SAND76-8055
Unlimited Release

Corrosion Testing of the General Electric Mantech GAU 8/A Penetrator

L. J. Weirick

Prepared by Sandia Laboratories, Albuquerque New Mexico 87115 and Livermore, California 94550 for the United States Energy Research and Development Administration under Contract AT (29-1) 789

Printed February 1977

When printing a copy of any digitized SAND Report, you are required to update the markings to current standards.

Sandia Laboratories

SF 2900 Q(7-73)

Issued by Sandia Laboratories, operated for the United States Energy Research and Development Administration by Sandia Corporation.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

SAND76-8055
Unlimited Release
Printed February 1977

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

L. J. Weirick
Metallurgy and Electroplating Division 8312
Sandia Laboratories

ABSTRACT

The corrosion resistance of the U-3/4 Ti alloy selected as the ammunition "kinetic energy penetrators" to be used in the U.S. Air Force rapid-fire gun (GAU-8/A) has been studied. Corrosion testing showed that neither the chemistry nor the metal processing variables examined caused a change of practical significance in the material's corrosion response in either salt fog or moist nitrogen. Based upon the data obtained, a coating system to protect the penetrators during long-term storage is not necessary.

*Funding for this program was provided by the U.S. Air Force under Project Order No. FYXPOO-76P-1113.

TABLE OF CONTENTS

	Page
Introduction	11
General Electric Mantech GAU 8/A Penetrator Program	11
Goals of Program	11
Uranium Alloy Corrosion	12
Metallic Coatings on Uranium Alloys	12
Material Specification	13
Chemistry	13
Metal Processing	13
Solution Treatment	14
Aging	15
Encapsulation	15
Corrosion Tests	15
Salt Fog Testing	15
Hot Moist Nitrogen Testing	16
Test Series I	17
Test Series II	30
Costed Penetrators	40
Rod Samples	40
Cold Straightened Penetrators	44
Encapsulated, Corrosion Tested, and Fire Tested	44
Summary	44
Conclusions	46
Appendix	47
References	49

ILLUSTRATIONS

Figure		Page
1.	Weight Loss Versus Time for AFML and Lot 1A Penetrators in Salt Fog	19
2.	Compilation of Weight Loss Data for Penetrators in Test Series I	20
3.	Weight Loss Versus Time for AFML and Lot 1A Penetrators in Moist Nitrogen	25
4.	Weight Loss Versus Time for Lots 6, 16, 19, and 21 in Moist Nitrogen	27
5.	Weight Loss Versus Time for Lots 2 and 14 in Moist Nitrogen	28
6.	Weight Loss Versus Time for Lots 3A and 3B in Moist Nitrogen	29
7.	Weight Loss Versus Time for AFML and Lot 11 Penetrators in Salt Fog	32
8.	Weight Loss Versus Time for AFML and Lot 6A Penetrators in Salt Fog	33
9.	Weight Loss Versus Time for AFML and Lots 2 and 10C Penetrators in Salt Fog	34
10.	Compilation of Weight Loss Data for Penetrators in Test Series II	35
11.	Weight Loss Versus Time for Lot 5, Test Series II, in Moist Nitrogen	36
12.	Weight Loss Versus Time for Lot 6A, Test Series II, in Moist Nitrogen	39
13.	Compilation of Weight Loss Data for Rod Samples in Salt Fog	43
14.	Response to Salt Fog of Cold Straightened Penetrators	45

TABLES

Table		Page
I.	Process Data for Forged DU Penetrators	18
II.	Test Series I--Salt Fog Results (Solution Treatment - 1500°F, 180 Minutes, Salt)	21
III.	Test Series I--Salt Fog Results (Solution Treatment - 1500°F, 30 Minutes, Pb)	22
IV.	Test Series I--Salt Fog Results (Solution Treatment - None)	23
V.	Production Plan: Test Series II	31
VI.	Test Series II Penetrators - Moist Nitrogen Results	38
VII.	Rod Samples - Salt Fog Test	41
VIII.	Rod Samples - Moist Nitrogen Test	42

CORROSION TESTING OF THE GENERAL ELECTRIC MANTECH 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 ground support aircraft. The ammunition for this gun is a new type called "kinetic energy penetrators." The material selected for the 30-mm round for the GAU-8/A is a uranium-0.75 weight percent titanium (U-3/4 Ti) alloy. General Electric's responsibility in terms of the ammunition was to demonstrate the technical and economic feasibility of manufacturing uranium alloy penetrators using full-scale production techniques.

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 also a major concern. Sandia Laboratories, Livermore (SLL) was requested by the Air Force to assist GE in examining the material produced by a number of suppliers using numerous production routes and to make a final recommendation on the necessity of protectively coating the alloy.

Goals of Program

The major goal of this study was to establish relationships between certain material chemistry or metal processing variables and the general corrosion resistance of the uranium alloy or its stress corrosion cracking (SCC) susceptibility. This corrosion testing program was a screening study rather than the development of a test procedure, costing system, or theoretical mechanism for uranium alloy corrosion. The primary chemistry

variables investigated were titanium content; carbon, hydrogen, oxygen, and nitrogen interstitial impurity effects; and some substitutional impurity (e.g., Fe, Ni, Cu, Si) effects. The primary processing variables were the process itself (extrusion versus swaging versus forging), the temperature at which this process was done, the solution heat treatment temperature, the aging temperature, and the severity of the quench.

The second goal of this corrosion testing was to identify any analogous variables in material chemistry or metal processing which prevented the proper application of a protective metallic coating.

Uranium Alloy Corrosion

Of the significant number of papers in the open literature concerning the corrosion of uranium and uranium alloys, two recently published manuscripts deserve special mention. First, a review paper by Orman[1] details the different corrosion mechanisms responsible for the widely different corrosion rates and corrosion products obtained when testing in differing environments. Briefly, Orman discusses the reasons for the increased corrosion rate measured for uranium alloys tested in moist nitrogen depleted of oxygen versus that obtained when testing in moist air. Similarily, the reasons for the increase in corrosion rate in the presence of chloride are outlined.

The second paper is of special interest because it documents the work done on the Air Force GAU 8 uranium alloy penetrators, which immediately preceded this present program. This paper by Weirick, Johnson, and Dini[2] gives the details of the electroplating process for applying the metallic coating, as well as its usefulness in preventing corrosion of the uranium alloy. Also included is the data on the corrosion response of "typical" uranium-3/4 titanium in moist air, moist nitrogen, and salt fog environments.

Metallic Coatings on Uranium Alloys

A recently published review paper by Weirick[3] on the use of protective coatings (oxides, organic films, and metallic platings) to improve the corrosion resistance of uranium alloys shows that metallic platings have been and continue to be the most promising. Extensive work at Sandia Laboratories, Livermore (SLL) has shown that good corrosion resistance is obtained for uranium and uranium alloys by plating with nickel.[4-6] For severe corrosive environments, a duplex coating of nickel plus electroplated zinc with a zinc chromate finish was found to provide even better results. Details of the electroplating process are given in the appendix.

Material Specification

Chemistry

Details on the chemistry of the material tested in this program are given in a Battelle Columbus Laboratories report.[7] Briefly, there were two main chemistry variables explored: carbon and hydrogen. The carbon content ranged from a minimum of 30 parts per million (ppm) to over 900 ppm. The carbon in the uranium alloy at the lowest level is most probably in solid solution, whereas the carbon at the highest level is most probably existing in the uranium matrix as titanium carbide particles. As stated in a previously referenced report,[2] carbide particles can significantly influence the corrosion resistance of a uranium alloy.

The hydrogen content of the material was either relatively low (2 ppm) or much higher (10 ppm). The difference was due to the manner in which the gamma solutionizing of the material was done. If the material is heat treated in vacuum, the hydrogen is extracted from the uranium alloy, whereas if the heat treating is done in a molten salt bath, more hydrogen ingresses into the material. Past experience suggests that the amount of hydrogen in the material may affect the stress corrosion cracking resistance of the material but should not affect the general corrosion resistance.

The only other chemistry variables with any significant variation were titanium, 0.6 to 1.0 percent, and iron, 188 to more than 400 ppm. The richer the alloy is in titanium, the more corrosion resistant it should be. The effect of iron as a substitutional impurity is unknown. The levels of copper, magnesium, and silicon were monitored but not systematically changed.

Metal Processing

The three techniques for metal processing investigated were extrusion, forging, and swaging. The details for extrusion are given in reports[8,9] submitted by Nuclear Metals, Inc. (NMI) and Reactive Metals, Inc. (RMI). The details for forging are documented[10] by Omark Industries and for swaging by NMI.[8]

Briefly, the major variables examined in the extrusion study were extrusion temperature and ram speed. Extrusion temperatures in the vicinity of 1150 to 1200°F caused the uranium alloy to be worked in the "α"

state. At 1275 to 1350°F, the microstructure of the uranium alloy is primarily "β". * Extruding the material in the "γ" state was done between 1500 and 1550°F. Ram speeds were increased with correspondingly higher extrusion temperatures. Past experience with uranium alloys, primarily in the uranium-niobium system, suggests that the "γ" alloys are the most corrosion resistant, "α" alloys the least corrosion resistant, and "β" alloys less consistent but usually in the middle in comparative corrosion resistance. Ram speed would not be expected to alter the corrosion resistance of a given material.

Forging was done on blanks made from extruded rod. The rod had been extruded in either the "α" or "γ" condition. Some blanks were forged in the as-extruded condition, and others were forged after a solution treatment. In addition to the remarks previously made concerning the relative corrosion resistance of α and γ material, one would predict no significant effect on corrosion resistance due to the sequence of forging and solutionizing. However, the differing states of cold work produced in the material by the alternate preparations may affect the stress corrosion cracking susceptibility of the material.

Swaging was done on blanks made from rod extruded in the "β" range, 1310°F. Some blanks were swaged in the as-extruded condition, and others were swaged after a solution treatment. As stated previously, these variables could produce a change in the SCC resistance of the material but the corrosion resistance was not expected to change.

All of the as-extruded, forged, or swaged blanks which were or were not subsequently solutionized and/or aged were final ground to the specified penetrator dimensions by Omark Industries.

Solution Treatment

The solutionizing treatment was done at 1500 to 1550°F for either 30 or 180 minutes. The heat transfer medium used was either a molten chloride salt or a molten lead or lead/tin bath. Heat treating material which has been either α or β extruded should improve its corrosion resistance. Heat treating material which had been γ extruded should have a minimal effect, regardless of whether the material is subsequently forged or swaged. However, solutionizing should relieve any internal stresses produced by the metal working processes and increase the material's resistance to SCC.

* For the purpose of brevity in this report, the nomenclature "β" will be used to symbolize an extrusion condition between 1275 and 1350°F. This is not meant to confer a precise definition of the metallurgical state of the alloy.

Aging

Aging treatments were done at temperatures between 775 and 1100°F for times from 50 to 960 minutes. The heat transfer mediums used were vacuum, dry argon, molten lead, or molten lead/tin. Some material was subsequently quenched in oil, some in water, and some material was left to slow cool. A previous publication[3] stated that aging U-3/4 Ti produced only a minimal change in the corrosion response. Thus no drastic changes in corrosion resistance were expected as a function of aging temperature, aging time, or aging medium.

Earlier work by Magnani[11] on the SCC susceptibility of U-3/4 Ti as a function of aging treatment showed that aging to a higher strength level caused a reduction in the resistance to SCC.

Encapsulation

A penetrator or two taken from each combination of material conditions was encapsulated by Aerojet Ordinance and Manufacturing Corp. (AOMC). 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 hermetically seal the uranium penetrator 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 was conducted to determine 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. The positioning was so that there was no interference between penetrators. Tests were run for five cycles with a continuous 48 hours per cycle.

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. The large diameter of each encapsulated penetrator was measured after each cycle in order to follow any possible swelling reaction. After the corrosion test, the encapsulation was removed 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.[12] 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 percent. The carrier gas for the humidity system is deoxygenated nitrogen with the oxygen content maintained below two ppm. Specimens are periodically weighed in situ through a nitrogen-purged glove box by means of a Mettler H315 microbalance.

Environment--The environment is deoxygenated nitrogen maintained at 70°C and containing 95 percent relative humidity. 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. The large diameter of each encapsulated penetrator was measured after each cycle in order to follow any possible swelling reaction. After the corrosion test, the encapsulation was removed and the penetrator examined for any evidence of deterioration.

