small flash suppressor of the three finger, conical type used on the M-16. However, the additional terminal effectiveness produced by the three-round burst principle is sufficient justification to warrant this requirement of the muzzle device used on the XM-19 Rifle. Also, by reducing the weapon impulse in conjunction with the high cyclic rate the effectiveness of the three-round burst is accented because variations in the extreme spread of the patterns normally produced by different gunners can be reduced. Minimizing the weapon impulse tends to accentuate weapon noise because more of the gases are diverted out the vane area of the muzzle device. Hence, some trade-off in design features is necessary to obtain acceptable impulse and noise levels.

AAI has studied numerous types of muzzle devices in an attempt to obtain a device which will perform the required functions acceptably and still remain light in weight and low in cost. Devices containing baffles, conical expansion sections with and without venting slots and holes, multiple expansion chambers, expansion chambers filled with heat absorbing particles, combined conical and volumetric expansion designs without a barrel extension, and many other devices have been designed, fabricated and tested on the SPIW weapon. However, each of these muzzle devices had some deficiency which prevented its use on the SPIW weapon. As a result of the knowledge gained from the theoretical and experimental investigations of these design configurations the present muzzle device evolved.

Muzzle device designs were extensively investigated in 1967 and the results of these investigations are presented in AAI Engineering Report ER-4897.* During these earlier efforts a number of barrel extension configurations were tested to generate comparable data relating to their influence on noise and flash levels, impulse, muzzle velocity and accuracy. Some of the designs contained holes, others had slots and a third concept employed combinations of holes and slots. Several of these experimental designs are illustrated in Figure 1.

The test results of these barrel extension studies revealed that the design with holes did not present sufficient area for the gases to enter the expansion chamber. Consequently, expansion of the gases was restricted which resulted in excessive noise and flash characteristics. In a second configuration with holes, the holes were slanted to act as a bore evacuator, thus preventing any propellant residue trapped in the expansion chamber from being vented back into the chamber area, weapon mechanism or magazine when the spent cartridge is extracted. In addition, by slanting the holes toward

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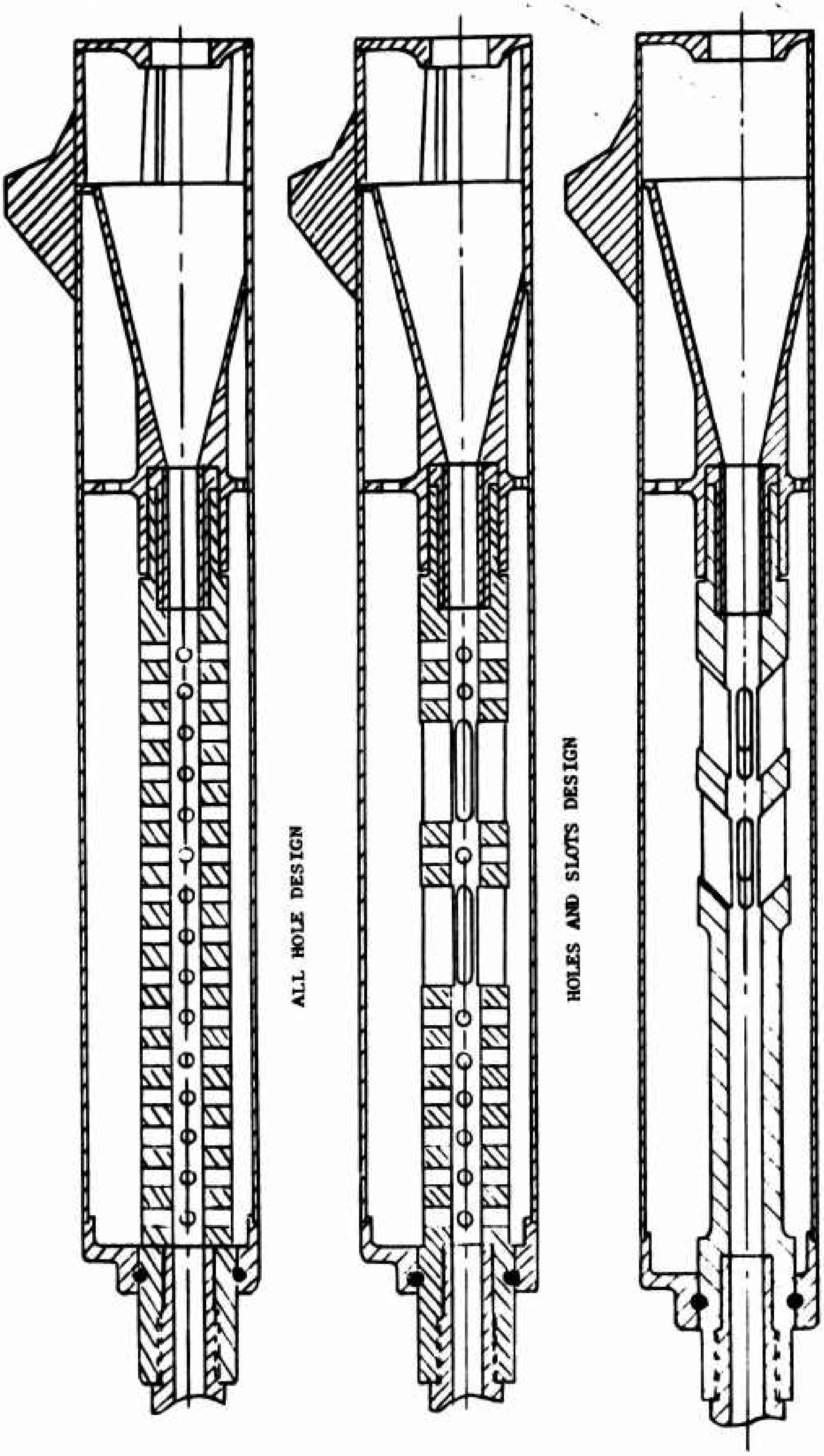
* SPIW Improvement Summary Report, USAWC Contract DAAF03-67-C-0036, AAI Engineering Report ER-4897, June 1967.



ALL HOLE DESIGN

HOLES AND SLOTS DESIGN

ALL SLOTS DESIGN

FIGURE 1. TYPICAL MUZZLE DEVICE CONCEPTS

the muzzle, the gases escaping from the expansion chamber evacuate the bore by "sucking" the gases in the bore out the muzzle. However with the vents oriented forward, expansion of the gas was impeded. In an effort to provide larger vents for the gases, the slotted design depicted in Figure 1 was designed. However, while some improvement was noted, the noise and flash produced with this configuration was still unacceptable. Also, the slot design experienced severe gas errosion since the gas flow was undisturbed and the high velocity gases were impinging directly on the forward ends of each slot. Subsequent investigation disclosed that by locating holes in front of the slots the gas flow was sufficiently disrupted to reduce the gas velocity adjacent to the bore surface. This resulted in a lessening of the errosion. The final barrel extension design selected as a result of these studies consisted of 28 holes and 8 slots arranged in sets of four (4) and located symetrically around the circumference of the barrel extension. The location, longitudinally, of the holes and slots is shown in Figure 2 - a cross-sectional view of this barrel extension. This design, with the proper expansion chamber, resulted in acceptable performance.

