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		Design Authority									
1	1	Cog. Eng. A. L. Pitner	A. L. Pitner	9/3/98	H0-40						
1	1	Cog. Eng. S. L. Hecht	[signature]	9-9-98	H0-40						
1		Cog. Mgr. D. W. Bergmann	[signature]	9/10/98	H0-40						
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ALUMINUM HYDROXIDE COATING THICKNESS MEASUREMENTS AND BRUSHING TESTS ON K WEST BASIN FUEL ELEMENTS

A. L. Pitner and S. L. Hecht
Duke Engineering and Services Hanford, Inc., Richland, WA 99352
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Abstract: Aluminum hydroxide coating thicknesses were measured on fuel elements stored in aluminum canisters in K West Basin using specially developed eddy current probes. The results were used to estimate coating inventories for MCO fuel loading. Brushing tests successfully demonstrated the ability to remove the coating if deemed necessary prior to MCO loading.

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September 1998

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The successful completion of this campaign involved the concerted and dedicated efforts of a number of Hanford contractors, including K Basins Spent Nuclear Fuel Project, Lockheed Martin equipment engineering group, the Numatec equipment development and engineering laboratories, nondestructive testing from COGEMA Engineering, chemical process development from PNNL, and B&Ws fuel supply shutdown group.

Two individuals are deserving of special mention for their outstanding contributions in this effort. The performance of P. J. MacFarlan in coordinating field activities was extraordinary and vital towards the completion of this task in its allotted time frame. Also, the development and application of the eddy current probes to collect reliable coating thickness data were accomplished chiefly through the perseverance and expertise of L. T. Pedersen.

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ALUMINUM HYDROXIDE COATING THICKNESS MEASUREMENTS AND BRUSHING TESTS ON K WEST BASIN FUEL ELEMENTS

1.0 SUMMARY

An intensive campaign was conducted in K West Basin to obtain measurements of aluminum hydroxide coating thicknesses on fuel elements stored in aluminum canisters. Nineteen canisters were opened and examined and some 211 measurements of coating thickness on 37 outer fuel elements and 8 inner fuel elements were obtained using specially developed eddy current probes. Measured coating thicknesses ranged from 0 mil to 6 mil (1 mil equals one thousandth of an inch).

Four of the 19 canisters examined had been previously opened and visually inspected, and were known to have coating on the fuel. However, of the remaining 15 randomly sampled aluminum canisters, 11 were found to have basically nil fuel coating.

Coatings measured on inner elements of fuel assemblies that protruded into the cover gas space above the water in the storage canister were notably thinner than found on the corresponding outer elements. This is believed to be due to the restricted water communication between these inner fuel elements and the aluminum canister wall. Limited data also suggested a dependence of coating formation on the pH level of the canister water (higher pH promotes coating formation).

Data quality was ensured by frequent calibration checks performed on the measurement probes. These data have been statistically evaluated (Jensen 1998) to provide estimates of coating inventories for the 20% of the fuel stored in sealed aluminum canisters in K West Basin. It is estimated that approximately 60% of the aluminum canisters may contain fuel with mean coating thicknesses that cannot be distinguished from zero. An upper limit (99% confidence level) of 10.6 kg of aluminum hydroxide was determined for Multi-Canister Overpack (MCO) fuel loading.

Another primary part of this campaign was to investigate the ability of a motorized underwater brushing system to remove the coating from the fuel elements if such processing were deemed necessary prior to MCO loading. A number of different brush types were tested, and all basically proved very effective in removing the coating. Coating removal was evident by visual observation and was confirmed by eddy current measurements following the brushing operations. Engineering data obtained during the brushing tests indicate it would take a 15 HP unit working about 1 minute to clean the thickest coating observed from the outer surface of an outer fuel element.

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2.0 BACKGROUND

Irradiated N Reactor fuel is stored underwater in canisters in Hanford's K East and K West Basins. Both aluminum and stainless steel canisters are used for fuel storage in the basins. In the K East Basin, fuel is stored in open canisters, while in the K West Basin it is stored in sealed canisters. Potassium nitrite (an oxygen scavenger) was added to the K West canisters as a corrosion inhibitor before they were sealed.

During previous in-basin visual examinations of fuel assemblies stored in the K West Basin (Pitner 1997), it was noted that some fuel elements stored in aluminum canisters had a visible translucent coating on them. Subsequent sampling and laboratory analysis of this coating identified it as aluminum hydroxide, $Al(OH)_3$. This material has a relatively high water content (35%) in a bound state, which has implications for gas accumulation during long term storage in Multi-Canister Overpacks (MCOs).

The cause of the $Al(OH)_3$ coating formation is not known. It is suspected that the corrosion inhibitor added to the canisters may be a factor in the formation of this coating. The heat generated by the irradiated fuel (about 1 watt per element) is also believed to play a part in its formation. This coating is not seen on fuel elements stored in the open canisters in the K East Basin.

Since some 20% of the canisters in K West Basin are aluminum (Pitner 1998a), a substantial portion of the fuel elements have the potential for displaying this coating. In order to obtain a better assessment for the maximum $Al(OH)_3$ inventory that could be loaded into a MCO, a campaign was undertaken to measure the fuel element coating thicknesses in a number of randomly selected aluminum canisters stored in K West Basin. A second major part of this campaign also involved underwater brushing of the fuel elements to determine if the coating could be removed if necessary prior to MCO loading and storage.

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3.0 EQUIPMENT DEVELOPMENT

Various techniques for measuring the coating thickness were investigated. The challenge lay in performing this operation remotely under 16 ft of water to an accuracy of one-half of one-thousandth of an inch, or 0.5 mil (Bridges 1998). The techniques considered included ultrasonic measurement, eddy current, X-ray fluorescence, and laser interferometry. It was determined that measurement by eddy current probes posed the most promising chance for success in this endeavor.

The Zetec, Inc. company in Issaquah, Washington was subsequently contracted to design and fabricate suitable eddy current probes for this application. The design developed for the probe is shown schematically in Figure 1. The design configuration consists of a nylon shoe or saddle that mates with the outside surface of the fuel element and provides the proper alignment for the spring-loaded eddy current coil located at the inside center of the shoe. Two probes sized to the appropriate diameters were fabricated for measuring the outside surfaces of both outer and inner fuel elements. A probe to measure coating thickness on the inner bore of the outer fuel element was also developed, but it did not provide credible measurement data in later field applications.

The probes were attached to 25 ft long poles for the underwater measurement of the coating thicknesses. Checkout and acceptance testing of the eddy current measurement system were conducted in the Cold Test Facility (CTF) in the 305 Building (Pitner 1998b). This facility is a K Basin mockup, with corresponding water depth and access grating replications.

Calibration standards consisting of various thickness shims affixed to zircaloy cylinders were also fabricated to test out the eddy current probes. Zircaloy is the cladding material on N Reactor fuel elements, and the plastic shims simulated the non-electrically conducting aluminum hydroxide coating on the fuel. The shim thicknesses selected for the calibration standards were 2 mil, 3 mil, 5 mil, and 10 mil. The zircaloy bare metal also represented a zero thickness calibration point. Figure 2 is a photograph of the standards fabricated for the outer and inner fuel elements. Separate standards were required for the outer fuel element and inner fuel element eddy current probes.

Concurrent with the eddy current probe development, a fuel brushing machine was designed and constructed to test coating removal capabilities in the K Basin. This motor powered machine was required to operate underwater and allow the changing out of various types of brushes for testing coating removal effectiveness. Fixturing on this machine also served to hold the fuel elements for eddy current measurements. Checkout and acceptance testing of this apparatus was also performed in CTF.

The results of the development and acceptance testing on the eddy current probes demonstrated in principle the capability to measure aluminum hydroxide coating thicknesses on K West Basin fuel elements. Acceptance testing of the brushing machine also demonstrated the functionality of this equipment. Once proof testing of the brushing and measurement equipment was completed, the apparatus was transferred to K West Basin for field application.

Figure 1. Schematic of Eddy Current Probe Design.

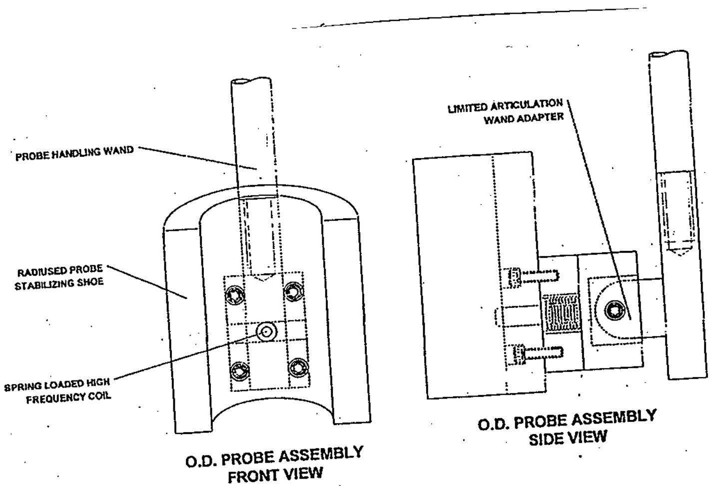
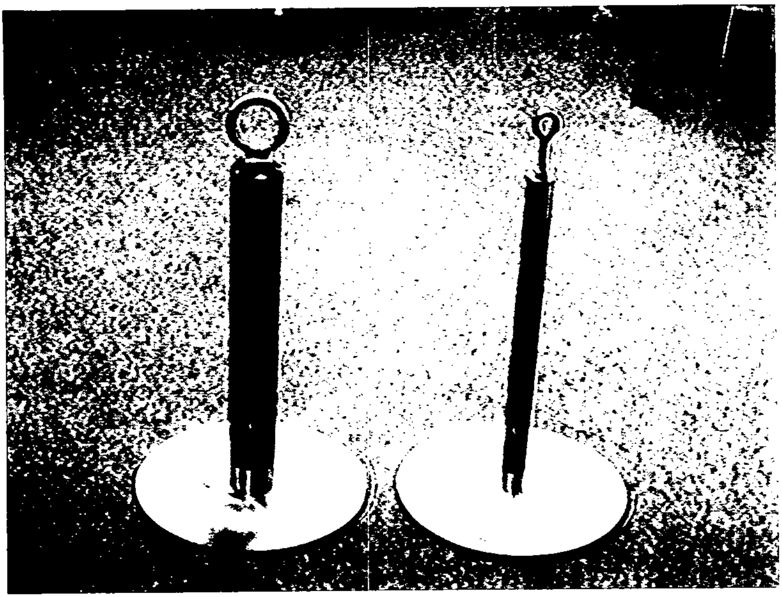


Figure 2. Eddy Current Calibration Standards.



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4.0 PROCESS DESCRIPTION

Modifications were made to the K West Basin dummy elevator pit to accommodate the equipment and processes required for this campaign. A list of candidate aluminum canisters was generated, with a maximum of 20 canisters allowed to be opened based on Radiological Air Permit restrictions. Four of the canisters identified included the aluminum canisters opened during the previous "lift and look" campaign conducted in the basin (Pitner 1997), while the remaining candidates were selected randomly from various basin locations using a random number generator technique (LOTUS spreadsheet, RAND function).

Once a candidate canister was retrieved from the basin, it was transferred to the dummy elevator pit via the monorail system. The lid of one of the Mark I canister barrels was removed by hydraulic pressurization, and individual fuel elements were extracted and transferred to the fuel brushing machine for coating thickness measurement and brush testing. Both inner and outer fuel elements were examined, with most emphasis on the outer elements. Typically two fuel elements from opposite sides of the canister barrel were extracted and examined.

Coating thickness measurements using the eddy current probes were generally performed at two or three elevation levels on two opposing sides of the fuel element. Figure 3 shows an eddy current measurement being performed above deck in the isolated work zone, while Figure 4 shows a closeup of the underwater probe placement on an outer fuel element supported in the fuel brushing machine. Repeated measurements were made at each location, with typically five good signals averaged to obtain each reading.

If substantial coating thicknesses were encountered, brushing tests would often be conducted at the measurement locations. Figure 5 shows an example where the coating has been locally removed by brushing. After brushing, the eddy current probes were again used to measure the remaining coating thickness.

Scraping tests were usually performed on the fuel elements examined using a sharp-bladed scraping tool. If coating were present, it was typically seen to be scratched and/or removed by the scraping action. Observed incidences of coating presence detected by scraping consistently correlated well with measured levels of substantial coating thickness. Figure 6 shows an area on an outer fuel element where the coating has been scratched and partially removed by the flat-bladed scraping tool.

All major operations were recorded on videotape by camera systems employed in the dummy elevator pit. All logbook records and data taking (Baker 1998) were correlated to the date and time imprinted on the videotapes.

At the end of each day, all fuel elements were returned to their canister, the lid was replaced, and the canister was transferred back to the fuel storage basin. The in-basin campaign ran for slightly more than 3 weeks, from July 14, 1998 to August 5, 1998.

Figure 3. Above Deck Eddy Current Measurement.

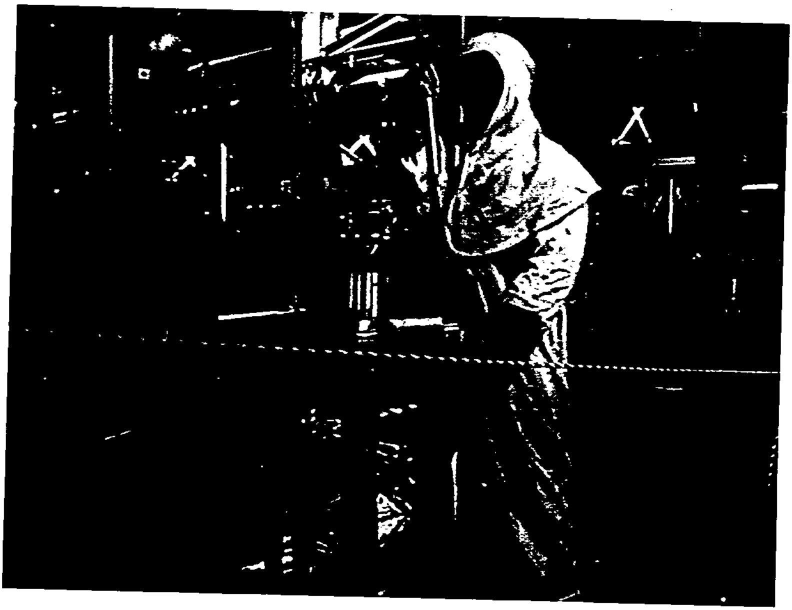


Figure 4. Eddy Current Probe on Fuel Element.

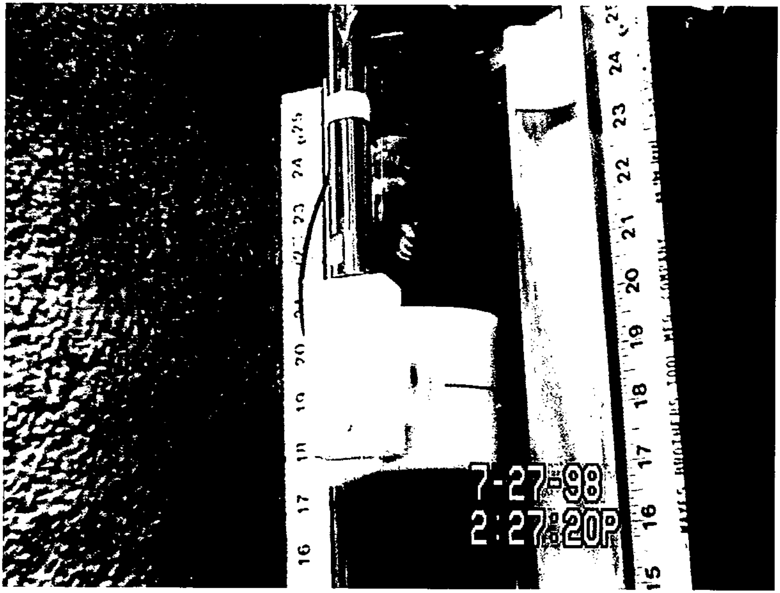


Figure 5. Brushed Area on Outer Fuel Element.

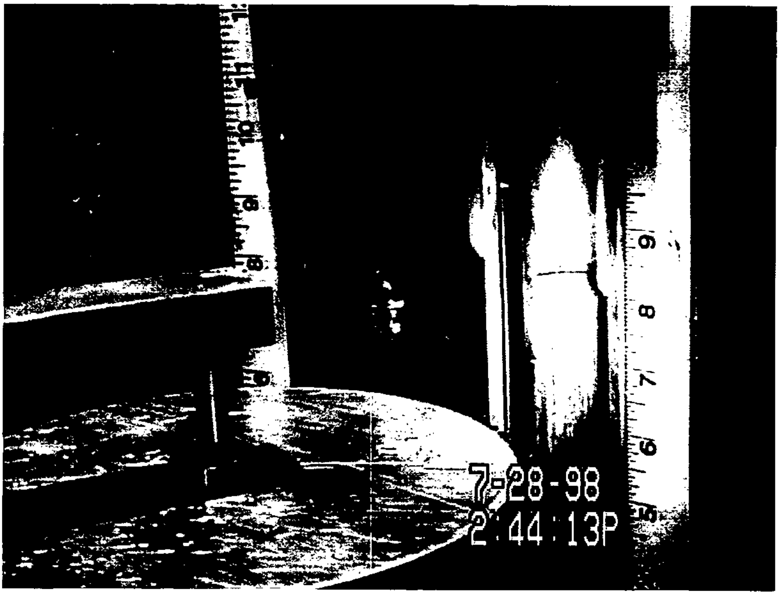
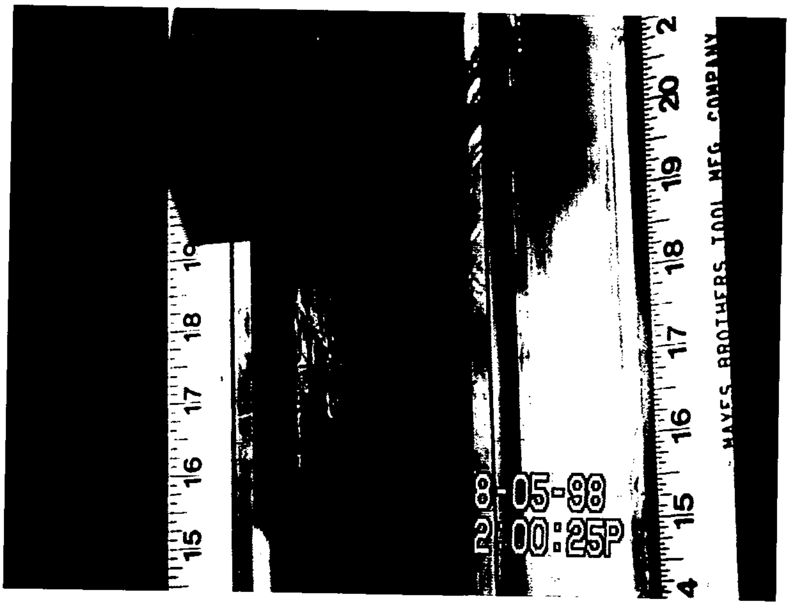


Figure 6. Fuel Surface Appearance After Scraping.



