

# ELECTROPLATING FISSION-RECOIL BARRIERS ONTO LEU-METAL FOILS FOR $^{99}\text{Mo}$ -PRODUCTION TARGETS

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## ABSTRACT

Electroplating experiments on uranium foil have been conducted in order to develop low-enriched uranium composite targets suitable for the production of  $^{99}\text{Mo}$ . Preparation of the foil surface prior to plating was found to play a key role in the quality of the resultant coating. A surface preparation procedure was developed that produces both zinc and nickel coatings with the desired level of coating adherence and coverage. Modifications of the existing plating processes now need investigation to improve to uniformity of the plating thickness, especially at the foil perimeter.

## INTRODUCTION

Molybdenum-99 ( $^{99}\text{Mo}$ ) is usually produced for medical applications by irradiating a high-enriched uranium (HEU) target. To convert targets to low-enriched uranium (LEU) will require five to six times more uranium for equivalent yield of  $^{99}\text{Mo}$ . In Cintichem targets, electrodeposited HEU oxide can be replaced by LEU-metal foil to keep target geometry constant. The target design under study for use in Indonesia is shown in Fig. 1. It consists of thin (~130- $\mu\text{m}$  thick) LEU uranium metal foil, approximately 10.2 cm by 8 cm, sandwiched between slightly tapered inner and outer tubes [1]. In test runs, difficulties have been encountered in removing the uranium foil from the target assembly. This problem has been attributed to bonding of the uranium to the inner and outer tubes due to ion mixing caused by fission fragments escaping from the uranium foil. A proposed solution is to add fission-fragment absorbing barriers between the uranium foil and the tubes [1,2].

The LEU composite (barrier layers and inner foil) must meet several critical requirements if it is to replace the conventional HEU target. The barrier layer thickness is dictated by the recoil range of fission fragments. The maximum recoil distance is ~7  $\mu\text{m}$  in candidate materials, such as nickel [3]. To provide a margin of safety, our goal is to have a barrier layer thickness that is approximately twice the recoil distance. The barrier layer must also completely cover the foil to preclude the possibility of localized bonding to the target. The composite also needs to be uniform in thickness to ensure a proper fit in the target for ease of assembly and proper heat dissipation during irradiation. Finally, substitution of the LEU composite for the existing HEU oxide requires that changes in downstream processing be minimal. Barriers that are too thick or made of materials that are incompatible with planned dissolution and separation schemes could reduce the yield or purity of  $^{99}\text{Mo}$  product.

This paper presents the work done to date on electroplating a metal barrier onto the uranium foil. In terms of cost and performance, electroplating is considered the best fabrication approach. For electrochemical, chemical, and mechanical reasons, nickel, copper, iron, and zinc were considered the best metals for this work. Zinc has the advantage that it can be used in targets for all current processes--

those that use acidic or basic dissolution of irradiated uranium. The other barrier metals can be dissolved only in nitric acid. The literature contains a modest number of publications on electroplating nickel on uranium [4-11]. No publications on electroplating uranium with the other potential barrier metals have been located. For this reason, and because of the amphoteric property of zinc, our work, thus far, has concentrated on electroplating nickel and zinc.

The principal difficulty in electroplating uranium is that it oxidizes readily in air and water, and the resulting oxide layer makes it impossible to obtain a metal-to-metal bond. A mechanical bond has been obtained by cleaning the surface of most of the uranium oxide, etching the uranium to obtain a rough surface, and electroplating. Uranium has been successfully electroplated in this way with nickel to prevent corrosion. Electroless nickel-plating of uranium has also been demonstrated [9]. The etchants reported in the literature, thus far, include concentrated solutions of nickel, ferric, stannous, cupric, or lithium chloride. Mixtures of hydrochloric and sulfuric acids have also been tried, as well as anodic etching procedures [10,11]. The most frequently used etchants have been the nickel- and ferric-chloride solutions. Surface preparation methods used prior to etching were buffing with pumice or calcium oxide, sand blasting, and immersion in 8M  $\text{HNO}_3$ .