Table I lists the numerous muzzle device designs tested, including the barrel extensions and the expansion chamber configurations, and the performance obtained with each concept. Due to the heating problems associated with the barrel extension and expansion chamber at high rates of fire, several high temperature materials were used. Waspaloy was used in the fabrication of the barrel extension to relieve the errosion of the slots and eliminate any bending in this component. Several other methods of relieving

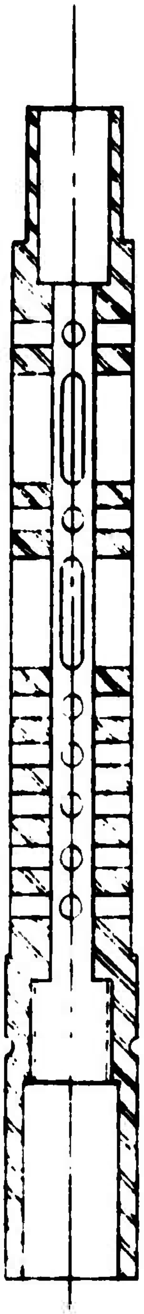


FIGURE 2. CROSS SECTIONAL VIEW OF 28 HOLE - 8 SLOT BARREL EXTENSION

TABLE I - MUZZLE DEVICE SUMMARY FOR SPIW IMPROVEMENT STUDY 1967

Barrel Extension			Expansion Chamber							
Configuration	Material	Outside Diameter (in.)	Configuration	Material	Wall Thickness (in.)	Pressure (psi)	Sound Level (db)	Impulse Reduction	Flash	Comments
(1) All holes, 60	4140 Stl.	.625	Off-set tank	4340 Stl.	.050	872	164.6	38%	None after 30 rounds	Sound level too high
(2) 16 holes, 8 slots	4140 Stl.	.625	Off-set tank	4340 Stl.	.050	903	160.3	38%	Small Flash	Expansion chamber wall split
(3) All slots, 8 tapered toward muzzle	Waspaloy	.627 at slots, .505 typ.	Off-set tank	A-286	.050	---	163.6	48%	Very low	Sound level too high, some erosion at fwd. end of slots
(4)(5)[1] 8 slots, tapered and 10 holes	Waspaloy	.627 at slots, .505 typ.	Off-set tank	A-286	.050	---	162.1	---	---	Sound level too high.
(6) 28 holes, 8 slots	4140	.625	Off-set tank shortened by 1½"	A-286	.025	1570[2]	161.7	41%	Slightly more than large tank	Expansion chamber wall bulged
(7) 28 holes, 8 slots	4140	.625	"	A-286	.050	---	---	---	---	Barrel extension bent after high rate tests .025" at end
(8) 28 holes, 8 slots w/glass filled teflon sleeve pressed on	4140	.625	"	A-286	.050	---	---	---	---	68 rounds disintegrated sleeve
(9) 28 holes, 8 slots	Titanium	.625	"	A-286	.050	---	---	---	---	Barrel extension bent .015 at end
(10) 28 holes, 8 slots, flame sprayed w/alum trioxide	4140	.625	"	A-286	.050	---	---	---	---	Barrel extension bent .020 at end
(11) 26 holes, 8 slots	Waspaloy	.625	"	A-286	.050	---	162	---	---	Barrel extension OK.

NOTES: 1 Test (5) was a velocity and accuracy measuring test only.

2 This pressure was computed by adiabatic expansion theory.

the problems attributed to the high temperatures generated in the barrel extension material were analyzed without success. The barrel extension surface was coated with aluminum-trioxide and a teflon sleeve was pressed into the barrel extension to insulate it and reduce heat input. However, the results were unsatisfactory. Experimental barrel extensions made from titanium were found to deform during testing. Consequently, Waspaloy was selected as the best material for this particular application.

The expansion chamber into which the hot gases were vented was also studied during the SPIW Improvement Program of 1967. Various size tanks and different materials were investigated to evolve a desirable configuration. The final configuration of the muzzle device which was developed as a result of these efforts is shown in Figure 3. Detailed test data pertaining to the number of rounds, mode of fire and total time to fire a given quantity of rounds, etc., is summarized in AAI Engineering Report ER-4897.*

Recent research and development studies conducted during Phase I of the current contract were concerned with determining the optimum vane size and angle, compensation area, and front plate hole size, to improve weapon accuracy and minimize impulse. The envelope of the expansion chamber was also investigated to determine its effect on muzzle flash, and, as expected, the amount of flash subsided with increased chamber sizes. The chamber length was ultimately increased from the 5-1/2 inches emanating from the SPIW Improvement Study to 7-1/2 inches. This modification was accompanied by a minimal increase (1/8 inch) in the diameter of the chamber. The barrel extension was

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* op. cit.

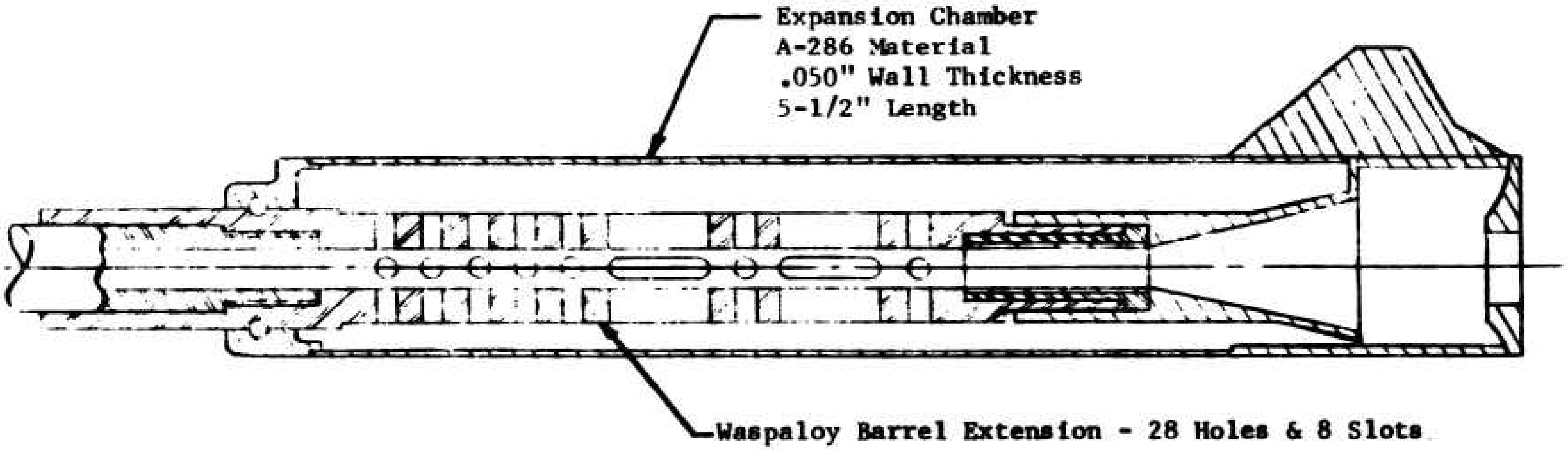


FIGURE 3. CROSS SECTIONAL VIEW OF MUZZLE DEVICE DEVELOPED DURING SPIW IMPROVEMENT STUDY - 1967

lengthened and an additional set of 4 slots and 4 holes was incorporated. The resulting improvement in flash was quite noticeable. Figure 4 is a cross-sectional view of the present muzzle device employed on the XM19 Rifle.

The present design has demonstrated that it is functionally acceptable insofar as suppressing noise and flash, reducing impulse and providing the necessary compensation. This muzzle device has proven reliable in numerous firing tests at all modes of fire and for sustained firing cycles.

