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INFORMAL AEC RESEARCH
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UC-25, Metallurgy and Ceramics
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(EURAEC-120)

Quarterly Technical Progress Report

# DEVELOPMENT OF CLAD CERAMIC FUEL PLATES BY SPRAY-COATING TECHNIQUES

ATL Job 4010

April-June 1961

UNITED STATES-EURATOM JOINT RESEARCH
AND DEVELOPMENT PROGRAM

for
The U. S. Atomic Energy Commission
Contract AT(04-3)-250
Project Agreement No. 4

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## STATEMENT OF PROBLEM

The over-all objective of this program is to develop plate-type uranium dioxide fuel elements using plasma-jet spraying techniques and to evaluate properties and potential cost savings of these fuel elements.

Phase I, currently in progress, is concerned with the development of plasma-jet spray-coating techniques suitable for producing clad ceramic fuel plates. Investigation of spray-coating variables and evaluation of coating characteristics are included in this portion of the program.

## SUMMARY OF PROGRESS TO DATE

Calcium-stabilized zirconia was sprayed initially to determine the effects of plasma-spray process variables on such coating characteristics as density and adherence to the substrate. Efficiency and rate of deposition also were studied. The plasma-spray equipment was modified to overcome initial shortcomings, especially with respect to the powder feed system. Under the conditions used in this program, zirconia coatings of 85% theoretical density and 300-psi tensile adherence were deposited with 50% efficiency. This portion of the program is now complete.

Previous progress report?

Operating conditions for producing UO$_2$ coatings of maximum density and deposition efficiency have been studied exhaustively, and the effect of all major variables is now known to a considerable extent. Uranium dioxide coatings of 87% theoretical density and O/U ratios of nearly 2.00 have been deposited regularly with efficiencies of about 40%. Maximum densities of 90% and efficiencies of 50% have been obtained.

Coating adherence has received major attention during the past quarter, and all related factors have been under investigation. UO$_2$ Adherent coatings up to 0.100 inch thick have been deposited on 0.030-inch-thick stainless steel and Zircaloy-2 substrates. Methods of substrate preparation have been studied. To date, the most effective method of preparing thin substrates is sandblasting, followed by straightening and annealing. The effect of spraying conditions and thermal history during spraying on resulting stress distribution in composites cooled to room temperature was studied by observing the bending of coated composites and coating adherence. Results indicate that coating temperature must be maintained below 870 C and the substrate below 450 C during deposition to assure soundness of the composite upon cooling to room temperature.

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A new, higher powered, plasma-spray torch was tested for spraying $UO_2$ in an attempt to obtain increased deposition rates at higher powder feed rates without losses in current levels of efficiency and coating density. This torch was rated at about 40-kw power input, as compared to 25 kw for the previous torch. Despite the use of higher power levels, plasma enthalpies for the two torches were equivalent, because the higher powered torch required higher arc-gas flows. Deposition rates and efficiencies were equivalent to those obtained using the 25-kw torch.

A preliminary analysis was made to determine the economic potential of plasma-sprayed fuel elements. This analysis indicated considerably lower fabrication costs using plasma-jet spraying: about \$100/kg U as compared to about \$150/kg U for oxide pellet-in-tube designs.

## PROGRESS APRIL-JUNE 1961

### A. Adherence of Uranium Dioxide Coatings

Uranium dioxide coatings were deposited on 0.030- to 0.035-inch-thick stainless steel and Zircaloy-2 substrates. These composites (1 inch wide by 6 inches long) were then bend tested by being formed around a 1-inch radius with the coating in tension. In addition, several coatings were tested in torsion, the composite being twisted until the coating spalled. Coating thicknesses up to 0.100 inch were studied.

#### 1. Substrate Surface Preparation Techniques

Substrate surfaces grit-blasted with silicon carbide, iron, garnet, and sand were compared by means of bend and torsion tests. All blasting was conducted in a pressure-blasting cabinet at 100-psi air pressure and 6- to 8-inch blasting distances. Coatings 0.010 to 0.030 inch thick were very adherent to stainless steel substrates, as indicated in Table I. Figure 1 shows four bend-tested coupons for coatings 0.047 to 0.054 inch thick on 0.031-inch-thick stainless steel. It can be seen that the coatings deposited on surfaces blasted with silicon carbide, iron, and garnet are cracked after bending, but are tightly adherent. The coating has lifted from the surface blasted with sand. Silicon carbide, iron, and garnet produce equivalent degress of surface roughness (400 to 450 microinches), while sand produces a smoother surface (200 microinches).

Figure 2a shows a bend-tested 0.054-inch-thick coating on a 0.032-inch-thick Zircaloy-2 substrate and Figure 2b a 0.098-inch-thick coating on a 0.031-inch thick stainless steel substrate. The thicker coating finally lifted from the substrate after withstanding a deflection of about 1 inch around a 1-inch radius. Figure 3 illustrates the effect of torsion tests on relatively thin $UO_2$ coatings.

Based on currently established spray conditions and the use of grit-blasted substrate surfaces, the status of the coating-adherence problem may be summarized as follows:

a) Thin coatings (less than 0.030 inch thick) can be made extremely adherent to the substrate.

b) Adherent coatings as thick as 0.100 inch can be deposited on thin (0.030-inch) stainless steel substrates, using spraying techniques developed during this program.

c) Rough surfaces prepared by blasting with silicon carbide, iron, or garnet are approximately equivalent. However, silicon carbide is preferred because it leaves a much cleaner surface. Sand is unsatisfactory as a blasting medium.

d) $UO_2$ coatings are even more adherent to Zircaloy-2 substrates than to stainless steel, probably due to greater compatibility of thermal properties.