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5.0 CALIBRATIONS AND DATA QUALITY

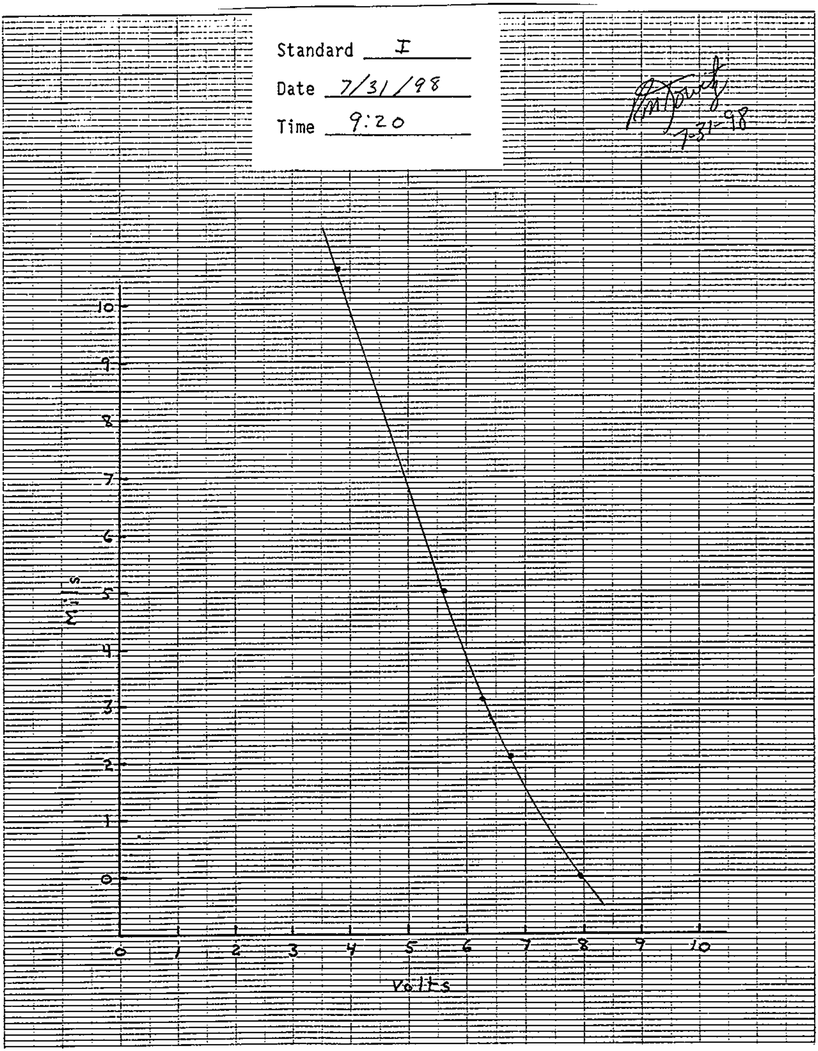
Calibration of the eddy current probe being used was performed at the beginning of each workday to generate a current calibration curve. The calibration of each probe in use was checked at intervals no longer than 4 hours apart. A final calibration check was also made at the end of the workday. Calibrations were newly generated each time an eddy current probe (outer or inner element) was changed out.

Figure 7 shows a representative calibration curve generated at the beginning of a work shift. The four shims and bare metal locations on the standard provided five measurements for generating the calibration curve of signal voltage versus shim thickness. Nominal shim thicknesses were 2 mil, 3 mil, 5 mil, and 10 mil, but actual thicknesses as measured on a laser measuring machine accurate to ±10 micro-inches (Appendix A) were used to generate the calibration curves. Once generated, these calibration curves were used to interpret the coating thickness measurements on the fuel elements.

All eddy current measurement operations were conducted under the auspices of a certified NDT technician. This measure was dictated by Office of Civilian Reactor Waste Management (OCRWM) requirements for long term storage of the fuel in the national repository. Training and qualification records for all characterization personnel involved were also documented (Bridges 1998). The signed Test Report for the eddy current measurements is included as Appendix A.

Calibration checks were consistently repeatable and met the 0.5 mil accuracy requirement for eddy current thickness measurements as specified in the Test Plan for this campaign (Bridges 1998). These results provide assurance of the quality of the coating thickness measurements obtained in this campaign.

Figure 7. Representative Eddy Current Calibration Curve.



6.0 COATING THICKNESS MEASUREMENTS

A total of 19 different aluminum canisters were sampled in the campaign. Eddy current measurements of coating thickness were performed on 37 outer fuel elements and 8 inner fuel elements. In all, 211 separate coating thickness measurements were made with the eddy current probes.

The results of the eddy current coating thickness measurements are presented in Table 1. The element identification gives the canister number from which the element was extracted and indicates whether it was taken from the marked (M) or unmarked (U) barrel. The second part of the element identification indicates it to be either an outer or inner fuel element, with the number signifying its location in the canister. The Number 1 element is the one closest to the canister top trunion, Number 2 is the next clockwise element, and so on, with Number 7 being the center element. The 0° orientation was arbitrarily designated as the first side examined, and subsequent orientations are clockwise locations from that zero reference. Elevation signifies inches from the bottom of the element. When the element was measured for coating thickness after brushing, that measurement immediately follows the pre-brushing measurement in the table. Finally, thickness values interpreted from the calibration curves are presented to the nearest tenth of a mil. Small negative values listed in the table actually indicate zero coating thickness within the 0.5 mil accuracy of the eddy current probes.

The results of the eddy current coating thickness measurements are also presented in summary form in Table 2. For each canister sampled, the range of thickness measurements are presented along with the mean and standard deviation of the measurements. Separate listings are presented for the outer and inner fuel elements.

The first four canisters listed in the table were previously visually examined and were known to have coating present, although zero coating thicknesses were measured in a few locations. The first canister opened (0161) was used extensively for coating thickness measurements and brushing tests, and the wide range of thickness values reflects the multitude of measurements made on fuel elements from this canister.

The next 15 canisters examined were selected randomly from the basin population of aluminum canisters. Coating thicknesses of 0.5 mil (the accuracy of the eddy current probe) or less were found on 11 of the 15 randomly selected canisters. The fuel in these canisters could be considered to have nil coating.

Figure 8 shows graphically the ranges of coating thicknesses measured for all the canisters sampled. Where inner fuel elements were measured, the results are shown immediately to the right of the corresponding outer fuel elements measured in that same canister.

In one instance only, fuel elements were examined from both barrels of a canister (Number 0309). Both barrels showed substantial coating levels, but they varied in magnitude. The mean and standard deviation of coating

Table 1. Eddy Current Coating Thickness Measurements.

Element	Orientation (Degree)	Elevation (in.)	Unbrushed	Brushed	Thickness (mil)
0161U / 1 Outer	0	20	X		0.6
"	0	20		X	0.6
"	0	9	X		3.6
"	0	9		X	0.2
"	0	5.5	X		5.0
"	0	5.5		X	0.0
"	90	15.5	X		0.8
"	90	15.5		X	0.0
"	90	9	X		0.7
"	90	9		X	0.0
"	90	6.5	X		0.6
"	90	6.5		X	0.0
"	180	20	X		0.8
"	180	20		X	0.0
"	180	15.5	X		0.8
"	180	15.5		X	0.0
"	180	9	X		1.0
"	180	9		X	0.0
"	180	5.5	X		0.5
"	180	5.5		X	0.1
"	270	15.5	X		0.7
"	270	15.5		X	0.0
"	270	9	X		1.0
"	270	9		X	0.0
"	270	5.5	X		1.1
"	270	5.5		X	0.0
"	45	5	X		1.8
"	45	9	X		1.4
0161U / 1 Inner	0	18.5	X		0.4
"	0	18.5		X	-0.2

Table 1. Eddy Current Coating Thickness Measurements. (Continued)

Element	Orientation (Degree)	Elevation (in.)	Unbrushed	Brushed	Thickness (mil)
0161U / 1 Inner	0	15.5	X		0.6
"	0	15.5		X	-0.1
"	0	8	X		2.2
"	0	8		X	0.0
"	0	5	X		2.4
"	0	5		X	-0.1
"	0	7	X		2.2
"	90	18.5	X		1.3
"	90	18.5		X	0.0
"	90	15.5	X		1.2
"	90	15.5		X	0.0
"	90	8	X		1.0
"	90	8		X	-0.2
"	90	5.5	X		1.1
"	90	5.5		X	0.2
"	180	19	X		1.4
"	180	19		X	0.0
"	180	15	X		1.6
"	180	15		X	0.0
"	180	8	X		1.3
"	180	8		X	0.0
"	180	6	X		1.7
"	180	6		X	0.0
0161U / 2 Outer	0	15.5	X		1.1
"	0	15.5		X	-0.1
"	0	9	X		2.7
"	0	9		X	0.0
"	0	7	X		2.7
"	0	7		X	0.0

Table 1. Eddy Current Coating Thickness Measurements. (Continued)

Element	Orientation (Degree)	Elevation (in.)	Unbrushed	Brushed	Thickness (mil)
0161U / 2 Outer	90	19	X		1.1
"	90	19		X	0.0
"	90	15.5	X		0.3
"	90	15.5		X	0.0
"	90	9	X		0.3
"	90	9		X	-0.1
"	90	5.5	X		0.3
"	90	5.5		X	-0.2
"	180	15.5	X		1.0
"	180	15.5		X	0.2
"	180	9	X		1.2
"	180	9		X	0.4
"	180	5.5	X		1.1
"	180	5.5		X	0.4
"	270	15.5	X		1.3
"	270	5.5	X		1.5
0161U / 3 Outer	0	19.5	X		0.6
"	0	19.5		X	0.0
"	0	15.5	X		0.3
"	0	9	X		0.4
"	0	6	X		1.1
"	0	6		X	-0.1
"	90	19.5	X		0.0
"	90	15.5	X		-0.3
"	90	6	X		-0.2
1860M / 1 Outer	0	23	X		4.0
"	0	23		X	0.1
"	0	16.5	X		4.8
"	0	7	X		5.0

Table 1. Eddy Current Coating Thickness Measurements. (Continued)

Element	Orientation (Degree)	Elevation (in.)	Unbrushed	Brushed	Thickness (mil)
1860M / 1 Outer	180	23	X		4.6
"	180	16.5	X		5.1
"	180	7	X		5.8
1860M / 4 Outer	0	18.5	X		4.7
"	0	17	X		4.1
"	0	8	X		4.6
"	180	17	X		4.4
"	180	9	X		5.7
0315U / 5 Outer	0	18	X		-0.1
"	0	9	X		0.0
"	0	6	X		0.0
"	180	23.5	X		0.0
"	180	18	X		0.0
"	180	6	X		-0.2
0315U / 6 Outer	0	24	X		2.1
"	0	18	X		0.0
"	0	8	X		0.2
"	180	24	X		0.1
"	180	18	X		0.0
"	180	8	X		0.1
0309M / 2 Outer	0	19	X		5.5
"	0	19		X	0.5
"	0	16	X		5.3
"	0	16		X	0.4
"	0	8	X		4.5
"	0	8		X	0.2
0309U / 4 Inner	0	21	X		0.0
"	0	16	X		0.3
"	0	8	X		0.0

Table 1. Eddy Current Coating Thickness Measurements. (Continued)

Element	Orientation (Degree)	Elevation (in.)	Unbrushed	Brushed	Thickness (mil)
0309U / 4 Inner	180	20	X		0.2
"	180	16	X		0.5
"	180	8	X		0.2
0309U / 1 Inner	0	20	X		0.7
"	0	16	X		0.7
"	0	8	X		1.1
"	180	20	X		2.1
"	180	15	X		2.5
"	180	8	X		2.3
0309U / 1 Outer	0	8	X		3.8
"	0	8		X	0.0
0309U / 4 Outer	0	23	X		3.1
"	0	17	X		4.6
"	0	7	X		3.0
"	180	17	X		3.1
"	180	8	X		2.8
0579M / 1 Outer	0	23	X		0.0
"	0	17	X		-0.3
"	0	8	X		0.1
"	180	19	X		-0.2
"	180	8	X		0.0
0579M / 4 Outer	0	23	X		-0.2
"	0	16.5	X		0.0
"	0	9.5	X		-0.1
"	0	5.5	X		0.5
"	180	18	X		-0.2
"	180	9	X		-0.2
"	180	7	X		-0.1

Table 1. Eddy Current Coating Thickness Measurements. (Continued)

Element	Orientation (Degree)	Elevation (in.)	Unbrushed	Brushed	Thickness (mil)
1575M / 4 Outer	0	18	X		-0.1
"	0	8	X		0.4
"	180	18	X		0.1
"	180	8	X		0.2
1575M / 1 Outer	0	18	X		0.0
"	0	8	X		0.1
"	180	18	X		-0.1
"	180	8	X		-0.1
9133M / 1 Outer	0	18	X		0.0
"	0	8	X		0.5
"	180	18	X		0.1
"	180	8	X		0.2
9133M / 4 Outer	0	16	X		0.2
"	0	8	X		0.1
"	180	16	X		0.0
"	180	8	X		0.4
9136M / 1 Outer	0	17	X		0.1
"	0	8	X		0.3
"	180	17	X		-0.1
"	180	8	X		-0.1
9136M / 4 Outer	0	17	X		0.0
"	0	8	X		0.4
"	180	17	X		0.1
"	180	8	X		0.6
0725M / 2 Outer	0	18	X		2.2
"	0	8	X		2.2
"	180	18	X		2.6
"	180	8	X		3.0

Table 1. Eddy Current Coating Thickness Measurements. (Continued)

Element	Orientation (Degree)	Elevation (in.)	Unbrushed	Brushed	Thickness (mil)
0725M / 5 Outer	0	18	X		2.3
"	0	8	X		2.3
"	180	18	X		1.2
"	180	8	X		1.2
0734M / 2 Inner	0	18	X		0.0
"	0	8	X		0.1
"	180	18	X		0.2
"	180	8	X		0.5
0734M / 4 Inner	0	18	X		0.0
"	0	8	X		0.0
0734M / 4 Outer	0	18	X		0.3
"	0	8	X		0.3
1876M / 1 Outer	0	18	X		-0.1
"	0	8	X		0.3
1876M / 4 Outer	0	18	X		0.3
"	0	8	X		0.2
1876M / 4 Inner	0	18	X		0.1
"	0	8	X		0.0
0673M / 1 Outer	0	18	X		0.2
"	0	8	X		0.2
"	180	18	X		0.1
"	180	8	X		0.1
0673M / 4 Outer	0	18	X		0.2
"	0	8	X		0.0
"	180	18	X		-0.2
"	180	8	X		0.0
0740M / 1 Outer	0	18	X		-0.1
"	0	8	X		0.0
"	180	18	X		-0.2
"	180	8	X		-0.3

Table 1. Eddy Current Coating Thickness Measurements. (Continued)

Element	Orientation (Degree)	Elevation (in.)	Unbrushed	Brushed	Thickness (mil)
0740M / 4 Outer	0	18	X		0.0
"	0	8	X		0.0
"	180	18	X		0.0
"	180	8	X		0.0
0326M / 1 Outer	0	18	X		1.4
"	0	8	X		0.8
"	180	18	X		0.6
"	180	8	X		0.5
0326M / 4 Outer	0	18	X		1.0
"	0	8	X		0.8
"	180	18	X		0.8
"	180	8	X		0.7
0326M / 1 Inner	0	18	X		0.3
"	0	8	X		0.4
"	180	18	X		0.2
"	180	8	X		0.1
0326M / 4 Inner	0	18	X		-0.2
"	0	8	X		0.2
"	180	18	X		0.6
"	180	8	X		0.3
0620M / 1 Outer	0	18	X		0.1
"	0	8	X		0.1
"	180	18	X		0.1
"	180	8	X		0.2
0620M / 4 Outer	0	18	X		0.0
"	0	8	X		0.0
"	180	18	X		0.0
"	180	8	X		0.0

Table 1. Eddy Current Coating Thickness Measurements. (Continued)

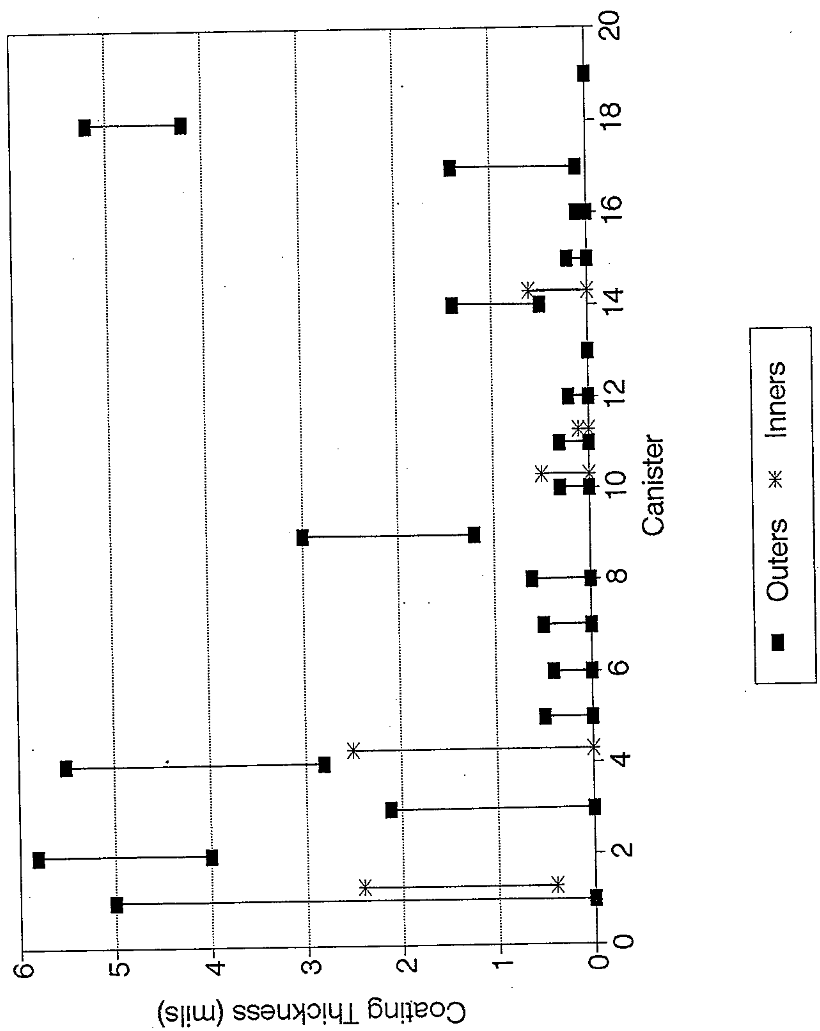
Element	Orientation (Degree)	Elevation (in.)	Unbrushed	Brushed	Thickness (mil)
1681M / 1 Outer	0	18	X		-0.1
"	0	8	X		-0.2
"	180	18	X		-0.2
"	180	8	X		-0.2
1681M / 4 Outer	0	18	X		0.0
"	0	8	X		0.1
"	180	18	X		0.1
"	180	8	X		0.0
0101M / 1 Outer	0	18	X		1.0
"	0	8	X		1.0
"	180	18	X		1.4
"	180	8	X		1.1
0101M / 4 Outer	0	18	X		1.0
"	0	8	X		0.7
"	180	18	X		0.5
"	180	8	X		0.1
0111U / 1 Outer	0	18	X		5.2
"	0	8	X		5.0
"	180	18	X		4.5
"	180	8	X		4.2
1619U / 7 Outer	0	18	X		-0.2
"	0	8	X		-0.4

Table 2. Summary of Eddy Current Thickness Measurements.

Canister	Coating Thickness (mil)			
	Outers		Inners	
	Range	Mean ± Std Dev	Range	Mean ± Std Dev
0161*	0 to 5.0	1.1 ± 1.1	0.4 to 2.4	1.4 ± 0.6
1860*	4.0 to 5.8	4.8 ± 0.6		
0315*	0 to 2.1	0.2 ± 0.6		
0309*	2.8 to 5.5	4.0 ± 1.0	0 to 2.5	0.9 ± 0.9
0579	0 to 0.5	-0.1 ± 0.2		
1575	0 to 0.4	0.1 ± 0.2		
9133	0 to 0.5	0.2 ± 0.2		
9136	0 to 0.6	0.2 ± 0.3		
0725	1.2 to 3.0	2.1 ± 0.6		
0734	0 to 0.3	0.3 ± 0.0	0 to 0.5	0.1 ± 0.2
1876	0 to 0.3	0.2 ± 0.2	0 to 0.1	0.1 ± 0.1
0673	0 to 0.2	0.1 ± 0.1		
0740	0	-0.1 ± 0.1		
0326	0.5 to 1.4	0.8 ± 0.3	0 to 0.6	0.2 ± 0.2
0620	0 to 0.2	0.1 ± 0.1		
1681	0 to 0.1	-0.1 ± 0.1		
0101	0.1 to 1.4	0.9 ± 0.4		
0111	4.2 to 5.2	4.7 ± 0.5		
1619	0	-0.3 ± 0.1		

*Previously visually examined and known to have coating.