Test Series I

Penetrators tested in this series consisted of material whose chemistry was controlled and metal processing was done primarily by Battelle. The chemistry and processing variables for this material, as identified by lots, are given in Table I. The chemistry and material processing history of Lot 1 is closely analogous to the material used in the previous study[2] for the Air Force Materials Laboratory (AFML). The material contained a carbon content near 50 ppm with a 10-ppm hydrogen level. The material was extruded into rods in the "α" condition, solutionized in a molten salt bath at 1500°F for 180 minutes, aged in a molten lead bath at 850°F for 75 minutes, and water quenched; this processing produced a hardness near 45 R_c. A plot of weight loss versus time for the AFML penetrators tested in salt fog is given in Figure 1 as the dashed curve. The data points shown are for the three penetrators tested from Lot 1A. The data shows that there was no measurable difference in the corrosion rates of the two classes of penetrators--i.e., GE Mantech Battelle versus AFML. Thus two material processors using analogous techniques have apparently produced penetrators with similar metallurgical properties.

In this environment, the penetrators lost weight because of the formation of nonadherent oxides and chloride complexes. The weight loss curve in Figure 1 shows 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[13] uranium dioxide which had been providing some protection to the uranium-titanium alloy. When this surface tarnish film was completely gone and the penetrator surface was being uniformily attacked, the corrosion rate became linear from two to ten days.

TABLE I

PROCESS DATA FOR FORGED DU PENETRATORS

Lot No.	Extrusion Temp (°F)	Carbon (ppm)	Hydrogen (ppm)	Solution Treatment Temp (°F)	Solution Treatment Time (min)	Solution Treatment Atmos -	Aging Treatment Temp (°F)	Aging Treatment Time (min)	Aging Treatment Atmos -	Aging Treatment Cooling -	Hardness (R_c)
1A	1200/1275	54	10	1500	180	salt	850	75	Pb	WQ	44
1B	1200	43	10	1500	180	salt	850	50	V	SC	46
2	1200/1275	64	10	1500	180	salt	-	none	-	-	34
3A	1200/1275	64	2	1500	30	Pb	850	50	V	SC	47
3B	1275	57	2	1500	30	Pb	850	50	Pb	WQ	46
4	1200/1275	60	2	-	none	-	-	none	-	-	33
5	1350	74	10	1500	180	salt	850	75	Pb	WQ	46
6	1350	111	2	-	none	-	-	none	-	-	37
7	1200	30	10	1500	180	salt	775	240	Pb	WQ	40
8	1350	127	2	-	none	-	850	720	V	SC	34
9	1350	80	2	1500	30	Pb	-	none	-	-	37
10A	1350	135	2	1500	30	Pb	850	50	A	SC	51
10B	1350	68	2	1500	30	Pb	850	50	Pb	WQ	49
11	1200	30	2	1500	30	Pb	775	240	V	SC	46
12	1200/1350	63	2	-	none	-	-	none	-	-	34
13A	1200	416	10	1500	180	salt	775	240	Pb	WQ	35
13B	1200	416	10	1500	180	salt	775	240	V	SC	38
14	1200	179	10	1500	180	salt	-	none	-	-	33
15A	1200	230	2	1500	30	Pb	850	75	Pb	WQ	46
15B	1200	218	2	1500	30	Pb	850	60	A	SC	46
16	1200	218	2	-	none	-	-	none	-	-	32
17	1200	913	10	1500	180	salt	-	none	-	-	28
18	1500	54	10	1500	180	salt	850	75	Pb	WQ	41
19	1500	54	10	1500	180	salt	1100	90	A	SC	37
20	1500	71	2	-	none	-	-	none	-	-	42
21	1500/1350	85	2	-	none	-	850	960	V	SC	39
22A	1500	79	10	1500	180	salt	850	75	Pb	WQ	45
22B	1500	79	10	1500	180	salt	850	60	A	SC	46
23	1500	79	10	1500	180	salt	-	none	-	-	41
24	1500	87	2	-	none	-	850	60	A	SC	38
25	1500	90	2	-	none	-	850	960	V	SC	40
26A	1500	85	2	1500	30	Pb	775	240	Pb	WQ	44
26B	1500	85	2	1500	30	Pb	775	240	V	SC	41
27	1500	101	10	1500	180	salt	775	240	Pb	WQ	40
28	1500	98	2	-	none	-	-	none	-	-	44
29A	1500	104	2	-	none	-	1000	120	Pb	WQ	37
29B	1500	133	2	-	none	-	1000	120	A	SC	38
30	1500	330	10	1500	180	salt	775	90	Pb	WQ	46
31	1500	330	10	1500	180	salt	1100	90	A	SC	38
32	1500	330	2	-	none	-	850	60	A	SC	46
33	1500	330	2	-	none	-	850	960	V	SC	38

Key

Pb - molten lead bath
salt - molten salt bath
A - argon gas
V - vacuum
WQ - water quench
SC - slow cool

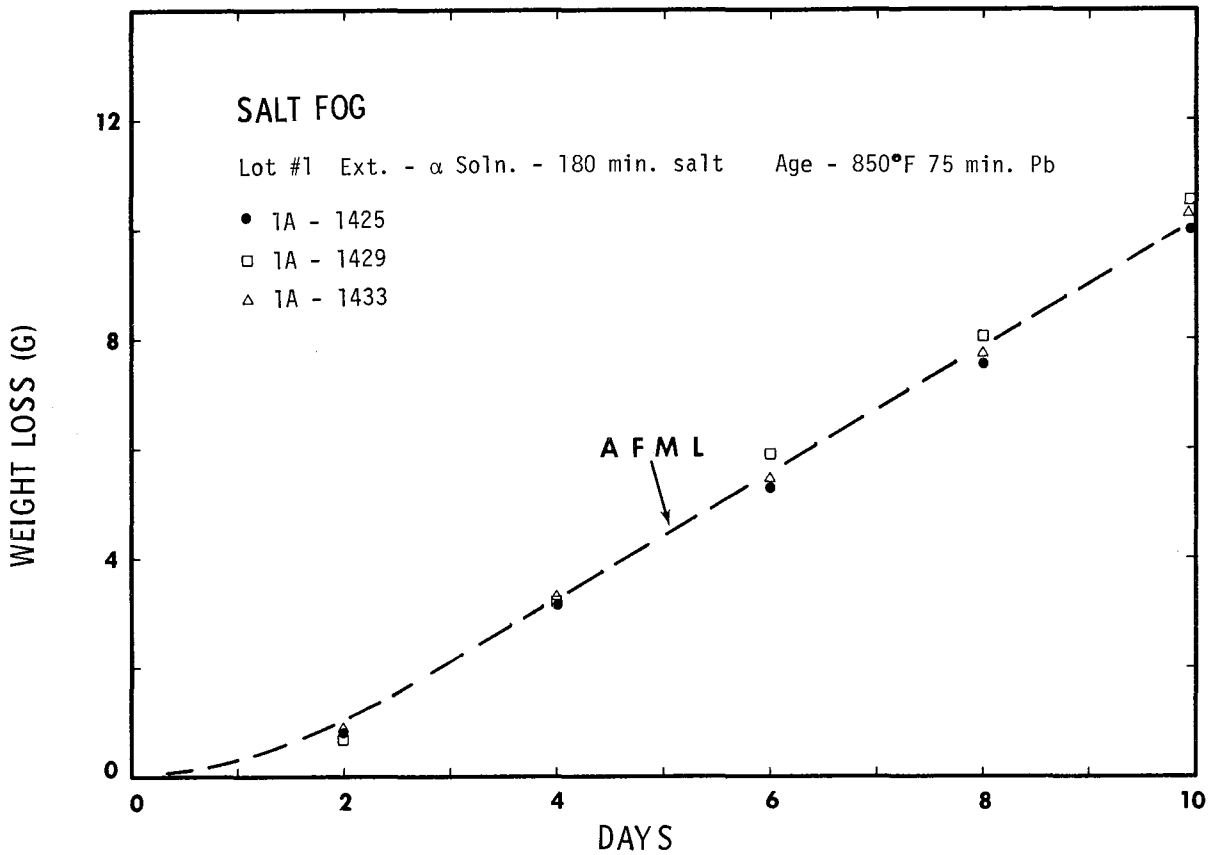

Figure 1. Weight Loss Versus Time for AFML and Lot 1A Penetrators in Salt Fog

Similar corrosion behavior was observed for all of the penetrators tested in salt fog for Test Series I. Figure 2 shows a compilation of all the weight loss data taken for penetrators in Test Series I; the curve for AFML material is also included for comparison. As can be seen from Figure 2, the corrosion response of the AFML material is bracketed by the corrosion rates observed for penetrators of various lots in Test Series I. Secondly, the bracket taking in all of the data points is very narrow, considering the numerous variables examined. The percentage increase in corrosion rate between the most and least corroded samples was approximately 70 percent; this number has statistical significance but is of very little, if any, practical significance. A factor of two change in corrosion response between material conditions cannot be used as a means of deciding between material conditions for these materials in this penetrator application.

Tables II, III, and IV summarize the corrosion response data for penetrators in Test Series I as catagorized by solution treatment. The corrosion response data point given for comparison was the final weight lost W_L. Varying one variable at a time resulted in the following observations:

- Carbon below 250 ppm has no influence on the corrosion rate
- Carbon above 325 ppm has statistically the biggest effect of all the variables on corrosion resistance; higher carbon, lower resistance

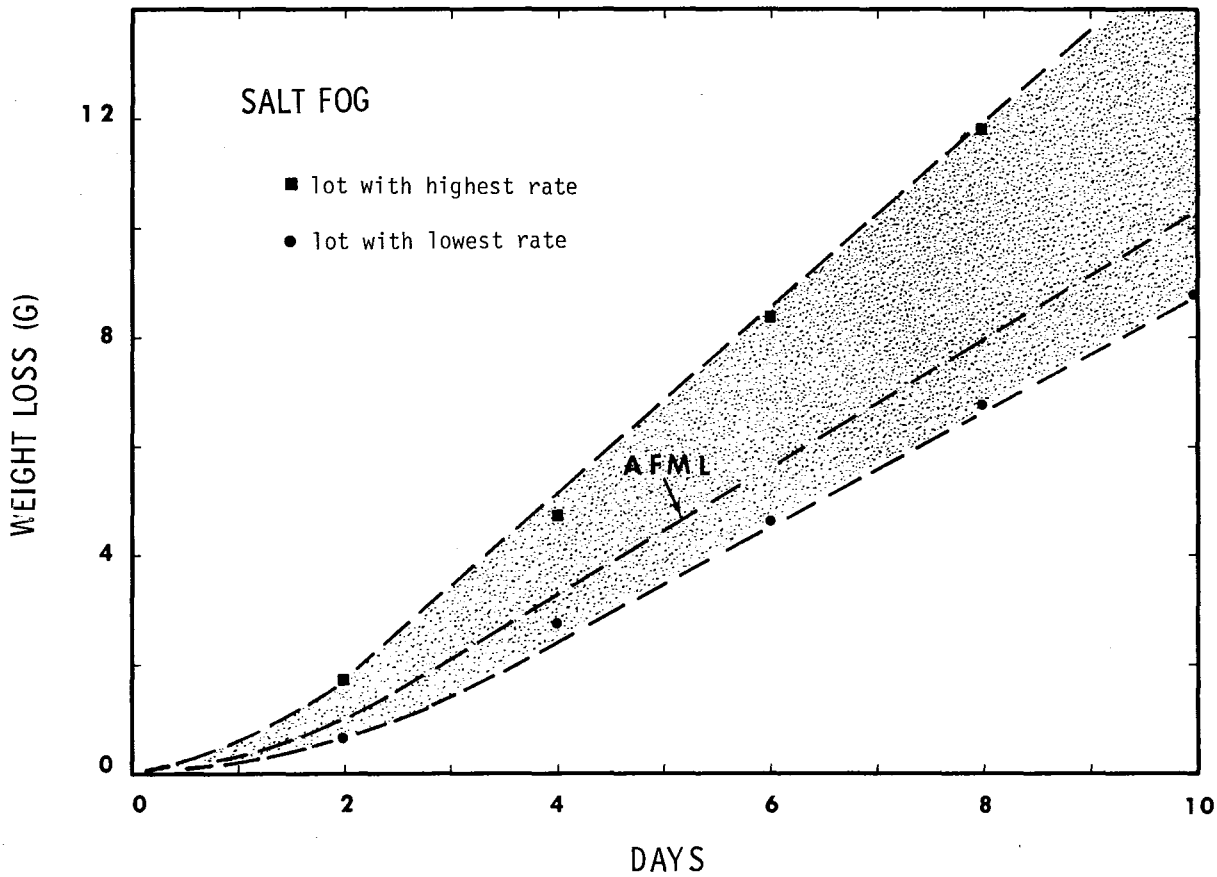

Figure 2. Compilation of Weight Loss Data for Penetrators in Test Series I

TABLE II

TEST SERIES I--SALT FOG RESULTS

Solution Treatment - 1500°F, 180 Minutes, Salt

Aging Treatment*	Lot	Ex Temp (°F)	C (ppm)	R_c	W_L**(g)
850°F, 75 Min, Pb, WQ	1A	1200/1275	54	44	10.014, 10.572 10.322
	5	1350	110	46	9.591
	18	1500	101	41	10.358
	22A	1500	87	45	10.971, 10.970
850°F, 50 Min, A, SC	1B	1200	43	46	10.435
	22B	1500	87	46	11.156, 11.329
775°F, 240 Min, Pb, WQ	7	1200?	150	40	11.764
	13A	1200	453	35	12.525
	27	1500	101	40	11.917, 12.073
775°F, 240 Min, V, SC	13B	1200	453	38	10.598
775°F, 90 Min, Pb, WQ	30	1500	330	46	11.144
1100°F, 90 Min, A, SC	19	1500	101	37	12.167
	31	1500	330	46	11.791
None	2	1200/1275	64	34	10.601, 10.977
	14	1200	230	33	8.796
	23	1500	87	41	11.757, 11.100