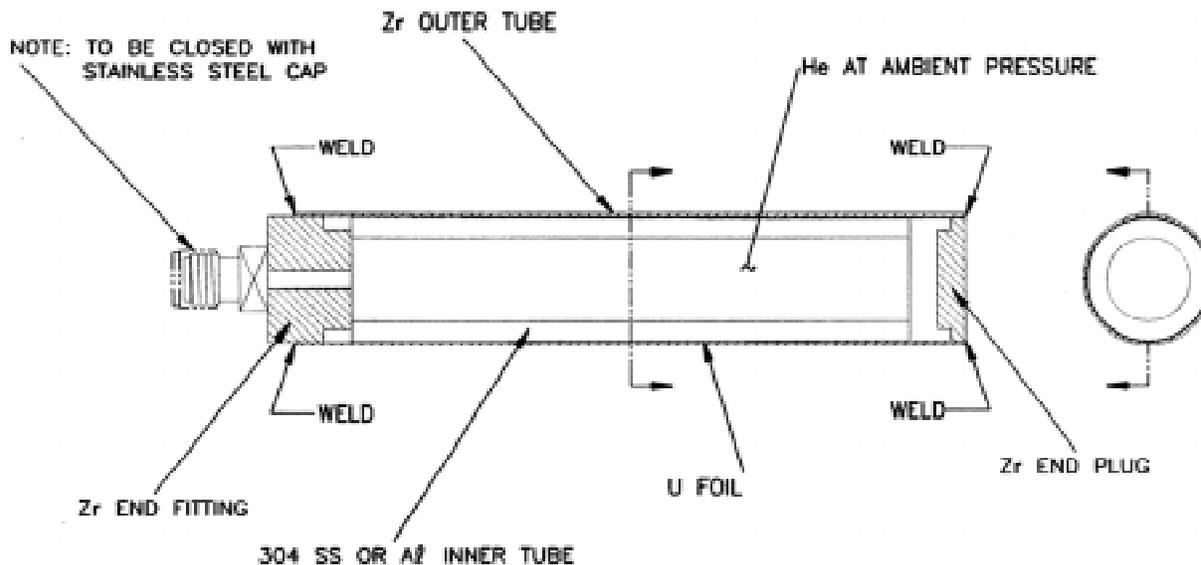


Fig. 1. LEU Metal-Foil Target

## EXPERIMENTAL PROCEDURE

### Sample Preparation

Depleted uranium (DU) foil was used for the bulk of the plating experiments performed because of the limited availability of LEU foil. The primary difference between the DU and the LEU foils was not the isotopic content. The main difference was that the DU foil was standard purity uranium metal. The LEU foils contained alloy additions of iron (450 ppm) and aluminum (1000 ppm) [2]. These additives refine the grain size of the uranium [12]. Indicative of the smaller grain size for the LEU foil

with this adjusted composition is that it dissolved at twice the rate of the pure uranium (DU) foil in 8M  $\text{HNO}_3$  at  $80^\circ\text{C}$ .

The procedure for preparing these uranium foils prior to actual plating proved to have a major impact on the quality of the plating. A descaling step was necessary to remove the pre-existing oxide scale. Then, an etching step was needed to roughen the surface and promote coating adherence. Without an irregular surface to mechanically key the plating, the substrate and plating readily separated. The etching agents investigated included chloride salts of iron, nickel, and zinc in concentrations that ranged from 0.45 to 9.0M. At times, the preparation procedure was augmented with immersions of the foil into strongly alkaline as well as strongly acidic solutions. Ultimately, the procedure we employed contained the following essential steps:

1. A sample of foil was cut, its dimensions measured, and its weight recorded. These samples were typically 15 to 50% of the full target size to provide a reasonably representative geometry; however, the first LEU samples were < 10% of full target size due to limited availability.
2. To degrease the foil, it was immersed in xylene or tetrachloroethylene for one minute, then immersed for one minute in methyl alcohol, ending with a one-minute rinse in deionized water.
3. The foil was pickled in an 8M nitric-acid solution to completely remove the thick oxide scale. This step took usually 5 to 10 minutes, depending on the thickness of the scale, and was followed by multiple immersions in deionized water for total time periods of 6 to 15 minutes.
4. The sample was etched in a stirred 5.33M ferric-chloride solution for 2 to 5 minutes at  $40^\circ\text{C}$  to roughen the surface. For this step only, a nylon strap replaced the Pt hanger securing the sample. Multiple rinses in deionized water again removed the etching solution. The total rinse time varied from 6 to 30 minutes, depending on factors like continued gas evolution in the rinse.
5. The sample was returned to the 8M  $\text{HNO}_3$  solution for 2 to 7 minutes to remove the black coating left by the etching treatment. Once again, multiple rinses in deionized water completed this step.

Weight and thickness were often measured after each rinsing operation to assess the amount of uranium removal. When these measurements were made, the fifth step was often repeated, but the immersion in the  $\text{HNO}_3$  solution was limited to less than one minute. The purpose of the repetition was to remove any oxide film caused by air exposure and to activate the surface for electroplating.

Copper foils were also plated to evaluate the operation and performance of the electroplating baths. A different and much simpler preparation procedure was used for the copper samples. Samples were cut to size, gently abraded with powdered calcium oxide, immersed in a 1M hydrochloric acid solution, and thoroughly rinsed in running deionized water. This treatment did not provide the same level of surface roughness as the treated uranium samples. Prior to placement in a plating bath, the weight and dimensions were measured for these samples.

Electroplating Solutions and Conditions

Pre-mixed, commercially obtained, electrolytes<sup>1</sup> were used for both the zinc and nickel plating experiments. The zinc electrolyte was an all-alkaline solution containing sodium zincate, sodium hydroxide, and an additive, STARZINC 595, to promote smooth, uniform, and adherent deposits. The polyethylene plating tank had interior measurements of 30 cm long by 16 cm wide and was filled to a depth of ~25 cm. The samples were hung from a central copper rod that was secured to the top of the tank at mid-length. The two zinc anodes (99.99% purity) were suspended from two parallel copper rods that flanked the central rod at spacings of 11.5 cm each. These anodes were removed from the bath during periods of nonuse to minimize dissolution of zinc into the bath. This plating bath was not agitated or filtrated, and plating was performed at ambient temperature.