Figure 8. Ranges of Measured Coating Thicknesses.



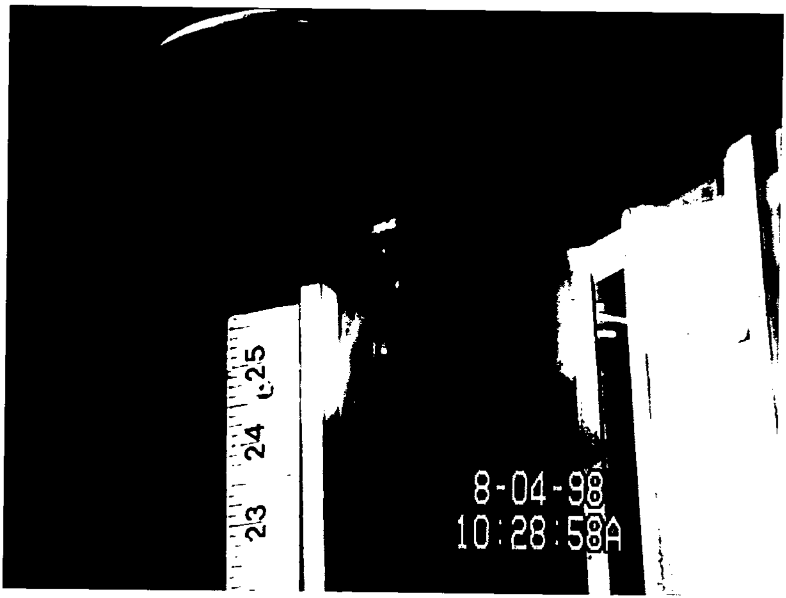
thickness measured on one outer fuel element in the marked barrel was 5.1 mil ± 0.5 mil, while that measured on two outer fuel elements in the unmarked barrel was 3.4 mil ± 0.7 mil.

An interesting observation can be made in comparing the relative coating thicknesses on outer and inner fuel elements. As shown in Table 2 and Figure 8, both types of fuel elements were measured in five canisters, with near zero coating thickness found in two of these cases (Canisters Number 0734 and Number 1876). Of the remaining three canisters with significant coating levels detected, one (Canister Number 0161) contained Mark IA type fuel and the other two (Canisters Number 0309 and Number 0326) contained Mark IV type fuel. Mark IA fuel is relatively short (about 21 in.), while the Mark IV fuel is longer (about 26 in.). The shorter Mark IA fuel was invariably submerged in water in the storage canister, while the longer Mark IV fuel sometimes extended into the gas pocket above the water line in the canister. In both Canisters Number 0309 and Number 0326, there was visual evidence that the fuel protruded into the gas pocket. This is exemplified in Figure 9 which shows a bare area about 1 in. long at the top of an outer fuel element extracted from Canister Number 0326. Extension of the fuel into the gas pocket would likely present a barrier to water and chemical communication between the inner fuel elements and the aluminum canister walls. This appears to be evidenced here, where the coating thicknesses on the longer inner fuel elements that protruded above the water line are less than measured on their corresponding outer elements (Canisters Number 0309 and Number 0326). Conversely, for the shorter fuel assemblies which were totally submerged in water, measured coating thicknesses for outer and inner elements are comparable (Canister Number 0161).

One other observation on a potential coating correlation with water pH level was noted in this campaign. Some canisters had been previously water sampled and chemically analyzed (Trimble 1997), and pH information was available for three of the canisters listed in Table 2. Canisters Number 1860 and Number 0111 were each found to have a pH level of 11.5, while Canister Number 1619 had a pH level of 8.0. Eddy current measurements showed that the canisters with the higher pH value (Number 1860 and Number 0111) had nearly 5 mil of coating on the fuel, while the lower pH canister (Number 1619) had no measurable coating on the fuel. These limited data are in relative agreement with laboratory studies of growing this type of coating on zircaloy specimens (Silvers 1998), which also showed a pH dependency for coating growth.

These measured coating thickness results have been statistically analyzed (Jensen 1998) to provide estimates of $Al(OH)_3$ coating inventories for MCO fuel loading. For the 20% of the fuel in K West Basin that is loaded in aluminum canisters, it is estimated that approximately 60% of these canisters may contain fuel with mean coating thicknesses that cannot be distinguished from zero. An upper limit (99% confidence level) of 10.6 kg of $Al(OH)_3$ was determined for a maximum MCO loading.

Figure 9. Bare top of Outer Fuel Element that Extended Above the Water Line in the Fuel Storage Canister.



7.0 BRUSHING TESTS

The objective of brushing tests were twofold. The first was to remove, or partially remove, the $Al(OH)_3$ coating on the fuel elements to verify the eddy current measurement (e.g., zero calibration). The second objective was to characterize the effectiveness of coating removal. Here various brush types and brushing parameters were investigated to provide data which can potentially be used in the design of a brushing machine to remove the coating from the fuel. The effects of brush type, wire material, wire size, brushing velocity and interference (bushing force) were all investigated.

7.1 BRUSHING TEST EQUIPMENT

The test equipment consists of the Brushing Test Machine and the associated operator control equipment. The brushing test machine will accept an assortment of wire wheel brushes in the range of 6 in. to 10 in. in diameter (see Section 7.2--Test Article) and can brush either inner or outer N Reactor fuel elements of various models.

The Brushing Test Machine (hereafter referred to as the " machine") is shown in Figure 10. The layout of the brushing equipment in the Dummy Elevator Pit is show schematically in Figure 11. The brushing machine detail drawings are given in Appendix B. The machine consists of a rigid frame, a submersible electric motor mounted on a vertical positioning mechanism, a quick release drive mechanism for the various wire wheel brushes, and fuel element cradles and clamps which are mounted on a horizontal positioning mechanism. The brush vertical position and the fuel element horizontal position along with the electric motor control are performed by control units on the operating deck (see Figure 11).

The submersible electric motor is a 1.5 HP-AC, 3 Phase, 460 V-3450 RPM unit, which powers the wire wheel brushes though a quick release drive system. The motor is controlled by a variable speed controller in which the motor shaft angular velocity (RPM) is set for a particular test. This controller is programmed for constant torque motor operation. The controller LED display gives RPM, electric current at the controller (percent power) and other information. The majority of the power of the motor is expended in rotation of the brushes to overcome hydraulic effects (centrifugal pumping and friction).

The quick release wire wheel brush drive mechanism consists of a hex-collet receptacle which mounts to the motor shaft, and a hold down arm and upper-bearing support which can be positioned to be either in hold-down mode or out-of-the way for brush removal and insertion.

Both positioning mechanisms are made from high-precision lead screw actuated linear slides. The vertical slide has a lead screw pitch such that one revolution of the hand wheel on the control unit is converted into 0.200 in. of vertical travel. For the horizontal slide, which drives the fuel element into the brush, the actuation ratio is finer. Here a right angle worm screw drive is employed such that each turn of the hand wheel translates

Figure 10. Brushing Test Machine.

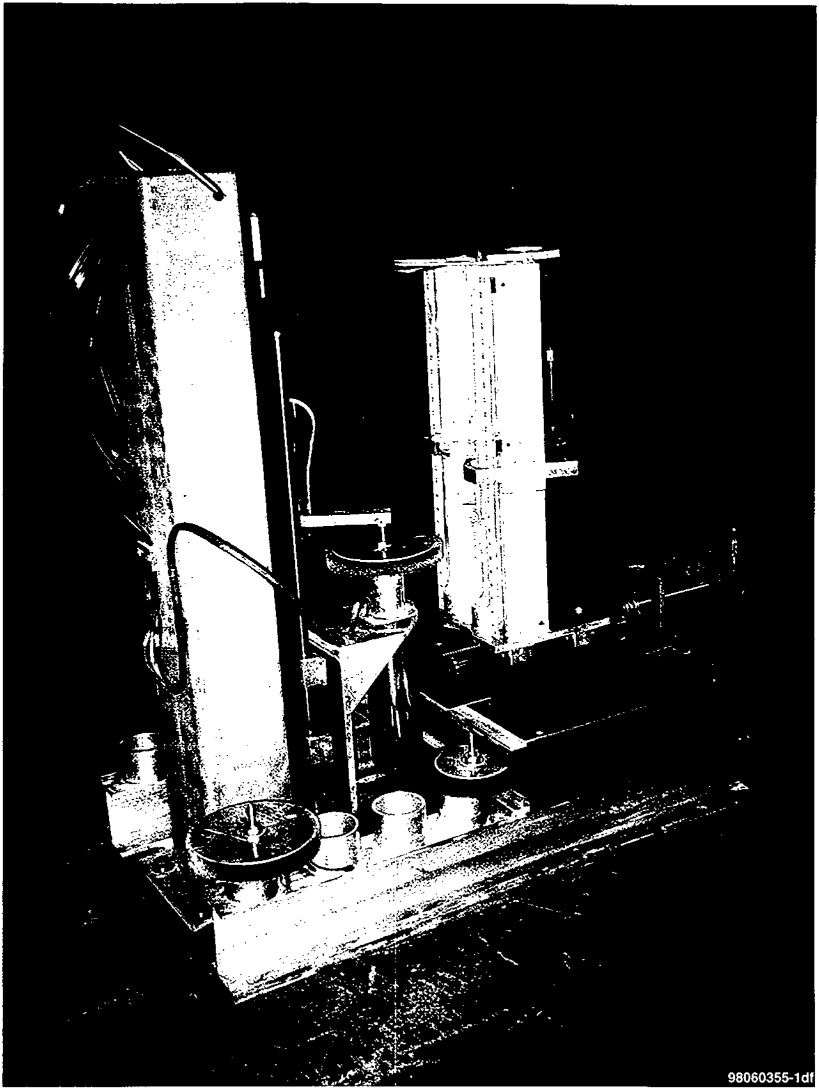
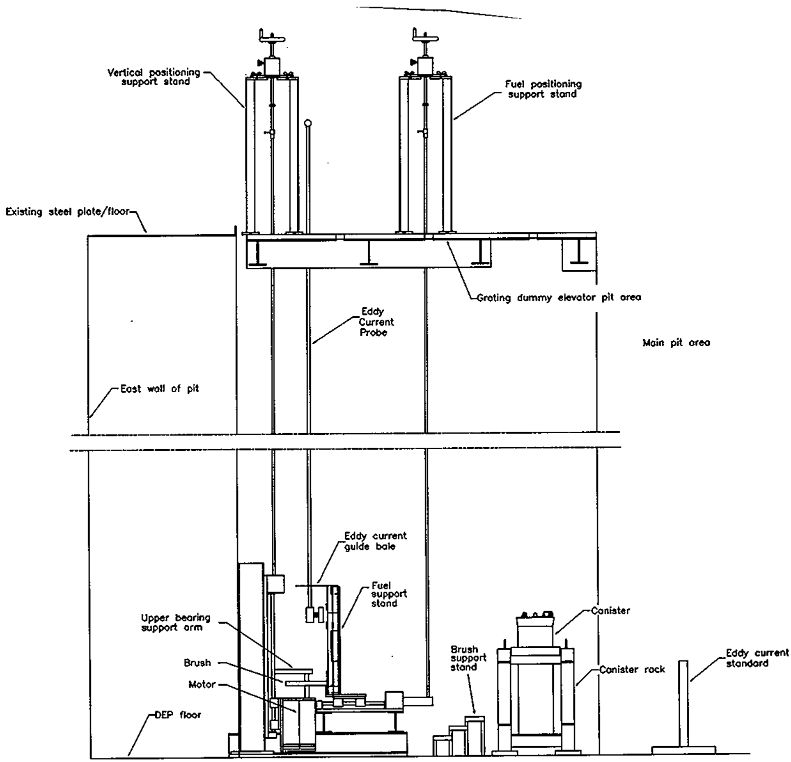


Figure 11. Schematic of Brushing Test Equipment Layout in the Dummy Elevator Pit.



into 0.040 in. of linear motion. The angular scale indicator on the control unit reads to the nearest degree, the slides/drives move 0.00011 in. for each degree of rotation. It is expected there is <0.005 in. "slop" in these slides/drives.

The frame is designed to be rigid, so that the deformation of the machine will not impact the results. The design goal was that the machine stiffness be at least a factor of ten greater than that of the stiffest brush. The machine was calibrated to determine this force-deflection relationship (Appendix C). Hence, the machine deflection can be factored-out (need be considered only for a few of the stiffest brushes) when analyzing brushing forces and deflection.

The vertical and horizontal position control units consist of tables which mount to the operating deck grating, radial bearings and locking devices, hand wheel cranks, and decouplable drive shafts. For the fuel-feed positional control, an angular scale is mounted on the top of the bearing block, and a precision torque wrench can be attach to top of the hand wheel. This shaft torque is related to the interference force between the fuel and brush. Calibrations were made to determine this torque-force relationship (Appendix C); however, these was not used in the final testing. A hydrophone is mounted on the machine to aid in determining when brush-fuel contact is first made.

7.2 TEST ARTICLE (BRUSHES)

Sixteen wheel type brushes were selected for testing. These are basically of three types: (1) wire, either carbon steel, stainless steel, or brass; (2) silicon-carbide grit impregnated into nylon filaments; and (3) Abrasive grit (aluminum oxide) resin bonded to a cloth flapper wheel. A number of these brushes were sandwiched (shrouded) between end-plates to minimize the hydraulic centrifugal pumping effect, allowing more power to be available for brushing at a given angular velocity. Theses brushes are mounted on spindles which mate with the brushing machine. Characteristic of theses brushes are given in Table 3. Individual brushes were given arbitrary numbers for reference purposes, and are used throughout this document. A photograph of brushes Number 1 to Number 12 is shown in Figure 12.

The brushes were calibrated to determine the normal and tangential stiffness. These force-deflection relationships were used in the determination of the brush-fuel force or interference during testing, and in the determination of the power that the wheel brush exerts on the fuel. Calibration was performed using a metal working lathe, with an arbor fixture for mounting the brush in the lathe's chuck. A load cell (300 lb full scale) was attached to a pipe section, roughly the size of an outer full element, which could be fed into the brush. Dial gages were used to determine the interference between the brush and pipe. Different fixtures were used for the normal and tangential stiffness. The set-up for the normal stiffness calibration is shown in Figure 13. The lathe was turned on at a low speed (higher speed introduced heating of the load cell and introduced errors), different interferences were introduced, and the load (maximum at a given setting) was recorded.

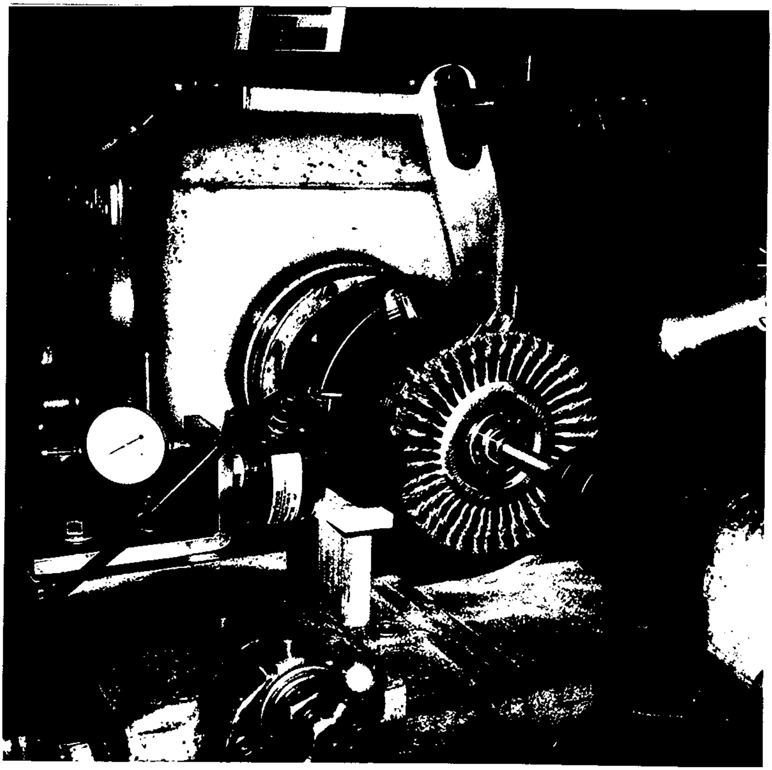
Table 3. Brush Characteristics.

BRUSH PARAMETERS								
BRUSH NO.	MATERIAL	WHEEL DIA. (in.)	WIRE SIZE (in.)	FACE WIDTH (in.)	TRIM LENGTH (in.)	OTHER	K-NORMAL * (lb/in.)	K-TANGENTIAL* (lb/in.)
1	SST	8	0.006	1.25	1.7		12	4
2	SST	8	0.012	1.125	1.5		54	77
3	CARB. STEEL	8	0.006	1.5	1.5		22	23
4	CARB. STEEL	8	0.014	1.125	1.5		20	13
5	CARB. STEEL	8	0.02	1.5	1.5		134	92
6	CARB. STEEL	8	0.0118	1	1.625	KNOT-TWIST	42	27
7	BRASS	6	0.01	1.25	1.375		11	19
8	BRASS	6	0.02	1.25	1.375		78	78
9	ABR. FILAMENT	8	80 GRIT	0.875	1.5		17	11
10	ABR. FILAMENT	8	120 GRIT	0.875	1.5		17	11
11	AIO -ARB. FLAP	8	180 GRIT	1	2			
12	AIO-ARB. FLAP	8	60 GRIT	1	2			
13	CARB STEEL	6	0.015	0.5	1.1			51
14	CARB. STEEL	6	0.006	0.5	1.1			8
15	CARB. STEEL	6	0.015	0.5	1.35	KNOT-TWIST		37
16	BRASS	6	0.011	0.0375	1.5			

NOTES: * Initial Steady

Figure 12. Brushes Number 1 (Upper Left) through Number 12 (Lower Right).

Figure 13. Setup for Normal Stiffness Calibration.



Results of the calibration are given in Figures 14 and 15 for brushes Number 1 through Number 10. Calibration curves for the other brushes can be found in Appendix C. Initial stiffness values from these curves are given in Table 3. A slight angular rotation rate dependency on stiffness was noted for softer brushes. However, attempts to quantify this were not very successful because heat effects introduced errors. It is expected that the end-plates, added to the brushes for hydraulic benefit (after the calibrations), would slightly increase the brush stiffnesses.

7.3 BRUSHING TEST PROCEDURE

Once it was determined that sufficient coating thickness was present and if time permitted, brushing tests were undertaken. The first step in the brushing procedure was to determine if the current brush installed on the machine was the appropriate brush. If not, the brush was removed and the appropriate brush was inserted onto the machine. Brushes typically were not re-used because the time required to change them out could be significant. A total of eight different brushes were tested (Number 1 through Number 6, Number 8 and Number 9). Because of time and brushing location constraints, only the most promising or representative brushes were tested (50% of those available).

The brush/motor-drive carriage was then moved to the appropriate pre-measured vertical location on the fuel element. The next step was to determine the point of first contact between the fuel and brush. This was done in two steps. First, with the motor shut off, the brush was "cranked into" the fuel element until visual (via video camera) contact was observed. At this position a "zero" mark was set on the horizontal control angular scale. Next, the brush was backed off approximately 0.2 in., and the brush drive motor was started. Prior to starting the motor, the motor controller was set to the desired test speed (RPM). The next step was to feed the brush towards the fuel until the clearance was approximately 0.04 in. The brush was then slowly fed towards the fuel while at the same time making four observations to ascertain contact: (1) visually; (2) observing an increase in the motors' load (electric current reading on the motor controller); (3) "feel" on the hand wheel crank; and (4) audio indications as picked up by the hydrophone (Note: a bearing squeal that developed on a brushing machine bearing made the hydrophone detection very difficult). This dynamically located "zero" was then marked on the horizonal position indicator. The brush was then fed into the fuel element to the desired interference, and brushing continued for the desired test duration, after which the brush was quickly backed off. The peak reading on the controller ammeter and test duration were recorded, along with the interference and motor speed values. This sequence was repeated for each brush testing, while generally varying the brushing parameters. Detailed procedures are given in Operating Procedure, OP-07-125W.