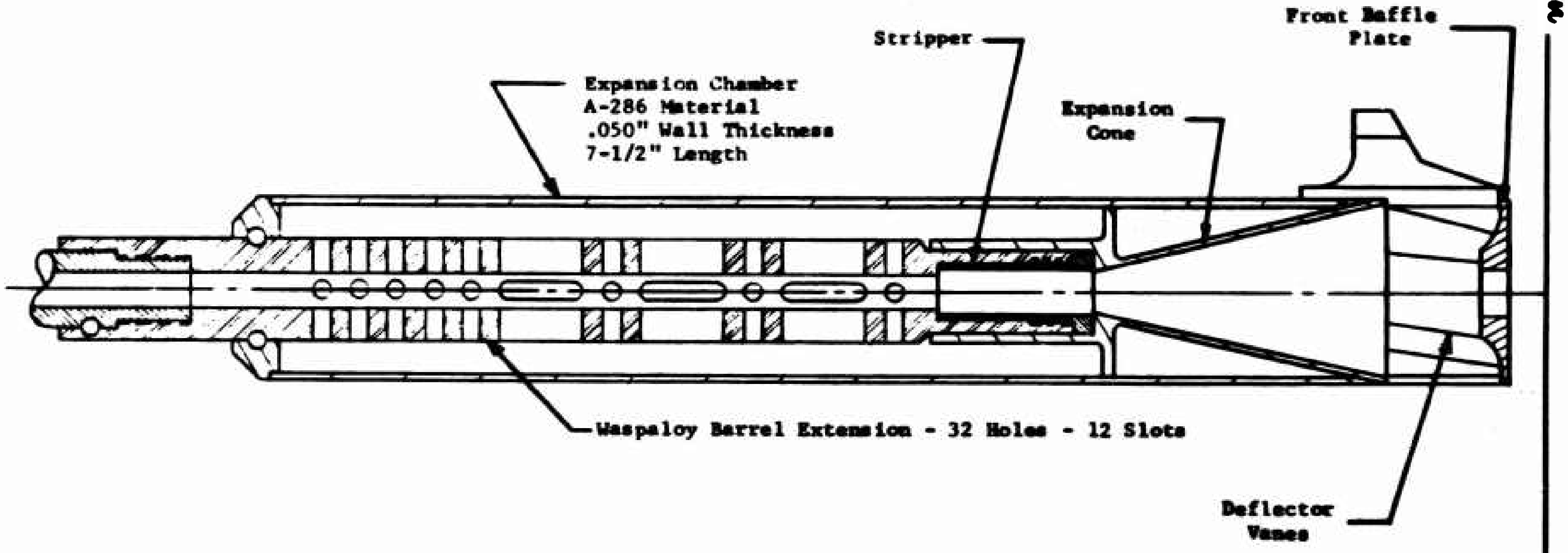


FIGURE 4. PRESENT MUZZLE DEVICE FOR XM-19 RIFLE

III. METHODS OF IMPROVING PRESENT DESIGN

A. Material Study

The SPIW muzzle device experiences very high temperatures due to the functions required of the design. The necessity to expand the gas in a large volume chamber at the muzzle allows the gas to transfer a significant amount of heat to the muzzle device. The barrel extension is being heated on the bore surface by the gases rushing past the holes and slots and on the outer surface by the gases being expanded in the chamber. After prolonged periods of firing, the temperature of the barrel extension approaches the steady-state temperature of the gases. (This is illustrated in the adiabatic gas expansion analysis of Appendix A.) The highest measured temperature on the surface of the barrel extension was 1320°F for the maximum recommended firing rate for the SPIW weapon, 100 rounds per minute. Figure 5 is a plot of the temperature-time history of the barrel extension surface and shows that near steady-state conditions are being reached. The adiabatic gas expansion temperature was computed to be 1340°F. This would indicate that the maximum material temperature has been experienced. Therefore, the material investigation conducted during this study was concerned with high temperature materials which could withstand temperatures of 1400°F without causing severe structural and errosion problems.

The previous (SPIW Improvement Study, 1967) material study was concerned with temperatures of 1600°F for the barrel extension, and consequently greatly limited the number of useable materials. Also, the material with the most desirable gas errosion resistance was selected regardless of

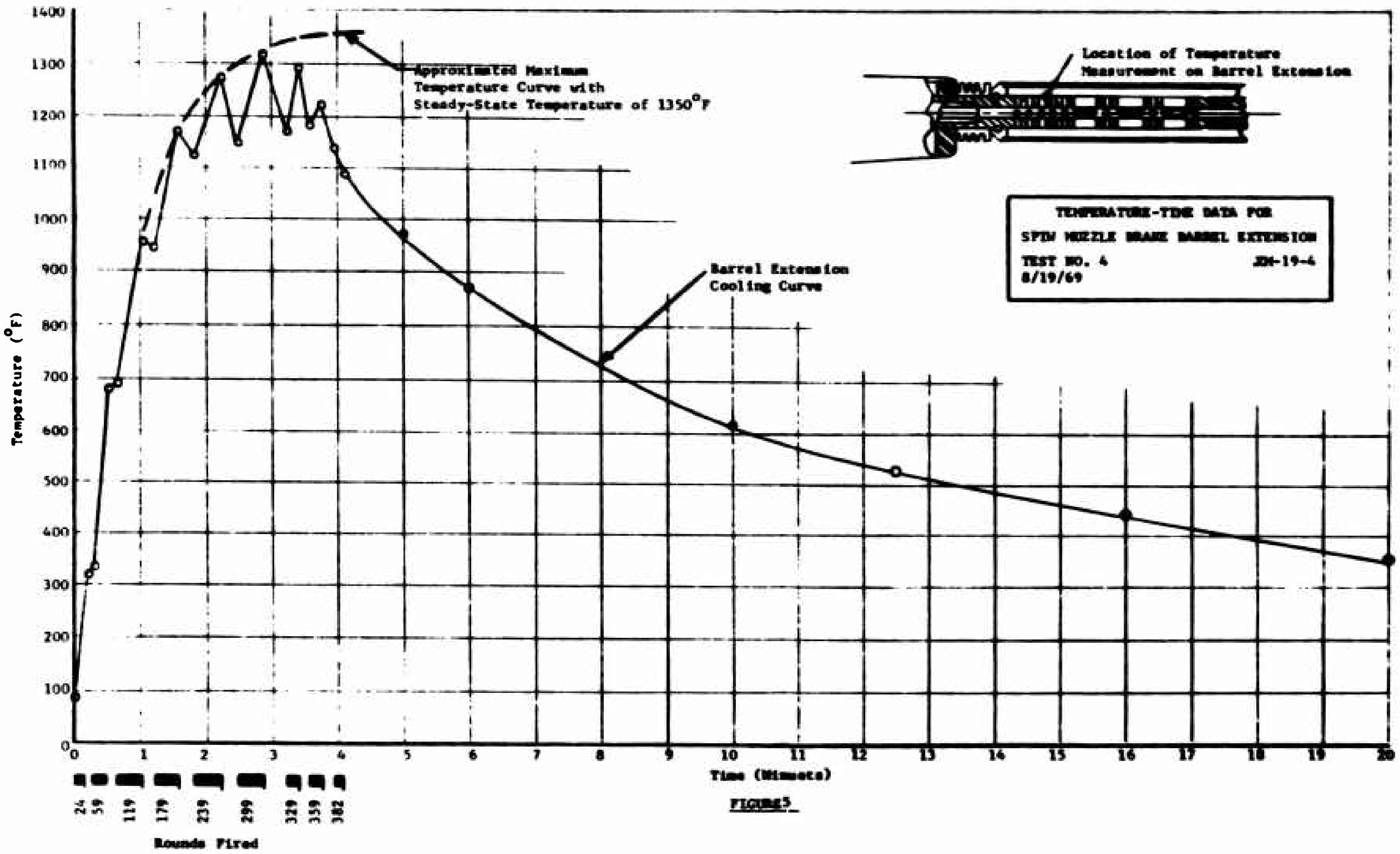

1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
Temperature (°F)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
Time (Minutes)
24
59
119
179
239
299
329
359
382
Rounds Fired
Approximated Maximum
Temperature Curve with
Steady-State Temperature of 1350°F
Barrel Extension
Cooling Curve
Location of Temperature
Measurement on Barrel Extension
TEMPERATURE-TIME DATA FOR
SPIW MUZZLE BRAKE BARREL EXTENSION
TEST NO. 4
JDM-19-4
8/19/69

FIGURE 5

the less desirable properties of the material. The feasibility of the design principle was of paramount importance; therefore, the material most suited for this performance was selected. The material selected was Unitemp Waspaloy because of its excellent corrosion resistance up to 1600°F against gaseous atmospheres encountered in jet engine operation. Turbine buckets and discs constructed of Waspaloy are very widely used in aircraft gas turbine engines. Because this material is a high cobalt content alloy (12-15%), the machineability of this alloy, in any condition of heat treat or fabrication, is somewhat more difficult than conventional materials.