Work has continued on developing satisfactory chemically etched grid patterns on stainless steel and Zircaloy-2 surfaces. Etchants that apparently produce satisfactory surfaces are: a) 9 to 1 ratio of $H_2O$ to HF for Zircaloy-2; b) 3 to 1 ratio of $H_2O$ to HCl (electrolytic) for stainless steel. However, it is extremely difficult to obtain consistent surfaces. Several substrates are currently being prepared for spraying and adherence testing for comparison with grit-blasted surfaces.

### 2. Special Metal-Ceramic Bonding Techniques

Studies were made to determine the feasibility of using a modified ceramic brazing technique to enhance the bond between coatings and substrates. The technique studied involves the hydride brazing method used for brazing ceramics to metals. A powder mixture of 84% Zr (in the form of $ZrH_2$) and 16% Fe was made. Upon decomposition, this mixture will form a Zr-Fe eutectic which melts at 935 C. Tests were made to determine wetting of $UO_2$, stainless steel, and Zircaloy-2 at 1000 and 1100 C. Fusion of the mixture was poor, and only very slight bonding was noted. On the basis of these results, no further tests are contemplated.

Molybdenum and stainless steel powders are on hand for forthcoming investigation of pre-sprayed bond layers and gradated coatings.

## B. Coating Density and Deposition Efficiency

### 1. Effect of Higher Power Levels

Previous studies indicated that coating density and deposition efficiency are directly proportional to power input for constant arc-gas flow rate. To investigate the effect of higher power levels, the plasma jet used throughout the previous part of the investigation was modified to extend the power limit from approximately 25 to 40 kw. This was accomplished by doubling the water flow through the cooling passages of the torch and increasing the plasma orifice from 0.316 to 0.437 inch in diameter. It was hoped that increased deposition efficiencies and coating densities could be obtained at increased powder feed rates.

The 40-kw plasma-spray torch was found to require arc-gas flows of 1.40 to 1.65 cfm to prevent excessive loss of electrode material. At 25-kw power input, these conditions produced a plasma enthalpy of 230 to 195 kcal/ft$^3$ argon. Enthalpies of 280 to 260 kcal/ft$^3$ argon were obtained for the previous 25-kw torch at 25-kw power input because lower gas flow was permitted (1.00 to 1.20 cfm). Since increased power was required to obtain these higher enthalpy values using the 40-kw torch, no advantage accrued from the available increased power.

Conditions for spraying with the 40-kw torch were rapidly established by deposition of $UO_2$ cones on stationary substrates. The height of the cones deposited per unit time was used as a criterion for establishing the best operating ranges. Best ranges or values were 1.40 cfm arc-gas flow (argon), 28 to 30 kw power input, and 0.133 to 0.150 cfm powder gas flow (argon), at 60 gm/min power feed rate, using -200, +325 mesh fused $UO_2$ powder. In addition, values of arc-gas flow producing good spray patterns were established at various power levels at a constant powder-gas flow of 0.10 cfm argon. These conditions were used for comparing various powder types and sizes.

Deposition-efficiency data are shown as a function of power input in Figure 4. Figure 5 shows the same data as a function of plasma enthalpy (heat content). These figures illustrate the following points:

a) The 40-kw torch requires higher power inputs to achieve equivalent enthalpies. Lower arc-gas flows would increase the heat content but would result in rapid deterioration of the electrodes.

b) At equivalent enthalpies, the 25- and 40-kw torches produce equivalent deposition efficiencies and rates.

## 2. Effect of Uranium Dioxide Type and Particle Size Range

Coatings were made to evaluate the influence of type and size ranges of $UO_2$ powders. These experiments were conducted under conditions that produced good spray patterns, and a flow of helium cover gas was used to minimize thermal gradients in the coating. Data obtained to date are summarized in Table II.

Highest densities were obtained using either the -200, +250 or the -250, +325 mesh, fused $UO_2$ powder. Slightly lower densities were obtained with -200, +250 mesh sintered powder, but deposition efficiencies were higher. Deposition efficiency of recycled powder also appears equivalent to that of fused powder. Studies are not complete, but the above trends are indicated by available results.

Powder size shown in Table II refers to the powder as placed in the hopper. Uranium dioxide powders are friable and break up in the feed system. The screen analysis of the powder fed to the torch versus the powder placed in the hopper is shown in Table III. Of the coarser mesh sizes, the recycled breaks down the most, followed by the fused, then the sintered. The -200, +325 mesh fused material is fed to the torch with negligible breakup.

## C. Determination of Thermal Stresses

Substrate and coating temperatures were measured by thermocouples welded to the substrate and positioned so that they were in the coating during spraying. Additional strips 1" × 12" × 0.031" thick were sprayed without thermocouples for comparison. Deflection of the coated strips due to residual stresses was measured after spraying and cooling to room temperature. Positive deflection was assigned to those composites in which the coating surface was convex, and negative deflection to concave surfaces. Table IV summarizes the data obtained from this investigation.

Considerable scatter was noted in the data, making analysis extremely difficult. However, certain definite conclusions were reached:

1) To obtain adherent coatings with minimum distortion from residual stresses, coating temperature should be held below 870 C, while stainless steel substrate temperatures should be held below 450 C. Lower temperatures can result from increased traverse rate, or spray distance, and from the use of cover gas to lower the thermal gradient in the coating.

2) The substrate must be annealed after the grit-blasting and straightening operations. Initial studies were made on un-annealed substrates, resulting in severe and extremely inconsistent deflection.

3) The results indicate no need to alter current spraying conditions.

4) Adherent coatings up to 0.100 inch thick can be deposited on 0.030-inch-thick substrates.

Several 0.020-inch-thick Zircaloy-2 coupons were sprayed also and the deflection measured. Deflections were smaller (0.11 to 0.58 inch over a 12-inch span) than with the stainless steel, and adherence was good.

Several 2" × 12" stainless steel sheets were sprayed. When cover gas was not used, the composites were deformed in a wavy manner. Relatively flat samples were prepared by using a flow of helium cover gas to cool the coating.