Because of the limitation on the motor power (1.5 HP) and the significant hydraulic resistances of the rotating brushes, only certain ranges of brush speed and interference combinations (brush dependent) were achievable in the testing (see Table 4). Within the matrix of the 67 individual brushing tests, parameter ranged as follows: brushed area ranged from 0.3 in^2 to 1.5 in^2; the fuel-brush interference ranged from 0.03 in. to 0.12 in.; the power ranged from 0.04 HP to 0.46 HP; the brush tip velocity ranged from 168 in./s to 315 in./s; and the testing duration ranged from 5 seconds to 3 minutes.

Figure 14. Brush Stiffness Characteristics (Normal Direction).

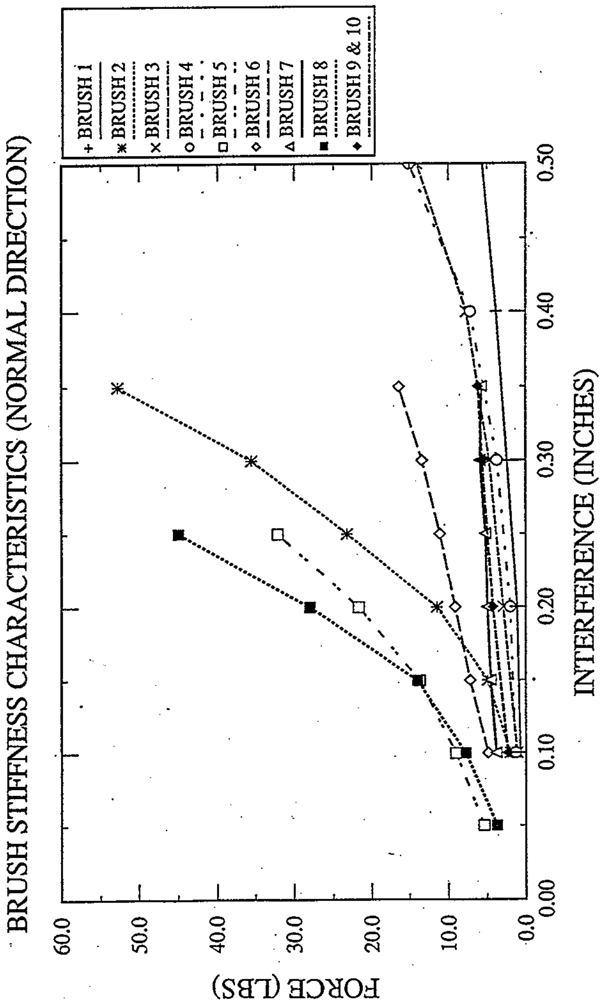


Figure 15. Brush Stiffness Characteristics (Tangential Direction).

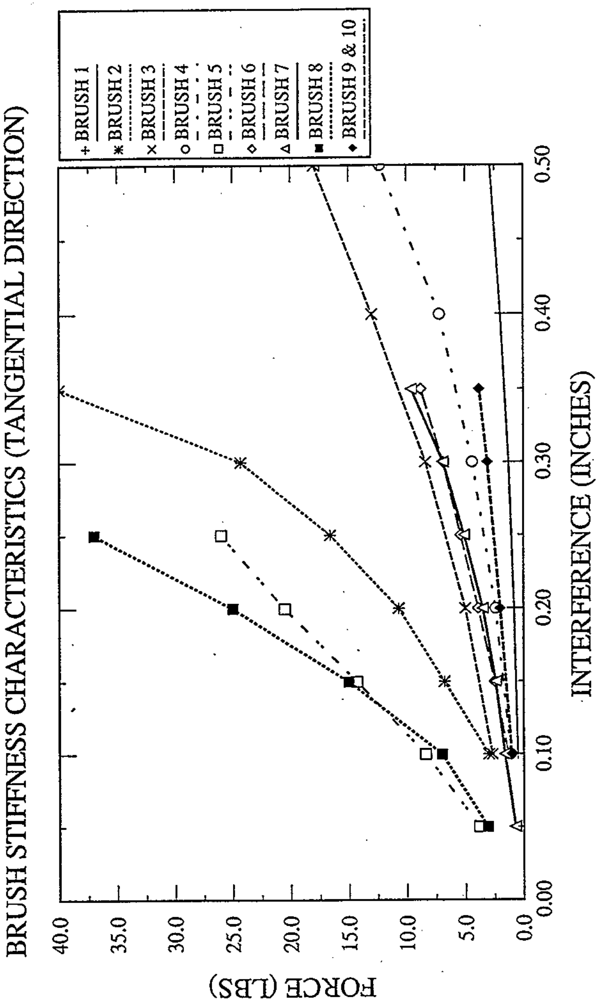


Table 4. Brushing Test Parameters and Results.

RESULTS: BRUSHING TESTS

TEST NO.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
BRUSH NO. - ELEMENT TYPE	2-O	2-O	2-O	2-O	2-O	2-O	2-O	2-O	2-O	2-O	2-O	2-O	2-O	2-I
DELTA % FULL POWER (fractional)	0.13	0.13	0.14	0.15	0.14	0.23	0.12	0.11	0.23	0.09	0.19	0.25	0.14	0.2
POWER (HP) ELECTRIC	0.208	0.208	0.224	0.24	0.224	0.368	0.192	0.176	0.368	0.144	0.304	0.4	0.224	0.32
INTERFERENCE (IN.)	0.08	0.08	0.063	0.08	0.08	0.06	0.06	0.06	0.08	0.05	0.06	0.08	0.06	0.08
INTERFERENCE (INFERRED)	0.038	0.04	0.024	0.065	0.062	0.038	0.03	0.023	0.06	0.042	0.038	0.029	0.03	0.03
FORCE - TANGENTIAL (LBS)	2.5	2.5	2.3	2.5	2.5	2.2	2.2	2.2	2.5	2.1	2.2	2.5	2.2	2.5
BRUSH - RADIUS (IN.)	4	4	4	4	4	4	4	4	4	4	4	4	4	4
TORQUE (IN.-LBS)	10	10	9.2	10	10	8.8	8.8	8.8	10	8.4	8.8	10	8.8	10
N (RPM)	400	400	400	550	550	550	700	700	700	400	550	550	700	550
POWER (HP) MECHANICAL	0.063	0.063	0.058	0.087	0.087	0.077	0.098	0.098	0.111	0.053	0.077	0.087	0.098	0.087
POWER (HP) - AVERAGE	0.136	0.136	0.141	0.164	0.156	0.222	0.145	0.137	0.240	0.099	0.190	0.244	0.161	0.204
TEST DURATION (SECONDS)	180	120	120	120	60	60	60	55	60	60	30	30	30	60
WORK (1000 IN.-LBS)	161.3	107.5	111.8	129.6	61.6	88.1	57.4	49.7	94.9	39.1	37.7	48.2	31.9	80.6
COATING INITIAL THICKNESS (IN.)	0.005	0.0036	0.0006	0.0006	0.0007	0.0008	0.0008	0.0008	0.001	0.0005	0.0007	0.001	0.0011	0.0004
% THICKNESS REMOVED	100	94	100	100	100	100	100	100	100	80	100	100	100	100
THEORECTICAL SURF AREA CLEANED (IN^2)	0.84	0.84	0.75	0.84	0.84	0.73	0.73	0.73	0.84	0.68	0.73	0.84	0.73	0.68
MEASURED SURFACE AREA CLEANED (IN^2)	0.66	0.7	0.55	0.82	0.8	0.68	0.77	0.47	0.85	0.69	0.75	0.61	0.51	0.43
CLEANING EFFECIENCY (FRACTIOANL)	0.785714	0.783333	0.733333	0.97619	0.952381	0.931507	1.054795	0.643836	1.011905	0.811765	1.027397	0.72619	0.69863	0.632353
WORK VOL. DENS. (10^6 IN-LB/IN^3)	48.9	45.4	338.9	263.4	110.1	161.9	93.1	132.2	111.6	141.6	71.8	79.1	56.8	468.9
WORK SURF AREA DENS (10^3 IN-LB/IN^2)	150.8	100.3	109.4	150.6	69.9	112.4	82.9	43.8	114.3	46.6	53.1	41.7	30.5	75.0
BRUSH TIP VELOCITY (IN/SEC)	168	168	168	231	231	231	204	294	294	168	231	231	294	231

TEST NO.	15	16	17	18	19	20	21	22	23	24	25	26	27	28
BRUSH NO. - ELEMENT TYPE	2-I	2-I	2-I	2-I	2-I	2-I	2-I	2-I	1-I	1-I	1-I	1-O	1-O	1-O
DELTA % FULL POWER (fractional)	0.22	0.3	0.33	0.19	0.05	0.13	0.05	0.29	0.04	0.09	0.1	0.06	0.05	0.09
POWER (HP) ELECTRIC	0.352	0.48	0.528	0.304	0.08	0.208	0.08	0.464	0.064	0.144	0.16	0.096	0.08	0.144
INTERFERENCE (IN.)	0.08	0.08	0.09	0.06	0.06	0.08	0.06	0.07	0.07	0.12	0.12	0.08	0.08	0.12
INTERFERENCE (INFERRED)	0.03	0.062	0.05	0.051	0.028	no -mea	0.021	0.03	0.034	0.051	0.054	0.021	0.019	0.037
FORCE - TANGENTIAL (LBS)	2.5	2.5	2.8	2.3	2.3	2.5	2.3	2.4	0.3	0.48	0.48	0.36	0.36	0.48
BRUSH - RADIUS (IN.)	4	4	4	4	4	4	4	4	4	4	4	4	4	4
TORQUE (IN.-LBS)	10	10	11.2	9.2	9.2	10	9.2	9.6	1.2	1.92	1.92	1.44	1.44	1.92
N (RPM)	550	550	550	550	700	700	400	400	500	500	500	500	600	600
POWER (HP) MECHANICAL	0.087	0.087	0.098	0.080	0.102	0.111	0.058	0.061	0.010	0.015	0.015	0.011	0.014	0.018
POWER (HP) - AVERAGE	0.220	0.284	0.313	0.192	0.091	0.160	0.069	0.262	0.037	0.080	0.088	0.054	0.047	0.081
TEST DURATION (SECONDS)	30	36	15	15	15	15	15	5	30	30	15	15	15	15
WORK (1000 IN.-LBS)	43.5	67.4	31.0	19.0	9.0	15.8	6.9	8.7	7.3	15.8	8.7	5.3	4.6	8.0
COATING INITIAL THICKNESS (IN.)	0.0006	0.0022	0.0024	0.0011	0.001	0.0012	0.0013	0.0017	0.0013	0.0016	0.0014	0.0011	0.0027	0.0027
% THICKNESS REMOVED	100	100	100	82	100	100	100	100	100	100	100	100	100	100
THEORECTICAL SURF AREA CLEANED (IN^2)	0.68	0.68	0.71	0.57	0.57	0.68	0.57	0.63	0.63	0.8	0.8	0.68	0.68	0.8
MEASURED SURFACE AREA CLEANED (IN^2)	0.43	0.68	0.63	0.66	0.49	0.68	0.43	0.32	0.7	0.84	1.07	0.9	0.56	0.83
CLEANING EFFECIENCY (FRACTIOANL)	0.632353	1	0.887324	0.949474	0.859649	1	0.754386	0.507937	1.111111	1.05	1.3375	1.323529	0.823529	1.0375
WORK VOL. DENS. (10^6 IN-LB/IN^3)	168.6	45.1	20.5	32.0	18.4	19.4	12.3	15.9	8.0	11.7	6.8	5.4	3.1	3.6
WORK SURF AREA DENS (10^3 IN-LB/IN^2)	40.4	99.1	38.7	31.7	13.6	23.2	9.1	7.0	12.8	20.7	14.5	10.4	5.6	10.4
BRUSH TIP VELOCITY (IN/SEC)	231	231	231	231	294	294	168	168	210	210	210	210	252	252

Table 4. Brushing Test Parameters and Results (Continued).

RESULTS: BRUSHING TESTS

TEST NO.	29	29A	30	31	32	33	34	35	36	37	38	39	40	41
BRUSH NO. - ELEMENT TYPE	1-O	1-O	9-O	9-O	9-O	9-O	9-O	9-O	9-O	9-O	8-O	8-O	8-O	8-O
DELTA % FULL POWER (fractional)	0.07	0.09	0.11	0.03	0.06	0.09	0.1	0.07	0.07	0.08	0.07	0.26	0.12	0.08
POWER (HP) ELECTRIC	0.112	0.144	0.176	0.048	0.096	0.144	0.16	0.112	0.112	0.128	0.112	0.416	0.192	0.128
INTERFERENCE (IN.)	0.12	0.12	0.12	0.08	0.08	0.09	0.1	0.08	0.08	0.08	0.06	0.08	0.07	0.06
INTERFERENCE (INFERRED)	0.037	0.061	0.029	0.013	0.051	0.051	0.044	0.041	0.037	0.041	0.018	0.02	0.018	0.02
FORCE - TANGENTIAL (LBS)	0.44	0.44	1.39	0.88	0.88	1	1.1	0.88	0.88	0.88	4.4	5.2	4.8	4.4
BRUSH - RADIUS (IN.)	4	4	4	4	4	4	4	4	4	4	3	3	3	3
TORQUE (IN.-LBS)	1.76	1.76	5.56	3.52	3.52	4	4.4	3.52	3.52	3.52	13.2	15.6	14.4	13.2
N (RPM)	600	500	500	500	600	600	600	600	600	500	550	550	550	550
POWER (HP) MECHANICAL	0.017	0.014	0.044	0.028	0.034	0.038	0.042	0.034	0.034	0.028	0.115	0.136	0.126	0.115
POWER (HP) - AVERAGE	0.064	0.079	0.110	0.038	0.065	0.091	0.101	0.073	0.073	0.078	0.114	0.276	0.159	0.122
TEST DURATION (SECONDS)	10	10	15	15	15	15	30	10	120	120	30	15	30	15
WORK (1000 IN.-LBS)	4.2	5.2	10.9	3.8	6.4	9.0	20.0	4.8	57.6	61.8	22.5	27.3	31.5	12.0
COATING INITIAL THICKNESS (IN.)	0.0011	0.0003	0.0003	0.0003	0.001	0.0012	0.0011	0.0013	0.0006	0.0011	0.004	0.0048	0.005	0.0046
% THICKNESS REMOVED	100	100	100	100	80	66	64	100	100	100	97	100	100	100
THEORECTICAL SURF AREA CLEANED (IN^2)	0.68	0.68	0.83	0.66	0.66	0.7	0.73	0.73	0.73	0.52	0.81	0.95	0.9	0.81
MEASURED SURFACE AREA CLEANED (IN^2)	0.78	1.34	0.45	0.29	0.76	0.76	0.63	0.59	0.51	0.59	0.5	0.53	0.52	0.39
CLEANING EFFECIENCY (FRACTIOANL)	1.147059	1.970588	0.542169	0.439394	0.921212	0.716571	0.552329	0.808219	0.69863	1.134615	0.598765	0.557895	0.577778	0.481481
WORK VOL DENS (10^6 IN-LB/IN^3)	5.0	13.0	80.7	43.2	10.5	15.0	45.1	6.3	188.3	95.1	11.6	10.7	12.1	6.7
WORK SURF AREA DENS (10^3 IN-LB/IN^2)	7.2	15.1	7.1	2.5	8.9	9.2	15.1	5.3	55.2	134.7	16.6	16.1	20.2	7.2
BRUSH TIP VELOCITY (IN/SEC)	252	210	210	210	252	252	252	252	252	210	173.25	173.25	173.25	173.25
TEST NO.	42	43	44	45	46	47	48	49	50	51	52	53	54	55
BRUSH NO. - ELEMENT TYPE	8-O	8-O	3-O	3-O	3-O	3-O	3-O	5-O	5-O	5-O	6-O	5-O	5-O	4-O
DELTA % FULL POWER (fractional)	0.26	0.13	0.11	0.15	0.12	0.06	0.13	0.17	0.08	0.06	0.07	0.04	0.23	0.06
POWER (HP) ELECTRIC	0.416	0.208	0.176	0.24	0.192	0.096	0.208	0.272	0.128	0.096	0.112	0.064	0.368	0.096
INTERFERENCE (IN.)	0.08	0.06	0.08	0.08	0.08	0.07	0.08	0.03	0.04	0.04	0.04	0.04	0.06	0.07
INTERFERENCE (INFERRED)	0.021	0.023	0.03	0.033	0.051	0.048	0.043	0.05	0.049	0.049	0.049	0.035	0.042	0.043
FORCE - TANGENTIAL (LBS)	5.2	4.4	2.4	2.4	2.4	2.1	2.4	3	4	4	4	4	6	0.91
BRUSH - RADIUS (IN.)	3	3	4	4	4	4	4	4	4	4	4	4	4	4
TORQUE (IN.-LBS)	15.6	13.2	9.6	9.6	9.6	8.4	9.6	12	16	16	16	16	24	3.64
N (RPM)	700	700	500	500	600	500	500	500	600	700	750	600	600	500
POWER (HP) MECHANICAL	0.173	0.147	0.076	0.076	0.091	0.067	0.076	0.095	0.152	0.178	0.190	0.152	0.229	0.029
POWER (HP) - AVERAGE	0.295	0.177	0.126	0.158	0.142	0.081	0.142	0.184	0.140	0.137	0.151	0.108	0.298	0.062
TEST DURATION (SECONDS)	30	30	30	15	30	45	40	45	30	15	15	15	15	15
WORK (1000 IN.-LBS)	58.3	35.1	25.0	15.7	28.1	24.2	37.5	54.5	27.8	13.6	15.0	10.7	29.5	6.2
COATING INITIAL THICKNESS (IN.)	0.0051	0.0058	0.0055	0.0053	0.0045	0.0038	0.0031	0.0046	0.003	0.0022	0.0022	0.0026	0.003	0.001
% THICKNESS REMOVED	100	100	91	92	95	100	100	100	100	100	100	100	100	100
THEORECTICAL SURF AREA CLEANED (IN^2)	0.95	0.81	1.13	1.13	1.13	1.08	1.13	0.74	0.8	0.8	0.8	0.8	0.68	0.73
MEASURED SURFACE AREA CLEANED (IN^2)	0.57	0.59	0.6	0.66	0.98	0.81	0.8	0.92	0.93	1.06	1.06	0.7	0.84	0.7
CLEANING EFFECIENCY (FRACTIOANL)	0.6	0.728395	0.483186	0.537345	0.823894	0.75	0.707965	1.243243	1.1625	1.325	1.325	0.875	1.235294	0.958904
WORK VOL DENS (10^6 IN-LB/IN^3)	20.1	10.3	8.3	4.9	6.7	7.8	15.1	12.9	9.9	5.8	6.4	5.9	11.7	8.8
WORK SURF AREA DENS (10^3 IN-LB/IN^2)	36.8	31.6	10.7	7.4	20.5	16.8	23.5	91.6	40.3	22.4	24.8	11.7	53.6	8.1
BRUSH TIP VELOCITY (IN/SEC)	220.5	220.5	210	210	252	210	210	210	252	294	315	252	252	210

Table 4. Brushing Test Parameters and Results Continued).