*See Key, Table I, for symbol explanation

**W_L - final weight loss

TABLE III

TEST SERIES I--SALT FOG RESULTS

Solution Treatment - 1500°F, 30 Minutes, Pb

Aging Treatment*	Lot	Ex Temp (°F)	C (ppm)	R_c	W_L** (g)
850°F, 50 Min, A, SC	3A	1200/1275	64	47	11.944, 11.976
	10A	1350	200	51	10.761, 10.882
					12.620, 11.956
	15B	1200	218	46	10.955
850°F, 75 Min, Pb, WQ	3B	1275	57	46	11.178
	10B	1350	94	49	11.752
	15A	1200	230	46	11.064
775°F, 240 Min, V, SC	11	1200	180	46	13.560
	26B	1500	85	41	12.346
775°F, 240 Min, Pb, WQ	26A	1500	85	44	10.964
None	9	1350	127	37	10.041, 8.797

*See Key, Table I, for symbol explanation

**W_L - final weight loss

TABLE IV

TEST SERIES I--SALT FOG RESULTS

Solution Treatment - None

Aging Treatment*	Lot	Ex Temp (°F)	C (ppm)	R_c	W_L** (g)
850°F, 50 Min, A, SC	24	1500	87	38	11.428, 11.178
850°F, 720 Min, V, SC	8	1350	127	34	12.195
850°F, 960 Min, V, SC	21	1500/1350	99	39	9.857, 10.586, 10.546, 11.780
	25	1500	90	40	10.749, 10.144,
	33	1500	330	38	13.390
1000°F, 120 Min, Pb, WQ	29A	1500	104	37	10.074, 11.855, 10.513
1000°F, 120 Min, V, SC	29B	1500	133	38	9.885, 10.452, 10.509
None	4	1200/1275	60	33	13.448, 10.887, 11.605
	6	1350	111	37	11.023
	12	1200/1350	120	34	13.935, 14.540, 14.685
	16	1200	218	32	10.465
	17	1200	753	28	15.185, 14.158 15.217
	20	1500	91	42	10.339, 10.244
	28	1500	98	46	10.677, 11.001
	32	1500	330	38	11.416, 10.572

*See Key, Table I, for symbol explanation

**W_L - final weight loss

- Solutionized material with no subsequent aging is the most corrosion resistant
- Nonsolutionized material with no aging is the most corrosion susceptible
- The general trend is that material extruded at 1350°F is the most resistant, followed closely by 1200 and 1200/1275°F material, with the least resistant being 1500°F extruded material
- Aging in vacuum versus lead or argon usually decreased the corrosion susceptiblity slightly
- Other aging factors showed no consistent trend

These results agreed with the patterns expected from these material variables as outlined and predicted earlier in this manuscript. Briefly, titanium carbide inclusions increase the corrosion reaction; therefore, a higher carbon content produces a higher corrosion rate. Secondly, γ-material is more corrosion resistant than α-material, therefore, a solutionized unaged material is the most corrosion resistant. Thirdly, aging had a minimal effect on the corrosion response, as did the hydrogen content. Lastly, there was no evidence of stress corrosion cracking for any of the penetrators tested.

The weight loss versus time curve for the AFML penetrators tested in 95% R.H. nitrogen is given in Figure 3. The shape of this curve suggests that the corrosion reaction was rapid initially and then slowed to a barely measurable rate after four days. What happens physically to the penetrator is that, in the absence of oxygen, moisture rapidly attacks and destroys the uranium dioxide tarnish film in a complete and uniform manner. Upon the destruction of the tarnish film, a double layer of uranium dioxide builds. The inner layer is composed of a dense, adherent, oriented film less than a micron thick. Simultaneously growing from this inner layer is a second layer of uranium dioxide which is porous, nonadherent and randomly oriented. This outer layer is also voluminous and thus accounts for the appreciable weight loss. However, when the inner layer grows to a final thickness of approximately one micron, it behaves as a protective layer and reduces the formation of the outer layer drastically, thus causing the measured corrosion rate to become very small.

Figure 3 also shows data points for penetrators tested in 95% R.H. nitrogen from Lots 1A, 9, 13A, and 17. As mentioned previously, Lot 1A is metallurgically analogous to the AFML material. As in the salt fog testing, these similar penetrators have responded to the corrosion environment in an identical manner. Penetrators from Lots 9, 13A, and 17 also exhibited corrosion rates very similar to Lot 1A, the differential being at most 35 percent. This small differential was observed in spite of the significant differences in the metallurgical condition and chemistry of the four lots.

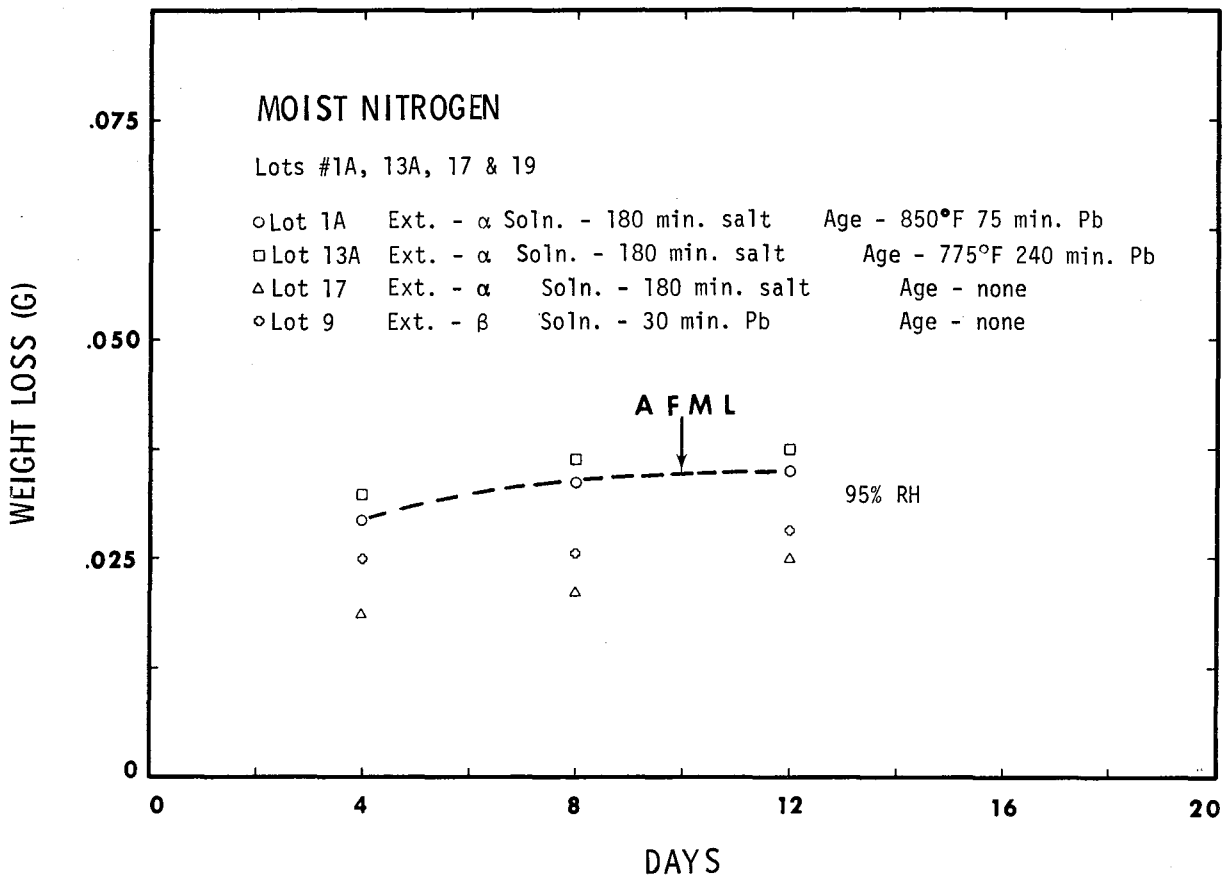

Figure 3. Weight Loss Versus Time for AFML and Lot 1A Penetrators in Moist Nitrogen

However, not all of the lots from Test Series I responded to the moist nitrogen environment in a similar manner. In fact, the first four lots discussed had the lowest total weight lost for the Test Series I penetrators. Figure 4 gives the data obtained for moist nitrogen testing of penetrators from Lots 6, 16, 19, and 21. The total weight lost for the penetrator from Lot 16 is a factor of ten higher than that of Lot 1A. Thus a penetrator which had not been solutionized nor aged showed the highest corrosion rate in moist nitrogen, a result analogous to that from salt fog testing. However, Lot 17, whose penetrators were also not solutionized nor aged, had the smallest corrosion response in moist nitrogen (see Figure 3) and the highest corrosion rate in salt fog. Penetrators from Lots 6, 19, and 21 also had significantly higher corrosion rates than those from the first group of four lots discussed.

The corrosion response of penetrators from Lots 2 and 14 is shown in Figure 5. The response of these penetrators to moist nitrogen was between that of the first two groups of lots discussed. The metallurgical condition of penetrators from Lots 2 and 14 was similar in that they were solutionized the same and had no subsequent aging treatment; the main difference was the carbon content. Thus it is not surprising that their corrosion response was very similar.

A similar comparison can be made for penetrators from Lots 3A and 3B. The only difference in these two lots was the medium used for aging, i.e., vacuum versus molten lead. Figure 6 shows that the corrosion response was identical. The reproducibility of the corrosion response for penetrators of identical or similar metallurgical condition in this moist nitrogen test appears to be very good.

Also shown in Figures 4, 5, and 6 are data points taken for penetrators tested in a 100% R.H. nitrogen environment. The total weight lost for a penetrator from a given lot was between two and three times larger due to this 5 percent increase in R.H. This result agrees with observations made previously by Orman[14] on unalloyed uranium and by Weirick[15] on the U-Ti alloy. The corrosion rate increases rapidly when a condensing environment is employed for testing. This sudden and significant increase in corrosion rate is most probably due to the additive affect of localized corrosion cells set up between adjacent areas of higher and lower titanium content when the environment becomes condensing. In addition to this observation of increased corrosion at 100% R.H., it was also observed that the reproducibility of the data and the patterns observed were analogous to those discussed for 95% R.H. None of the penetrators tested in moist nitrogen showed any evidence of stress corrosion cracking.

