MANTECH II GAU 8/A Penetrator

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CORROSION TESTING OF THE GENERAL ELECTRIC-
MANTECH II GAU 8/A PENETRATOR

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ABSTRACT

The corrosion performance of investment-cast U-0.75 wt. % Ti penetrators for the U.S. Air Force rapid-fire gun (GAU-8/A) has been studied in salt-fog and moist-nitrogen environments. The corrosion tests disclosed (1) no evidence of stress corrosion cracking, (2) higher corrosion rates for as-cast lots than those from solution heat-treated and aged lots, and (3) no degradation for encapsulated penetrators in a salt-fog environment. On the basis of the data obtained from these tests it is concluded that heat-treated and aged investment-cast penetrators perform as well as wrought penetrators from the MANTECH I Program.

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CORROSION TESTING OF THE GENERAL ELECTRIC- MANTECH II GAU 8/A PENETRATOR

Introduction

General Electric MANTECH GAU 8/A Penetrator Program

General Electric, Armament Systems Department, Aircraft Equipment Division, Burlington, Vermont, is the prime contractor for the U.S. Air Force rapid-fire gun (GAU-8/A) for the A-10 close support aircraft. Ammunition developed for this gun includes an armour-piercing incendiary round which has a kinetic-energy penetrator fabricated from a depleted-uranium 0.75 wt. % titanium (U-3/4 Ti) alloy. As the prime contractor, GE is also responsible for directing and managing the Manufacturing Technology (MANTECH) Program for casting depleted-uranium-alloy penetrators. This MANTECH II Program was a natural extension to the previous MANTECH program, designed to demonstrate high-volume, cost-effective, production techniques for the manufacture of depleted-uranium-alloy penetrators.

The main criterion used to evaluate the adequacy of the material produced was ballistic performance. However, because U-3/4 Ti is a lean uranium alloy, the corrosion resistance of the uncoated alloy was of major concern. Previously, Sandia Laboratories, Livermore, (SLL) was asked by GE through the Air Force to assist in examining the material produced by a number of suppliers using a variety of production routes and to make a recommendation on the necessity of protectively coating the alloy. The results of this early work¹ showed that (1) all the material had essentially the same response to corrosive environments, (2) the penetrators could be coated without difficulty, and (3) a protective coating system was not required to protect the penetrators during long-term storage.

Since metal casting techniques were not evaluated as a production method for making penetrators on the first contract, a follow-on program (MANTECH II) was initiated to evaluate these processes as a means for

making penetrators economically. Again Sandia was asked to evaluate the performance of these penetrators in corrosive environments.

Goals of Program

Investment-cast U-3/4 Ti alloy penetrators were produced by Nuclear Metals, Inc. (NMI). The major goal of this study was to determine the relative resistance of the penetrators to the effects of salt-fog and hot-moist-nitrogen environments. Some of the penetrators were encapsulated by Aerojet Ordinance and Manufacturing Corporation (AOMC) and were to be evaluated only in a salt-fog environment. The corrosion testing program was primarily to determine if there were any major differences in corrosion response between penetrators produced by investment casting and those produced for the first MANTECH Program.¹ These corrosion testing programs were mainly for screening purposes, and it was understood that the tests, as designed, were to be a reasonable simulation of natural storage environments, to which the rounds are to be exposed. Details of the mechanism of corrosion for uranium alloys were taken as those given in a recent publication.²

Material Specification

Chemistry

The details on the chemistry of the material tested in this program were furnished by Battelle Columbus Laboratories and are shown in Table I. The chemistry was consistent between the top and bottom tiers for each casting and fairly uniform from casting to casting. Table II relates the penetrator with the casting and the test environment.

Heat Treating

The penetrators in Lots 1A and 2A were in the as-cast condition. All other penetrators were solution treated at 843°C for one hour and aged at 400°C for six hours. Table III shows the metallurgical and finishing history for the various lots.