RESULTS: BRUSHING TESTS

TEST NO.	56	57	58	59	60	61	62	63	64	65	66
BRUSH NO. - ELEMENT TYPE	4 - O	4 - O	4 - O	6 - O	6 - O	5 - O	6 - O	2 - O	2 - O	8 - O	8 - O
DELTA % FULL POWER (fractional)	0.12	0.13	0.16	0.1	0.13	0.12	0.11	0.33	0.17	0.29	0.43
POWER (HP) ELECTRIC	0.192	0.208	0.256	0.16	0.208	0.192	0.176	0.528	0.272	0.464	0.688
INTERFERENCE (IN.)	.05	0.06	0.06	0.06	0.08	0.08	0.08	0.09	0.08	0.08	0.08
INTERFERENCE (INFERRED)	0.048	0.045	0.045	0.082	0.088	0.09	0.088	0.036	0.037	0.03	0.045
FORCE - TANGENTIAL (LBS)	0.65	0.78	0.78	1.62	2.16	2.16	2.16	2.7	2.5	5.3	5.3
BRUSH - RADIUS (IN.)	4	4	4	4	4	4	4	4	4	4	4
TORQUE (IN.-LBS)	2.6	3.12	3.12	6.48	8.64	8.64	8.64	10.8	10	21.2	21.2
N (RPM)	500	550	600	600	550	500	550	550	550	700	700
POWER (HP) MECHANICAL	0.021	0.027	0.030	0.062	0.075	0.069	0.075	0.094	0.087	0.236	0.236
POWER (HP) - AVERAGE	0.106	0.118	0.143	0.111	0.142	0.130	0.126	0.311	0.180	0.350	0.462
TEST DURATION (SECONDS)	15	15	15	15	15	15	10	10	5	15	15
WORK (1000 IN.-LBS)	10.5	11.6	14.1	11.0	14.0	12.9	8.3	20.5	5.9	34.6	45.7
COATING INITIAL THICKNESS (IN.)	0.0008	0.0008	0.0007	0.001	0.001	0.0014	0.0011	0.001	0.001	0.0005	0.0001
% THICKNESS REMOVED	100	100	100	100	100	100	100	100	100	100	100
THEORECTICAL SURF AREA CLEANED (IN^2)	0.68	0.73	0.73	0.65	0.75	0.75	0.75	0.92	0.84	0.95	0.73
MEASURED SURFACE AREA CLEANED (IN^2)	0.78	0.76	0.77	1.53	1.01	1.13	1.04	0.77	0.73	0.73	0.84
CLEANING EFFECIENCY (FRACTIOANL)	1.147059	1.041096	1.054795	2.353846	1.346667	1.506667	1.386667	0.836957	0.869048	0.768421	1.150685
WORK VOL. DENS. (10^6 IN-LB/IN^3)	16.9	19.2	26.2	7.2	13.9	8.2	7.3	26.7	8.1	94.9	544.2
WORK SURF AREA DENS (10^3 IN-LB/IN^2)	17.8	16.6	20.4	39.7	25.2	25.9	15.3	18.7	6.1	28.0	72.1
BRUSH TIP VELOCITY (IN./SEC)	210	231	252	252	231	210	231	231	231	294	294

7.4 BRUSHING TEST DATA AND RESULTS

Brushing data recorded during testing are given in the test logbook (Baker 1998). Here parameters such as brush angular velocity (RPM), motor power differential, fuel-brush interference, and brushing duration are recorded. In addition to these data, post test measurement were taken from the video tape to determine the extent (size) of the cleaned area. Most of this data can be found in Table 4.

Cleaning effectiveness is evaluated here by the amount of work (W) per unit volume of coating removed. Hence, the brushing parameter which "cleans" at the lowest work density is the most effective.

The amount of work is determined by two independent methods; electrical and mechanical measurements. By comparing these two methods, confidence (or lack thereof) can be demonstrated. In both cases, the power is determined and multiplied by the test duration (time) to obtain the total integrated work.

The electrical power used in brushing is determined by measuring (as percent power on the motor control unit) the difference in electric current (I) just before brushing (hydraulic + friction) and at brushing (hydraulic + friction + brushing) at a given speed. Power, P, is determined by:

$$P(kW) = V*\Delta I*E/1000.$$

where:

V is the voltage (460 V)

I is the current in amperes and is determined from
(Δ% full power)*3.4 amps (full power rating of controller)

and

E is the motor efficiency as given by the manufacture (0.77)

Hence,

$$P\ (kW) = 1.20*\Delta\%\ \text{full power measurement}$$

or in terms of horsepower (HP):

$$P\ (HP) = 1.60*\Delta\%\ \text{full power measurement}$$

It is believed that the calculated power from electrical measurement is conservative. This is because the motor efficiency given by the vendor is a maximum value near the full rated speed. These tests, however, ran at 12% to 22% of full rated speed, where a lower efficiency is expected. This was evident in testing when the motor slowed and even stalled in some instances.

The brushing mechanical power is determined by:

P (HP) = T*N/63,000.

where:

T is the torque in in.-lb
N is angular velocity in RPM

Here the torque, T, is determined from:

$T = r*F_t$

Here, r is the radius of the brush (inches) and F_t is the tangential force (lb) as determined from brush calibrations. F_t is determined from the calibration curves as given in Figure 14, using the measured interference. Correction factors for brush stiffnesses to account for the machine stiffness were not felt necessary as the error introduced was less than 10% in all but two brushes (Number 5 and Number 8) in vertical locations above the clamp, where the maximum error was in the range of 20%. This reduction in effective stiffness is expected to be somewhat offset by the increased stiffness due to the addition of the end-plates.

Brushing efficiency, E_b, is defined as the measured cleaned area multiplied by the percent thickness cleaned divided by the theoretical brushed area. The theoretical brushed area is defined as the brush face width multiplied by the interference arc between the fuel and the brush, as given in Appendix C.

Results of all the brushing tests, along with brushing data and intermediate reduced data, are given in Table 4 (Excel spread-sheet). The calculated power used in the work calculations is the average of the electrical and mechanical power values, and hence is expected to be conservative. Results in work/unit volume and work/unit surface area are presented. The latter is expected to be of importance if the coating removal were by a "brittle" mechanism.

One of the goals in testing was to determine removal threshold values. On the one hand, early test runs were of long durations because of a "lack of knowledge", and gave very conservative work values. On the other hand, short test durations (<10 s) are not easy to accurately assess because of the effect of "feed-in" and "feed-out" time durations. Hence, test runs were generally not of short enough durations to assess thresholds. Data from long runs (>45 s) were generally not evaluated.

Figure 16 shows the amount of work/volume of coating removed as a function of fuel-brush interference for each of the regular wire wheel steel (carbon and stainless) brushes. Figure 17 gives the same type plot for the other brushes, i.e., knot-twist, brass, and ceramic grit impregnated filaments. These plots also show the effect, if any, of brushing velocity for each of the brushes. Figure 18 shows the brushing efficiency of the eight brushes as a function of brush tip velocity. This figure shows data for a selected run duration (15 s) only to evaluate the relative performance of the various brushes. It is important to point out that the results in Figure 18 are not

Figure 16. Brushing Test Results--Work/Unit Volume of Coating Removed. (Regular Steel Wire Brushes)

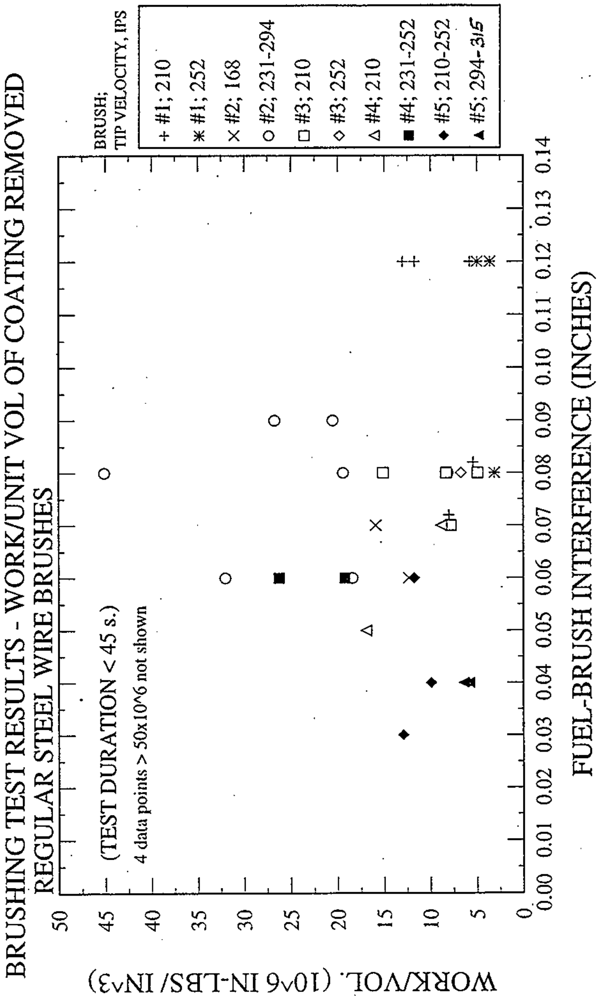


Figure 17. Brushing Test Results--Work/Unit Volume of Coating Removed. (Brushes Number 6, Number 8, and Number 9)

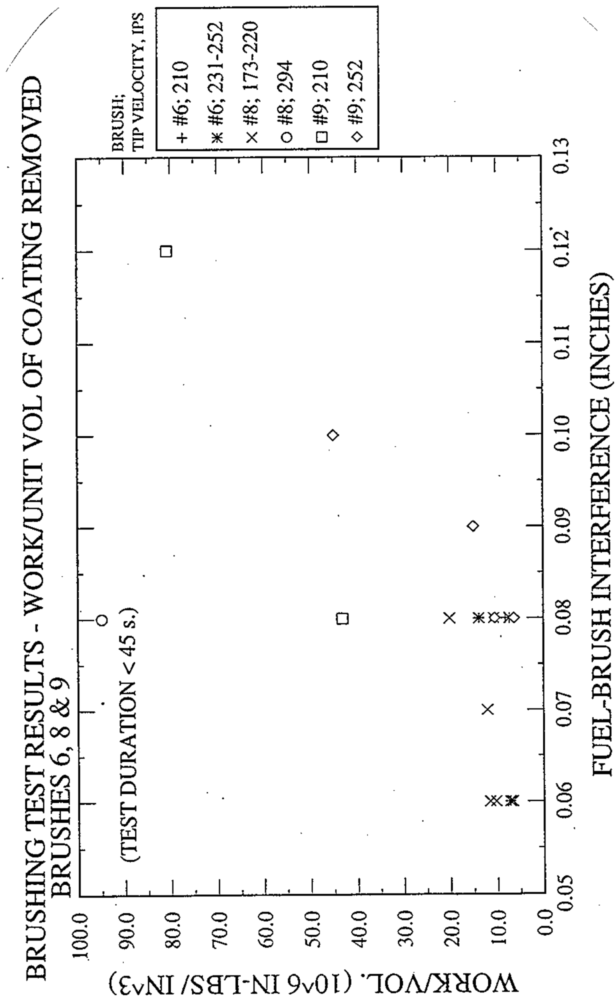
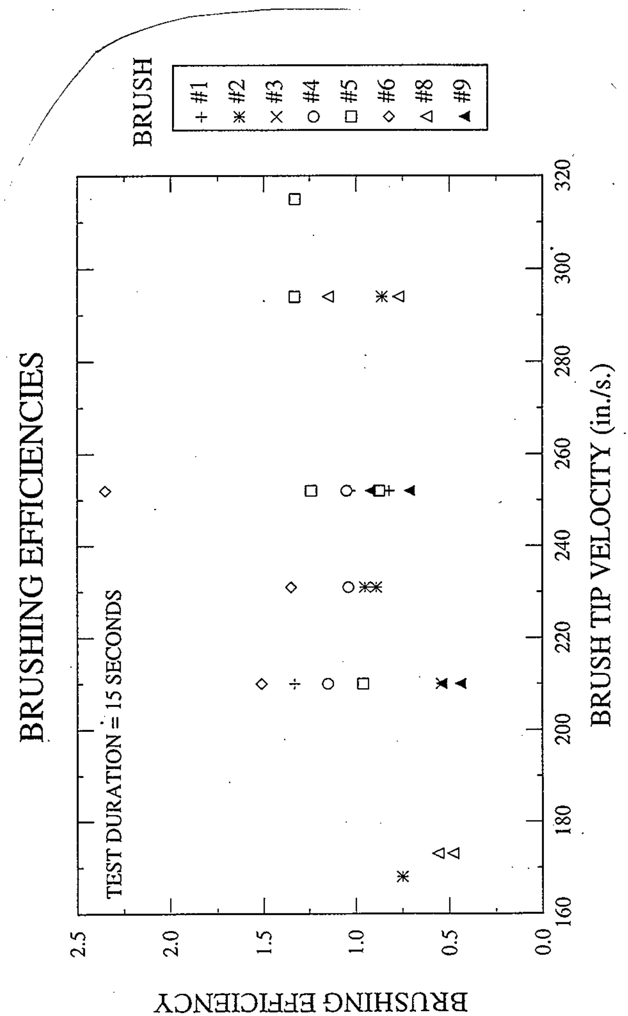


Figure 18. Brushing Efficiencies.



based on a uniform coating, and hence results may be misleading (see Section 7.5). Figures 19 and 20 show the work/surface area of coating removed as a function of interference and velocity for the two groups of brushes.

7.5 DISCUSSION OF BRUSHING RESULTS AND QUALITATIVE OBSERVATIONS

All brushing tests removed or partially removed the $Al(OH)_3$ coating. Hence, given sufficient time and power, the coating could be removed by any of the brushes tested. The coating did not generally appear to be brittle in nature (i.e., did not flake off readily) but appeared to behave like a painted surface. A primary goal here is to determine which brushes and operation conditions are the most effective in coating removal.

The results given in Figures 16 and 17, i.e., the work/volume of coating removed, is the primary design data objective of this study. Unfortunately, these data are conservative values and represent an over-cleaned condition. Here, cleaning thresholds were not ascertained, primarily due to the minimum test durations and the limited coating levels on the majority of the elements. Furthermore, additional conservatism is likely introduced due to the manner in which the work was calculated (see Section 7.4). For the most representative data, i.e., short duration and moderate to thick coating, work/volume values generally range from 3 to 12 x 10^6 in.-lb/in^3 (see Table 4). (An exception to this was the non-wire brush, Number 9, which required higher work densities). Based on the above, a design value of 5 x 10^6 in.-lb/in^3 is suggested. For the thickest coating of 0.006 in., this translate to 30,000 in.-lb of work per square inch of surface area cleaned, which is consistent with the results given in Figures 19 and 20. Putting this into perspective with respect to a production brushing machine, it would require a 15 HP unit working 1 minute to clean a 0.006 in. thick coating from the outer surface (197 in^2) of an outer fuel element.

Results presented in Figures 16 and 17 do not show any noticeable effect of brush-fuel interference on the work density required for cleaning over the ranges tested. Additionally, there is no general effect of brushing velocity on cleaning effectiveness, with the possible exceptions of Brush Number 5 (the stiffest and largest wire diameter brush) and Brush Number 9 (an abrasive action brush). Both of these brushes appear to exhibit increased cleaning effectiveness with increased velocity.

In comparing the relative merits of the various brushes, several factors need to be taken into considerations. A key factor is that the amount of coating available for testing was not uniform and was basically determined by the "luck of the draw" for a given test or brush. This variation in thickness could significantly effect the amount of conservatism inherent in the results. Testing with Brushes Number 3 and Number 8 was performed on thick coating, whereas testing with Brushes Number 4 and Number 9 occurred on thin coating. The use of work/unit volume values is an attempt to normalize this data; however, it probably only impacts the amount of conservatism in the data. Tests on thick coating are less conservative (closer to threshold) than tests on thin coating, all else being equal.

Figure 18 gives the brushing efficiencies (as defined in Section 7.4) as a function of velocity for the eight brushes tested. Data evaluated were for the same test durations (15 s), but varied in coating thickness. In general

Figure 19. Brushing Test Results--Work/Unit Surface Area of Coating Removed. (Regular Steel Wire Brushes).

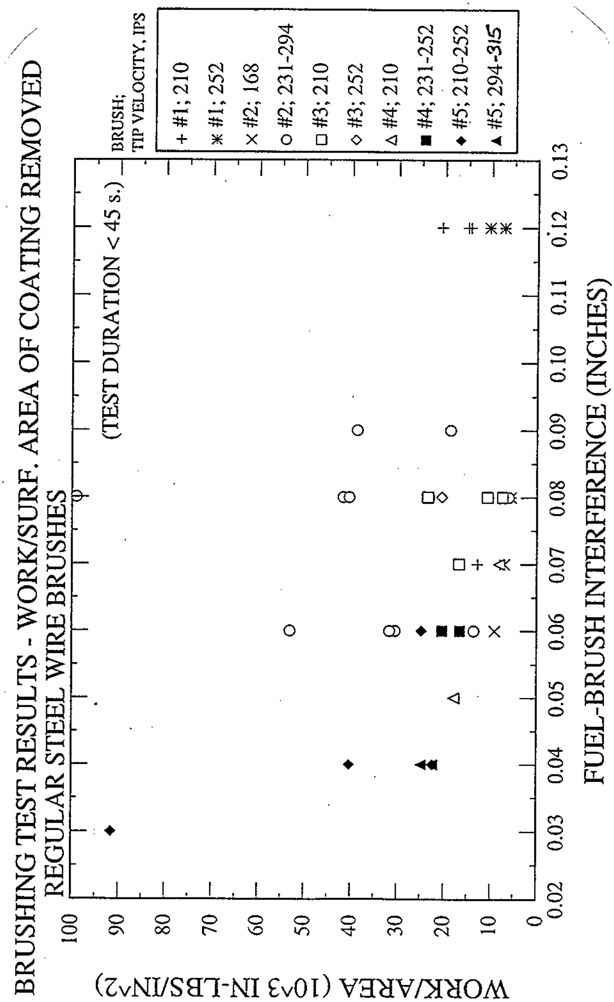
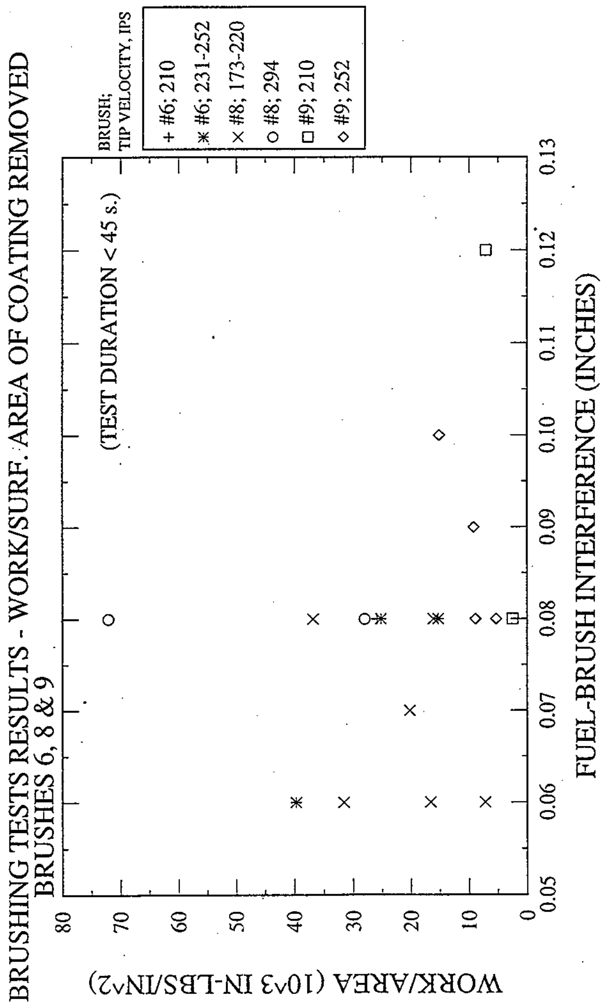


Figure 20. Brushing Test Results--Work/Unit Surface Area of Coating Removed. (Brushes Number 6, Number 8, and Number 9).



there appears to be an increase in brushing efficiency with increasing velocity, but most of this can probably be attributed to the additional work done at the higher velocities for a given time duration. Results presented in Figure 18 indicate that Brush Number 6 (the knot-twist) and Brush Number 5 (the stiffest and largest wire diameter) are the most effective. These brushes also show relatively low work/volume values in Figures 16 and 17. Observations made in reviewing video tape showed that these two most aggressive brushes exhibit a slight "chipping" behavior in removing coating; small chips (~0.1 in.) were found to have flaked off beyond the extent of the contact brushing area. This suggests some slight brittle nature of the coating under the "beating" action of these brushes. This behavior was not noticed in any of the other brushes. Another observation made was that Brush Number 5 left significant scratch marks on the coating, which could cause cladding damage on degraded fuel elements.