Measurements on the large diameter of the encapsulated penetrators indicated that no significant corrosion was taking place internally such as to cause a swelling reaction. Removal of the encapsulation confirmed this

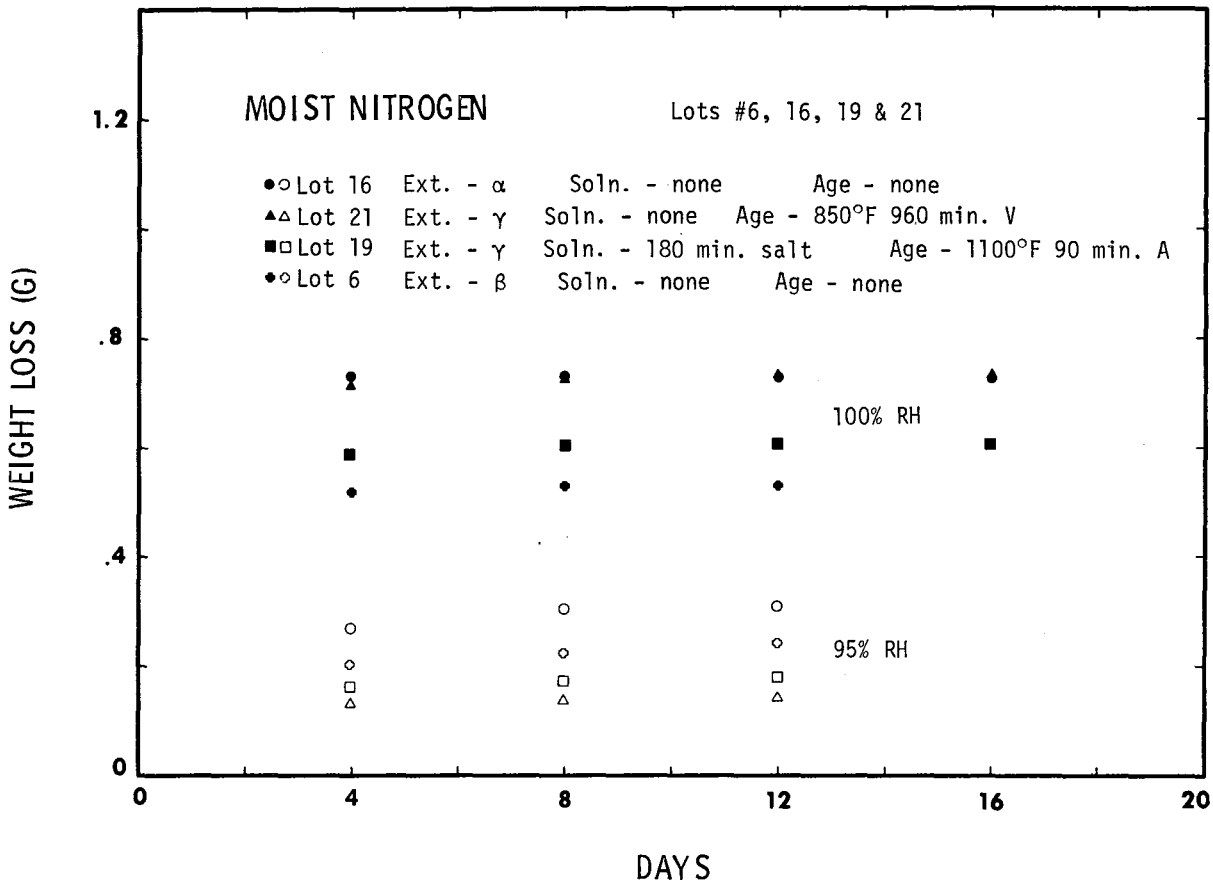

Figure 4. Weight Loss Versus Time for Lots 6, 16, 19, and 21 in Moist Nitrogen

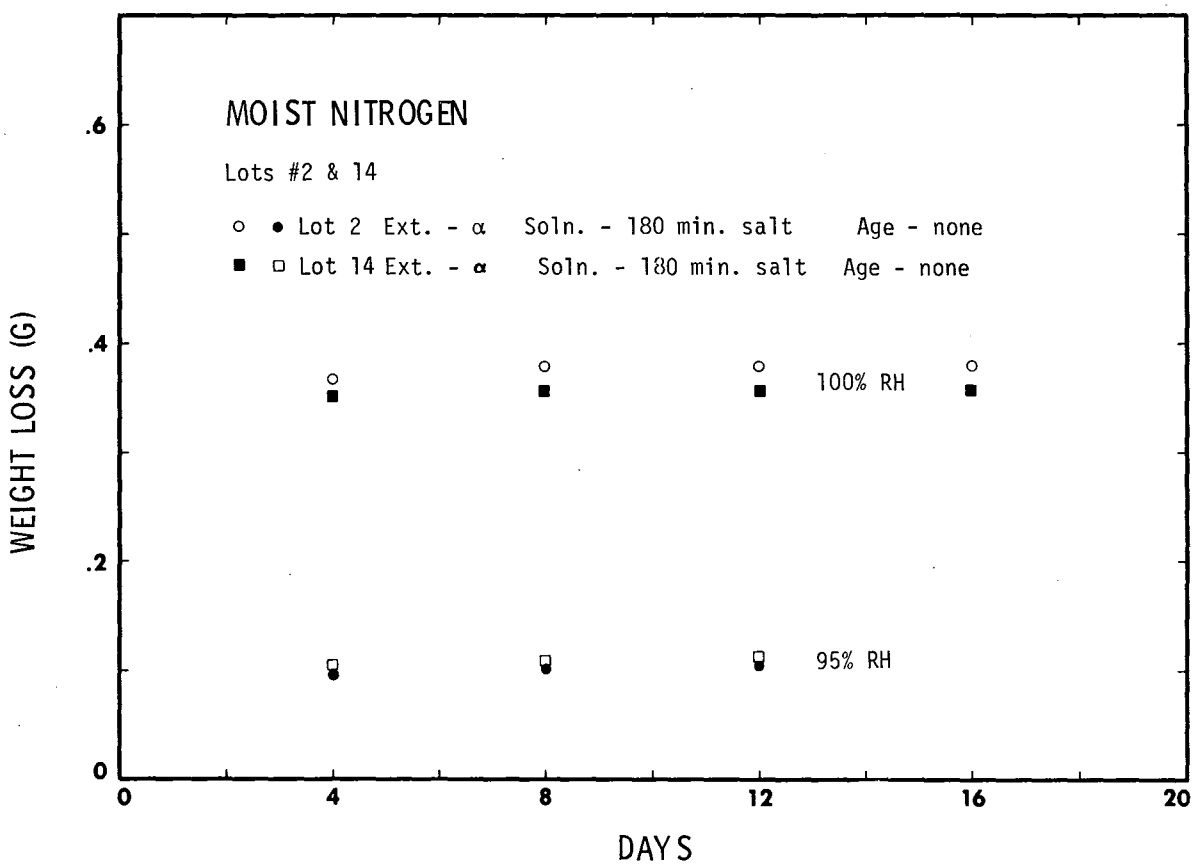

Figure 5. Weight Loss Versus Time for Lots 2 and 14 in Moist Nitrogen

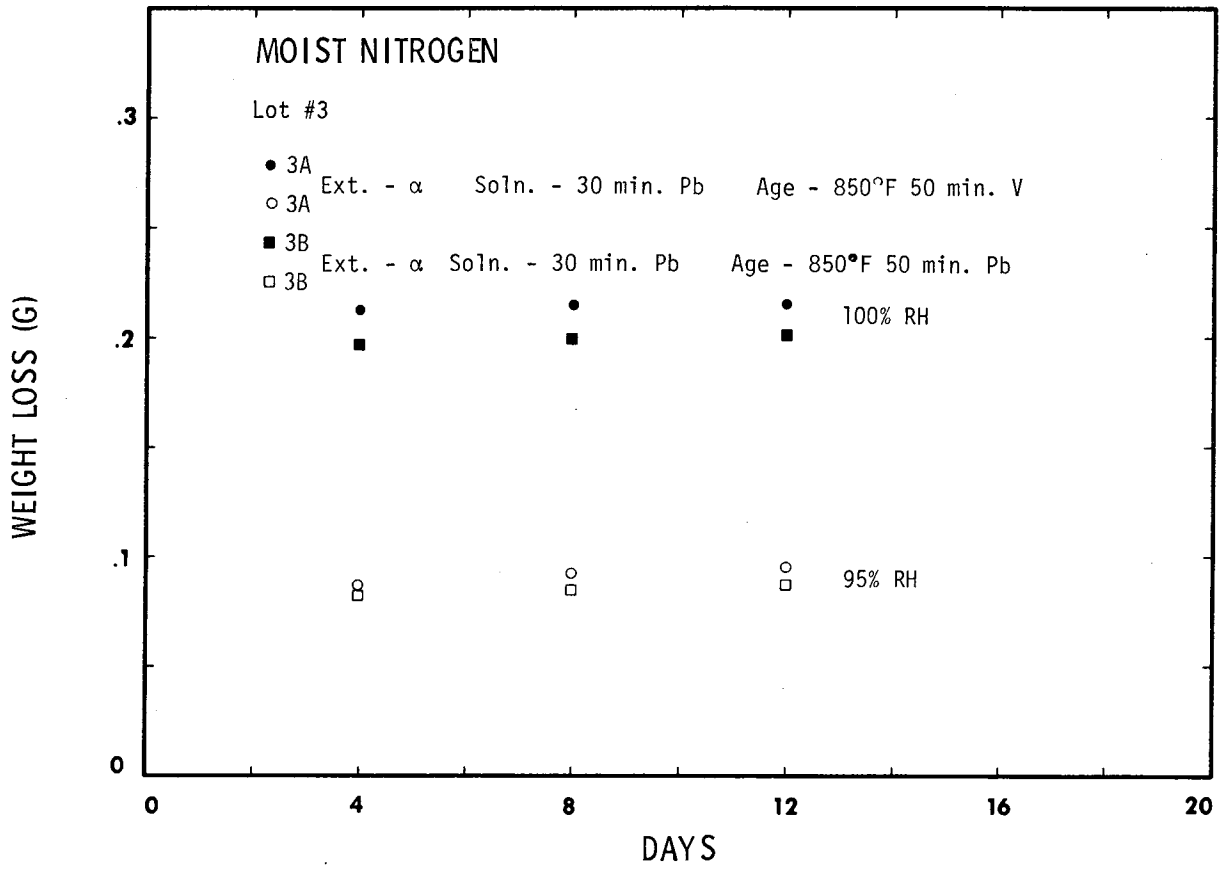

Figure 6. Weight Loss Versus Time for Lots 3A and 3B in Moist Nitrogen

indication. After salt fog testing, the tarnish film on the penetrator had darkened slightly but there was no evidence of appreciable uranium dioxide formation and no oxide spallation. For those that had been tested in moist nitrogen, the penetrator appearance had changed somewhat in that a thicker, darker film had formed, with some of the oxide being loose. The only significant point observed from these tests is that the different appearance of the penetrators caused by the two environments does prove they are not hermetically sealed by the encapsulation.

Test Series II

The penetrators tested in Test Series II were manufactured according to the production plan shown in Table V. Starting with Lot 11, Figure 7 compares the corrosion response of these penetrators with that of the AFML material. The corrosion response was essentially identical, which was not surprising in that the AFML materials was made by NLO, α-extruded at RMI, solutionized, aged, and final ground. Thus the metal manufacturers as well as the process sequence and conditions used were almost identical between the AFML material and material in Lot 11.

Figure 8 compares the corrosion response of penetrators from Lot 6A with the AFML material. It can be seen that the results from Lot 6A bracket the AFML curve. Again this result was expected in that material from Lot 6A was made similarily to the AFML material with only the ingot supplier being different. An analogous comparison is made in Figure 9 for penetrators from Lots 2 and 10C. These penetrators differ in metal processing from those discussed previously in that Lot 2 was β-extruded and Lot 10C was γ-extruded. They all were subsequently cold worked (swaged or forged), solutionized, aged, and ground. As seen in Figure 9, the corrosion response again bracketed the AFML standard. Figure 10 is a compilation of the test results from all the penetrators salt fog tested in Test Series II. The bracket obtained for Test Series II is almost identical to that obtained and previously described for Test Series I. The total spread from the least to the most corroded samples was only a factor of two. The penetrators manufactured by the various routes in this production plan all exhibited essentially the same corrosion response, and thus no selection of procedure can be made using corrosion response from salt fog tests as a guideline.

The good reproducibility of the corrosion response for penetrators from a given lot as tested in moist nitrogen is shown in Figure 11. These five penetrators represented the largest number tested from any one lot. The highest and lowest weight loss varied from the average by only eight percent; a very small variation in response of uranium alloy material to corrosion in moist nitrogen. As discussed in the moist nitrogen testing of Series I penetrators, the shape of the curve suggests the formation of an inner, protective layer which retards the corrosion reaction with time.