TABLE I
CHEMICAL ANALYSIS OF CASTINGS USED TO
MAKE PENETRATORS FOR CORROSION TESTS

Casting No.	Sample Location(a)	Wt% Ti	Impurities (ppm)				
			C	Si	Fe	Ni	Cu
A4	T (top)	0.73	50	71	19	6	1
A4	B (bottom)	0.75	50	41	12	7	2
A5	T	0.79	50	22	13	5	2
A5	B	0.73	50	75	11	5	2
A6	T	0.77	60	25	24	2	<1
A6	B	0.76	60	31	12	1	<1
A7	T	0.75	50	41	21	2	<1
A7	B	0.75	60	24	21	2	<1
A9	T	0.68	75	32	32	1	<1
A9	B	0.67	60	24	24	1	<1
A10	T	0.62	70	10	10	<1	<1
A10	B	0.65	70	9	9	1	<1
S4	T	0.75	35	33	106	26	15
S4	B	0.72	35	35	80	22	14

(a) Top location was penetrator No. 405 on the outermost ring on the top tier. Bottom location was penetrator No. 101 on the innermost ring on the bottom tier.

TABLE II
PENETRATOR CORROSION TEST

Lot No.	Penetrator ID	Casting (a)	Test Environment		
			Salt Fog	Moist N ₂	Encapsulated ^(b)
1A	2	A4-T	*(c)		
1A	4	A4-T			*
1A	12	A4-B			*
1A	15	A4-B	*		
1A	16	A5-T	*		
1A	17	A5-T	*		
1A	21	A5-B		*	
1A	23	A5-B		*	
1A	28	A6-T			*
1A	30	A6-T			*
1A	36	A6-B		*	
1A	37	A6-B			*
1A	38	A6-B			
2A	3	A4-T	*		
2A	4	A4-T	*		
2A	5	A4-T	*		
2A	6	A4-T	*		
2A	7	A4-T	*		
2A	8	A4-T	*		
2A	9	A4-T	*		
2A	12	A4-T	*		
2A	14	A4-T	*		
2A	14-1	A4-B			*
2A	17	A4-T	*		
2A	19	A4-B	*		
2A	20	A4-B		*	
2A	24	A4-B		*	
2A	25	A4-B		*	
2A	29	A4-B			*
2A	30	A4-B		*	
2A	32	A5-T		*	
2A	36	A5-T		*	
2A	40	A5-T		*	
2A	43	A5-T		*	
2A	43-1	A7-T			*
2A	44	A5-T		*	
2A	45	A5-T		*	
2A	46	A5-T		*	
2A	50	A5-T		*	

TABLE II (continued)

Lot No.	Penetrator ID	Casting(a)	Test Environment		
			Salt Fog	Moist N ₂	Encapsulated(b)
1B	12	A7-B	*		
1B	38	A9-B		*	
1B	49	A10-B		*	
2B1	4	A5-B	*		
2B1	5	A5-B	*		
2B1	6	A5-B	*		
2B1	7	A5-B			*
2B1	8	A5-B			*
2B1	9	A5-B	*		
2B1	10	A5-B	*		
2B1	13	A5-B			*
2B1	15	A5-B	*		
2B1	20	A5-B	*		
2B1	21	A5-B		*	
2B1	24	A6-T		*	
2B1	25	A6-T		*	
2B1	29	A6-T		*	
2B1	30	A6-T			*
2B1	31	A6-T		*	
2B1	37	A6-B		*	
2B1	39	A6-B			*
2B1	47	A6-B		*	
2B1	48	A6-B		*	
2B1	49	A6-B			*
2B2	4	A7-T	*		
2B2	5	A7-T	*		
2B2	9	A7-B			*
2B2	20	A7-B	*		
2B2	22	A7-B			*
2B2	30	A9-T			*
2B2	36	A9-B		*	
2B2	39	A9-B		*	
2B2	40	A9-B			*
2B2	46	A9-B		*	

TABLE II (continued)

Lot No.	Penetrator ID	Casting ^(a)	Test Environment		
			Salt Fog	Moist N ₂	Encapsulated ^(b)
2B3	20	A10-B			*
2B3	21	A10-B			*
2B3	28	A10-B			*
2B3	45	S4-B			*
2B3	49	S4-B			*
2B3	50	S4-B			*
3	17-1B	A7-B			*
3	24-1B	A9-T			*
3	28-2B1	A6-T			*
3	12-2B3	A10-T			*
3	3-3	A5-T			*
3	5-3	A5-B			*

(a) T indicates that the penetrator came from the top tier of the indicated casting, and B indicates the penetrator was from the bottom tier.