## D. Economics of Plasma-Sprayed Uranium Dioxide Fuel Elements

An initial cost estimate was made of plasma-sprayed uranium dioxide fuel elements, and a comparison was made with estimated costs of current pellet-in-tube elements.[1] This cost estimate is outlined below.

It can be seen that with plasma-spray torch designs able to handle high powder feed rates efficiently, it should be possible to make sprayed fuel elements at significant cost savings as compared to current fabrication methods. Further information is being received and recent data are being reviewed to further refine this estimate for various fabrication lot sizes, enrichments, and changes in spraying procedure. Recent U.S. AEC fuel-price modifications will also be incorporated into this estimate.

### Cost Estimate for Production of $UO_2$-Sprayed Fuel Plates

1. Assumptions

Production capacity is 28,800 kg of $UO_2$ coating per year.

Two shifts normal operation at 80% plant factor.

Four production lines on normal operation.

Deposition-rate average is 40 gm/min per line, or 2.4 kg/hr per line.

Deposition efficiency is 40%, with 65% over-all efficiency after 3 recycles, 34% returns (too fine for spraying), and 1% loss.

A total of 44,400 kg of $UO_2$ powder is processed per year.

Coating density is 90% of theoretical.

Reference fuel plate for discussion is 3.6" × 0.21" × 54" nominal outside dimension and 3.3" × 0.17" × 51" nominal core diameter, requiring 4.84 kg of $UO_2$ at 90% density.

Cladding materials are Zircaloy-2 and stainless steel.

$UO_2$ is fused and milled grade, sized to -200, +325 mesh (95%). Enrichment is 3%, analysis 88% U.

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[1] Nuclear Power Plant Cost Evaluation Handbook, United States Atomic Energy Commission, Evaluation and Planning Committee, Civilian Reactors, Division of Reactor Development, December 31, 1960.

## 2. Capital Costs

| | | |
|---|---|---|
| Building (5000 $ft^2$ at $\$10/ft^2$) | | $ 50,000 |
| Internals (hoods, blowers, furniture, benches, etc.) | | 18,000 |
| Inert-Atmosphere Chambers, complete with vacuum equipment and handling fixtures (4 at $15,000 each) | | 60,000 |
| Plasma-Spray Equipment (4 complete units) | | |
| 8 power supplies (2/unit) | $20,000 | |
| 4 consoles | 12,000 | |
| 4 heads + 2 spares | 15,000 | |
| 4 powder feed systems | 4,000 | |
| Misc. leads, gages, etc. | 1,000 | |
| | | 50,000 |
| Vacuum or Atmosphere Brazing Furnace | | 20,000 |
| Powder-Sizing Equipment | | 3,000 |
| Machine Tools | | 3,000 |
| Grit-blasting Equipment | | 1,000 |
| Water-Recirculation Systems | | 2,000 |
| Misc. Tools and Instruments | | 1,000 |
| Total | | $208,000 |

## 3. Operating Costs, Based on Yearly Production Capacity

| | | $/kg $UO_2$ Coating |
|---|---|---|
| Depreciation | | $ 0.73 |
| Direct Labor | | |
| 16 operators (2 shifts) | $3.33 | |
| 2 engineers (2 shifts) | 0.69 | |
| 1 administrative assistant (2 shifts) | 0.31 | |
| 2 health physicists (2 shifts) | 0.56 | |
| Total Direct Labor | | 4.89 |
| Overhead at 100% | | 4.89 |
| Direct Materials and Supplies: | | |
| Electrodes (200 at $60/pair, 100-hr life) | $0.42 | |
| Argon (1,250,000 $ft^3$ at 7¢/$ft^3$) | 3.02 | |
| Miscellaneous | 0.35 | |
| Total Direct Materials and Supplies | | 3.79 |
| Electrical Power (direct current for plasma at 14 mills/kwh, 16.7 kwh/kg $UO_2$ coating) | | 2.32 |
| Subtotal | | $16.62 |
| G&A at 10% | | 1.66 |
| Profit at 10% | | 1.66 |
| Subtotal | | $19.94 |
| Inspection Costs | | 25.00 |
| Total | | $44.94 |

4. Raw-Materials Cost, Based on Referenced Fuel Element

| | $/kg $UO_2$ Coating |
|---|---|
| Uranium Dioxide (based on total of 44,400 kg $UO_2$ handled) | |
| Conversion $UF_6 \rightarrow UO_2$ | $17.70 |
| Fuse and Mill | 17.70 |
| License Charge (4% × value × ¼ year) | 3.70 |
| Loss (1% production loss) | 3.25 |
| Total | $36.35 |
| Zircaloy-2 Cladding | |
| 2 lb/fuel plate or 0.414 lb/kg $UO_2$ at $12.00/lb | $ 4.96 |
| Stainless Steel Cladding | |
| 2.4 lb/fuel plate or 0.500 lb/kg $UO_2$ at $1.00/lb | $ 0.50 |

5. Summary of Fabrication Costs

| | Zircaloy Clad $/kg $UO_2$ Coating | Stainless Steel Clad $/kg $UO_2$ Coating |
|---|---|---|
| Operating Costs | $44.94 | $44.94 |
| Uranium Dioxide Cost | 36.35 | 36.35 |
| Cladding Cost | 4.96 | 0.50 |
| Total | $86.25 | $81.79 |
| Total Costs, $/kg U | $98.00 | $93.00 |

6. Comparison of Fabrication Costs for Tubular versus Sprayed Plate-Type Fuel Elements (Zircaloy Cladding)

| | Tubular ($/kg U) | Sprayed Plate ($/kg U) |
|---|---|---|
| Fabrication Lot | 19.8 MTU Pellets | 24.3 MTU Coatings |
| Processing (conversion and fabrication) | $143.00 | $ 90.00 |
| Shipping | 3.03 | 3.03 |
| Use Charge | 2.40 | 4.20 |
| Uranium Loss | 4.80 | 3.80 |
| Totals | $153.23 | $101.03 |

## CONCLUSIONS

Uranium dioxide coatings of up to 90% theoretical density and O/U ratios equivalent to the powder being sprayed can be deposited at efficiencies of about 40%, using fused $UO_2$ powder in the size range of -200, +325 mesh. Adherent coatings as thick as 0.100 inch can be deposited on stainless steel and Zircaloy-2 cladding materials of 0.030-inch thickness. On the basis of a preliminary analysis, plasma-sprayed fuel elements are economically competitive with current designs. It can be concluded, therefore, at this stage, that plasma-sprayed oxide plate-type fuel elements appear to be both technically and economically feasible.