TABLE V

PRODUCTION PLAN: TEST SERIES II

NMI

(1) Extrude 1310°F, swage, and grind

(2) Extrude 1310°F, swage, solution treat,[a] age,[b] grind to R_c 44/48

(3A) Extrude 1310°F, solution treat, swage to R_c 41/48, and grind

(3B)[c] Extrude 1310°F, solution treat, swage to R_c 41/48, and grind

(3C) Extrude 1310°F, solution treat, swage to R_c 41/48, and grind; Omark thermal age and O.Q.[d] to R_c 44-51, and grind

(4A) Extrude high-carbon material (NMIB-1, -2), swage, solution treat, age to R_c 44/48, and grind

(4B)[c] Extrude high-carbon material (NMIB-1, -2), swage, solution treat, age to R_c 44/48, and grind

Omark

α-extruded ELO-CVC (No. 4.3 inch ϕ)

(5) Forge and grind

(6A) Forge, solution treat, age to R_c 44/48, and grind

(6B)[c] Forge, solution treat, age to R_c 44/48, and grind

(7) Forge Rod 128, solution treat, age to R_c 44/48, and grind

(8) Solution treat, forge, age to R_c 44/48 (or maximum), and grind

(9) Forge bar ends (front and back), solution treat, age to R_c 44/48, and grind

γ-extruded ELO-CVC - Use rod from 7.95 inch billets

(10A) Forge and grind

(10B)[c] Forge and grind

(10C) γ-extrude; forge, solution treat, age to R_c 44/48, and grind

NLO α-extruded material

(11) Forge, solution treat, age to R_c 44/48, and grind

---

[a]Solution treat: minimum 5 minutes at 1475 to 1550°F

[b]Age: 700 to 850°F - higher temperature, shorter time preferred

[c]Series B are for encapsulation, corrosion testing, and fire testing

[d]O.Q. - oil quench

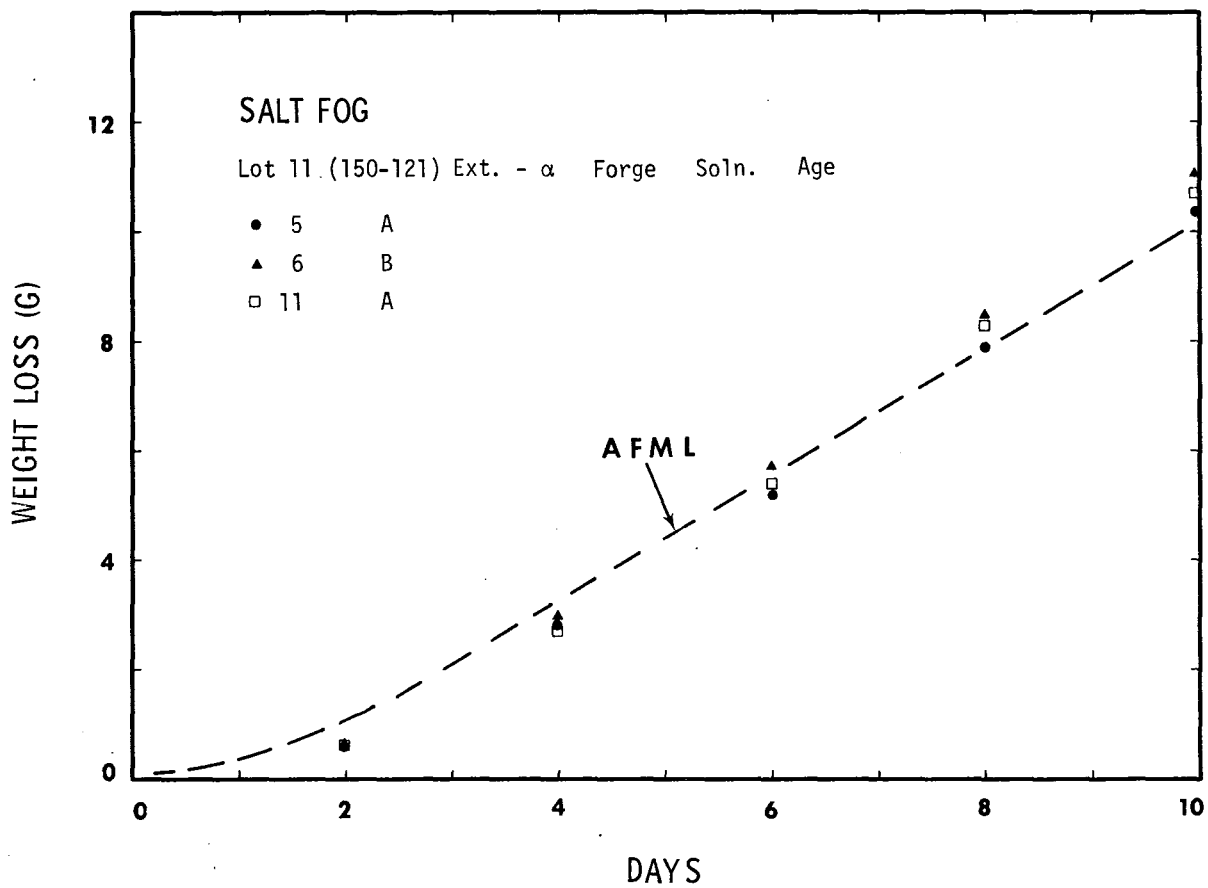

Figure 7. Weight Loss Versus Time for AFML and Lot 11 Penetrators in Salt Fog

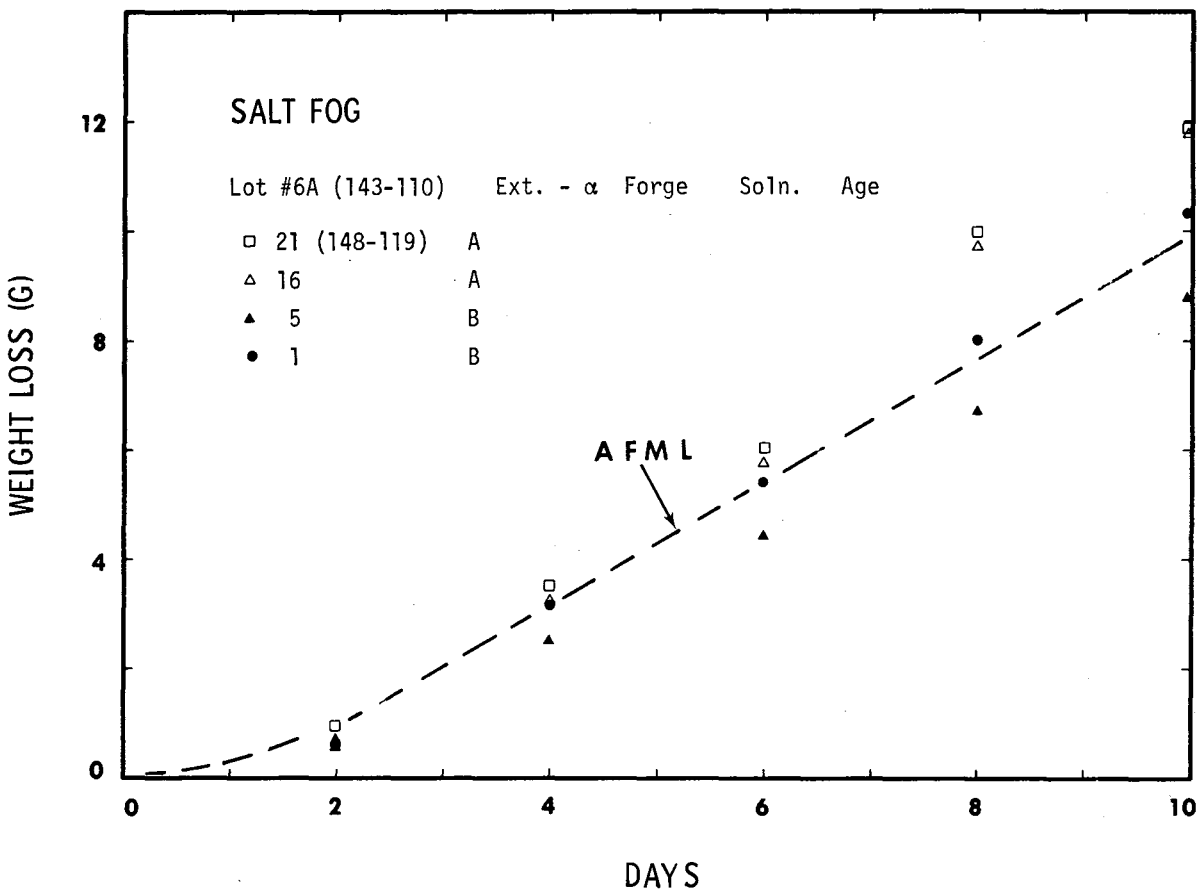

Figure 8. Weight Loss Versus Time for AFML and Lot 6A Penetrators in Salt Fog

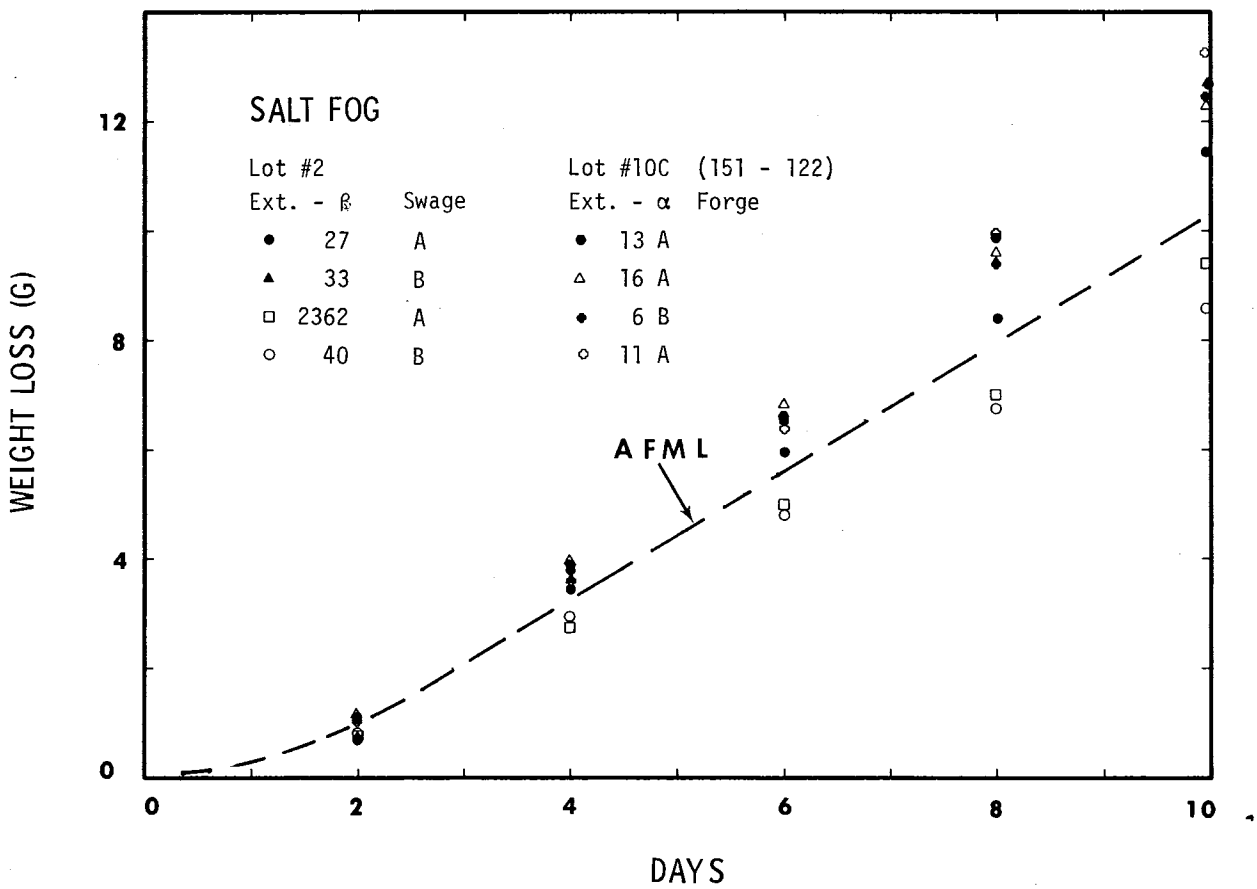

Figure 9. Weight Loss Versus Time for AFML and Lots 2 and 10C Penetrators in Salt Fog