(b) All encapsulated parts were tested in a salt-fog environment.

(c) Asterisks indicate the type of environment to which penetrators alone were subjected, and which penetrators were encapsulated.

TABLE III
METALLURGICAL AND FINISHING HISTORY OF VARIOUS LOTS

Lot No.	Metallurgical and Finishing History
1A	As-cast condition (no heat treating or straightening); finished all over
2A	As-cast condition (no heat treating or straightening); finished all over
1B	Solution heat treated; straightened aged; finished all over
2B1	Solution heat treated; aged; finished all over
2B2	Solution heat treated; straightened; aged; shank ground only
2B3	Solution heat treated; straightened; aged; finished all over

Encapsulation

Penetrators from each lot were furnished to AOMC for encapsulation, and returned to SLL for evaluation. Details of the encapsulation materials and process are competition sensitive and, therefore, have not been included. Briefly, the point of concern is that the encapsulation is not meant to seal the uranium penetrator hermetically from the environment. Therefore, any air cavity around the penetrator could communicate with the external atmosphere, which could possibly contain significant amounts of water vapor.

Corrosion Tests

Salt-Fog Testing

Purpose--The salt-fog test determines the resistance of materials to the effects of a salt atmosphere. Because it is an accelerated corrosion test, the results may not correlate with any realistic environment. However, the relative resistance of specimens or coatings on specimens to a salt atmosphere can usually be determined from the results of a salt-fog test.

Apparatus--The apparatus used for the salt-fog testing was a Model MX-9204 salt-fog chamber manufactured by Associated Environmental Systems. The chamber is of double-wall construction with air at 35°C continuously recirculating inside each wall. The salt atmosphere is generated by a nozzle which uses compressed air to siphon the salt solution from the reservoir and atomizes it into a fog. The compressed air is first heated and saturated by bubbling it up through 50°C water in the saturation tower.

Solution--The salt solution is prepared by dissolving 5 parts by weight of sodium chloride in 95 parts of hot, distilled water. The salt used is "analyzed reagent grade" sodium chloride. The solution pH is maintained between 6.5 and 7.2.

Preparation of Test Specimens--The specimens were cleaned with acetone, rinsed with methanol, and air dried.

Performance of Test--The penetrators were positioned vertically with their butt ends resting on a plexiglass base so that there was no interference between penetrators. Tests were run for five 48 hour cycles. After each cycle the corrosion products were removed under flowing water with a stiff brush, allowed to dry, and weighed.

Evaluation of Results--Photographs of specimens were taken before and after tests for visual documentation of test results. (No photographs are included, since they would reveal competition-sensitive details.) The change in weight due to exposure for each specimen was plotted as a function of time to determine relative corrosion rates. The large diameter of each encapsulated penetrator (projectile assembly) was measured after each cycle in order to follow any possible swelling reaction. After the corrosion test, the forward portion of the encapsulation was removed by machining and the penetrator examined for any possible deterioration.

Hot-Moist-Nitrogen Testing

Purpose--The hot, moist nitrogen test was conducted to determine the resistance of materials to the effects of hot water vapor in the absence of oxygen. This test is particularly applicable to uranium alloys because their corrosion resistance is significantly lower in water-containing environments that are also deoxygenated. This test is thus extremely useful for determining the relative resistance of uranium specimens or coatings on uranium specimens to humid environments.

Apparatus--The apparatus used was custom built from a design developed at the Lawrence Livermore Laboratory.³ Briefly, the specimens are suspended from a lazy susan contained within a stainless-steel chamber that is submerged in an oil bath maintained at 70°C. Connected to the chamber is a gas saturator set to control the dew point at 65°C, thus maintaining the relative humidity at 95%. The carrier gas for the humidity system is de-oxygenated nitrogen with the oxygen content maintained below 2 ppm.