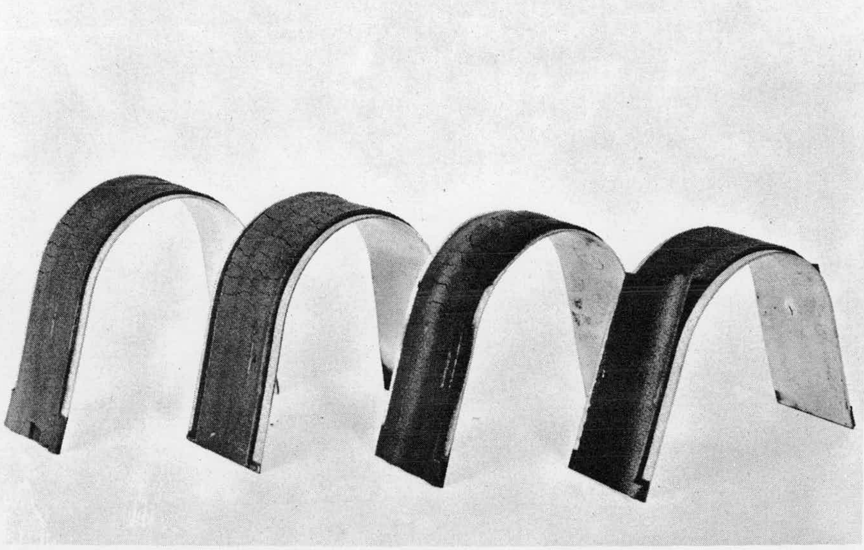
## PLANS FOR FUTURE WORK

The program will be directed primarily toward the fabrication of simulated fuel-element designs. The following tasks are contemplated during the next quarter.

1. Completion of the study of coating adherence.
2. Completion of the evaluation of powder types and sizes.
3. Fabrication of simulated fuel plates.
4. Refinement of the economic evaluation.

## PRINCIPAL INVESTIGATORS

Investigators on this project include: N. E. Weare, Metallurgist and Project Leader; E. Buchanan, Metallurgist; Dr. H. Marchandise, participating as EURATOM representative. Over-all supervision is exercised by Dr. D. R. Mash, Manager, Materials Laboratory.



| No. 18 | No. 16 | No. 16 | No. 16 |
|---|---|---|---|
| IRON | GARNET | SiC | SAND |

BLASTING MEDIA

Spraying Conditions

| | | | |
|---|---|---|---|
| Powder Type: | Fused $UO_2$ | Traverse Rate: | 70 in./min |
| Powder Size: | -200, +250 mesh | Powder Feed Rate: | 52 gm/min |
| Power Input: | 25 kw | Powder-Gas Flow: | 0.1 cfm (argon) |
| Arc-Gas Flow: | 1.46 cfm (argon) | Cover-Gas Flow: | 6.67 cfm (helium) |
| Spray Distance: | 3 inches | | |

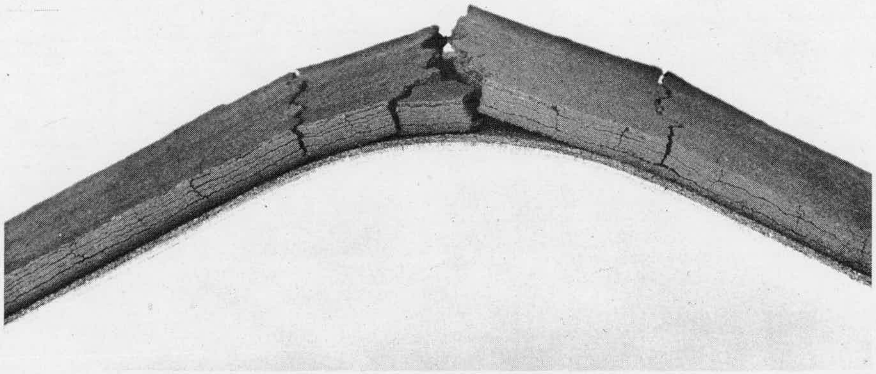
Substrate Thickness: 0.031 inch
Coating Thickness: 0.047-0.054 inch

BEND-TESTED COUPONS OF
URANIUM DIOXIDE ON STAINLESS STEEL SUBSTRATES

FIGURE 1

a. 0.054" Thick $UO_2$ Coating on 0.032" Thick Zircaloy-2 Substrate (1" Radius Bend, Full 2" Deflection)

b. 0.098" Thick $UO_2$ Coating on 0.031" Thick 304 Stainless Steel Substrate (1" Radius Bend, 1" Deflection)