The nickel electrolyte was a nickel sulfamate solution to which nickel bromide was added to improve anode efficiency and reduce stress in the deposited nickel. Boric acid was also added to stabilize the pH at 4, which also lowered stress in the deposits. This polyethylene plating tank had interior measurements of 30 cm long by 30 cm wide and was filled to a depth of 30 cm. The spacing between adjacent copper rods for electrode connections was 12.5 cm. The two nickel anodes were believed to be 99.99% in purity. This bath was filtered continuously, via connections to an external pump, to remove any suspended solids. The pumping action caused a steady circulating motion in the electrolyte. The bath temperature was maintained at ~40°C through the use of an immersion heater. Control of temperature provided another means of minimizing stress in the deposited nickel. Deionized water was added periodically to make up evaporative losses from both baths.

For both types of plating experiments, the sample was secured by means of a clipped hook. The length of the clipped hook was sized to provide complete immersion of the sample in the bath with minimal exposure of the clip to the electrolyte, once the hook was suspended from the energized central Cu rod. For some tests, a direct lead from the power supply was also connected to the clipped hook. The second connection made the plating circuit immediately active once any part of the sample contacted the electrolyte. The power supplies provided constant-current output at preset levels. Current levels were calculated on the basis of the sample geometry and the desired current density.

Bath temperature, current, and voltage were recorded both at the beginning and the end of an experiment. The current density and the time of plating were the two main variables. The plating duration was predetermined based on the intended current density and the expected plating efficiency. Upon completion of a plating experiment, the sample was rinsed, dried, and weighed.

#### Assessment of Plated Samples

The quality of the plating was assessed by three methods. First, the weight gain was used to calculate the average plating thickness based on a fully dense coating. Second, micrometer measurements were taken to quickly gauge the uniformity of the plating thickness. Third, the sample was sectioned and examined microscopically. Sectioning was done in a manner that provided a fully representative cross section, generally along a diagonal of these rectangular samples.

Standard preparation procedures for metallographic samples were followed, with 0.3 µm alumina powder and Metadi™ fluid as the lubricant for the final polishing. The local coating thickness was then determined from photomicrographs taken at multiple locations on the sample. In addition, optical

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<sup>1</sup> Starlite Chemicals, Inc., 1319 West North Avenue, Chicago, IL 60622.

microscopy provided estimates of coating coverage, indications of coating adherence, and the degree of substrate roughening developed during the preplating steps.

## ZINC PLATING RESULTS

Chronologically, the first plating experiments were conducted using the zinc bath, and many issues regarding proper preparation of the foil surface were resolved during the early plating experiments. For instance, we found the simplest and most consistent method of descaling the foil surface was immersion in 8M HNO<sub>3</sub>. Thus, this solution became the preferred method of removing the oxide. In trials of various etchants, nickel chloride (containing nitric acid) proved too vigorous for 130- $\mu$ m-thick foils, and its usage was discontinued. The ferric-chloride etchant was ultimately chosen, but not before a number of concentrations were tried. The 5.33M FeCl<sub>3</sub> became the standard based on its ability to dissolve a predictable quantity of uranium in a reasonable time span.

As time progressed, the zinc-plating bath proved to be an ideal medium for determining the influence of the etching on plating quality. As shown in Table 1, plating coverage tended to decrease as the amount of foil dissolution increased. This inverse relationship was not exact because other factors, such as coating thickness, also influenced coverage. Nevertheless, this correlation stressed the need to counterbalance the need for maximum surface roughness to obtain maximum adherence. Microscopy revealed that the source of this relationship was nonuniform dissolution of the foil surface. Numerous deep crevices and/or irregular pits were present in the substrate, where essentially no deposition occurred during electroplating. Overetching increased the number of deep depressions, and the limited throwing power of the zinc bath prevented plating in these areas.

Table 1. Influence of Pre-plating Weight Loss on Plating Coverage for Zinc-Plated Samples

Number of Samples	Range in Pre-plating Weight Loss (%)	Range in Plating Coverage (%)
6	6 to 15	100
3	10 to 30	90 to 99
3	36 to 43	<90

The results of plating thickness measurements from recent zinc-plating experiments are summarized in Table 2. The samples whose designations begin with “ZnDU” had DU foil substrates, whereas those beginning with “ZnLEU” had LEU foil substrates. Thickness determinations by three different methods are given, with the exception of three samples (ZnDU17-19) for which the preparation and plating steps intentionally were not interrupted for intermediate weight and thickness measurements. The micrometer measurements provided a fast assessment of plating uniformity but overstated the plating thickness due to overemphasis of the thicker edge and corner values. Through Faraday’s law, the weight measurements gave the most accurate indication of the amount of deposited metal, but no insight into the uniformity of the deposition. The comparatively lengthy process of optical microscopy gave the best indication of the range in coating thickness. The reported value typifies plating thickness over most of the sample but specifically excludes measurements taken at the edge.

Samples ZnDU17-20 were highly and deeply etched by the ferric chloride. The resultant zinc coatings were discontinuous and coverage was incomplete. In extreme cases, such as that shown in Fig. 2, the plating consisted of discrete and isolated nodules. Where deposition occurred, it tended to be thick. Thus, microscopy measurements of thickness, which were not adjusted for lack of coverage,

tended to overstate the thickness in comparison to the calculations based on weight change. The estimated plating coverage ranged from 74% for ZnDU20 to 93% for ZnDU17. As shown in Fig. 3, the morphology of the deposited zinc on ZnDU17 still retained nodular characteristics, even though the general coating appearance was much improved.