The present heat treatment consists of heating at 1975°F for four hours and air cooling with material stabilization at 1550°F for 24 hours followed by air cooling. The last step is to age or precipitation harden by treating at 1400°F for 16 hours and air cooling. The total heat treat time, not including the air cooling between steps is 44 hours. Therefore, the present material investigation has considered heat treatment time and process, and machinability in addition to the material strength, elongation and temperature effects. However, the most desirable materials for this application must exhibit high strength at temperatures in the 1400°F region. Alloys which develop the best high temperature strengths are iron base, nickel base and cobalt base types. The 18-8 (AISI type 304) type stainlesses and modified 12% chromium steels do not maintain their strength at 1400°F and have been eliminated from consideration. Some cobalt base alloys and alloys with a high percent of cobalt were listed in the material comparison chart but were not selected for consideration because of the difficulty normally associated with machining high cobalt content alloys. The hardness properties of cobalt result in excellent high strength characteristics at elevated temperatures. In the event fabrication techniques, other than machining can be employed, the use of Waspaloy should be reconsidered - especially in view of its strength characteristics. (This is discussed in detail in Part B, Fabrication Methods.) However, present casting methods are not adequate to hold the tolerances necessary for the barrel extension.

Table II summarizes the pertinent properties of the most desirable metals investigated. By excluding the metals with a high cobalt content, the metals which develop the highest yield strength at 1400°F are Udimet D979 and the Inconel Alloy 718. The strengths of these two nickel base alloys are approximately the same; however, the heat treat time of Inconel 718 is less than the D979 by 7 hours which would result in appreciable savings. Consequently, Inconel alloy 718 has been selected as the most desirable material for fabricating the muzzle device. This age-hardened alloy can be readily fabricated into complex parts and exhibits a combination of good tensile, fatigue, creep, and rupture strength at elevated temperatures. The cobalt percent is insignificant at 1% and apparently does not affect the machinability of this material. Published literature by the material manufacturer states that this alloy can be readily machined, but its high strength and work-hardening characteristics must be considered in the selection and use of proper tool materials and design, operation speeds and coolants. The actual machinability must be determined by fabricating the barrel extension from this material.

TABLE II. HIGH TEMPERATURE MATERIAL COMPARISON

Material	Yield Strength (psi)			Elongation		Machineability	Corrosion Resistance	Weldability	Heat Treatment Time (hrs)	Major Elements	Percent Cobalt	Application
	70°F	1200°F	1400°F	70°F	1400°F							
(1) Udimet 700	130,000-160,000	140,000	125,000	--	--	Use carbide tools	Excellent	Weldable by standard methods	48	Nickel	14-20%	Gas turbine blades & disc in 1400-1800°F range
(2) Udimet D-979	130,000	125,000	120,000	--	--	Use carbide tools	Good	Weldable by standard methods	26	Nickel-Iron	None	Turbine disc up to 1200-1400°F
(3) Inconel 718	163,000	140,000	116,000	21%	5%	Readily machined	Excellent	Excellent	19	Nickel-Chromium	1%	Liquid rockets, turbine cryogenic tanks - 423 t 1300°F
(4) Unitemp 500	125,000	114,000	113,000	31%	39%	Very difficult in any condition	Excellent to 1650°F in gaseous atm. of jet engines	Not practical	46	Nickel	13-20%	Highly stressed turbine buckets
(5) Hayne R-41	120,000	116,000	107,000	18%	11%	Good in annealed condition	Excellent	Weldable	20	Nickel-Chromium	11%	After burner parts
(6) Udiment 520	120,000-150,000	115,000	105,000	--	--	Use carbide tools	Excellent	Weldable	24	Nickel-Chromium	12%	Gas turbine blades
(7) Unitemp Waspaloy	115,000	100,000	99,000	28%	28%	Very difficult	Excellent to 1600°F	Not weldable	44	Nickel-Chromium	13.5%	Turbine buckets and disc
(8) Unitemp M-252	98,000	91,800	87,200	25%	25%	Very difficult	Very good to 1600°F	Not practical	19	Nickel-Chromium	9-11%	Turbine buckets
(9) Udimet V-57	120,000	110,000	80,000	--	--	Use carbide tools	--	Weldable	--	Iron-Nickel	None	--
(10) Udimet 901	120,000	110,000	80,000	--	--	Use carbide tools	--	Weldable	30	Iron-Nickel	None	Turbine & compressor rotors.
(11) Udimet Ni-80A	90,000	80,000	73,000	--	--	Use carbide tools	--	Weldable	--	Nickel-Chromium	1.1%	--
(12) Inconel X-750	90,000	82,000	68,000	20%	10%	Readily machined at economical rates	Excellent at high temp	Weldable	48	Nickel-Chromium	None	Turbine blades, wheels, bolts
(13) Inconel 625	70,000	60,000	60,000	45%	60%	Very good	Excellent at high temp	Excellent	Mill-annealed 1 hr.	Nickel-Chromium	1.0%	Jet engine components
(14) Unilov A-286	93,500	86,000	54,000	24%	18.5%	Readily machined like stainless steels	Excellent to 1300°F	Weldable in solution treat condition	17	Iron-Nickel-Chromium	None	Turbine components
(15) Unitemp L-605	87,000	55,000	48,000	40%	12%	More difficult than SS with strong tendency to work harden.	Excellent to hot atm.	Good welding characteristics	Used in annealed state	Cobalt-Chromium-Tungsten	5%	After burner parts

The yield strength of Inconel 718 and Waspaloy are compared in Figure 6. The high strength of the Waspaloy is retained to a higher temperature than the Inconel 718; however, sufficient strength exists at 1400°F for Inconel 718 to allow its use in the muzzle device.

The expansion chamber, compensator vanes and remaining parts of the muzzle attachment are fabricated from A286 material. Uniloy A-286 is a precipitation hardening type alloy which develops optimum properties from a solution treatment followed by a precipitation hardening. This metal is readily machinable by the methods used for austenitic stainless steels. It is designed to provide high strength up to 1300°F with corrosion resistance against all atmospheres encountered in jet engines and turbosuperchargers applications.

The present chamber design has proven acceptable at the prolonged firing rates which SPIW has been exposed to. This design has a wall thickness of .050 inch. Previous tests conducted at AAI have shown that a .025 inch wall thickness is unacceptable. (The stress analysis in Appendix B shows the detailed calculations.) For the A-286 material to yield with the .025 inch wall thickness the temperature had to equal 1420°F. Using this temperature the recommended material, Inconel 718, exhibits a yield strength which is more than twice that of A-286 (see Figure 7). Since the firing rate schedule of 100 rounds per minute presently recommended is less than the rate at which the chamber yielded, the temperature of 1420°F should not be encountered. However, to assure a safe design with the new material this temperature has been used as the design limit and a safety factor of 1.5