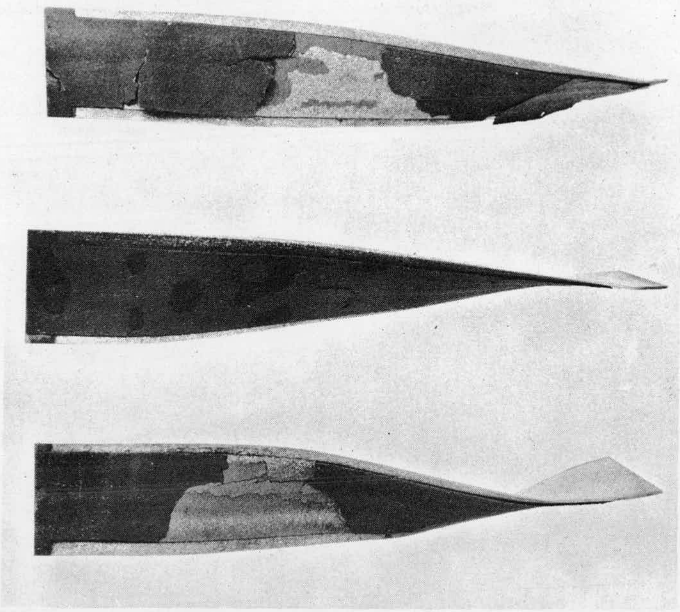


Spraying Conditions

Powder Type: Fused $UO_2$
Powder Size: -200, +250 mesh
Power Input: 25 kw
Arc-Gas Flow: 1.46 cfm (argon)
Spray Distance: 3 inches
Traverse Rate: 70 in./min
Powder Feed Rate: 52 gm/min
Powder-Gas Flow: 0.1 cfm (argon)
Cover-Gas Flow: 6.67 cfm (helium)

CLOSEUP OF BEND AREA FOR THICK $UO_2$ COATINGS SPRAYED ON ZIRCALOY-2 AND STAINLESS STEEL OF FUEL-ELEMENT-CLADDING THICKNESS

FIGURE 2



| | Blasting Media | Torsional Deflection to Failure |
|---|---|---|
| Top | No. 16 Sand | 110° |
| Middle | No. 18 Iron | 110° |
| Bottom | No. 16 Silicon Carbide | 120° |

Spraying Conditions

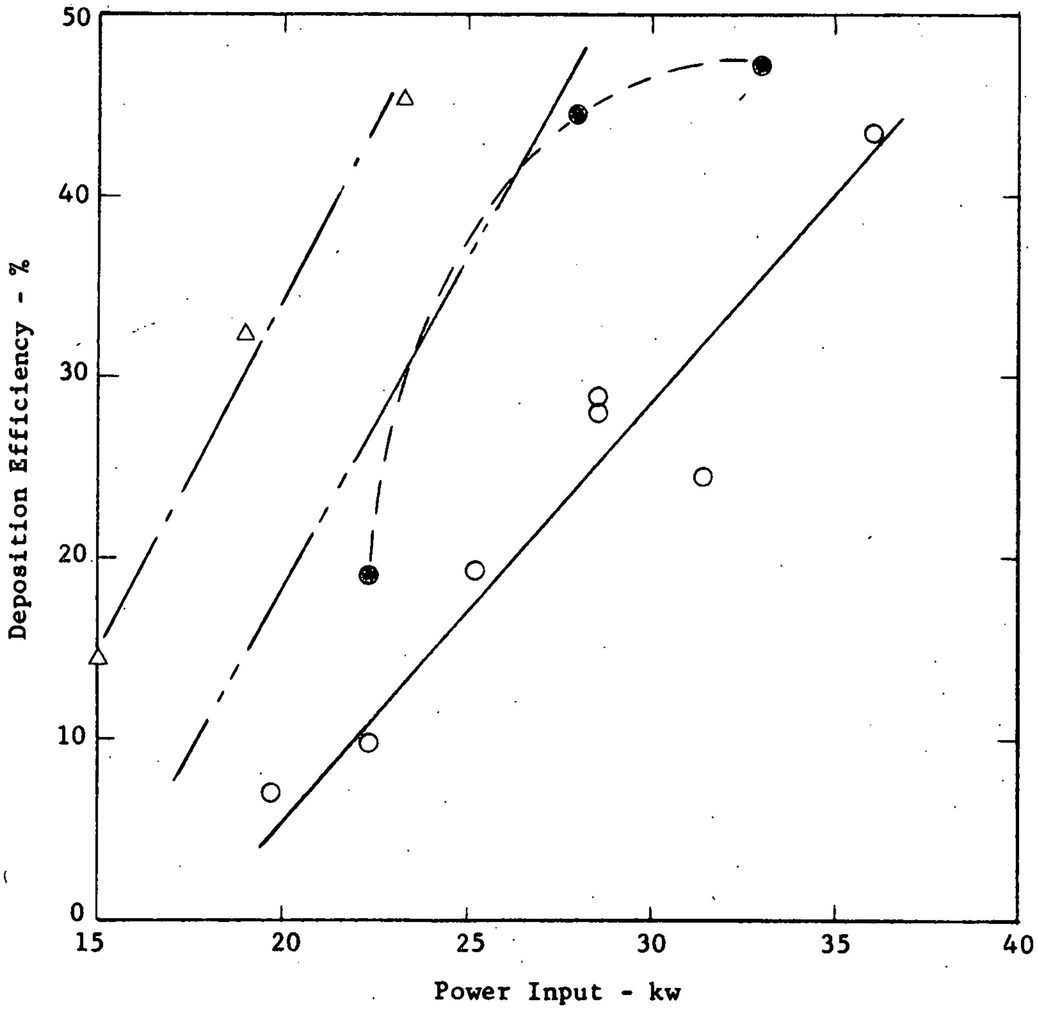
| | | | |
|---|---|---|---|
| Powder Type: | Fused $UO_2$ | Traverse Rate: | 70 in./min |
| Powder Size: | -200, +250 mesh | Powder Feed Rate: | 57 gm/min |
| Power Input: | 35 kw | Powder-Gas Flow: | 0.1 cfm (argon) |
| Arc-Gas Flow: | 1.81-1.83 cfm (argon) | Cover-Gas Flow: | 6 cfm (helium) |
| Spray Distance: | 3.5 inches | | |