Table 2. Plating Thickness (in  $\mu\text{m}$ ) for Zinc-Plated Substrates by Three Different Methods

Sample Identification	Thickness via Micrometer	Thickness via Weight Gain	Thickness via Microscopy
ZnDU17	N.M. <sup>a</sup>	N.M.	12
ZnDU18	N.M.	N.M.	17
ZnDU19	N.M.	N.M.	7
ZnDU20	25	10	18
ZnDU21	80	41	57
ZnLEU22	112	52	58
ZnDU23	34	14	7
ZnLEU24	27	16	27

<sup>a</sup>N.M. = not measured.

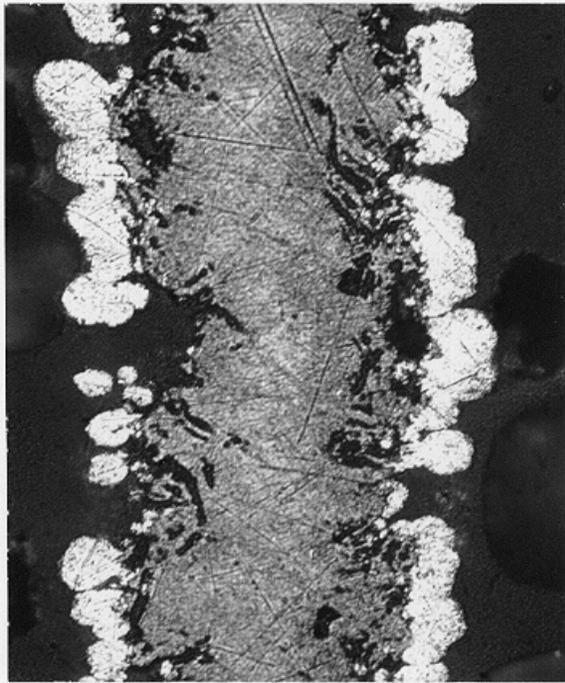


Figure 2. Discontinuous Coverage and Nodular Zinc Deposits on a Severely Overetched DU Substrate (ZnDU20, 350X)

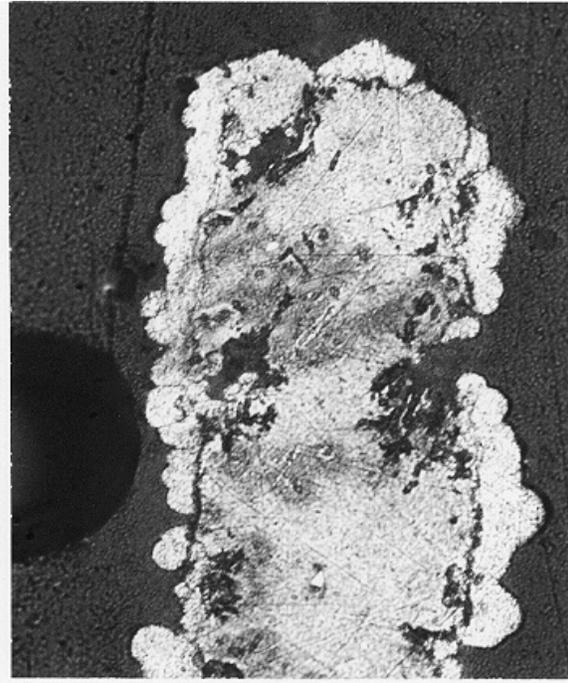


Figure 3. Improved Coverage and Semi-nodular Zinc Plating on an Overetched DU Substrate (ZnDU17, 350X)

The behavior of ZnDU21 was unusual. The 2.54 cm x 5.08 cm piece of foil did not react in 8M  $\text{HNO}_3$  at room temperature in over 20 minutes, although other pieces of the same (3-in. x 4-in.) large foil were freed of the oxide in <10 minutes. The oxide scale was finally removed in 3 minutes when the temperature of the descaling solution was raised to 50°C. There was also a problem with the electroplating bath due to corrosion scales on the clipped hook and copper rods. The current did not reach the desired value until the scales were removed, and consequently the current varied widely during the electroplating. The coulombs that were passed was not known. In spite of these difficulties, zinc coverage was complete. As shown in Fig. 4, the plated layer was overly thick but uniform. The substrate showed no evidence of being deeply etched, which was consistent with the measured pre-plating weight

loss of 7.8%. The improvement in coating coverage again correlated with minimization of etching treatment.

Samples ZnLEU22 and ZnLEU24 were the first adjusted uranium foils electroplated. The surface of these foils was only slightly oxidized, as opposed to the pure uranium foils, and the surfaces cleaned up well in 8M HNO<sub>3</sub>. Sample ZnLEU22 was tested in the as-received state, while sample ZnLEU24 was heat-treated in a vacuum for 10 minutes at 720°C before testing. The zinc plating on ZnLEU22 was about four times the desired thickness. In large part, the thick plating was due to an atypical increase in coulombic efficiency to 80%, twice the value of the expected efficiency used in calculating the plating time. The plating on ZnLEU24 was about one-third greater than the desired 15 μm. Once again, the coulombic efficiency of 78% was greater than the 60% assumed in calculating the plating time. (The unpredictable variation in efficiency continues to be a major challenge for zinc plating. In early experiments plating efficiencies were as low as 20%. The trend has been to better efficiencies as our plating experience increases.) Both of these samples had coatings that were smooth and relatively uniform. The thick plating on ZnLEU22 separated from most of one side, but the ZnLEU24 plating generally exhibited good adhesion, as shown in Fig. 5. These results indicate that there is no inherent problem in plating adjusted-uranium foils as opposed to pure-uranium foils; in fact, our limited experience shows superior results for plating of the adjusted uranium.