The moist-nitrogen test was run in two test chambers because the test samples could not fit into one chamber. Equipment problems with one of the test chambers, early in the test program, resulted in the relative humidity being controlled at 80% rather than the 95% at which the other chamber was controlled.

Environment--The environment is deoxygenated nitrogen maintained at 70°C and containing 95% relative humidity (RH). It is controlled in a near static condition, with only a slight positive pressure being maintained.

Preparation of Test Specimens--The specimens were cleaned with acetone, rinsed with methanol, and air dried.

Performance of Test--A platinum wire loop was spot-welded to the tip of each penetrator to provide a means of suspending the penetrator in a vertical position in the chamber, as well as allowing in situ weight measurements. The positioning of penetrators was such that there was no interference between penetrators. Weight measurements were made after each 96-hour cycle, with a total of eight cycles per test.

Evaluation of Results--Photographs of specimens were taken before and after tests for visual documentation of test results. The change in weight due to exposure for each specimen was plotted as a function of time to determine relative corrosion rates.

Test Results

Salt Fog

Plots of weight loss versus time for each lot of the penetrators are shown in Figures 1 through 6. In this environment, the penetrators lose weight because of the formation of non-adherent oxide and chloride complexes. The weight-loss curves in Figures 1-6 suggest that there was an incubation time of about one day during which the corrosion process was beginning and accelerating. During this time period, the chloride ion in the salt fog was progressively destroying the tarnish film of titanium-rich uranium dioxide which had been providing some protection to the uranium-titanium alloy. After 2 days, when this surface tarnish film was completely gone and the penetrator surface was being uniformly attacked, the corrosion rate became linear. Figure 7 shows the spread in the corrosion rate for all the penetrators.

The corrosion rate was fairly consistent within each lot, and lots 1A and 2A, the as-cast material, had the highest corrosion rate. Figure 8, a comparison of the weight-loss data for all penetrators of this program with those from test Series 1 of the previous program (Reference 1), shows that the weight-loss data for the cast penetrator are bracketed by those for wrought material. The percentage increase in corrosion rate between the least and most corroded samples was approximately 70%. As pointed out previously by Weirick¹ this difference has no practical significance.

There was no evidence of stress corrosion cracking for any of the penetrators tested. Table IV shows the weight-loss data for this test.

Moist Nitrogen

The results from the moist-nitrogen tests are shown in Figures 9 through 18. The samples which were solution heat treated and aged and which were tested in a 95% relative humidity environment performed in a manner similar to those previously tested by Weirick,¹ that is, the corrosion reaction was rapid initially and then slowed to a much lower rate after the first four days. The explanation given in Reference 1 for this type of corrosion in moist nitrogen is as follows: In the absence of oxygen, the moisture

TABLE IV
WEIGHT-LOSS RESULTS FROM SALT-FOG TEST

Lot No.	Penetrator No.	Total Weight Loss (g)
1A	2	11.273
1A	15	11.184
1A	16	12.782
1A	17	12.192
2A	3	12.644
2A	4	10.789
2A	5	10.818
2A	6	11.831
2A	7	12.349
2A	8	12.160
2A	9	12.570
2A	12	12.624
2A	14	13.963
2A	17	12.809
2A	19	12.251
1B	12	8.632
2B1	4	9.589
2B1	5	9.395
2B1	6	9.983
2B1	9	9.723
2B1	10	9.296
2B1	15	10.430
2B1	20	10.931
2B2(a)	4	11.004
2B2(a)	5	10.786
2B2(a)	20	11.208

(a) Penetrators with unfinished nose tapers.

rapidly attacks and completely destroys the tarnish film on the penetrator. After this oxide is destroyed completely, an inner and outer layer of uranium oxide is formed. The inner oxide layer is a dense, adherent, oriented film less than a micrometer thick. Growing from the inner layer is a second layer which is porous, non-adherent, randomly oriented, and voluminous, and which accounts for the appreciable weight loss. However, when the inner layer grows to a thickness of approximately $1\text{ }\mu\text{m}$, it behaves as a protective layer and reduces drastically the rate of formation of the outer layer, thus causing the measured corrosion rate to become very small. The cumulative weight losses from these samples are similar to those Weirick (Reference 1) reported for wrought material; that is, they fall within the 0.1- to 0.4-g range.