FIGURE 6

YIELD STRENGTH VS. TEMPERATURE COMPARISON
FOR INCONEL 718 AND WASPALOY

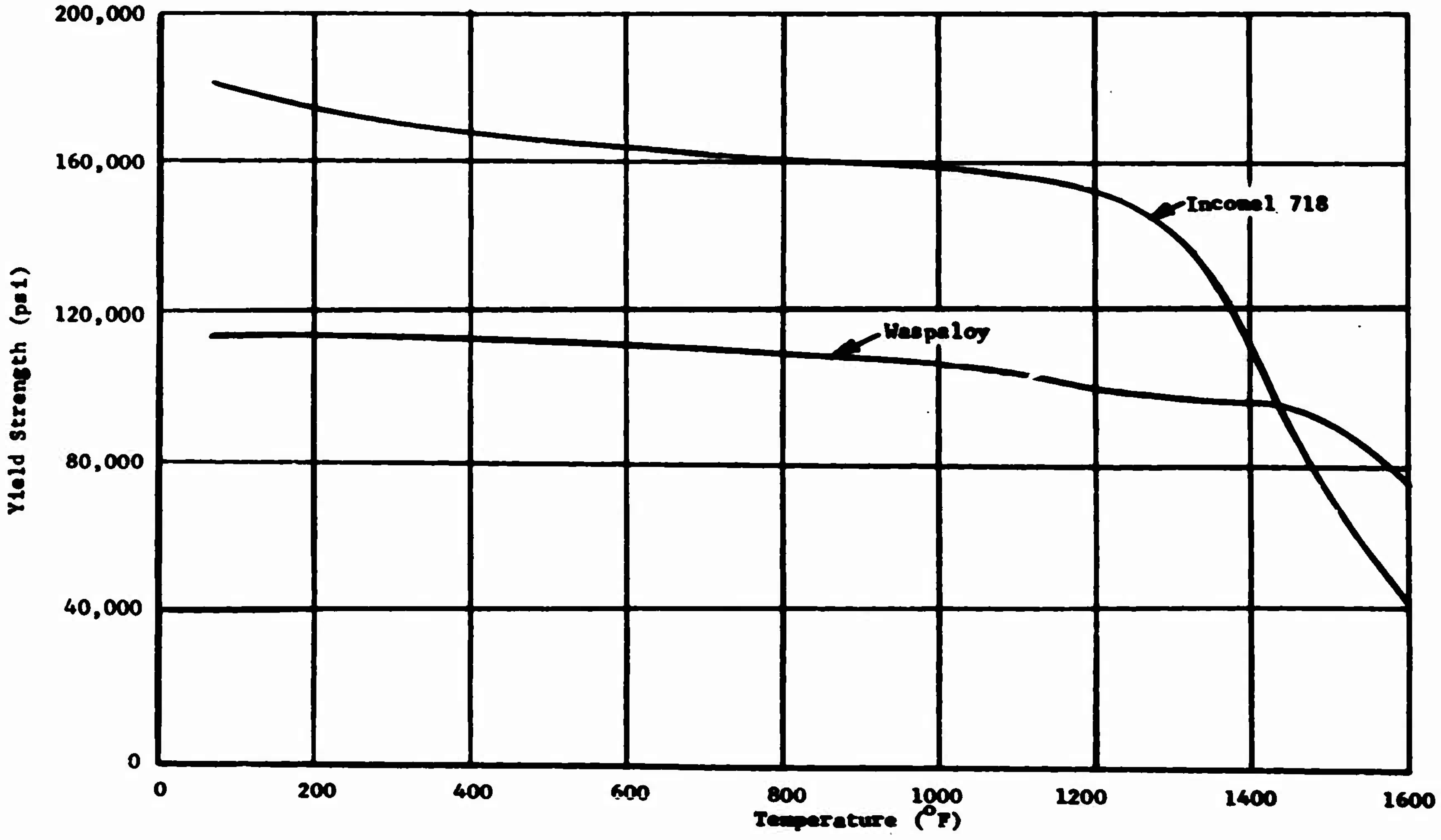
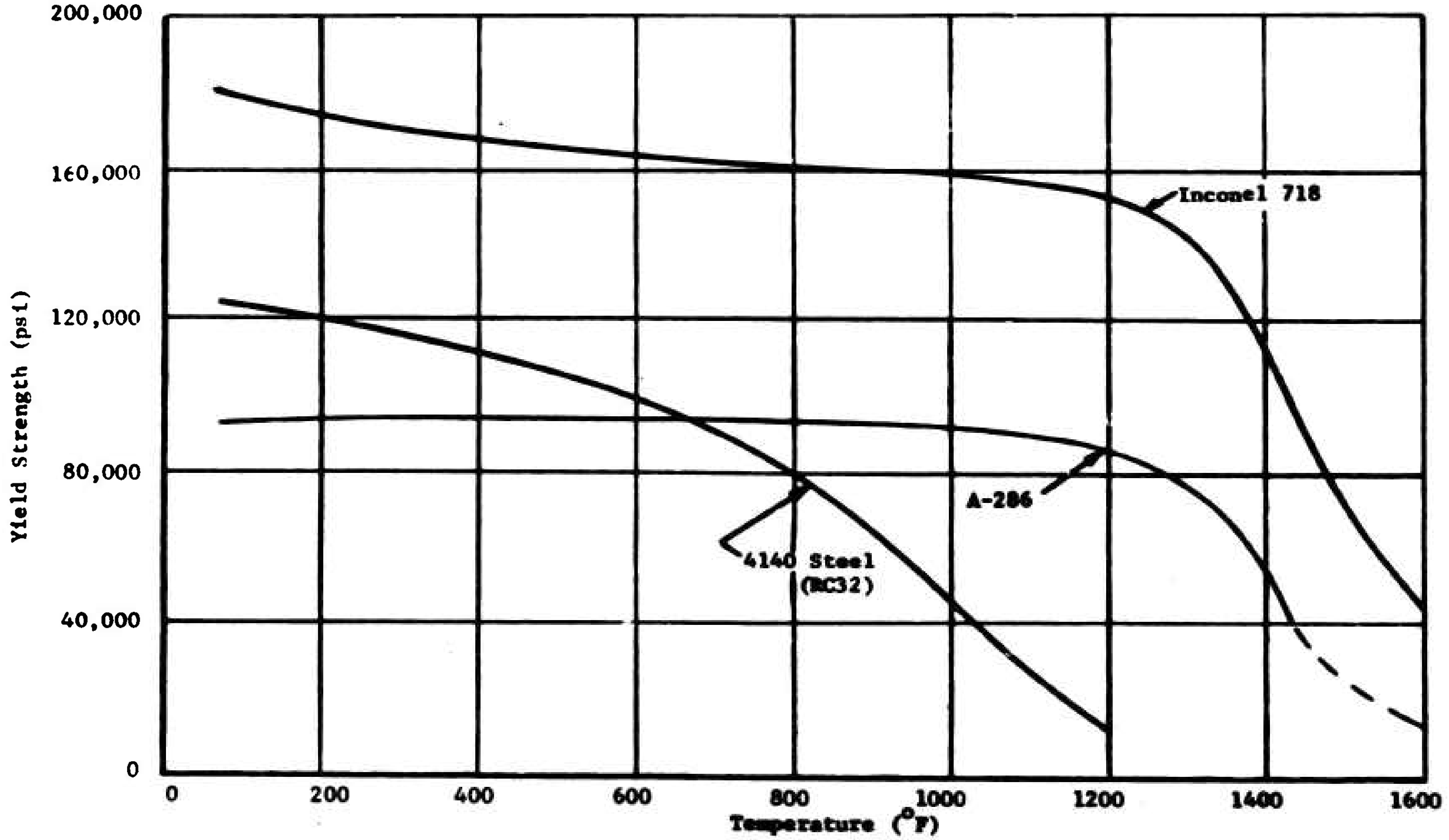


FIGURE 7

YIELD STRENGTH VS. TEMPERATURE COMPARISON
FOR INCONEL 718, UNILOY A-286 AND 4140 STEEL (RC32)



imposed on the material wall thickness. The recommended wall thickness is .018 inch which will reduce the tank weight and material cost. Fabrication methods discussed in Section B show that Inconel 718 can be investment cast which will further reduce the cost of the muzzle device.

The final acceptability of this alloy will be determined from controlled firing tests. These tests are essential to determine the operation of this material at the elevated temperatures experienced in the weapon. This material's operational temperature range is optimum to 1300°F and, based on present data, can be extended to 1400°F. However, temperatures of 1600°F cause the strength to rapidly decrease. Figure 7 illustrates the strength versus temperature for Inconel 718. The area of most concern is the errosion of the holes and slots in the barrel extension. The strength of the expansion chamber appears acceptable and should be no problem structurally. The errosion of the openings in the muzzle device beyond the barrel extension is not a problem provided the barrel extension bore is true (concentric) and the holes are of the proper size.