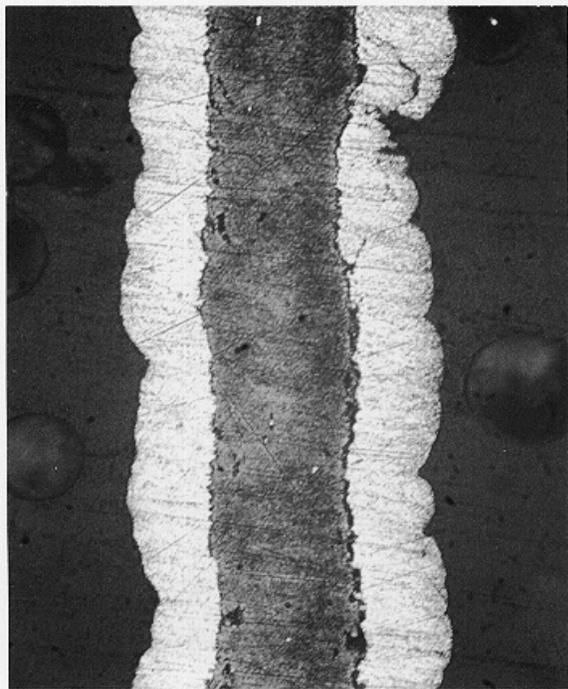


Figure 4. Uniform and Continuous Zinc Plating on a Properly Etched Pure-Uranium Substrate (ZnDU17, 180X)



Figure 5. Uniform and Continuous Zinc Plating on a Properly Etched Adjusted-Uranium Substrate (ZnLEU24, 220X)

Sample ZnDU23 was 7.02 cm x 5.08 cm in size. It was the largest foil plated thus far, and demonstrated the ability to plate larger foils. The average thickness based on weight gain was 14 μm, essentially our desired thickness. Microscopy found that the trends observed previously for smaller samples were qualitatively true for the larger sample. In a few areas of localized overetching, coverage was discontinuous. The bulk of the surface, however, had an adherent plating that was free of nodular

characteristics. Variations in thickness were clearly related to sample geometry. At corner and edge locations, the thickness was two to three times the thickness in the central areas of the surfaces.

The dependence of plating thickness on sample geometry is presented more rigorously in Fig. 6 for ZnDU23 and other samples from the ZnDU series. To normalize for the difference in sample size, the abscissa is expressed as the distance from the center divided by one-half of the diagonal distance. To adjust for sample-to-sample variations in thickness, the ordinate is the thickness at a given location divided by the thickness found at the center of that particular sample. Scaling up the sample size apparently exacerbated the center-to-edge variation in coating thickness because the ZnDU23 data are the uppermost points in Fig. 6.

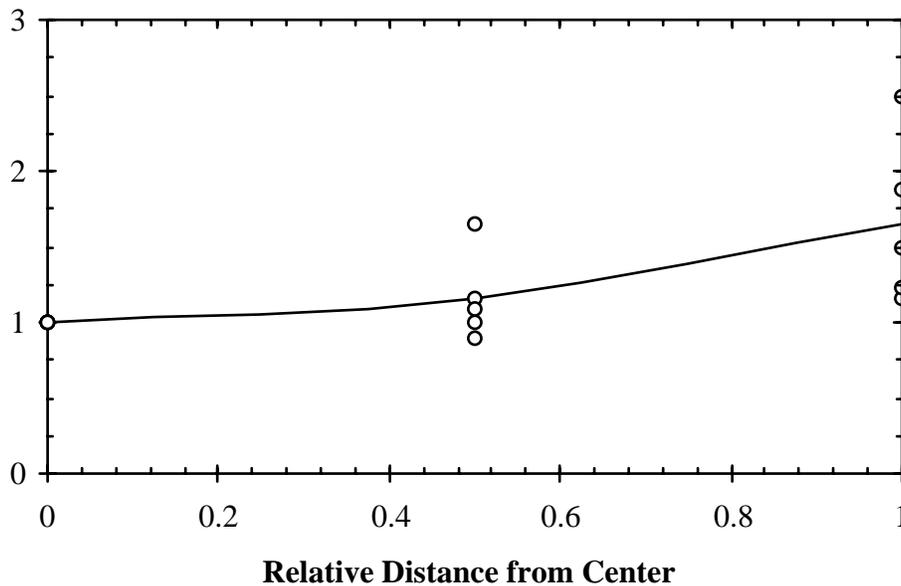


Figure 6. Relative Thickness of Zn Plating as a Function of Distance from the Sample Center