The as-cast samples from lots 1A and 2A tested in 95% moist nitrogen had considerably higher corrosion rates, not unexpected since as-cast uranium alloys typically have a higher corrosion rate than material that is solution heat treated and aged. As a result of solidification segregation, corrosion cells are set up between adjacent areas of higher and lower titanium content. These cells are more active than those present in a material which is solution heat treated and aged and in which the titanium content would be more constant throughout the part. In addition, between 12 and 16 days of testing all samples from these two lots, except sample No. 30 from lot 2A, experienced an abrupt additional weight loss approximately equal to the initial weight loss.

For the samples tested in the 80% moist nitrogen environment, the weight-loss curves showed a steady loss of weight with time which was almost linear after eight days. These samples did not experience the initial loss of weight as those tested in the 95% RH environment. However, given sufficient time at 80% RH, we would expect the tarnish film to be destroyed and the protective oxide formed, as discussed earlier in this section. The samples tested in the 95% environment typically had a weight loss 5 to 10 times higher than those tested at 80% RH. None of the penetrators tested in moist nitrogen showed any evidence of stress corrosion cracking. The weight-loss data for these tests are shown in Table V. Figure 19 shows a comparison of the weight-loss data for all penetrators in MANTECH II with those for MANTECH I that were tested in 95% RH moist nitrogen. If the data from the as-cast lots from MANTECH II are eliminated, the remainder of the MANTECH II data is bracketed by MANTECH I data.

TABLE V
WEIGHT-LOSS RESULTS FROM MOIST NITROGEN

Lot No.	Penetrator No.	Moist-Nitrogen Results
		Total Weight Loss (g)
1A	21	1.293
1A	23	1.303
1A	36	0.270
1A	38	0.147
2A	20	1.384
2A	24	1.486
2A	25	1.409
2A	30	0.910
2A	32	1.483
2A	36	1.503
2A	40	0.101
2A	43	0.085
2A	44	0.088
2A	45	0.165
2A	46	0.105
2A	50	0.084
1B	38	0.284
1B	49	0.033
2B1	21	0.121
2B1	24	0.262
2B1	25	0.219
2B1	29	0.220
2B1	31	0.027
2B1	37	0.020
2B1	47	0.015
2B1	48	0.025
2B2(a)	36	0.3615
2B2(a)	39	0.335
2B2(a)	46	0.059

(a) Penetrators with unfinished nose tapers.

Encapsulated Penetrators

Measurements were made on the large diameter of the aluminum case before and after the test using 20X magnification on a shadowgraph. Measurements were also made with a micrometer. No change in diameter was noted on any of the specimens after testing. This indicates that no significant corrosion took place internally that would cause swelling. Removal of the front part of the encapsulation by machining confirmed this. (The only discrepancies noted were that adhesive was present on a large number of penetrators, and on penetrator number 2B2-30 the windshield was not bonded to the aluminum sleeve.) The observations on these penetrators are found in Table VI. The weight gain shown for the penetrators is attributed mainly to the corrosion of the unanodized counter bore on the bottom of the aluminum case. No evidence of stress cracking was found on any of the penetrators.