B. Fabrication

The present method of fabricating the muzzle device involves machining the components from solid material and welding the muzzle attachment components together. While the barrel extension was machined from Waspaloy, the remaining components of the muzzle device - the cone, bottom plate, front plate, chamber, back plug, rear vane plates and the front sight were machined from solid A-286 material and assembled using a special fixture to align the holes in the front plate and the cone.

One method of greatly reducing the fabrication time and cost of the muzzle device is to investment cast those parts which can be cast acceptably. The barrel extension cannot be investment cast due to the close tolerance on the "total indicated reading" of the bore concentricity. The present tolerance is .001 inch TIR and test firings have shown that readings exceeding this value have caused the holes in the cone and the front plate to erode badly causing a degradation in weapon accuracy. Investment castings can achieve a TIR of .005 inch per linear inch. Consequently, the only method of improving the barrel extension machinability is to change materials. The recommended Inconel 718 material should relieve the machining problem associated with the Waspaloy barrel extension. The remaining parts of the muzzle device can be individually investment cast. Also, the possibility of casting the muzzle attachment into one or two sections is being investigated. Numerous tolerances must be changed to investment cast these components and a set of investment casting drawings is presently being prepared for release to casting manufacturers for price quotations. The two holes in the muzzle attachment, one in the cone and the other in the front plate, must be machined to assure proper concentricity, but the remaining parts have few critical dimensions.

The holes in the cone and front plate are critical areas in which gas erosion occurs. In the event that the Inconel 718 material is not adequate to withstand the gas velocities causing erosion, these parts can be investment cast from Waspaloy.

In the event that Waspaloy must be used for the barrel extension and alternate method of fabrication would be an electric discharge machine (EDM). The bore, gas holes and slots can be cut in with the EDM and this would save in fabrication time and increase tool life over present methods. However, the blind hole and threads would still be cut using present machining methods utilizing carbide tools with recommended lubricants and feed speeds.

Final studies will summarize the total cost savings of the investment casting process over the machining operations presently being used.

C. Weight Reduction

The present muzzle device weight can be reduced by using the material recommended in part A of this section. Also, investigation of previous muzzle device studies has shown that the minimum size barrel extension was not determined in these studies. The original barrel extension was machined from heat-treated 4140 steel (RC32) and had an outside diameter of .625 inch. This barrel extension bent after repeated high rate firing cycles. As a result of these tests, the barrel extension material was changed to Waspaloy; however, the same outside diameter was used. Since the Waspaloy material exhibits a much higher yield strength at high temperatures than the 4140 heat-treated steel it would appear that the barrel extension wall thickness could be reduced. Stress analysis of this part (see Appendix B) revealed that the size could be reduced for the Waspaloy material. Also, the use of Inconel 718 material allows the present size of the barrel extension to be reduced, resulting in an 18% weight reduction of the barrel extension.

The bending stress in the present barrel extension is caused by the momentum transferred from the gases to the muzzle device. This action is due to the compensator vanes deflecting a portion of the gases upward. The bending stress was computed in Appendix B to be 43,000 psi. Figure 7 shows that the original 4140 barrel extension should not have been operated at a temperature exceeding 1010°F at this stress level. Tests results revealed that the outside wall temperature of the barrel extension exceeded this temperature on several occasions without the barrel extension yielding noticeably. Consequently, this method of analysis can be used to redesign the barrel extension for the recommended material, Inconel 718. Calculations in Appendix B show that the wall thickness can be reduced from .215 inch to .177 inch. The resulting weight saving, estimated to be .08 pound, would reduce the weight of the barrel extension from .447 to .367 pound.

The muzzle attachment, consisting of the expansion chamber, front sight, rear vane plates, back plug, front plate, bottom plate, and cone weighs .756 pounds, a significant proportion of the total weapon weight. Previous studies have been concerned with muzzle device performance rather than its total weight. However, this weight can be appreciably reduced by the use of Inconel 718 material which was selected in Section II A. This material exhibits twice the yield strength of the presently used A-286 muzzle attachment material at 1400°F, the design temperature. Therefore, the thickness of most components in the muzzle attachment can be halved. The expansion chamber weight is over 60% of the total muzzle attachment weight and has been given special emphasis in this study. The stress analysis of Appendix C shows that a thickness of .018 inch is acceptable for the chamber using Inconel 718 material provided the temperature does not exceed 1530°F. This would reduce the chamber weight from .40 pounds to .28 pounds. Investigation of the remaining muzzle attachment parts reveals that the weight of several of these parts could also be reduced by changing materials. Optimistically, the size of most of these parts could be halved due to the increased strength of Inconel 718 over A-286. Further studies of these parts for weight savings will be incorporated in the second portion of this program in which actual parts will be fabricated to determine their minimum sizes. It appears that the size of the sight, back plug, and front plate cannot be reduced because of their specific functions. However, the remaining components can be reduced in size. Preliminary weight analysis shows that the total muzzle attachment weight could be reduced from the present .756 pound weight to .348 pounds.

Therefore, the muzzle device weight, including the barrel extension, can be reduced from 1.203 pounds (.756 + .447) to .715 pound (.348 + .367). While the stress analyses performed on the component parts contributed to this weight reduction, the most significant factor was provided by the transition in the material to be employed.

D. Related Investigations

While it is not being performed within the scope of the muzzle device study, a product improvement program is being undertaken relative to the propellant and the results may be germane to this effort. The program, being conducted with the assistance of the Olin Corporation, entails two major phases.

The purpose of Phase I is to identify the materials in the residue accumulated in the weapon mechanism, isolate their source and, if feasible, recommend modifications to the propellant. Phase II - product improvement - includes altering the propellant formulation to reduce the contents of the residue that are related to the propellant. Also, revisions will be made which change the burning characteristics of the propellant. The ultimate goals of these research efforts are to reduce muzzle pressure and, more importantly, muzzle flash. If, through propellant development, the flash can be lessened significantly, then the envelope of the muzzle device can be reduced. This has the additional desirable feature of providing a smaller reservoir in which to entrap the gases and other products which are ultimately vented into the weapon upon extraction of the case.

Certainly any improvements which can be incorporated in the muzzle device as a result of the findings generated from this propellant study should be considered. It should be noted that, if significant reduction in the envelope of the muzzle device can be achieved, benefits are automatically realized regarding ease of fabrication, weight reduction and overall cost.

IV. RECOMMENDATIONS

As a result of the engineering study, AAI Corporation recommends the following efforts be performed to achieve the goals outlined for the muzzle device study.

A. Utilizing the present muzzle attachment, manufacture and test one barrel extension fabricated from Inconel 718 material.

B. Utilizing Inconel 718 material manufacture and test one expansion chamber with the proposed wall thickness of .018 inch.

C. Continue investigation into feasibility of employing investment casting techniques for manufacturing the muzzle attachment parts.

D. Evaluate propellant developed during propellant study to establish relative flash characteristics and determine ultimate configuration of the muzzle device based on the results obtained.

E. Conduct evaluations of most desirable materials - Inconel 718, Udimet D-979, Haynes 41, and Udimet 520, to confirm their machinability.

To determine the acceptability of the designs emanating from this program it is proposed to subject the configurations to the following ballistics tests. To examine the structural integrity of the barrel extension and expansion chamber a test will be conducted in which a total of 350 rounds will be fired at a rate of 100 rounds per minute. In addition, photographic evidence will be accumulated to insure that the flash level is acceptable. Sound data will be recorded to guarantee suitable noise levels. Accuracy evaluations, both single shot and three round burst, will be performed to insure that these performance characteristics have not been compromised by design changes.

APPENDIX A

EXPANSION OF GASES

The present muzzle device utilizes a tank into which the hot propellant gases are expanded. By assuming that the gases are expanded adiabatically, the gas pressure and temperature in the tank can be computed. The necessary equations are,

$$\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^{\gamma}$$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\gamma-1/\gamma} = \left(\frac{V_1}{V_2}\right)^{\gamma-1}$$

where P_1, T_1, and V_1 are the pressure, temperature and volume of the gases contained in the chamber and bore prior to the beginning of the barrel extension slots,

P_2, T_2, and V_2 are the pressure, temperature, and volume of the gases after the gases are expended in the tank, and

γ is the ratio of the specific heats.