#### NICKEL PLATING RESULTS

The initial tests in the nickel-plating bath used copper rather than uranium as the substrate. The four samples in the NiCu series were plated at different current densities to determine the range in coulombic efficiency for this bath. The target current densities were 10, 20, 40, and 80 mA/cm<sup>2</sup>, and the plating time was adjusted between 0.25 and 2.0 h to produce a nominally constant plating thickness of 25 μm. The only serious difficulty encountered in this series of experiments involved the sample plated at the lowest current density. The power supply failed to maintain the preset current setting and drifted up with time. The total charge passed was estimated as the average of the initial and final currents, which did not vary appreciably for the other three experiments. The net weight gains were used to calculate the quantity of charge that went into plating. The coulombic efficiencies ranged from 85 to 98%. The greatest uncertainty was associated with the 98% value because this value was obtained from the compromised test. Figure 7 illustrates the inverse relationship between current density and coulombic efficiency found for these data. The decline in efficiency at higher current densities was relatively modest over this range.

The nickel-plated copper samples possessed the following characteristics. In all cases, coverage was 100% except for small areas (~ 2 mm<sup>2</sup>) covered by the electrical connection. The surface of the

plating was smooth except for the edges of the sample. At the edges, excess localized plating took the form of large rounded deposits with a characteristic diameter of  $\sim 20\ \mu\text{m}$ . The plating thickness was very close to the intended thickness of  $25\ \mu\text{m}$  with the exception of the sample plated at the lowest current density. As shown in Table 3, the three different methods used to determine thickness gave values that differed, but the variation tended to be consistent.

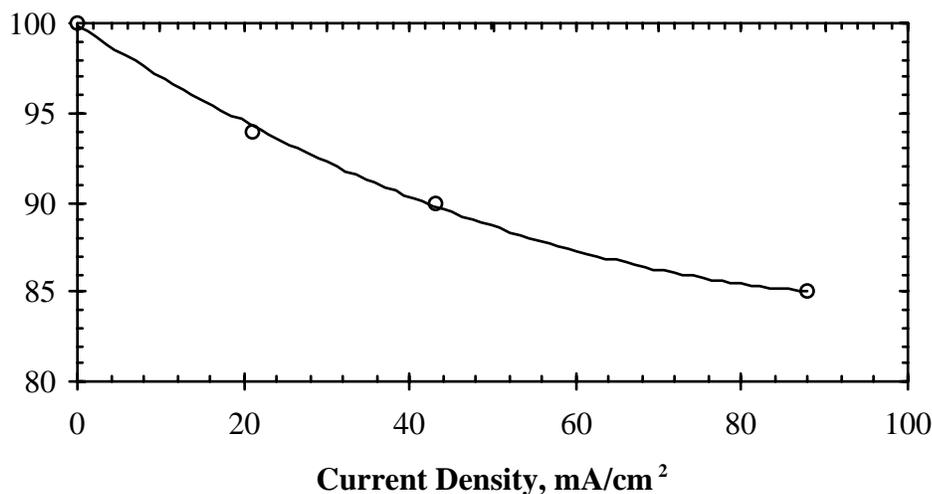


Figure 7. Effect of Current Density on Plating Efficiency for the Nickel Sulfamate Bath at  $40^\circ\text{C}$

Table 3. Plating Thickness (in  $\mu\text{m}$ ) for Nickel-Plated Substrates by Three Different Methods

Sample Identification	Thickness via Micrometer	Thickness via Weight Gain	Thickness via Microscopy
NiCu10	47	40	30
NiCu20	36	25	21
NiCu40	37	24	19
NiCu80	32	23	18
NiDU1	14	18	14
NiDU2	30	N.M. <sup>a</sup>	16
NiDU3	19	15	15
NiDU4	19	15	10

<sup>a</sup>N.M. = not measured.

The intent of the early nickel-plated uranium samples (NiDU series) was to establish which steps in the intricate sample preparation procedure have the greatest impact on plating quality. Thus, plating parameters were not intentionally altered for these four samples. Based on the results for the copper substrates, the current density was fixed at a nominal value of  $32\ \text{mA}/\text{cm}^2$ , the plating time was set at 25 minutes, and the bath temperature was held at  $40^\circ \pm 2^\circ\text{C}$ . Under these conditions, the nickel-plated uranium samples were expected to have an average thickness of  $15\ \mu\text{m}$ .

Pretreatment of sample NiDU1 included all of the previously described degreasing, descaling, etching, and pickling steps, whereas sample NiDU2 was only descaled in 8M HNO<sub>3</sub>, followed by four 2-minute rinses in deionized water. Sample NiDU1 had a 34.8% metal weight loss beyond the weight loss associated with descaling. The resulting roughened surface, however, greatly improved the adherence of the nickel coating. As shown in Fig. 8, nickel deposited on all exposed substrate surfaces, even those pitted areas well below the original surface. As a consequence, the nickel coating was able to mechanically lock into the uranium substrate. In contrast, the plating on sample NiDU2 failed to adhere well to its smooth substrate, as Fig. 9 illustrates. Plating coverage was 100% for both samples, and, as summarized in Table 3, the typical coating thickness was essentially the same. The poor adherence for the NiDU2 sample was due to the smooth substrate. These experiments confirmed that some degree of surface roughening is a prerequisite for well-bonded coatings, as was previously found for the zinc-plated samples.