Summary

1. Heat-treated and aged investment-cast penetrators are equivalent in corrosion response to the wrought penetrators evaluated in MANTECH I.
2. Penetrators with unfinished tapers are equivalent in corrosion response to penetrators finished all over.
3. An important result from this study was that no penetrator tested showed any evidence of stress corrosion cracking. This is consistent with the results on wrought penetrators for MANTECH I.
4. For the samples tested in a salt-fog environment, the corrosion response was fairly consistent within each lot, and the lots in the as-cast condition had the highest corrosion rate. The data produced from the salt-spray tests were bracketed by the salt-spray data from wrought material from MANTECH I.
5. Samples exposed to hot-moist-nitrogen environments also showed a higher corrosion rate for as-cast penetrators. When comparing 95% RH moist-nitrogen data from the two MANTECH Programs, it is observed that the corrosion data are again bracketed by data from MANTECH I, if we eliminate the as-cast lots (1A and 2A). Penetrators from the same lot but exposed to a 80% RH moist-nitrogen environment had corrosion rates 1/5 to 1/10 of those exposed to 95% RH moist nitrogen.
6. Encapsulated penetrators tested in a salt-fog environment showed no evidence of swelling or attack of the penetrators.

TABLE VI
SALT-FOG RESULTS ON ENCAPSULATED PENETRATORS

Penetrator No.	Δ Diameter (in.)	Δ Weight Gain (g)	Remarks
3-3	0	0.0897	a
3-5	0	0.0993	a, b
3-12	0	0.1113	a
3-17	0	0.0916	a, b
3-24	0	0.1091	a, b
3-28	0	0.0985	a
1A-4	0	0.0886	a, b
1A-12	0	0.1014	a
1A-28	0	0.0913	a, b
1A-30	0	0.1010	a, b
1A-37	0	0.1141	a, b
2A-14	0	0.0947	a, b
2A-29	0	0.0871	a, b
2A-43	0	0.1357	a
2B1-7	0	0.1082	a
2B1-8	0	0.0866	a, b
2B1-13	0	0.1064	a, b
2B1-30	0	0.1014	a, b
2B1-39	0	0.1023	a, b
2B1-49	0	0.1018	a, b
2B2-9 ^e	0	0.0839	a, b, c
2B2-22 ^e	0	0.1132	a, b, c
2B2-30 ^e	0	0.0977	a, b, c, d
2B2-40 ^e	0	0.0849	a, b, c
2B3-20	0	0.1390	a
2B3-21	0	0.1107	a
2B3-28	0	0.1028	a, b
2B3-45	0	0.0940	a
2B3-49	0	0.1015	a
2B3-50	0	0.0947	a, b

^aNo degradation in salt spray

^bAdhesive on penetrators

^cAs-cast surface taper

^dWindshield not bonded to Al sleeve

^ePenetrators with unfinished nose tapers

Figure 1. Weight Loss Data for Penetrators in Salt Fog

Figure 2. Weight Loss Data for Penetrators in Salt Fog

Figure 3. Weight Loss Data for Penetrators in Salt Fog

Figure 4. Weight Loss Data for Penetrators in Salt Fog

Figure 5. Weight Loss Data for Penetrators in Salt Fog

Figure 6. Weight Loss Data for Penetrators in Salt Fog

Figure 7. Compilation of Weight Loss Data for Penetrators in MANTECH II

Figure 8. Comparison of Weight Loss Data for Penetrators From MANTECH II (solid line) to Those From MANTECH I (dotted line)

Figure 9. Weight Loss Versus Time for Lot 1A in Moist Nitrogen

Figure 10. Weight Loss Versus Time for Low 2A in Moist Nitrogen

Figure 11. Weight Loss Versus Time for Lot 1B in Moist Nitrogen

Figure 12. Weight Loss Versus Time for Lot 2B1 in Moist Nitrogen

Figure 13. Weight Loss Versus Time for Lot 2B2 in Moist Nitrogen

Figure 14. Weight Loss Versus Time for Lot 1A in Moist Nitrogen

Figure 15. Weight Loss Versus Time for Lot 2A in Moist Nitrogen

Figure 16. Weight Loss Versus Time for Lot 1B in Moist Nitrogen

Figure 17. Weight Loss Versus Time for Lot 2B1 in Moist Nitrogen

Figure 18. Weight Loss Versus Time for Lot 2B2 in Moist Nitrogen

Figure 19. Comparison of Weight-Loss Data for Penetrators from MANTECH II (solid line) to Those From MANTECH I (dashed line)

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