TORSION-TESTED 0.015 TO 0.018-INCH-THICK $UO_2$ COATINGS ON 0.031-INCH-THICK STAINLESS STEEL

FIGURE 3

| LEGEND | TORCH RATING (kw) | ARC-GAS FLOW (ARGON) (cfm) | TRAVERSE RATE (in./min) | POWDER FEED RATE (gm/min) | POWDER GAS FLOW (ARGON) (cfm) | REMARKS |
|---|---|---|---|---|---|---|
| ○ | 40 | 1.40 | 70 | 56.8 | 0.133 | - |
| ● | 40 | 1.40 | 70 | 27.8 | 0.133 | - |
| △ | 25 | 1.00 | 50 | 29.4 | 0.085 | - |
| — - - — | 25 | 1.00 | 50 | 60.7 | 0.100 | Estimated Curve |

POWDER TYPE: Fused $UO_2$
POWDER SIZE: -200, +325 mesh
SPRAY DISTANCE: 4 in.

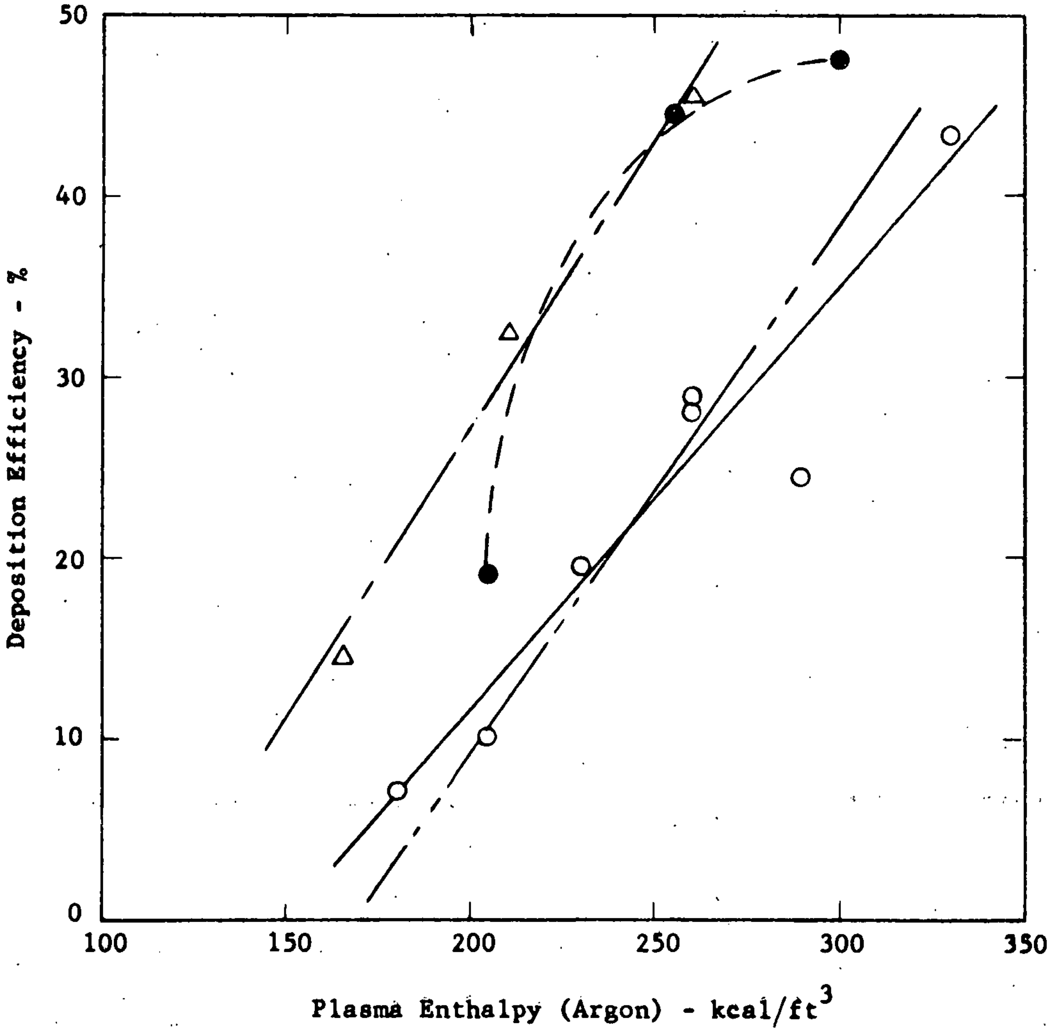


EFFECT OF POWER INPUT ON DEPOSITION EFFICIENCY OF $UO_2$ COATINGS, USING PLASMA TORCHES RATED AT 25 AND 40 KW

FIGURE 4

| LEGEND | TORCH RATING (kw) | ARC GAS FLOW (ARGON) (cfm) | TRAVERSE RATE (in./min) | POWDER FEED RATE (gm/min) | POWDER GAS FLOW (ARGON) (cfm) | REMARKS |
|---|---|---|---|---|---|---|
| ○ | 40 | 1.40 | 70 | 56.8 | 0.133 | - |
| ● | 40 | 1.40 | 70 | 27.8 | 0.133 | - |
| △ | 25 | 1.00 | 50 | 29.4 | 0.085 | - |
| —··— | 25 | 1.00 | 50 | 60.7 | 0.100 | Estimated Curve |

POWDER TYPE: Fused $UO_2$
POWDER SIZE: -200, +325 mesh
SPRAY DISTANCE: 4 in.