Two experiments performed subsequently sought to reduce the quantity of uranium lost during pretreatment yet still provide sufficient bonding. One key factor observed in most of the tests with uranium substrates was that most of the weight loss did not occur during the actual FeCl<sub>3</sub> etching step but during the subsequent pickling and rinsing operations. These simple immersions were not removing entrapped etchant completely, and often vigorous reaction continued to occur. Magnetic stirring was introduced to improve the effectiveness of these removal operations. Samples NiDU3 and NiDU4 also served a dual purpose in that they came from different sheets of foil. Standard sample preparation and plating were performed on the two samples concurrently, thus eliminating potential procedural differences as a source of differences in plating response.

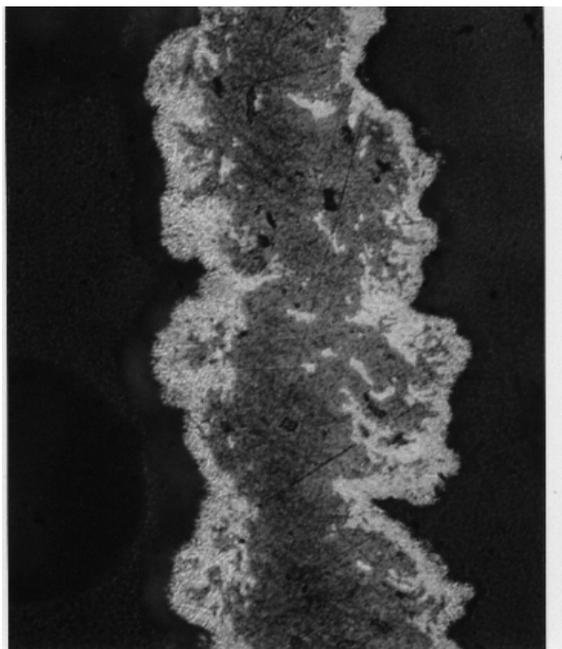


Figure 8. Complete Coverage and Adherence for Nickel Plating on a Severely Overetched DU Substrate (NiDU1, 350X)

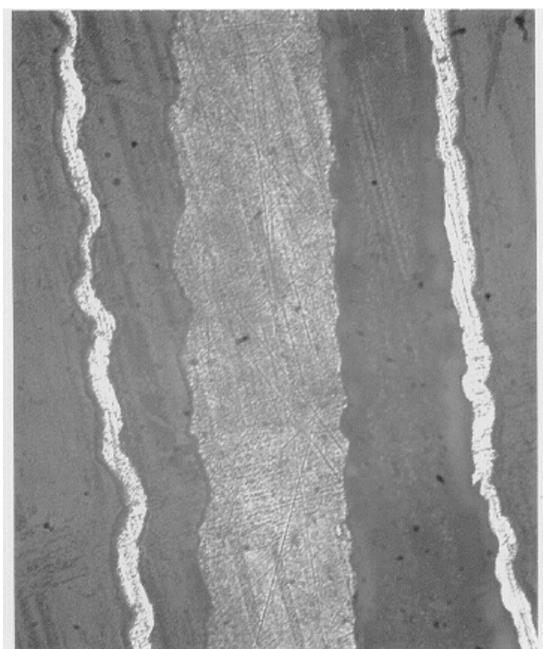


Figure 9. Delaminated Nickel Plating on an Unetched DU Substrate (NiDU2, 180X)

The weight losses of these two samples at intermediate processing stages were comparable with the exception of the descaling step. During descaling, sample NiDU3 (foil A) lost 1.5% of its weight, whereas sample NiDU4 (foil B) lost 1.1%. After etching and pickling, the respective losses were

virtually identical: 5.5% and 4.4% for NiDU3 and 5.6% and 4.5% for NiDU4. The smaller weight losses after etching were attributed to the effectiveness of magnetic stirring. The post-plating weight gains were identical at 12.6%, which met the thickness goal on a gravimetric basis. Subsequent studies judged the plating quality to be good. Coverage was 100% and, as shown in Fig. 10, a relatively smooth coating maintained good contact to a substrate that was sufficiently roughened. As was noted for the Cu-substrate samples, the edges of the uranium samples also overplated. The ball-shaped edge deposit shown in Fig. 11 was typical of this condition. Two key findings from these concurrent experiments were (1) variations in plating results are not attributable to differences in uranium foils, and (2) the quantity of uranium lost in pretreatment can be controlled at acceptable levels (~10%) without losing plating adherence if adequate agitation is used for subsequent aqueous processing steps.