Results given in Figure 18 indicate that the least effective brushes tested were Brush Number 9 (ceramic grit impregnated nylon filaments) and Brush Number 8 (brass - large wire diameter). Brush Number 9 did not clean through the full thickness of the coating in a number of test runs. This is most likely due to the abrasive cleaning action of this type of brush, where discrete layers are removed at a time. For the brass brush, the cleaned area was significantly smaller than the theoretical brush contact area (50% to 60%). This is likely due to the "softness" of brass relative to the steel in the other brushes, and therefore less effectiveness in abrading. Brass was in fact observed to be deposited onto the fuel cladding during the brushing process. There does not appear to be any significant performance difference between carbon and stainless steel brushes of the same geometric design.

Figures 19 and 20 show the work/unit surface area cleaned for various bushes and velocities as a function of fuel-brush interference. These values, like those of Figures 16 and 17, are not threshold values and hence are conservative. If the values here were threshold cleaning values, it might be possible to determine if cleaning were a brittle mechanism; i.e., not dependent on coating thickness. These plots also provide confirmation of the work density design value of 30,000 in.-lb/in^2 as derived from the results presented in Figures 16 and 17.

7.6 CONCLUSION AND RECOMMENDATIONS ON BRUSHING

The majority of the brushes tested effectively removed the $Al(OH)_3$ coating from the fuel elements. Standard wire wheel or knot-twist brushes made of steel (carbon or stainless) were more effective in cleaning than either brass wire wheel or ceramic impregnated filament type brushes of the same size. Should a production brushing machine be designed for removal of the $Al(OH)_3$ coating from fuel elements; the following parameters are suggested:

Work required:	30,000 in.-lb/(in^2 of cladding surface area)
Brush type/material:	Standard wire-wheel of stainless steel
Brush wire diameter:	0.006 in. to 0.014 in.
Brush trim length:	1.3 in. to 1.7 in.
Brush packing density:	High to moderate
Brush tip velocity:	>200 in./s
Brush-fuel interface:	0.03 in.-0.12 in.

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Silvers, K. L., 1998, "Formation of Aluminum Hydroxide Coating on Zirconium (Zircaloy 2) Tubing Coupons in Support of KW Fuel Element Processing," Letter 28964-03, Rev. 1, dated ??, 1998, Pacific Northwest National Laboratory, Richland, Washington.

Trimble, D. J., 1997, *Analysis of Water from K West Basin Canisters (Second Campaign*, HNF-SD-SNF-TI-048, Rev. 0, Duke Engineering & Services Hanford, Inc., Richland, Washington.

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A P P E N D I X A

EDDY CURRENT PROCEDURE AND TEST REPORT

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Westinghouse Hanford Company

EDDYCURRENT PROCEDURE AND TEST REPORT

NONDESTRUCTIVE EXAMINATION
306 BLDG., 300 AREA - TEL. 376-5401

Job No.: 98-1
Request/Inst. No.: N/A

Requester (client)	Company	MSIN	Bldg.	Area	Project/System
AL Pitner / A.E. Bridges	DESH	H0-40	3770	300	Fuel Element Coating Removal and Measurement Testing, Work Package 1H-98-01887/W
QA Rep.	X NA	MSIN	Bldg.	Area	

Acceptance Std. Section Para. Date X NA
Dwg. No. X NA
NCR X NA
RCT

PART INFORMATION	
Material	ZR-2
Wall/Material Thickness	X NA
Diameter	X NA
Schedule	X NA

TYPE INSPECTION
- ☐ Flaw Detection
- ☒ Thickness Measurement
- ☐ Sorting
- ☐ Other

HEDL PROCEDURE NO.
- ☒ NDT-ET-2000 Rev. 3
- ☐ Other

Special Tech. No. NDT-ET-2003-3
☐ NA

AREA TO BE INSPECTED
- ☐ Full Inspection: 100% of Area Requested.
- ☒ Other Areas Designated by Test Engineer

INSTRUMENTATION

Tester Mfg'r: ZETEC
Model #: MIZ-40 S/N: 233
Standards Lab #: SEE PAGE 2
Expiration Date:

INSTRUMENTATION SETTINGS

Test Frequency: N/A kHz 6 MHz
R Balance: N/A X Balance: N/A
Phase: Rotate Signal To Vertical Sensitivity: 13
Inductance (L): N/A
Capacitance (C):

RECORDINGS

CHART RECORDER X N/A
Mfg'r: Model #:
PM #: Expiration Date:
Chart Speed: Diff. Recording ☐ Yes ☐ No
Sensitivity (1):

TAPE RECORDER X N/A
Mfg'r: Model #:
Stds Lab. #: Expiration Date:
Tape Speed: Diff. Recording ☐ Yes ☐ No
Mag Tape Reel #: Side:

CALIBRATION STANDARD ☐ N/A

Standards Lab #: SEE PAGE 3
Expiration Date:
☐ FBH Diameter Depth
☐ Notch Width Depth Length
☐ Side Drilled Hole Diameter Length

- ☐ Coil
- ☒ Probe Mfg'r ZETEC S/N 291836, 291837, 291973, 291974
- ☒ Absolute
- ☐ Differential
- ☐ Cross-Axis

PART NO. OR SERIAL NO.	ACC.	REJ.	No Ind.	REMARKS
Fuel Elements	—	—	—	SEE Log book HNF-N-1351 for Calibration
SEE Log book for Element				Data and Coating Thickness Measurements
ID.				
				SEE Page 2 for Instrument Calibration
				SEE Page 3 for Standards Calibration

Technician	ET Level	Interpreted by	ET Level II	ET Level III Review
KM Kowitz (signature)	II	Robert M Kowitz (signature)	II	Charles N. Jackson Jr (signature)
Date 7-14-98 Thru 8-5-98		Date 7-14-98 Thru 8-5-98		Date 8/6/98

BD-7330-065 (6-87)

Page 2 of 3

ZETEC
1370 NW Mall St. • PO Box 140
Issaquah, WA 98027-0140 USA
(800) 643-1771 • (206) 392-5316
FAX • (206) 392-2086

Z-OA 8A REV. 17

CONDITION CODE: B
OWNER: ZETEC MANUFACTURING

Zetec, Incorporated hereby certifies that the following instrument meets or exceeds all manufacturer's specifications.

Instrument: MIZ-40
Serial Number: 233

The calibration of this instrument is controlled by approved, documented procedures which meet or exceed ASME Section XI, Appendix IV and ASME Section V Article 8, Appendix I, through 1989 Edition December 1990 Addenda.

Calibration has been performed using standards whose accuracies are traceable to the National Institute of Standards and Technology.

STANDARDS USED: / 1817 / 1137 / 2881 / 019		
CALIBRATION DATE:	30 Jun 1998	
CALIBRATED BY:	DAN KOWITZ	Dan Kowitz TECHNICIAN
CERTIFICATION DATE:	30 Jun 1998	
EXPIRATION DATE:	30 Dec 1998	
CERTIFIED BY:	GRIFF NUTTALL	G. Nuttall

COMMENTS: UNIT HAS TWO ANALOG CARDS & DI/O OPTION.
ABOVE 1 MHZ UNIT MEETS MFG. SPECIFICATION ONLY.

OCRWM

CERTIFICATE NUMBER A: 58560

Page 3 of 3

WASHINGTON PUBLIC POWER
SUPPLY SYSTEM

FUNCTIONAL TEST REPORT
WPPSS STANDARDS LABORATORY

TESTED FOR: AL PITNER

MANUFACTURER	MODEL NO.	SERIAL NO.
PRECISION	NONE	NONE

P. O. NO.	CONDITION
NONE	PASSED

TEST REQUIREMENTS
Measure and report the thickness of the shims to a value of +/- 0.0001 inches (+/-0.1 Mils).

TEST PERFORMED

The shims were measured with a Hewlett-Packard 5508A Laser Measurement System, Cal Code # C019012-00, Calibrated 20 February, 1998, Due for recalibration 20 February, 1999, Coupled to a Pratt & Whitney Laser Measuring Machine, Cal Code # 45044-00, Calibrated 7 April, 1998, Due for recalibration 7 April, 1999. The accuracy of this system is +/- 10 Micro Inches (+/-0.01 Mils) from 0 to 1.5 inches.

EXPECTED READING	ACTUAL READING	CONDITION	
1.000 Mils	1.036 Mils	PASS	AMBER
2.000 Mils	2.094 Mils	PASS	RED
3.000 Mils	3.101 Mils	PASS	GREEN
5.000 Mils	4.977 Mils	PASS	BLUE
7.500 Mils	7.743 Mils	PASS	MATTE
10.000 Mils	10.604 Mils	PASS	BROWN

PASS CRITERIA IS +/- 10% OF EXPECTED VALUE.

OCRWM

TESTED BY	DATE	REVIEWED BY	DATE
[signature]	7-9-98	[signature]	7-9-98

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APPENDIX B

BRUSHING TEST SYSTEM DRAWINGS, SKETCHES, AND DESIGN INFORMATION

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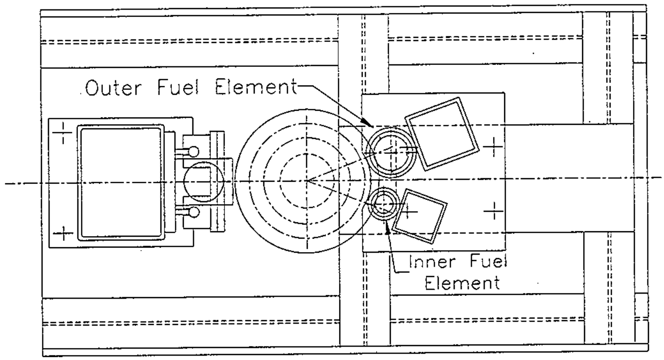
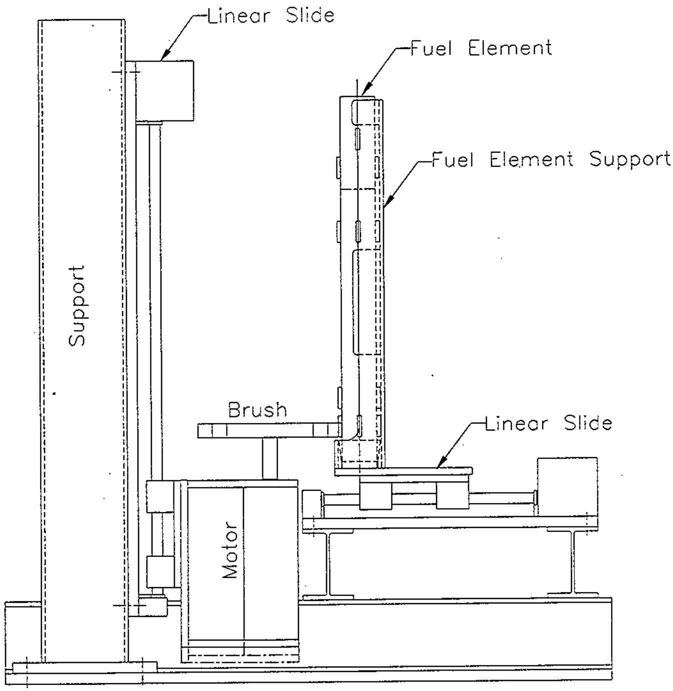
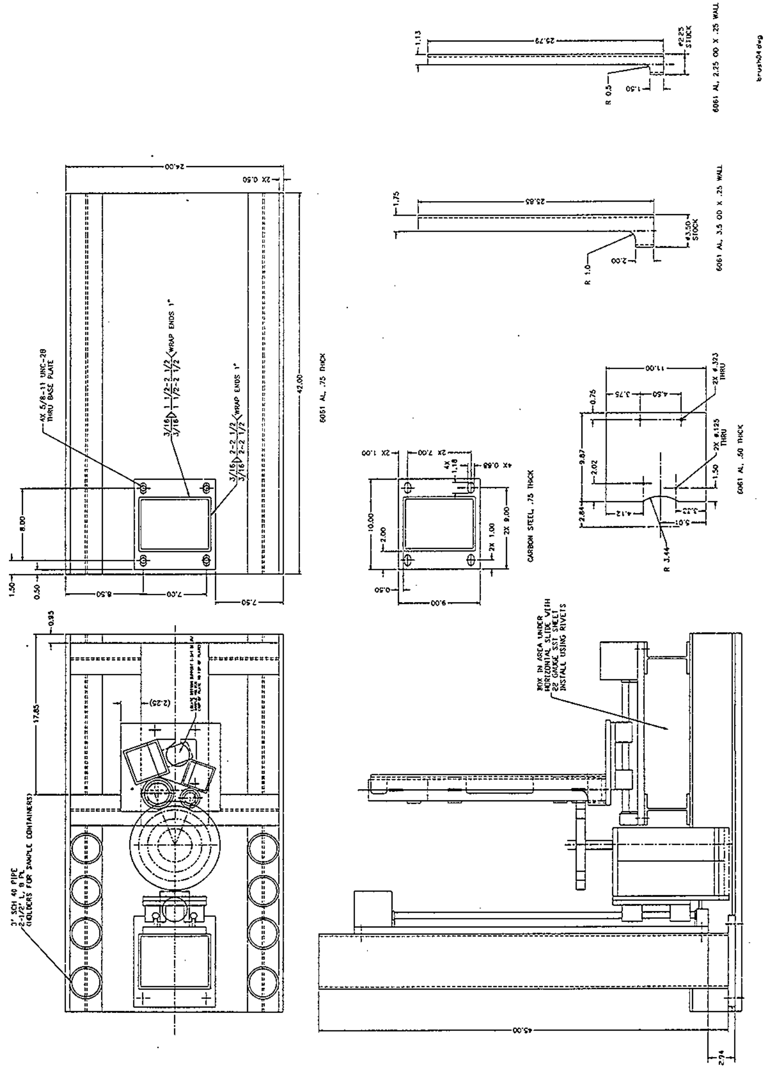
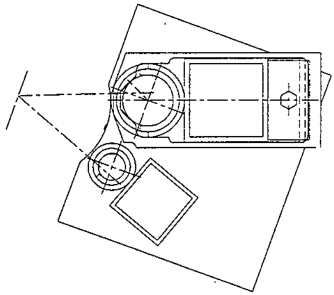

Outer Fuel Element
Inner Fuel Element

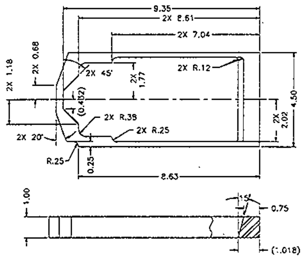

Linear Slide
Fuel Element
Fuel Element Support
Support
Brush
Linear Slide
Motor


6061 AL 2.25 OD X .25 WALL
6061 AL 3.5 OD X .25 WALL
6061 AL .75 THICK
CARBON STEEL .75 THICK
6061 AL .50 THICK
4X 5/8-11 UNC-2B THRU BASE PLATE
BOX IN AREA UNDER HORIZONTAL SLIDE WITH 22 GAUGE SST SHEET INSTALL USING RIVETS
3" SCH 40 PIPE 2-1/2" L, 8 PL (HOLDERS FOR SAMPLE CONTAINERS)