EFFECT OF PLASMA ENTHALPY (HEAT CONTENT) ON THE DEPOSITION EFFICIENCY OF $UO_2$ COATINGS, USING PLASMA TORCHES RATED AT 25 AND 40 KW

FIGURE 5

## TABLE I

## SUMMARY OF BEND AND TORSION TEST RESULTS

(See next page for spraying conditions.)

| Coating Thickness (mil) | Blasting Media | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | No. 16 SiC | | No. 18 Iron | | No. 16 Garnet | | No. 16 Sand | |
| | Bend | Torsion | Bend | Torsion | Bend | Torsion | Bend | Torsion |
| 5-7 | $\frac{1}{2}$" radius Spalling | 120° | | | | | | |
| 8-10 | | | | | | | $\frac{1}{2}$" radius Spalling | 90°, 110° |
| 11-13 | | 110° | | | | | | |
| 14-15 | | >90°, 90°<br>120°, 85° | | 110° | | | | 110° |
| 16-18 | | >90° | | 110° | | | | |
| 20-25 | $\frac{1}{2}$" radius Spalling | >90°, 100° | | | | | | |
| 26-30 | | 120°, 130° | | | | | | |
| 47-54* | 1" radius No spalling** | | 1" radius No spalling | | 1" radius No spalling | | 1" radius Lifting | |
| 98* | 1" radius<br>Lifting<br><1" deflection | | | | | | | |

* Spraying condition II.

** Both stainless steel and Zircaloy-2.

| Spraying Conditions | I* | II |
|---|---|---|
| Powder Type | Fused | Fused |
| Powder Size, mesh | -200, +250 | -200, +250 |
| Power Input, kw | 35 | 25 |
| Arc-Gas Flow, cfm (argon) | 1.83 | 1.46 |
| Spray Distance, in. | 3½ | 3 |
| Traverse Rate, in./min | 70 | 70 |
| Powder Feed, gm/min | 56 | 52 |
| Powder-Gas Flow, cfm (argon) | 0.10 | 0.10 |
| Cover-Gas Flow, cfm (helium) | 6.0 | 6.67 |

* Spraying Condition I used in all cases except as noted.

## TABLE II

## SUMMARY OF COATING DENSITY AND DEPOSITION CHARACTERISTICS, USING VARIOUS TYPES AND SIZES OF $UO_2$ POWDER

(40-kw Plasma Torch)

| Powder Type | Powder Size (mesh) | Spraying Conditions* | | | Coating Density (% theor.) | Deposition | |
|---|---|---|---|---|---|---|---|
| | | Power (kw) | Arc-Gas Flow, Argon (cfm) | Plasma Enthalpy (kcal/ft$^3$) | | Rate (gm/min) | Efficiency (%) |
| Sintered | -200, +250 | 21 | 1.30 | 200 | 77.3 | 18.5 | 33.0 |
| " | " | 32 | 1.60 | 270 | 80.9 | 11.9 | 21.3 |
| " | " | 34 | 1.83 | 245 | 78.9 | 10.0 | 17.8 |
| " | " | 42 | 1.87 | 300 | 74.9 | 7.3 | 13.0 |
| Fused | " | 21 | 1.28 | 205 | 74.5 | 11.2 | 20.2 |
| " | " | 33 | 1.60 | 270 | 81.3 | 10.1 | 18.4 |
| " | " | 34 | 1.83 | 245 | 83.7 | 8.9 | 16.0 |
| " | " | 42 | 1.87 | 300 | - | 7.2 | 13.1 |
| " | -250, +325 | 22 | 1.28 | 205 | - | 11.0 | 19.75 |
| " | " | 36 | 1.68 | 290 | - | 14.0 | 25.3 |
| " | " | 44.4 | 1.87 | 320 | - | 11.6 | 20.5 |

* Other conditions are constant:

Spray Distance - 3.5 in.
Traverse Rate - 70 in./min
Powder Feed Rate - 56 gm/min
Powder-Gas Flow - 0.10 cfm (argon)
Cover-Gas Flow - 6.67 cfm

## TABLE II
(concl.)

| Powder Type | Powder Size (mesh) | Spraying Conditions* |  |  | Coating Density (% theor.) | Deposition |  |
|---|---|---|---|---|---|---|---|
|  |  | Power (kw) | Arc-Gas Flow, Argon (cfm) | Plasma Enthalpy (kcal/ft$^3$) |  | Rate (gm/min) | Efficiency (%) |
| Fused | -250, +325 | 20 | 1.12 | 210 | 77.2 | 2.4 | 4.1 |
| " | " | 32 | 1.48 | 280 | 80.8 | 8.0 | 14.4 |
| " | " | 40 | 1.52 | 350 | 82.6 | 13.0 | 23.4 |
| Recycled** | -200, +250 | 20.3 | 1.17 | 210 | - | 4.8 | 8.6 |
| " | " | 32 | 1.48 | 280 | - | 15.0 | 27.3 |

* Other conditions are constant:

Spray Distance - 3.5 in.
Traverse Rate - 70 in./min
Powder Feed Rate - 56 gm/min
Powder-Gas Flow - 0.10 cfm (argon)
Cover-Gas Flow - 6.67 cfm

** Powder that has been fed through torch and recovered (overspray).

## TABLE III

## SCREEN ANALYSIS OF VARIOUS TYPES AND SIZES OF $UO_2$ POWDER AS FED TO THE PLASMA TORCH

| Powder Type | Screen Size Powder Placed in Hopper (mesh) | Powder Fed to Torch (%) | | |
|---|---|---|---|---|
| | | -200,+250 | -250,+325 | -325 |
| Sintered | 95% -200,+250 | 71.5 | 25.1 | 3.4 |
| Fused | 95% -200,+250 | 53.0 | 44.5 | 2.5 |
| Fused | 95% -250,+325 | - | 91.0 | 9.0 |
| Recycled | 95% -200,+250 | 18.8 | 72.6 | 8.6 |