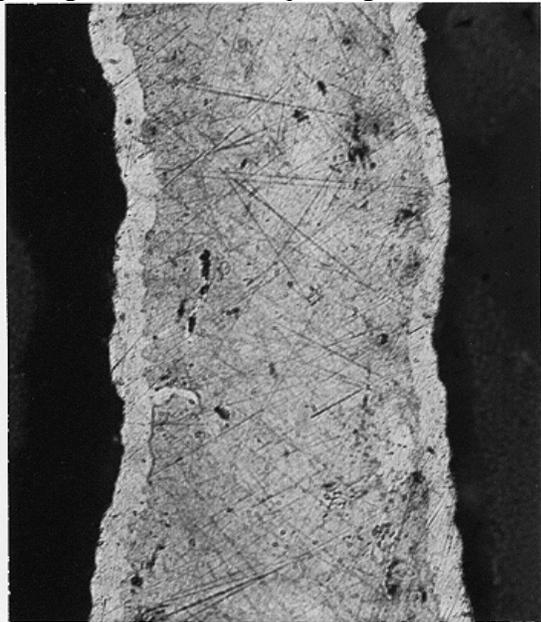


Figure 10. Uniform and Continuous Nickel Plating on a Properly Etched DU Substrate (NiDU4, 350X)



Figure 11. Rounded Nickel Deposits and Localized Loss of Adherence at an Overplated Edge (NiDU3, 180X)

The microscopic studies of the nickel-plated samples showed a greater proclivity toward overplating at the edges than was noted for zinc-plated samples. Systematic analysis of the photomicrographs revealed that the effect was relatively independent of the substrate. The results of this analysis are presented in Fig. 12, a dimensionless plot similar to Fig. 6. In Fig. 12 the abscissa is unchanged from Fig. 6, but the ordinate is now the ratio of the measured plating thickness at a location divided by the gravimetrically determined average thickness. At center and intermediate positions, the data overlapped for the eight datasets. At edge positions, the data again overlapped, but the Cu samples tended to have greater values. The measured thickness was relatively constant for the central region and was approximately 80% of the gravimetric thickness. The change in thickness increased at an accelerated rate as the corners were neared. Typically, the measured thickness was three times greater than the gravimetric thickness, but the spread in the data was much greater. The severity of overplated edges was clearly more pronounced with nickel plating than with zinc plating.

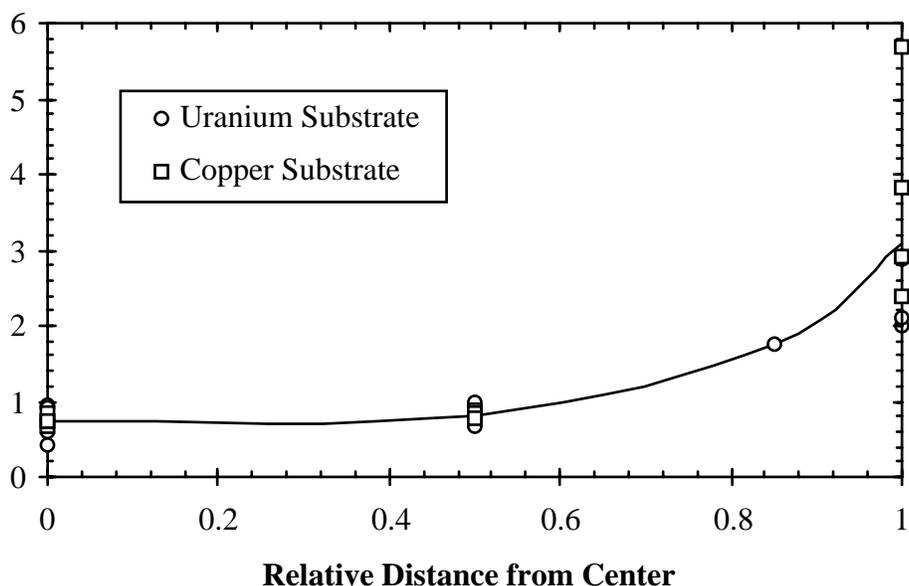


Figure 12. Relative Thickness of Ni Plating as a Function of Distance from the Sample Center

## CONCLUSIONS

The feasibility of electroplating zinc or nickel barrier layers on uranium foils has been demonstrated. The plating conditions can be controlled to provide a barrier layer with a nominal (gravimetric) thickness of  $15\ \mu\text{m}$  that also provides complete coverage of the substrate. Although these techniques were developed through work on pure-uranium foils, our limited work with adjusted uranium has indicated that the transition to this material will proceed smoothly.

Our work has also revealed the importance of the surface preparation prior to plating. A roughened surface is essential to bind the plating to the substrate. Excessive dissolution of the foil during etching, however, creates localized crevices that fail to plate in the zinc bath and result in discontinuous coverage. Overetched foils plated in the nickel bath did not exhibit a loss in coverage; however, the deposits in the crevices often fell below the minimum requirement of  $7\ \mu\text{m}$ . The preparation procedure outlined in this paper provides reasonable control of total uranium dissolution. By limiting this loss to  $<10\%$ , the subsequent plating can be expected to combine full coverage with sufficient adherence. Better control of the etching process is expected in the near future as improvements, such as ultrasonic cleaning, are incorporated into the preparation procedure.

These experiments have also highlighted a concern about adequate control of the as-plated coating thickness over the full foil. Overplating at the edges, especially in the nickel bath, may exceed the tolerances needed to maintain the desired fit within the target, and our preliminary indication with larger foils was that the degree of overplating increases with foil size. Future work will address changes in the design of the plating bath (*i.e.* auxiliary anodes, robber cathodes, and perimeter shielding of the cathode) that could potentially reduce the center-to-edge variation in thickness for full-sized foils. If thickness control cannot be significantly improved with these refinements in bath design, other options will be studied. These options include rolling the plated foil to a uniform thickness and plating of oversized foils with edge trimming to the final size.

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