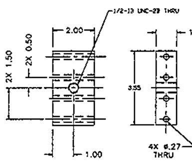
LARGE CLAMP DETAILS



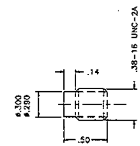
A – A



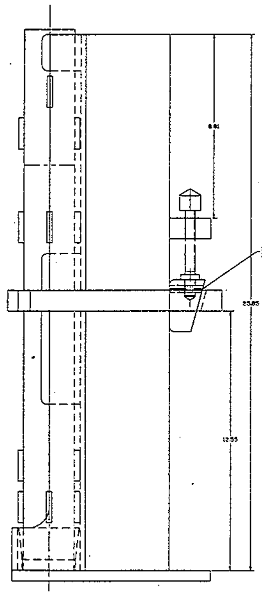
LARGE CLAMP



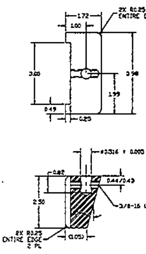
LARGE BLOCK



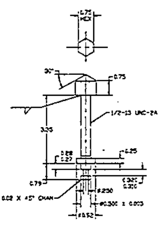
SET SCREW
4X



B – B

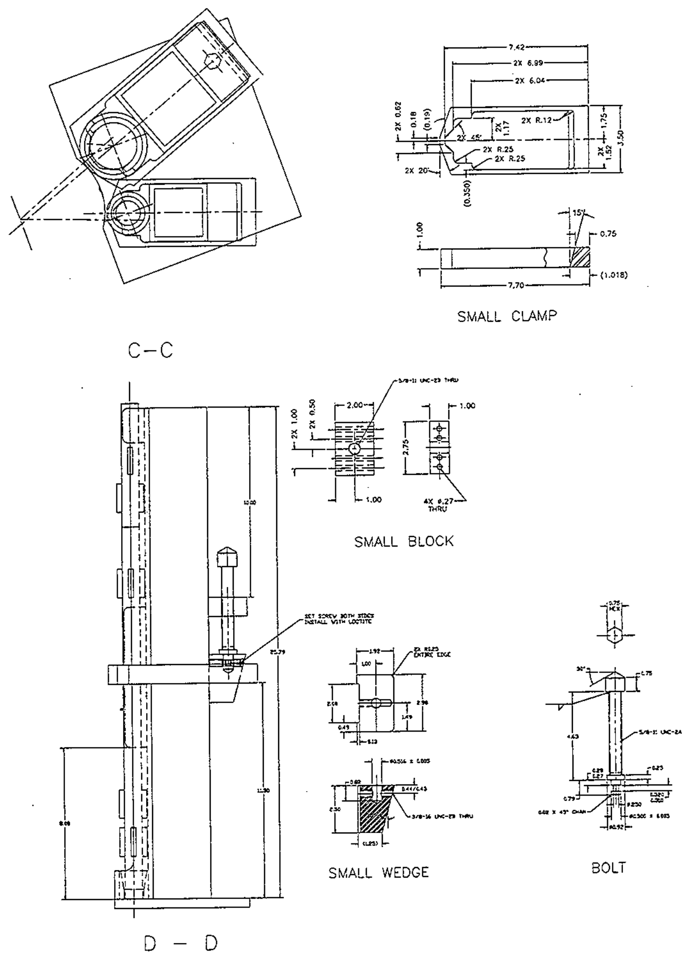


LARGE WEDGE

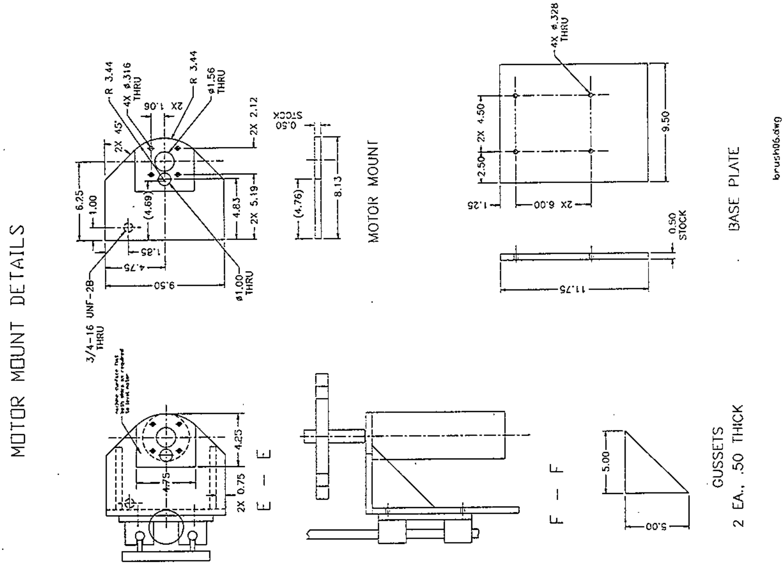


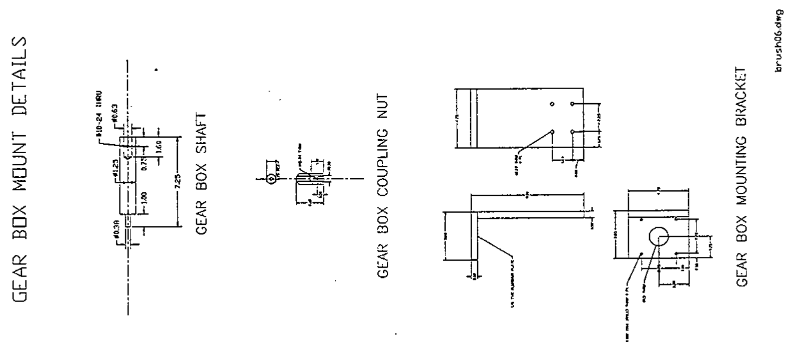
BOLT

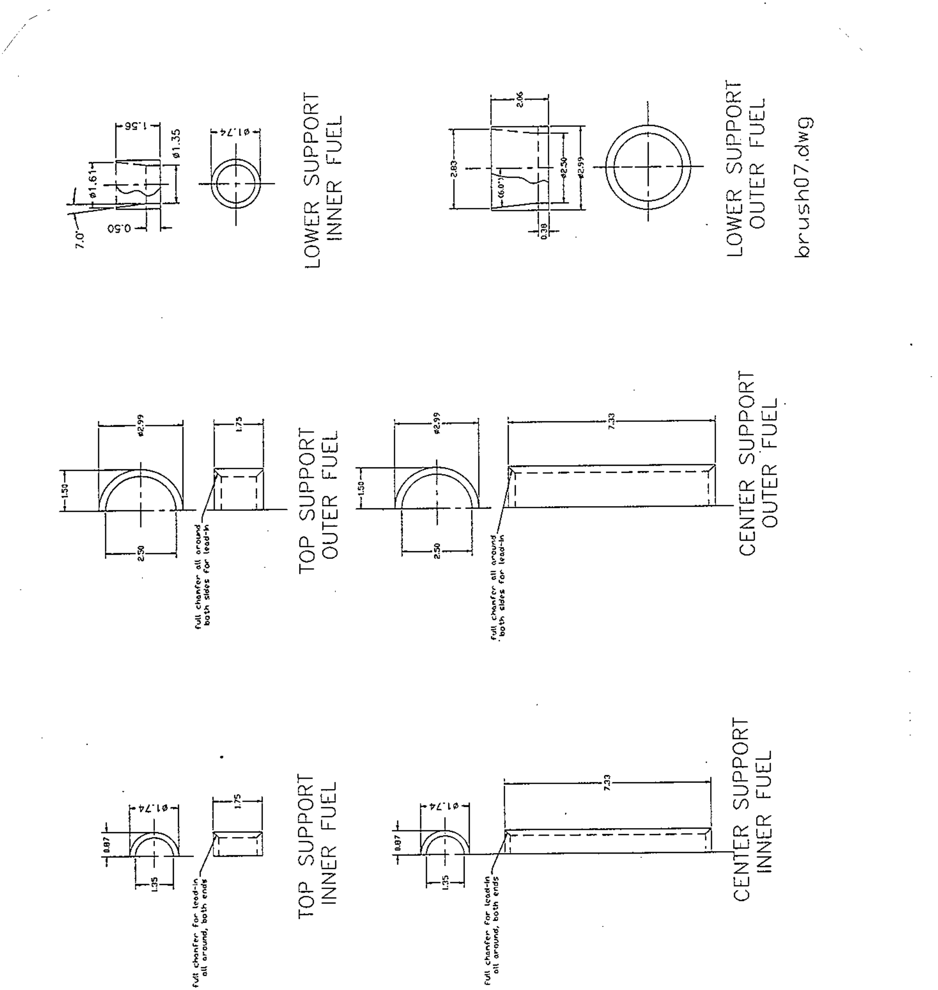
brush03.dwg

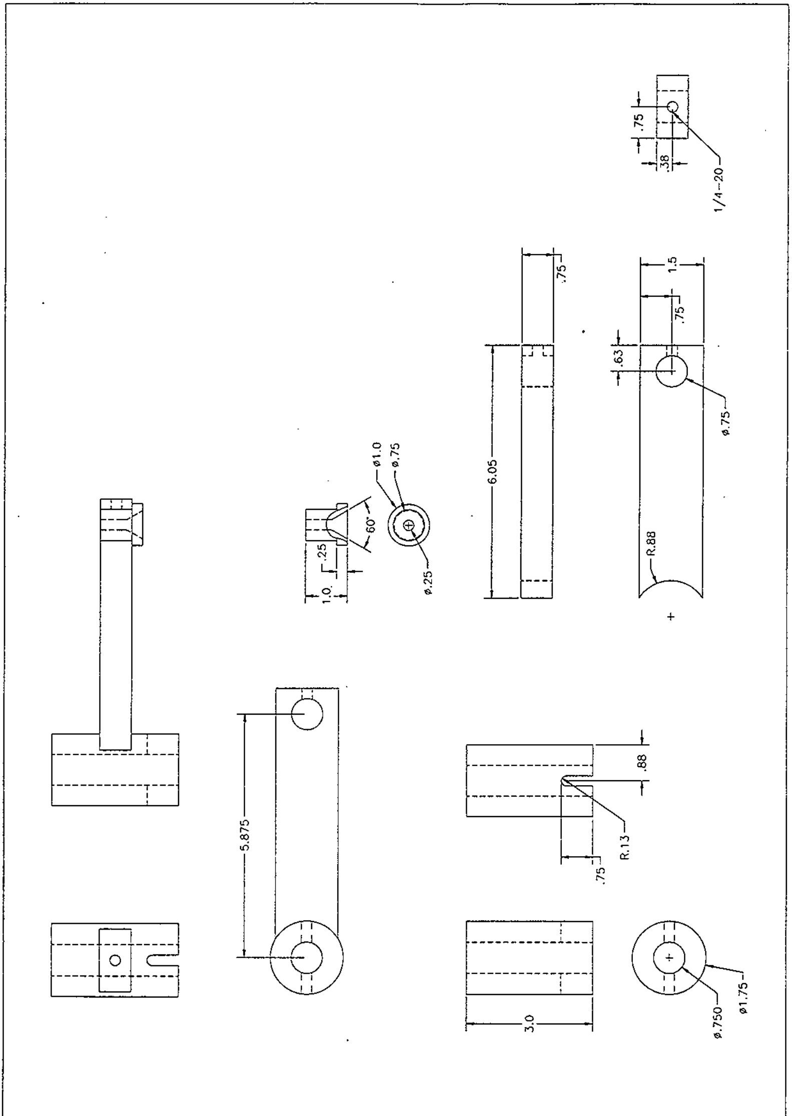

7.42
2X 6.99
2X 6.04
2X 0.62
0.18
(0.19)
2X 45°
2X 1.17
2X R.12
1.75
3.50
2X 1.52
2X R.25
2X R.25
2X 20°
(0.350)
15°
1.00
0.75
(1.018)
7.70
SMALL CLAMP
C–C
5/8-11 UNC-2B THRU
2.00
2X 1.00
2X 0.50
1.00
1.00
2.75
4X ⌀.27 THRU
SMALL BLOCK
SET SCREW BOTH SIDES INSTALL WITH LOCTITE
SMALL WEDGE
BOLT
D – D

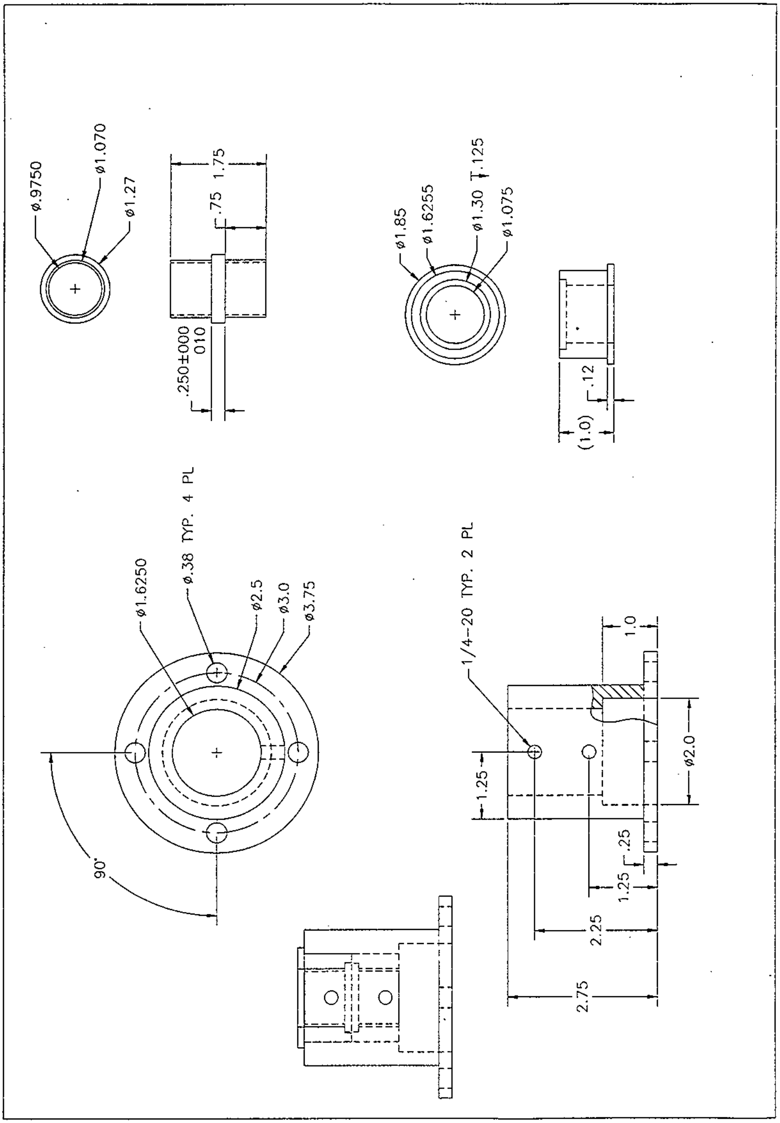
brush05.dwg


MOTOR MOUNT DETAILS
MOTOR MOUNT
BASE PLATE
E – E
F – F
GUSSETS
2 EA., .50 THICK
brush06.dwg

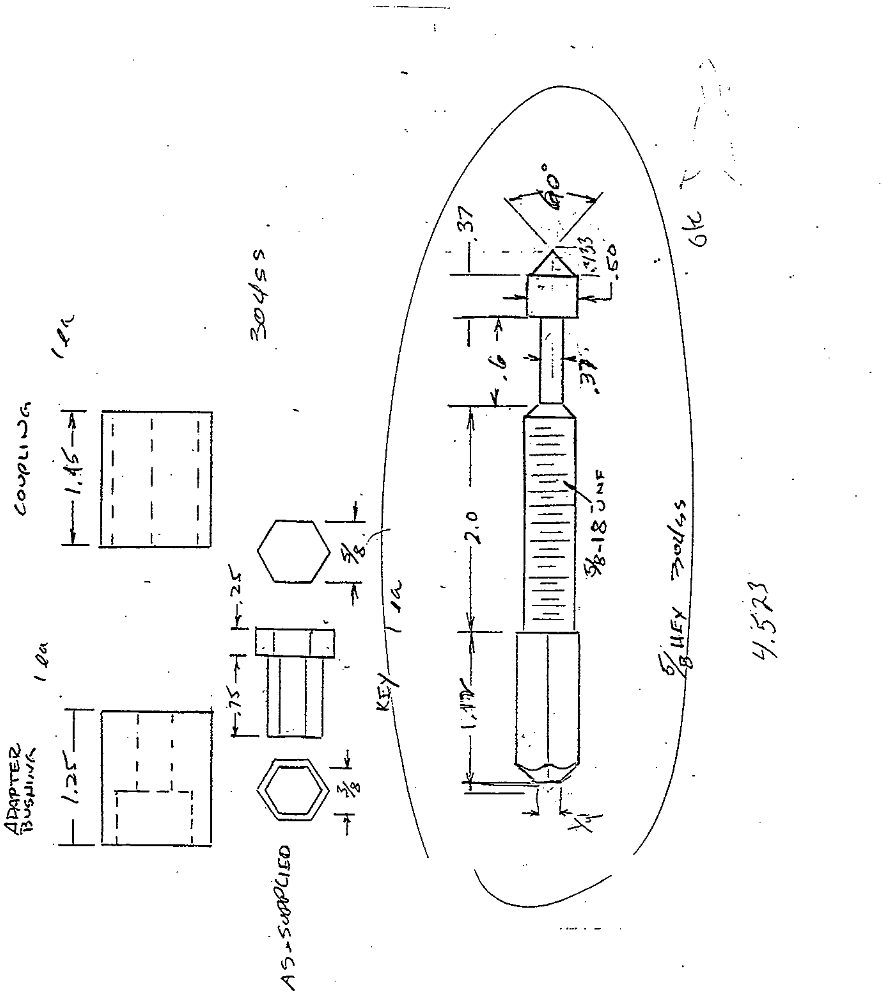

GEAR BOX MOUNT DETAILS
GEAR BOX SHAFT
GEAR BOX COUPLING NUT
GEAR BOX MOUNTING BRACKET
brush06.dwg

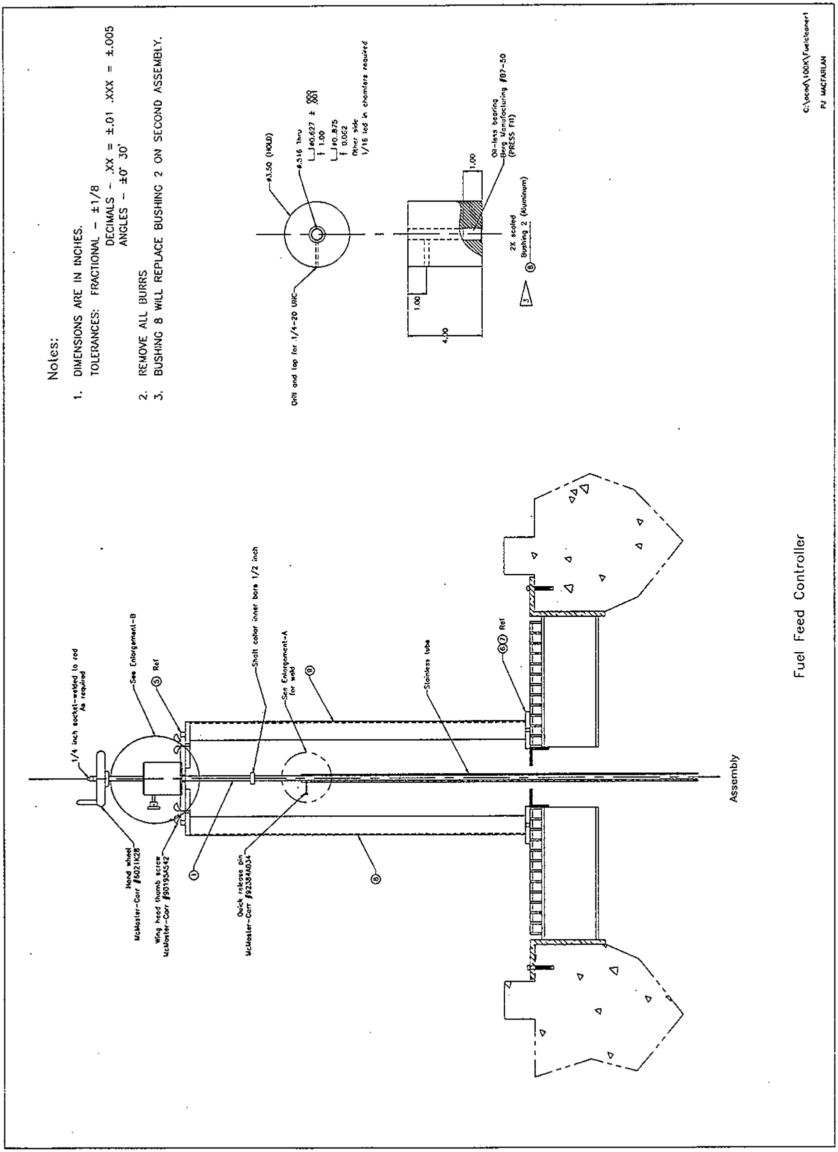

LOWER SUPPORT
INNER FUEL
LOWER SUPPORT
OUTER FUEL
brush07.dwg
TOP SUPPORT
OUTER FUEL
CENTER SUPPORT
OUTER FUEL
TOP SUPPORT
INNER FUEL
CENTER SUPPORT
INNER FUEL
full chamfer all around
both sides for lead-in
full chamfer for lead-in
all around, both ends

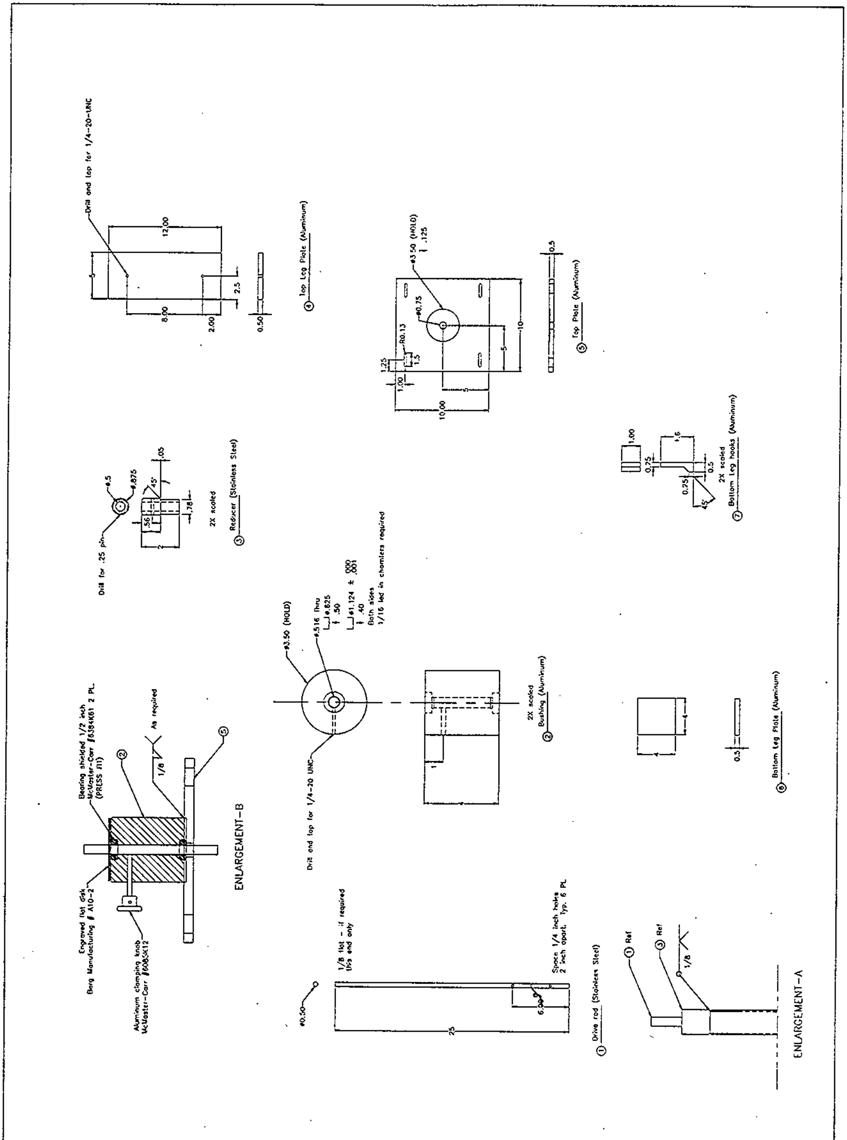

.75
.38
1/4-20
.75
1.5
.75
.63
ø.75
6.05
ø1.0
ø.75
60°
.25
1.0
ø.25
R.88
5.875
.88
R.13
.75
3.0
ø.750
ø1.75