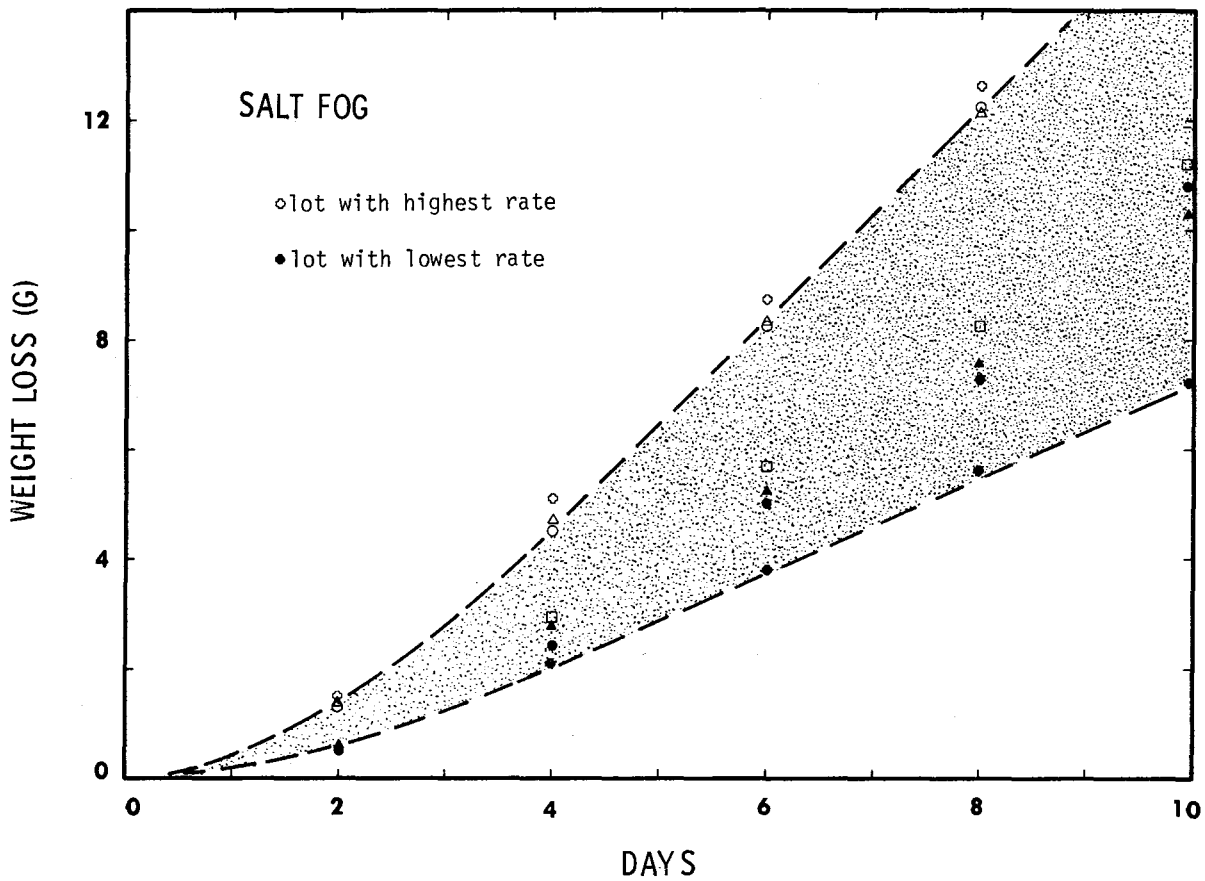

Figure 10. Compilation of Weight Loss Data for Penetrators in Test Series II

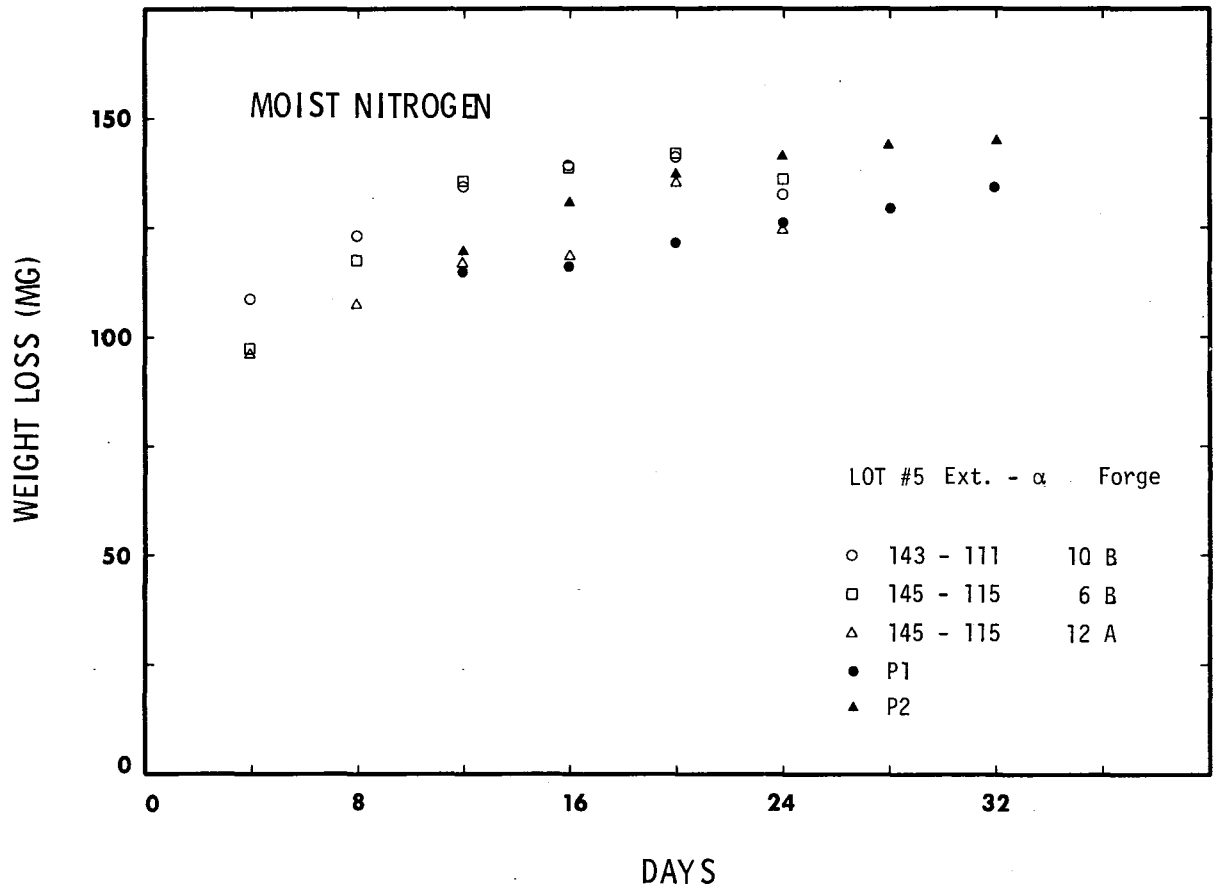

Figure 11. Weight Loss Versus Time for Lot 5, Test Series II, in Moist Nitrogen

The corrosion response from this Lot 5 in Test Series II was similar to that observed for the analogous material tested in Test Series I.

The final weight lost for each of the penetrators tested in moist nitrogen in Test Series II is tabulated in Table VI. There are some similarities between the data taken in Test Series I and II. First, material which had been either α- or β-extruded, cold worked by either forging or swaging with no subsequent solutionizing nor aging treatment exhibited the largest weight losses. Thus penetrators from Lots 1 and 5 had final weight losses which were five to ten times larger than those of other penetrators. In contrast, the corrosion response of penetrators in Lot 10A, which had been γ-extruded and forged with no subsequent heat treatments, was the smallest of any in Test Series II.

Secondly, the penetrators with a history similar to the AFML material (i.e., α-extruded, forged or swaged, solutionized and aged) such as Lots 11 and 6A, gave very similar responses to Test Series I material. The corrosion response data for Lot 6A, shown in Figure 12, is additionally interesting in that while three penetrators made from one piece of bar stock showed identical corrosion behavior, their behavior differed from that of a fourth penetrator in this lot made from another piece of bar stock. This result suggests that there are metallurgical differences from bar to bar within the same lot.

Thirdly, the remaining lots within Test Series II had a corrosion response similar to each other and bracketing Lot 11. This result was expected in that these materials underwent a solution treatment and some an additional aging treatment. Thus differences in processing treatment in this category resulted in no difference in corrosion response. In summary, except for γ-extruded material, solutionizing the material either before or after the cold working process does improve the resistance of the material to a moist nitrogen environment.

No stress corrosion cracking was observed in any of the Test Series II penetrators.

The encapsulated penetrators showed no signs that any swelling reaction took place. The changed appearance of the tarnish film on the penetrators was analogous to that discussed for the Test Series I penetrators. The penetrators that had been salt fog tested showed a darkened but adherent film, whereas those which had been tested in moist nitrogen had a film that was appreciably thicker and partially nonadherent. These results prove again that the encapsulation does not provide a hermetic seal.

TABLE VI

TEST SERIES II PENETRATORS - MOIST NITROGEN RESULTS

Lot	S/N	Condition	W_L* (g)	Lot	S/N	Condition	W_L* (g)
1	5	A	0.1929	6A	4	B	0.0100
1	6	A	0.1999	6A	24	A	0.0207
1	13	B	0.1810	6A	26	A	0.0207
				6A	28	B	0.0208
2	7	A	0.0206				
2	10	B	0.0352	7/9	6	A	0.0282
2	19	B	0.0183	7/9	18	A	0.0287
2	26	A	0.0055				
				8A	4	B	0.0305
3A	30	A	0.0464	8A	7	A	0.0279
3A	33	B	0.0278	8A	9	A	0.0236
3C	8	A	0.1967	9	15	A	0.0155
3C	18	B	0.0180	9	17	B	0.0087
4A	7	A	0.0088	10A	14	A	0.0041
4A	10	B	0.0078	10A	54	B	+0.0006**
5	6	B	0.1489	10C	20	A	0.0252
5	10	B	0.1446	10C	23	B	0.0264
5	12	A	0.1252				
5	P1	B	0.1467	11	8	B	0.0219
5	P2	B	0.1448	11	9	B	0.0216
				11	12	A	0.0243

*W_L - final weight loss

**+ - weight gain

*A - Acceptable surface condition

*B - Unacceptable surface condition

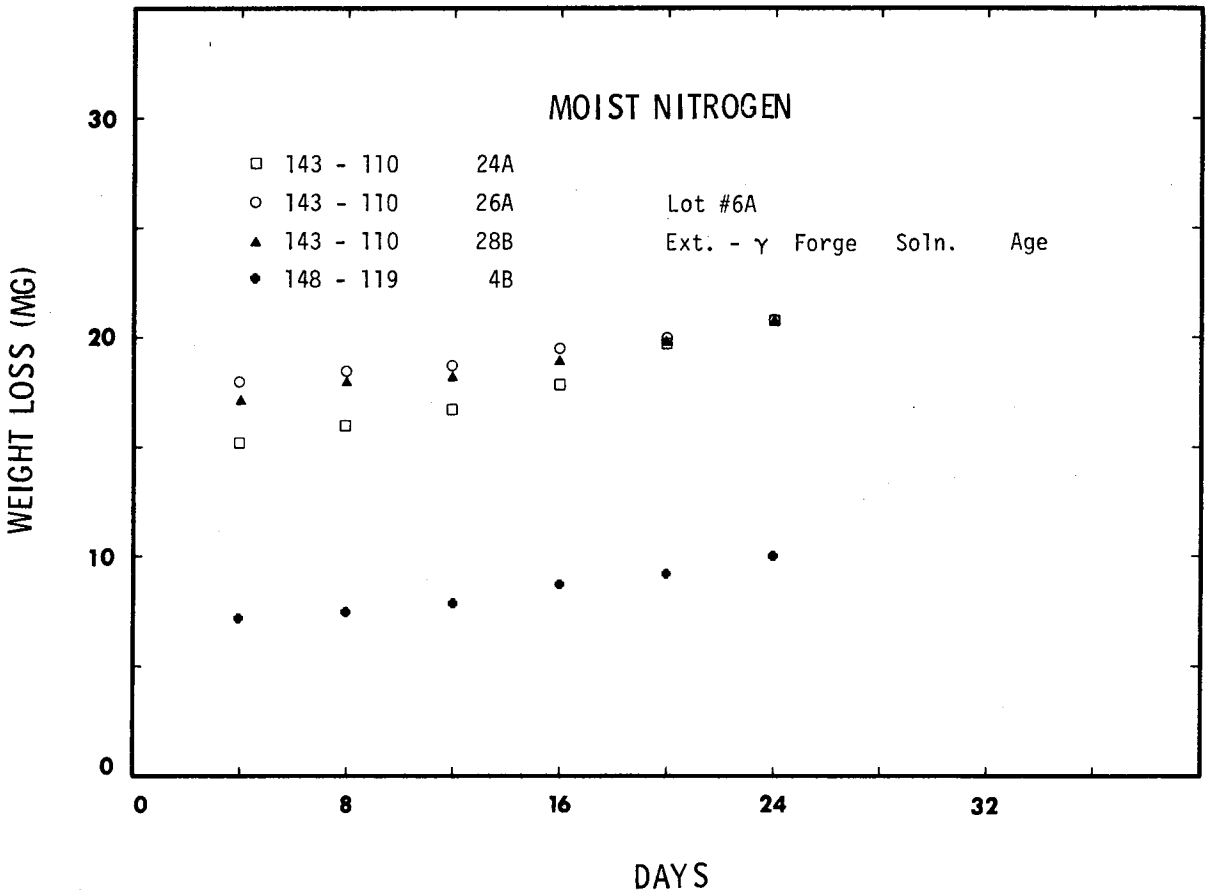

Figure 12. Weight Loss Versus Time for Lot 6A, Test Series II, in Moist Nitrogen

Coated Penetrators

A few penetrators were selected from each lot of Test Series II and coated with electroplated nickel plus electroplated zinc and zinc chromate finishes. (See appendix for plating details.) No difficulty was encountered in applying the coating. The only corrosion observed on the coated units, which was barely measurable, was the slight oxidation of the zinc overlayer to a powdery, white zinc oxide tarnish film. Therefore, the coating protected all the penetrators very well.