## TABLE IV

### SUMMARY OF THERMAL-STRESS DATA

(See third page of table for spraying conditions)

| Power Input (kw) | Arc-Gas Flow, Argon (cfm) | Plasma Enthalpy (kcal/ft$^3$) | Spray Distance (in.) | Traverse Rate (in./min) | Cover-Gas Flow, Argon (cfm) | Coating Temp. (°C) |  | Substrate Temp. (°C) |  | Coating Thickness (mil) | Longitudinal Deflection (in.) | Relative Adherence |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  |  | Max. | Min. | Max. | Min. |  |  |  |
| 23-25 | 1.23 | 230 | 2.5 | 71 | None | Thermocouple broken |  |  |  | 6,<br>9, 24 | +0.03,[a]<br>+0.03, +0.03 | Good |
| 23.6 | " | " | " | 48 | " | - | - | - | - | 10 | -0.43 | Poor[b] |
| 22 | 0.92 | 255 | " | 71 | " | 940 | 440 | 440 | 240 | 12,<br>11 | +0.03,[a, b]<br>-0.23 | Poor[b] |
| " | " | " | " | 48 | " | - | - | - | - | 10 | -0.65 | Poor[b] |
| 25-26 | 1.24 | 230 | 3 | 71 | " | 915 | 515 | 520 | 350 | 19,<br>22 | +0.03,[a]<br>+0.10 | Poor |
| 25 | " | " | " | " | " | - | - | - | - | 21,<br>27 | -0.30,<br>-0.31[c] | Good |
| " | 1.21 | 255 | " | 48 | " | - | - | - | - | 19 | +0.03[c] | Poor |
| 20-24 | 0.92 | 230-280 | " | 71 | " | 930 | 520 | 515 | 230 | 18.<br>38, 26 | +0.04,[a]<br>+0.02, 0[b] | Poor |
| 23 | " | 270 | " | " | " | 860 | 440 | 340 | 180 | 29 | +0.05[a] | Good |

a. Instrumented sample.

b. Poor spraying atmosphere, slight oxidation of the coating, contributing in part to poor adherence.

c. Deflection concentrated at one end of sample.

## TABLE IV
(cont.)

| Power Input (kw) | Arc-Gas Flow, Argon (cfm) | Plasma Enthalpy (kcal/ft$^3$) | Spray Distance (in.) | Traverse Rate (in./min) | Cover-Gas Flow, Argon (cfm) | Coating Temp. (°C) |  | Substrate Temp. (°C) |  | Coating Thickness (mil) | Longitudinal Deflection (in.) | Relative Adherence |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  |  | Max. | Min. | Max. | Min. |  |  |  |
| 23-24 | 0.92 | 270-280 | 3 | 36 | None | 1060 | 420 | 670 | 300 | 21, 21 | -0.15, +0.03 | Poor |
| 26 | 1.24 | 260 | 4 | 71 | " | 850 | 525 | 490 | 370 | 31, 21 | -0.05,[a] +0.05 | Good |
| " | " | " | " | 48 | " | 850 | 390 | 470 | 250 | 29, 32 | +0.18,[a] +0.05 | Good |
| " | " | " | " | 24 | " | 1260 | 440 | 780 | 290 | 24, 24 | -0.40,[a] -0.33 | Poor |
| 22-23 | 0.95 | 260-265 | " | " | " | 860 | 240 | 435 | 130 | 33, 28, 21 | +0.03,[a] -0.21, -0.37 | Good |
| 24 | 0.96 | 275 | " | " | " | - | - | - | - | 10 | -0.43 | Poor |
| 24-25 | 1.26 | 240-245 | 2.5 | 71 | 7 | 940 | 260 | 450 | 205 | 49, 13 | +0.05,[a] -0.47 | Good |
| " | " | " | " | 48 | " | 1040 | 250 | 530 | 185 | 16, 18, 19 | -0.16, -0.60, -0.45[a] | Good to Poor |
| 22-25 | 1.00 | 250-280 | " | 71 | " | 830 | 180 | 400 | 185 | 32, 35 | -0.20,[a] +0.08 | Fair |
| 24-25 | " | 270-280 | " | 48 | " | 1100 | 230 | 480 | 220 | 19, 30 | -0.52,[a] 0 | Fair |

a. Instrumented sample.

## TABLE IV
(concl.)

| Power Input (kw) | Arc-Gas Flow Argon (cfm) | Plasma Enthalpy (kcal/ft$^3$) | Spray Distance (in.) | Traverse Rate (in./min) | Cover-Gas Flow, Argon (cfm) | Coating Temp. (°C) | | Substrate Temp. (°C) | | Coating Thickness (mil) | Longitudinal Deflection (in.) | Relative Adherence |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Max. | Min. | Max. | Min. | | | |
| 25 | 1.26 | 245 | 3 | 71 | 7 | 700 | 300 | 350 | 165 | 16, 16 | +0.29,[a] -0.02 | Good |
| " | " | " | " | 48 | " | 960 | 330 | 465 | 210 | 34, 31, 39 | +0.25,[a] -0.12, +0.06 | Good |
| " | " | " | " | 24 | " | 885 | 300 | 535 | 230 | 43, 41 | -0.17,[a] -0.57 | Poor |
| 22-24 | 0.96 | 255-280 | " | 71 | " | 640 | 320 | 410 | 250 | 31, 32 | +0.15, +0.22[a] | Good |
| 22-25 | 0.95 | 255-290 | " | 48 | " | 630 | 220 | 345 | 165 | 45, 23, 10, 40 | +0.11,[a] -0.16, -0.21, +0.04 | Good |
| 23-24 | " | 265-275 | " | 24 | " | 770 | 230 | 470 | 140 | 110, 54 | -0.63, -0.07[a] | Good to Fair |

### Constant Spraying Condition

Powder Type: Fused $UO_2$
Powder Size: -200, +325 mesh
Powder Feed Rate: 30 gm/min
Powder-Gas Flow: 0.085 cfm (argon)
Substrate: 0.031 in. thick stainless steel

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[a] Instrumented sample.

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