The gas pressure, P_1, before the gas enters the tank was computed initially using the AAI Interior Ballistics Computer Program. This pressure was 14,000 psi and is used to compute the expanded gas pressure. The necessary volumes are

$$V_1 = V_{chamber} + V_{bore}$$

$$V_{chamber} = .0865 \text{ in}^3$$

$$V_{bore} = \frac{\pi}{4}(.227)^2(14.04 - 2.13 - .725) = .453 \text{ in}^3$$

$$V_1 = .540 \text{ in}^3$$

$$V_2 = V_{tank} + V_1$$

$$V_2 = 4.54 + .54 = 5.08 \text{ in}^3$$

Solving for P_2,

$$P_2 = 14000 \left(\frac{.540}{5.08}\right)^{1.24} = 868 \text{ psi}$$

The propellant gas pressure at the beginning of the barrel extension was measured experimentally to be 15,000 psi and hence P_2 becomes 930 psi. Further test measurements revealed that the assumption of adiabatic expansion was reasonably correct, since the tank pressure measured experimentally was 902 psi. Therefore, the assumption of adiabatic expansion can be used to compute the gas temperature also. The temperature of the gases at the barrel extension slots was obtained from the Interior Ballistic Computer Program and used in the computation below.

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1}$$

$$T_2 = 3100 \left(\frac{.540}{5.08}\right)^{(1.24-1)} = 1780^{\circ}\text{R } (1320^{\circ}\text{F})$$

or

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\gamma-1/\gamma}$$

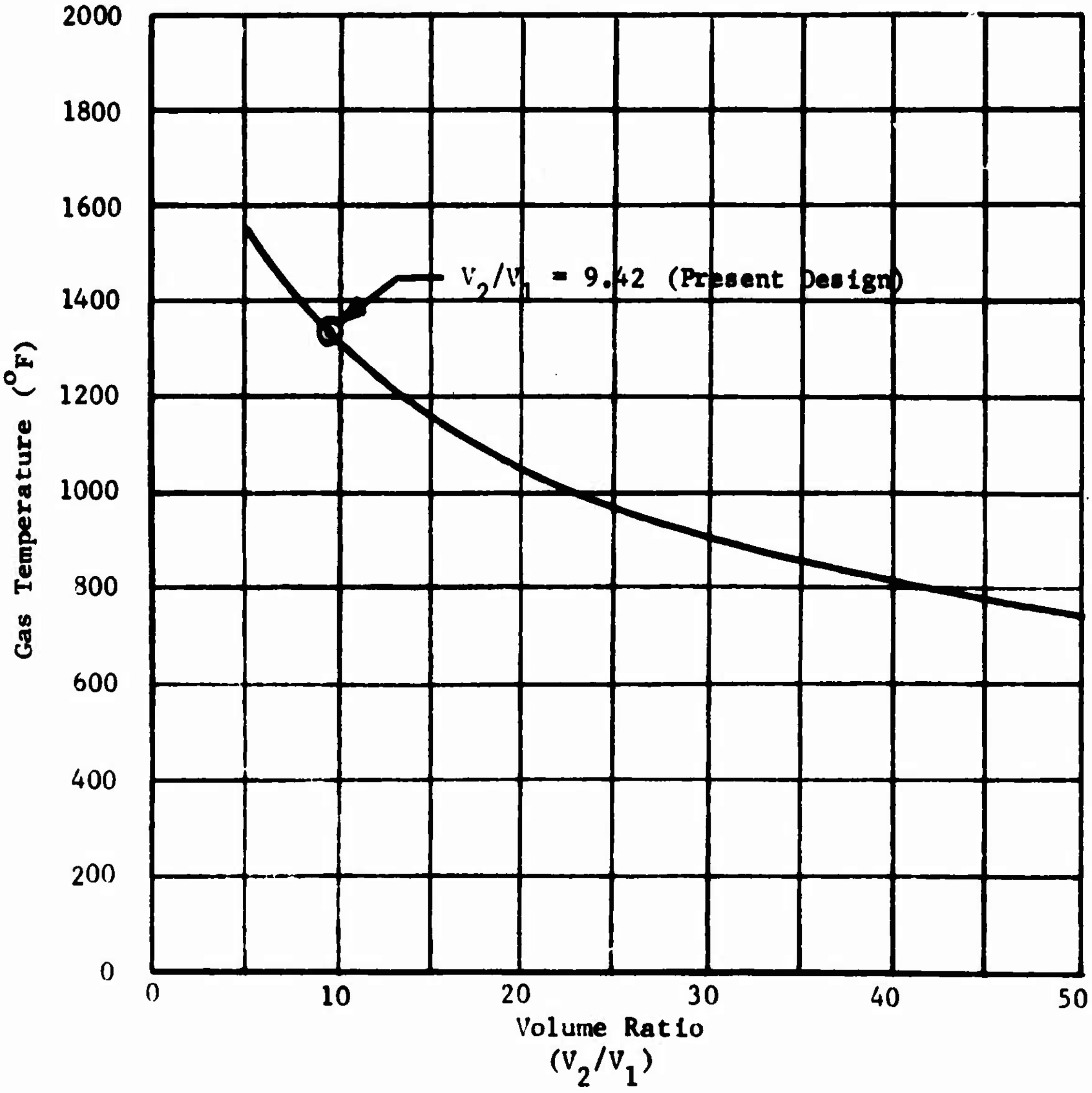
$$T_2 = 3100 \left(\frac{908}{15,000}\right)^{(1.24 - 1/1.24)} = 1801^{\circ}\text{R } (1341^{\circ}\text{F})$$

The above results show that the larger the tank volume, V_2, the lower the propellant gas pressure and temperature. Plotting the propellant gas temperature versus the volume expansion ratio, V_2/V_1, illustrates the effect of tank volume on the gas temperature after expansion (see Figure A-1).

The material studies reveal that the material temperature must be reduced to 1000°F to allow using 12% chromium or 18-8 stainless type materials. These materials would be a significant improvement over the vacuum melt metals listed in Table II. However, the volume ratio at a gas temperature of 1000°F is 23:1 requiring a 12.88 cubic inch tank which is 2.8 times larger in volume that the present tank. Constructing a tank this size is not feasible because of the excessive length and/or diameter of the tank required. Also, the tank weight would be appreciably increased.

FIGURE A-1

GAS TEMPERATURE VS. VOLUMETRIC
EXPANSION RATIO FOR ADIABATIC EXPANSION
AND INITIAL GAS TEMPERATURE OF 3100°R

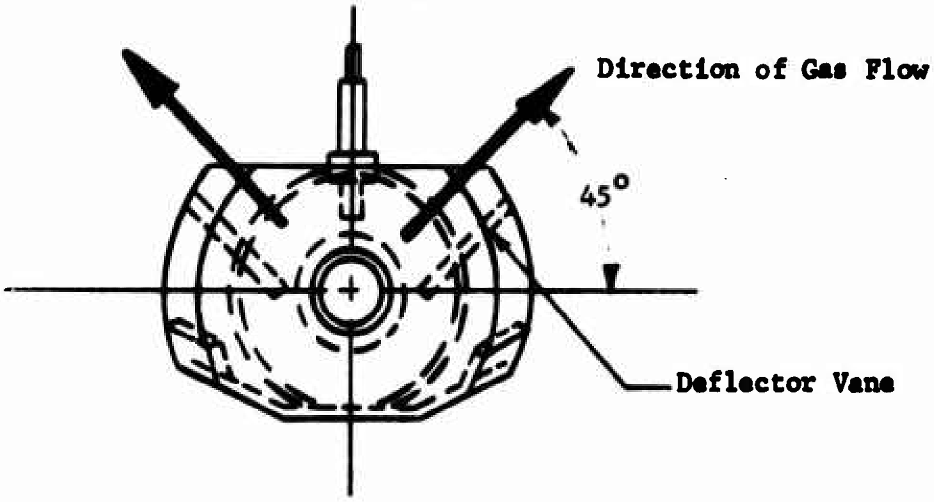


APPENDIX B

STRESS ANALYSIS OF BARREL EXTENSION

The barrel extension experiences a bending load caused by the transfer of momentum from the propellant gases being deflected upward by the compensator vanes to the weapon. This load was sufficient to bend the barrel extension when 4140 steel (RC32) material was used and the weapon was fired at prolonged high rates. The stress analysis of this Appendix computes the bending stress and shows that the 4140 steel barrel extension was under-designed for the temperatures it experienced.