Rod Samples

The primary purpose in testing pieces of rod in the as-extruded condition was to observe the material for any propensity to SCC in this non-stress relieved state. The possibility for SCC in the manufacturing process, if the material is susceptible to SCC, is high in that long delays between extrusion and cold working, and/or cold working and solutionizing are possible.

Tables VII and VIII list the material processors, the billet sizes, and the extrusion conditions used for obtaining the rods tested in both salt fog and moist nitrogen. The four-inch lengths of rod were tested in the as-received condition. There was no indication of SCC in any of the rods after either salt fog or moist nitrogen testing. Figure 13 shows a compilation of the weight loss data for the rods tested in salt fog. In agreement with the results from Test Series I and II, the total spread in corrosion response was less than a factor of two. Table VII shows that the primary reason for this spread was the difference in corrosion response between α- and γ-extruded rod. One interesting point extracted from the data of Table VII is that NLO material which is subsequently extruded at RMI is more corrosion resistant than analogously extruded material made at ELO. This pattern holds true for both α- and γ-extruded material. The β-extruded material from NMI corroded similarily to the best γ-extruded material from NLO. Increasing the carbon content did have a significant detrimental effect on the corrosion resistance of this material, as seen in Lot 5B.

Examining the results listed in Table VIII for moist nitrogen testing of this rod material indicates an almost complete reversal of the patterns just described. The α-extruded material is more corrosion resistant than the γ-extruded material, and the ELO material is more corrosion resistant than the analogous NLO material. Also, increasing the carbon content in NMI material did not change the corrosion response. The best conclusion from these observations is that the rank order of material by corrosion response is a strong function of the test environment when the corrosion response is very similar.

TABLE VII

ROD SAMPLES - SALT FOG TEST

S/N	Processor	Extrusion Condition	Billet Size	W_L*(g)
27-1	NMI	β-extruded	Standard product	15.47
27-2	"	"	"	16.71
5B-1	NMI	β-extruded	High-carbon	21.75
5B-2	"	"	"	21.37
158-3	ELO	α-extruded	5.1 CVC	19.01
158-4	"	"	"	19.98
138-1	ELO	α-extruded	5.1 DF	25.07
138-2	"	"	"	22.63
239-1	ELO	γ-extruded	7.95 CVC	20.16
239-2	"	"	"	19.94
247-1	ELO	γ-extruded	7.95 DF	20.48
247-2	"	"	"	19.85
149-1	NLO	α-extruded	5.1	19.13
149-2	"	"	"	18.67
244-1	NLO	γ-extruded	7.95	14.88
244-2	"	"	"	16.20

*W_L - final weight loss

TABLE VIII

ROD SAMPLES - MOIST NITROGEN TEST

S/N	Processor	Extrusion Condition	Billet Size	W_L*(g)
27-3	NMI	β-extruded	Standard product	0.061
27-4	"	"	"	0.087
5B-3	NMI	β-extruded	High carbon	0.064
5B-4	"	"	"	0.088
158-1	ELO	α-extruded	5.1 CVC	0.027
158-2	"	"	"	0.032
138-3	ELO	α-extruded	5.1 DF	0.041
138-4	"	"	"	0.057
239-3	ELO	γ-extruded	7.95 CVC	0.034
239-4	"	"	"	0.047
247-3	ELO	γ-extruded	7.95 DF	0.062
247-4	"	"	"	0.084
149-3	NLO	α-extruded	5.1	0.072
149-4	"	"	"	0.067
244-3	NLO	γ-extruded	7.95	0.111
244-4	"	"	"	0.058

*W_L - final weight loss

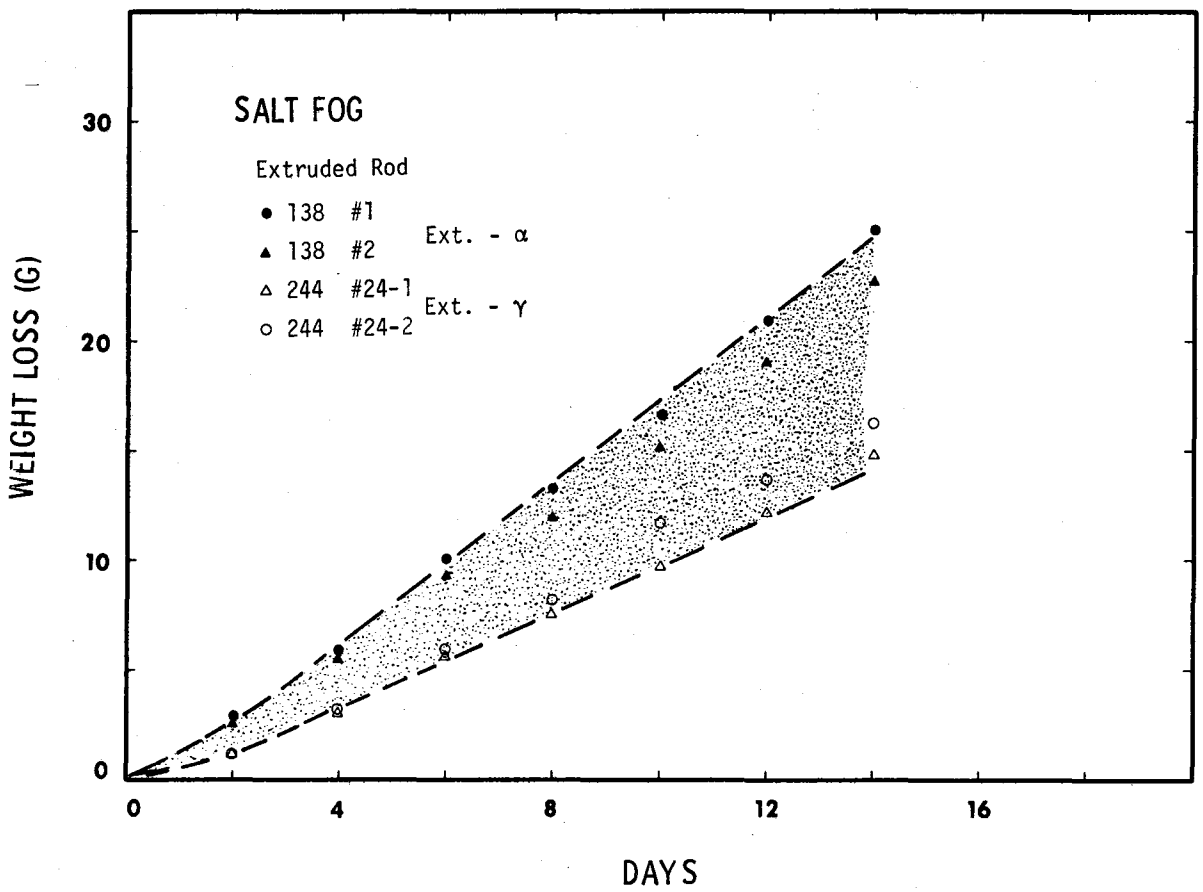

Figure 13. Compilation of Weight Loss Data for Rod Samples in Salt Fog

Cold Straightened Penetrators

The primary purpose in testing penetrators which had been cold straightened to meet inspection specifications was to observe any propensity to SCC in this nonstress relieved material. Twelve penetrators were produced per Lot 6 requirements of Test Series II which were significantly out of specification before cold straightening. Six were selected for moist nitrogen testing and six for salt fog. No evidence of SCC was seen on any of these penetrators after testing. Figure 14 is a plot of weight loss versus time for the six tested in salt fog. This data is given to primarily show the good reproducibility in corrosion response when the penetrators are "identical." The variation in the highest and lowest rate from the average is only five percent, which is a very small variation for response to corrosion.

Encapsulated, Corrosion Tested, and Fire Tested

Twenty penetrators each were taken from Lots 3B, 4B, 6B, and 10B (Table V), encapsulated at AOMC, corrosion tested in a salt fog environment at SLL, and fire tested at AOMC. The ballistic results from these penetrators were no different than the results from similarly prepared penetrators which had not undergone the exposure to a corrosive environment. Thus, the slight increase in the oxide tarnish film thickness due to the environmental exposure had no effect on ballistic performance.

Summary

The most important result from this study was that no penetrator tested showed any evidence of SCC. Thus no chemistry nor metal processing variable examined caused the uranium-titanium alloy to be more susceptible to stress corrosion cracking than "standard" material. Secondly, the largest difference in corrosion response to the salt fog environment between any two lots of material was a factor of two. The material with the highest corrosion rate had been α-extruded and forged with no subsequent solutionizing nor aging treatment, and it also had an extremely high carbon content. The material with the lowest corrosion rate had been β-extruded and swaged, solutionized but not aged, and composed of nominal chemistry.

Somewhat different results were obtained from moist nitrogen testing. In this case the most corrosion susceptible material had been either α- or β-extruded, cold worked by either forging or swaging, no subsequent solutionizing nor aging treatment, and composed of nominal chemistry. The analogously prepared material with high carbon content was significantly more corrosion resistant. The material with the lowest corrosion rate in

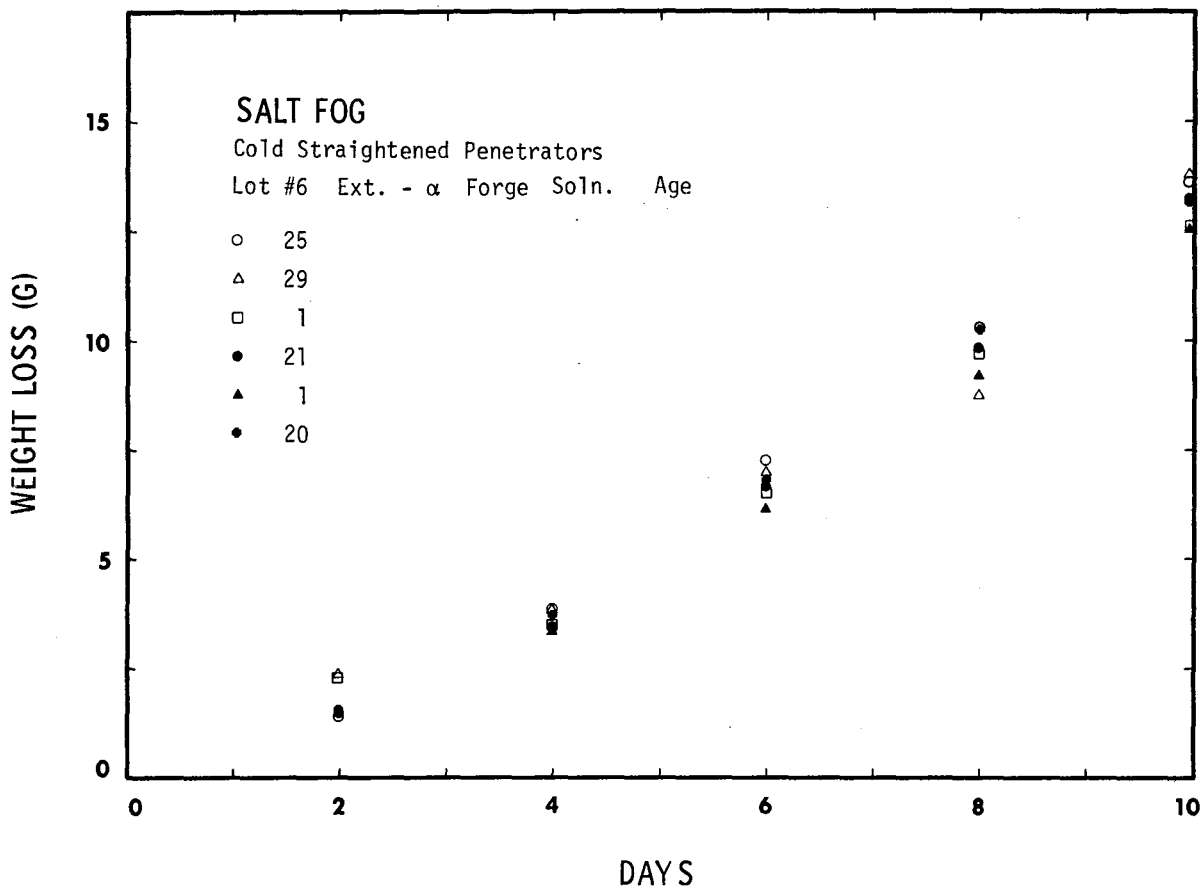

Figure 14. Response to Salt Fog of Cold Straightened Penetrators

moist nitrogen had been γ-extruded and forged with no subsequent heat treatments. The difference in the final weight lost between the most and least corroded material was a factor of ten. In that the weight loss for even the most susceptible was very small, these differences are indeed small. The differences in the corrosion rates from lot to lot are even smaller than the final weight loss projects, since the weight loss curves versus time approach flatness after a few days of test time.

The coating of electroplated nickel plus electroplated zinc with a zinc chromate finish performed extremely well on all the penetrators coated and corrosion tested.

Cold straightened penetrators did not show any evidence of SCC after corrosion testing, and their corrosion response was analogous to those previously tested from the same lot.

Pieces of rod tested in the as-extruded conditions had corrosion responses similar to the analogously treated penetrators. They also did not show any signs of a propensity to SCC.

Encapsulation did provide some protection of the penetrator from the test environment. However, the encapsulation does not provide a hermetic seal, and thus the external environment does communicate with the penetrator. The communication of the salt fog with the penetrator in the encapsulant with subsequent thickening of the oxide tarnish film did not produce a change in the ballistic response of the penetrator.

Conclusions

The primary conclusion from this study is that no variations in the uranium-titanium chemistry nor in the route or technique of metal processing examined caused a change of practical significance in the corrosion response of the material as tested in either salt fog or moist nitrogen. Therefore, the data assembled for corrosion response of the various lots cannot be used in selecting one lot over another. In the context of this study, all the material performed in an identical manner.

Secondly, the penetrators could be coated without difficulty in spite of changes in material chemistry and the metal processing route.

The combined encapsulation, corrosion, and fire tests indicated that a coating system to protect the penetrators during long-term storage is not necessary.

APPENDIX

ETCHING AND PLATING PROCEDURES

1. Vapor degrease in trichloroethylene
2. Caustic soak for 5 minutes at 70° to 80°C
3. Water rinse
4. Scrub surfaces with pumice
5. Water rinse
6. Pickle in 35 percent (by weight) solution of nitric acid at room temperature for 2 minutes
7. Water rinse
8. Etch in 1400 g/l ferric chloride solution for 10-15 minutes at 49°C
9. Water rinse
10. Pickle in 35 percent (by weight) solution of nitric acid at room temperature for 2 minutes
11. Water rinse
12. Caustic soak for 5 minutes at 70° to 80°C
13. Water rinse
14. Pickle in 35 percent (by weight) solution of nitric acid at room temperature for 2 minutes
15. Water rinse
16. Plate in nickel sulfamate solution
17. Plate in zinc cyanide solution
18. Chromate in Granodine 90

(Solution Composition and Operating Conditions)

Nickel Sulfamate Solution

Nickel sulfamate	450 g/l
Boric Acid	30 g/l
Surface Tension	34-38 dynes/cm
pH	3.8 - 4.0
Temperature	48 to 50°C
Anodes	sulfur depolarized nickel
Filtration	continuous
Current Density	270 A/m^2

(Solution Composition and Operating Conditions for Zinc Plating and Chromating)

Cyanide Zinc Solution

Zinc	22.5 g/l
Sodium Cyanide	56.5 g/l
Sodium Hydroxide	80.0 g/l
Cyanide/Zinc Ratio	2.5/1
Temperature	22°C
Current Density	270 A/m^2

Chromate

Granodine 90*	10% by volume

*Product of Amchem Products, Inc., Ambler, PA.

REFERENCES

1. S. Orman, "Oxidation of Uranium and Uranium Alloys," Physical Metallurgy of Uranium Alloys, J. J. Burke, D. A. Colling, A. E. Gorum, and J. Greenspan (eds.), Brook Hill Publishing Company, Chestnut Hill, MA, 1976.

2. L. J. Weirick, H. R. Johnson, and J. W. Dini, Corrosion and Protection of Uranium Alloy Penetrators, Sandia Laboratories, Livermore, SAND75-8243, June 1975.

3. L. J. Weirick, "Protective Coatings for Uranium Alloys," Physical Metallurgy of Uranium Alloys, J. J. Burke, D. A. Colling, A. E. Gorum, and J. Greenspan, (eds.), Brook Hill Publishing Company, Chestnut Hill, MA, 1976.

4. L. J. Weirick, Evaluation of Metallic Coatings for the Corrosion Protection of a Uranium-3/4 Weight Percent Titanium Alloy, Sandia Laboratories, Livermore, SLL-73-5024, January 1974.

5. H. R. Johnson and J. W. Dini, Protective Coating Studies for the W75 Program, Sandia Laboratories, Livermore, SLL-73-0058, October 1973.

6. L. J. Weirick and D. L. Douglass, "The Effect of Thin Electrodeposited Nickel Coatings on the Corrosion Behavior of U-0.75 Ti," CORROSION, 32, No. 6, June 1976, pp. 209-216.

7. A. L. Hoffmanner and G. H. Meyer, Chemistry and Metal Processing Study for the General Electric Manufacturing Technology GAU 8/A Penetrator Program, Battelle Memorial Institute, Columbus, Ohio, to be published.

8. N. M. Weare, Extrusion and Swaging Processes for the General Electric Manufacturing Technology GAU 8/A Penetrator Program, Nuclear Metals, Inc., Concord, MA, to be published.

9. N. F. Brewer, Extrusion Parameters for the General Electric Manufacturing Technology GAU 8/A Penetrator Program, Reactive Metals, Inc., Ashtabula, Ohio, to be published.

10. D. G. Spring, Forging and Grinding Processes for the General Electric Manufacturing Technology GAU 8/A Penetrator Program, Omark Industries, El Segundo, California, to be published.

11. N. J. Magnani, "Stress Corrosion Cracking of Uranium Alloys," Physical Metallurgy of Uranium Alloys, J. J. Burke, D. A. Colling, A. E. Gorum, and J. Greenspan (eds.), Brook Hill Publishing Company, Chestnut Hill, MA, 1976.

12. C. A. Colmenares, D. R. McKenzie, and T. E. Shell, "Multiple-Specimen Thermogravimetric Gas-Flow Apparatus for Oxidation Studies," J. of PHYSICS E: SCIENTIFIC INSTRUMENTS, 6, p. 1121, 1973.

13. L. A. West, "Relative Sputtering Yields and Quantitative Surface Analysis by Auger Spectroscopy," J. VAC. SCI. TECHNOL, 13, No. 1, January/February 1976.

14. M. McD. Baker, L. N. Less, and S. Orman, "Uranium + Water Reaction: Part 1. Kinetics, Products, and Mechanism," TRANS. FARADAY SOC, 62, pp. 2513-54, 1966.

15. L. J. Weirick, unpublished research work, 1976.

UNLIMITED RELEASE

INITIAL DISTRIBUTION

U.S. Energy Research & Development Administration
Albuquerque Operations Office
Branch Special Programs Division
Reimbursable Activities
Albuquerque, NM 87115

Attn: J. R. Cotton, Chief	ERDA-SAO
H. N. Hill, Director	ERDA-ALO
R. R. Malone, Chief	ERDA-SAO

Wright-Patterson Air Force Base
Ohio 45433

Attn: S. Inouye	AFML/LTM
F. H. Meyer	AFML/MXA
Dr. C. T. Lynch	AFML/LLN

Eglin Air Force Base
Florida 32542

Attn: J. Jenus, Jr.	AFATL/DLDA
A. Lopez	AFATL/DLOU

Headquarters U.S. Air Force
Washington, D.C. 20330

Attn: Major D. E. Spongberg	ASAF/RDRI

Andrews Air Force Base
Washington, D.C. 20334

Attn: R. W. Hartmeyer	AFSC/SDW

Air University Library
Maxwell Air Force Base
Alabama 36112

Deputy Chief of Staff for Operations
U.S. Army
Washington, D.C. 20330

Attn: Major Ramsey	DAMO-RQD

Army Materiel Command
5001 Eisenhower Avenue
Alexandria, VA 22333

Attn: Capt. G. Tonn	AMCRD-EA

Army Materials and Mechanics Research Center Watertown, MA 02172 Attn: Dr. F. Larson M. Levy	AMMRC-Bldg. 312 Metals Research Division
Frankford Arsenal Bridge and Tacony Street Philadelphia, PA 19137 Attn: R. E. Edelman	Pitman-Dunn Laboratory
Picatinny Arsenal Dover, NJ 07801 Attn: R. P. Davitt (2)	SARPA-AD-D-A-2
Lake City Army Ammunition Plant Independence, MI 64056 Attn: E. Knight	Army Technology Division Remington Arms Company
Naval Ordnance System Command Washington, D.C. 20360 Attn: Mr. B. Tabb	ORD 55-20B
SEA Systems Command Washington, D.C. 20362 Attn: B. B. Rosenbaum	Code 03523
Naval Weapons Laboratory Dahlgren, VA 22448 Attn: Dr. S. G. Fishman	GWR
Defense Documentation Center Alexandria, VA 22314 (2)	
AAI Corporation Cockeysville, MD 21030 Attn: M. M. Rottenberg	
Aerojet Ordnance & Manufacturing Company 9236 East Hall Road Downey, CA 90241 Attn: J. J. Joyce	
Aerospace Corporation 2350 East El Segundo El Segundo, CA 90245 Attn: Dr. E. G. Kendall	

Amron Corporation
P. O. Box 47
525 Progress Avenue
Waukesha, WI 53186

Battelle Northwest
Richland, WA 99352
Attn: R. S. Kemper
G. E. Zima

Battelle Columbus Laboratories
505 King Avenue
Columbus, OH 43201
Attn: Dr. A. Hoffmanner
Dr. G. A. Meyer

Eldorado Nuclear Limited
215 John Street
Port Hope, Ontario, Canada LIA 3A1
Attn: Dr. R. Barclay

General Electric Company
Lakeside Avenue
Burlington, VT 05401
Attn: R. A. Schell (5)
F. Adamske

Honeywell, Inc.
Government & Aeronautical Division
New Birghton, MN 55112
Attn: A. M. House N2540
M. Williams N2540
F. Lemer N2540

National Lead Company of Ohio
P. O. Box 39158
Cincinnati, OH 45239
Attn: L. M. Levy
C. E. Polson

N. L. Industries
1130 Central Avenue
Albany, NY 12205
Attn: H. M. Drucker

Nuclear Metals, Inc.
2229 Main Street
Concord, MA 01742
Attn: P. Loewnstein
N. E. Weare

Omark Industries
1415 East Grand Avenue
El Segundo, CA 90245
Attn: D. G. Spring

RMI Company Extrusion Plant
P. O. Box 579
Astabula, OH 44004
Attn: N. F. Brewer

Atomic Weapons Research Establishment
Building A2.2
Aldermaston, Reading RG7 4PR
ENGLAND
Attn: C. Calow
S. Antony
G. Picton
B. Ward
A. Kay

Los Alamos Scientific Laboratory
P. O. Box 1663
Los Alamos, NM 87544
Attn: D. J. Sandstrom

Union Carbide Corporation
Nuclear Division
Y-12 Plant Records Dept., Bldg. 9711-5
P. O. Box Y
Oak Ridge, TN 37830
Attn: J. Koger
G. L. Powell
J. S. Bullock, IV
W. Tewes

Rockwell International
Atomic International Division
Rocky Flats Plant
Golden, CO 80401
Attn: R. Krenzer
R. Mah

C. A. Colmenares, LLL, L460
L. W. Roberts, LLL, L426
D. H. Wood, LLL, L426

R. S. Claassen, 5800: Attn: R. G. Kepler, 5810
R. L. Schwoebel, 5820
H. J. Saxton, 5840
M. J. Davis, 5830
N. J. Magnani, 5831
S. L. Pohlman, 5831
T. B. Cook, Jr., 8000; Attn: C. H. DeSelm, 8200
W. C. Scrivner, 8400
L. Gutierrez, 8100
D. E. Gregson, 8150
G. N. Beeler, 8157; Attn: H. Hanser
R. D. Cozine, 8160
D. J. Bohrer, 8167
B. F. Murphey, 8300; Attn: T. S. Gold, 8320
G. W. Anderson, 8330
J. L. Wirth, 8340
J. F. Barham, 8360
D. M. Schuster, 8310
D. R. Adolphson, 8312
J. W. Dini, 8312
H. R. Johnson, 8312
M. W. Mote, 8312
K. A. Pashman, 8312
L. J. Weirick, 8312 (15)
R. W. Mar, 8313
C. W. Schoenfelder, 8313
D. B. Dawson, 8314
A. J. West, 8314
W. R. Hoover, 8314
Technical Publications and Art Division, 8265, for TIC (2)
F. J. Cupps, 8265/Technical Library Processes Division, 3141
Technical Library Processes Division, 3141 (2)
Library and Security Classification Division, 8266-2 (3)