The momentum of the propellant gases is computed by assuming that the gas velocity is approximately Mach 4 or 4400 fps and that only the vertical component of the gases is effective.



Also, the percent of the gas being diverted through the vanes was computed by ratioing the area of the vane opening to the total gas exit area (the vane openings plus the hole in the front plate).

Gas momentum:

$$(mv)_{gas} = A_R \times m_{gas} \times v_{gas} \cos 45^\circ$$

where: A_R = area ratio of the vane area to the vane plus front plate hole area

m_{gas} = mass of propellant gas

v_{gas} = propellant gas velocity after being expanded by cone in the muzzle attachment

$$(mv)_{gas} = \left(\frac{2.066}{2.1366}\right) \times \left(\frac{22}{7000 \times 32.2}\right) \times 4400 \cos 45^\circ$$

$$= .292 \text{ slugs ft/sec}$$

Equating the gas momentum to the rotational momentum of the weapon allows the angular velocity of the weapon, ω, to be computed:

$$(mv)_{gas} \times \bar{r} = I\omega$$

$$\omega = \frac{(mv)_{gas} \times \bar{r}}{I}$$

where: $(mv)_{gas}$ = gas momentum

$\bar{r}$ = moment arm of the gas momentum

I = moment of inertia of the weapon about the firer's shoulder, assume the barrel is the most significant component.

ω = angular velocity of the weapon

Solving for the moment of inertia:

$$I = m \left[\left(\frac{r_1^{\,2} + r_1^{\,2}}{4}\right) + \frac{\ell^2}{12} \right]$$

where: m = weapon mass

r_1 = barrel outside diameter

r_2 = barrel inside diameter

ℓ = weapon length

$$I = \frac{8}{32.2}\left[\frac{(.625)^2 + (.227)^2}{4} + \left(\frac{36}{12}\right)^2\right]\frac{1}{144}$$

$$= .186 \text{ slugs-ft}^2$$

$$\therefore \omega = \frac{.292 \times 18/12}{.186} = 2.35 \text{ rad/sec.}$$

The rotational energy of the weapon is computed and equated to the strain energy of the barrel extension in bending to determine the bending force. The rotational energy is,

$$E_R = \frac{1}{2} I \omega^2$$

$$= \frac{1}{2}(.186)(2.35)^2 = .512 \text{ ft-lb.}$$

The strain energy is,

$$E_s = \frac{1}{2} K \delta^2 = \frac{1}{2} \frac{P^2}{K}$$

where: K = spring rate of the barrel extension in bending

P = bending force developed from the momentum transfer

δ = deflection

The spring rate of the barrel extension is computed from the deflection equation of a cantilever beam.

$$\delta = \frac{P x^3}{3EI_o}$$

$$K = \frac{P}{\delta} = \frac{3EI_o}{x^3}$$

where: I_o = area moment of inertia of the barrel extension

$$= \frac{\pi}{64}\left[(.625)^4 - (.227)^4\right] = .00736 \text{ in}^4$$

x = barrel extension length = 8"

E = material modulus of elasticity = 30×10^6 psi.

Solving for the spring rate,

$$K = \frac{3(30 \times 10^6)(.00736) \times 12}{(8)^3} = 1.552 \times 10^4 \text{ lb/ft}$$

Now, equating the strain and rotational energies and solving for P,

$$E_R = E_S$$

$$P = \sqrt{2K\,E_R}$$

$$P = \left[2(1.552 \times 10^4)(.512)\right]^{\frac{1}{2}} = 126 \text{ lb.}$$

The bending stress of the barrel extension can be computed from the following equation:

$$S = \frac{Mc}{I_o}$$

where: $M = Px$, the bending moment caused by the force P

$$c = \frac{.625}{2} = .3125$$

$I_o = .00736 \text{ in}^4$, see calculation previously

$$S = \frac{126(8)(.3125)}{.00736} = 43{,}000 \text{ psi.}$$

Using this bending stress level to determine the temperature limit at which the 4140 (RC32) steel could be used reveals that the maximum temperature is 1010°F (see Figure 7). Temperature measurements of the barrel extension during firing tests showed that this temperature was exceeded. Temperatures in excess of 1300°F have been recorded which illustrates that 4140 steel is unacceptable. However, the acceptable temperature at which the present Waspaloy barrel extension could be operated is in excess of 1600°F. Therefore, the present Waspaloy barrel extension thickness could be appreciably reduced since the operating temperature of the barrel extension does not exceed 1400°F.

Since Inconel 718 material has been recommended for use in the barrel extension the minimum wall thickness was computed using the preceding equations to be .177 inch. To illustrate the relative size and weight of the three barrel extension materials discussed, the following table was generated.

Material	Bending Stress	Allowable Yield Strength (psi) at 1400°F	Barrel Extension		
			Outside Dia. (in.)	Thickness (in.)	Weight (lb.)
4140 Steel (RC32)*	43,000	--	.625	.199	.431
Inconel 718	46,400	111,000	.580	.177	.367
Waspaloy Present Design	41,000	98,000	.656	.215	.447

* This material has relatively no strength at 1400°F.

This method of analysis to determine the dynamic force developed in the barrel extension is generally found to be conservative, and consequently, the material thickness may be further reduced if actual firing results prove the structural integrity of the barrel extension. Also, the low stress level of the proposed barrel extension indicates that the material thickness could be reduced.

APPENDIX C

STRESS ANALYSIS OF EXPANSION CHAMBER

The expansion chamber (tank) of the muzzle device must withstand the pressure of the hot propellant gases which are vented through the barrel extension holes and slots and are expanded into the chamber. The maximum pressure in the expansion chamber was measured and computed by using adiabatic expansion theory in Appendix A. During the muzzle device test conducted at AAI and presented in AAI Engineering Report ER-4897,* the expansion chamber yielded when a .025 inch wall thickness was used. The material was A-286. The pressure measured in this test was 938 psi and computing the stress gives,

$$S = \frac{PD}{t}$$

where S = maximum stress caused by internal pressure (hoop)

P = internal pressure in chamber

D = mean chamber diameter

t = wall thickness

$$S = \frac{938 \times 1.21}{.025} = 45{,}300 \text{ psi}$$

Since the material yielded at this stress, the temperature at which yielding occurred can be determined from a yield strength versus temperature plot for A-286 (see Figure 7). The resulting temperature is 1420°F. To resolve this problem the material thickness was doubled which halves the stress; however, this only increases the operating temperature to 1500°F for A-286

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* SPIW Improvement Summary Report, USAWC Contract No. DAAF03-67-C-0036, AAI Engineering Report ER-4897, June 1967.

material. The material recommended to replace A-286 is Inconel 718 which exhibits a significantly high yield strength between 1400 and 1500°F than A-286. At 1420°F the Inconel 718 has a yield strength of 95,600 psi. Using a safety factor of 1.5 the new material thickness is computed.

$$t = \frac{PD}{S} \times 1.5 = \frac{938 \times 1.21 \times 1.5}{95,600}$$

$$t = .0178''$$

This design would allow operation to temperatures of 1530°F before any yielding should occur. This temperature level is 30°F higher than the present .050 inch thick expansion chamber can operate at.