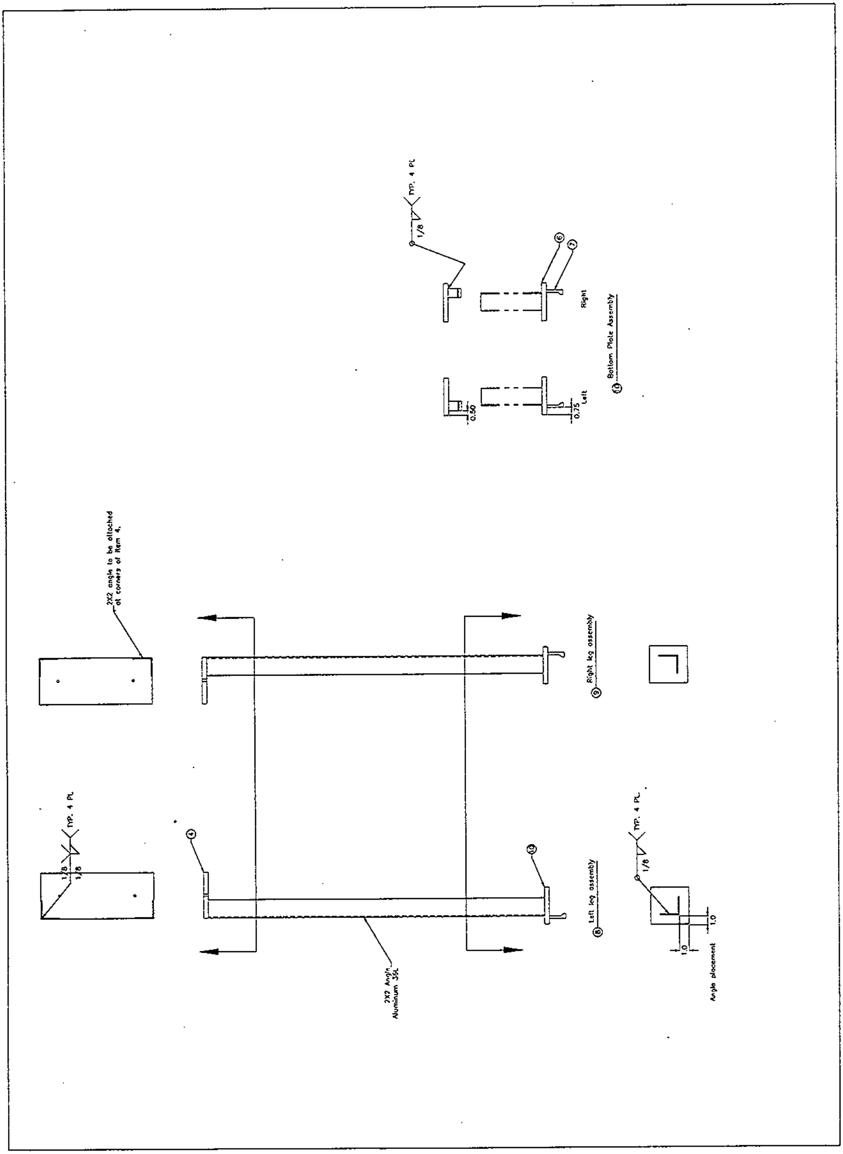


ϕ.9750
ϕ1.070
ϕ1.27
1.75
.75
.250±000
010
ϕ1.85
ϕ1.6255
ϕ1.30 T.125
ϕ1.075
.12
(1.0)
ϕ1.6250
ϕ.38 TYP. 4 PL
ϕ2.5
ϕ3.0
ϕ3.75
90°
1/4-20 TYP. 2 PL
1.0
ϕ2.0
1.25
.25
1.25
2.25
2.75


COUPLING
1.45
1 ea
ADAPTER BUSHING
1.25
1 ea
AS-SUPPLIED
304SS
.75
.25
5/8
3/8
KEY
1 ea
60°
.37
.133
.50
.6
.37
2.0
5/8-18 UNF
1.17
5/8 HEX 304SS
4.573
ok


Notes:
1. DIMENSIONS ARE IN INCHES.
TOLERANCES: FRACTIONAL - ±1/8
DECIMALS - .XX = ±.01 .XXX = ±.005
ANGLES - ±0° 30'
2. REMOVE ALL BURRS
3. BUSHING 8 WILL REPLACE BUSHING 2 ON SECOND ASSEMBLY.
1/4 inch socket-welded to rod As required
Hand wheel McMaster-Carr #6021K28
See Enlargement-B
Wing head thumb screw McMaster-Carr #90195A542
5 Ref
1
Quick release pin McMaster-Carr #92384A034
Shaft collar inner bore 1/2 inch
See Enlargement-A for weld
9
8
Stainless tube
6 7 Ref
Assembly
ø3.50 (HOLD)
Drill and tap for 1/4-20 UNC
ø.516 thru
ø0.627
1.00
ø0.875
0.062
Other side
1/16 led in chamfers required
1.00
4.00
1.00
Oil-less bearing
Berg Manufacturing #B7-50
(PRESS Fit)
2X scaled
3
8
Bushing 2 (Aluminum)
Fuel Feed Controller
C:\acad\100K\Fuelcleaner1
PJ MACFARLAN


Drill and tap for 1/4-20-UNC
④ Top Leg Plate (Aluminum)
⑤ Top Plate (Aluminum)
③ Reducer (Stainless Steel)
2X scaled
⑦ Bottom Leg hooks (Aluminum)
2X scaled
② Bushing (Aluminum)
2X scaled
⑥ Bottom Leg Plate (Aluminum)
Drill and tap for 1/4-20 UNC
Both sides
1/16 led in chamfers required
ENLARGEMENT-B
Bearing shielded 1/2 inch McMaster-Carr #6384K61 2 PL (PRESS FIT)
As required
Engraved flat disk Berg Manufacturing # A10-2
Aluminum clamping knob McMaster-Carr #6083K12
1/8 flat - if required this end only
Space 1/4 inch holes 2 inch apart. Typ. 6 PL
① Drive rod (Stainless Steel)
① Ref
③ Ref
ENLARGEMENT-A


TYP. 4 PL
1/8
Right
Left
0.50
0.75
Bottom Plate Assembly
2X2 angle to be attached at corners of Item 4.
Right leg assembly
Left leg assembly
2X2 Angle Aluminum 35L
1.0
1.0
Angle placement

Vendor Products:

Motor:

Franklin Electric Model 234524
(4" Super Stainless Submersible)

Motor Controller:

Rockwell – Reliance Electric
(SP500 AC Drive Model # 1SU44002)

Linear Actuators:

Ball Screw & Actuators
(Model # 's T3406-A.2 & T3424-A.2)

Right Angle Drive:

(5:1 reduction worm screw)

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APPENDIX C

BRUSHING TESTS SUPPORTING INFORMATION

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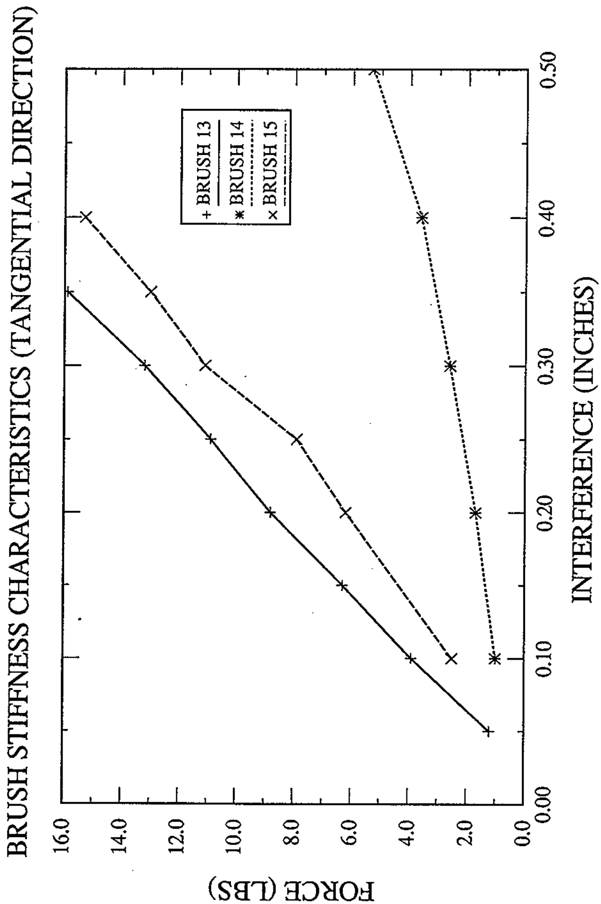
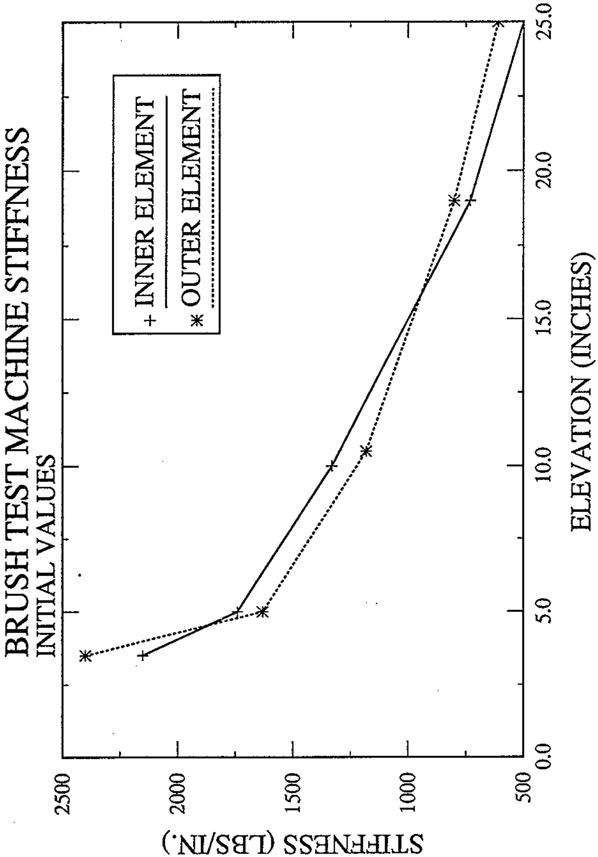
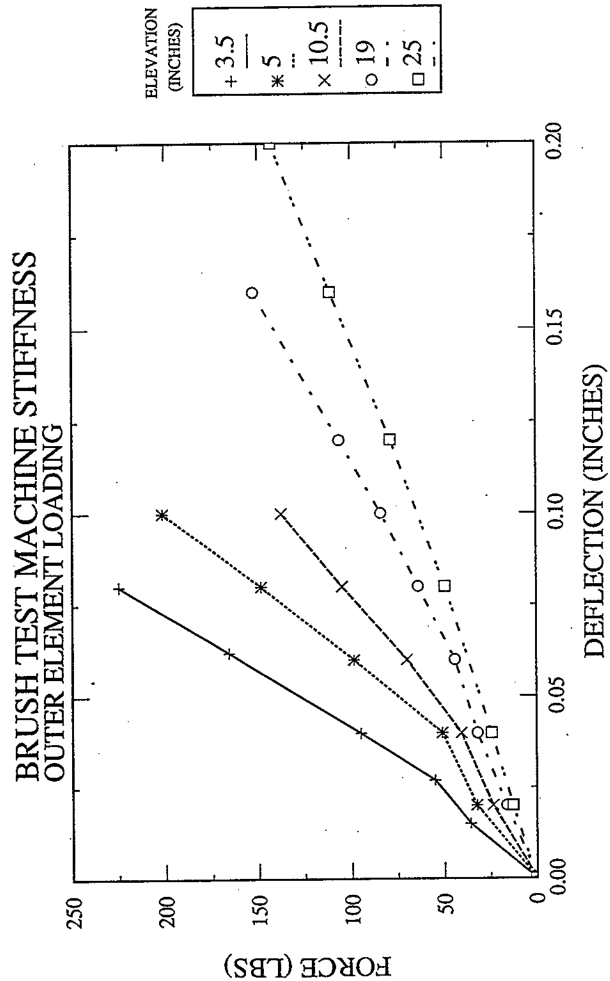
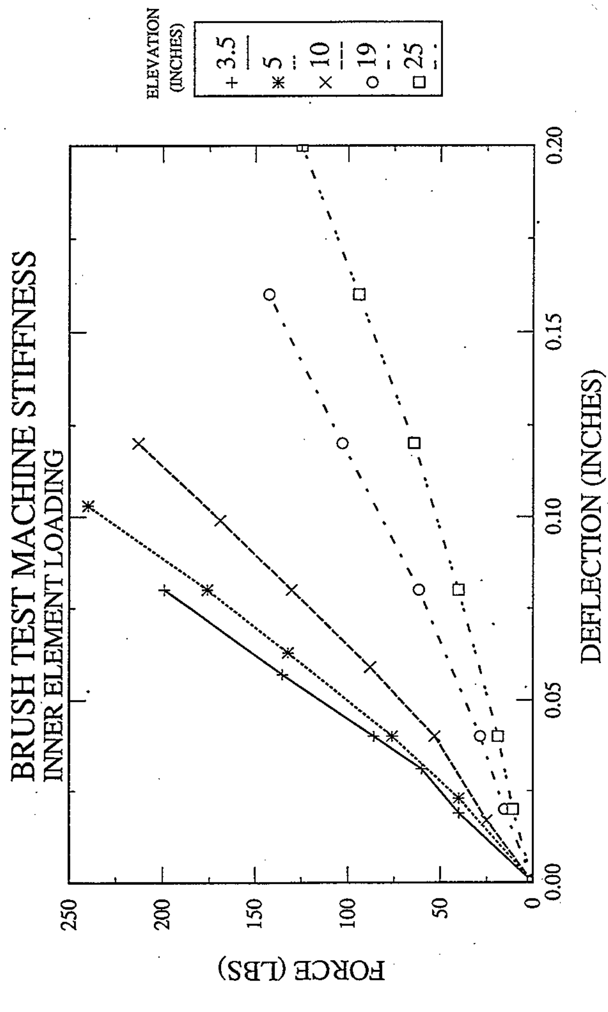
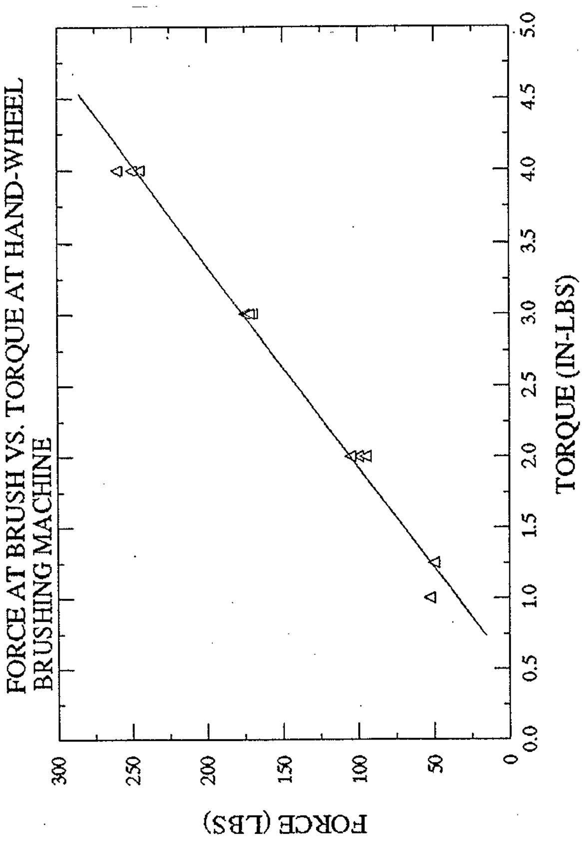

BRUSH STIFFNESS CHARACTERISTICS (TANGENTIAL DIRECTION)
FORCE (LBS)
INTERFERENCE (INCHES)
BRUSH 13
BRUSH 14
BRUSH 15
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
0.00
0.10
0.20
0.30
0.40
0.50


BRUSH TEST MACHINE STIFFNESS
INITIAL VALUES
INNER ELEMENT
OUTER ELEMENT
ELEVATION (INCHES)
STIFFNESS (LBS/IN.)
0.0
5.0
10.0
15.0
20.0
25.0
2500
2000
1500
1000
500



BRUSH TEST MACHINE STIFFNESS
OUTER ELEMENT LOADING
FORCE (LBS)
DEFLECTION (INCHES)
0
50
100
150
200
250
0.00
0.05
0.10
0.15
0.20
ELEVATION
(INCHES)
3.5
5
10.5
19
25


BRUSH TEST MACHINE STIFFNESS
INNER ELEMENT LOADING
FORCE (LBS)
DEFLECTION (INCHES)
ELEVATION (INCHES)
3.5
5
10
19
25
0
50
100
150
200
250
0.00
0.05
0.10
0.15
0.20


FORCE AT BRUSH VS. TORQUE AT HAND-WHEEL
BRUSHING MACHINE
FORCE (LBS)
TORQUE (IN-LBS)
0
50
100
150
200
250
300
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0

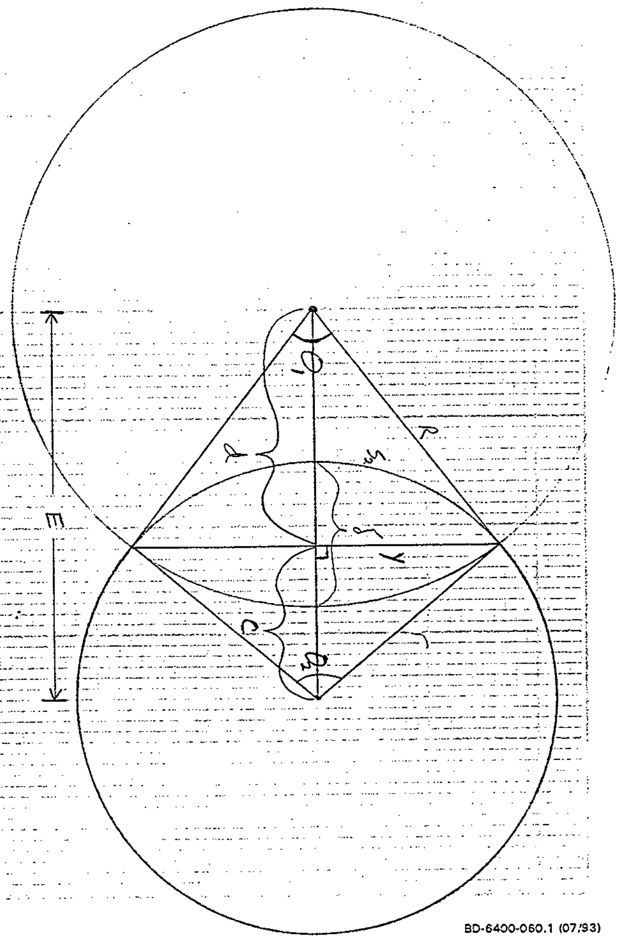
ANALYTICAL CALCULATIONS

Page 1 of 2

Subject Intersection of two circles. "What is the arc length of the smaller circle?"

Originator Daniel Maassen Date 6/15/98

Checker Date



BD-6400-060.1 (07/93)

ANALYTICAL CALCULATIONS

Page 2 of 2

Subject: Intersection of two Circles, "What is the arc length of the smaller circle?"

Originator: Daniel Maassen   Date: 6/15/98

Checker: ______   Date: ______

$$E = d + c = R + r - \delta \qquad d = E - c$$

$$d^2 + y^2 = R^2$$

$$c^2 + y^2 = r^2 \qquad E^2 = (R + r - \delta)^2 = R^2 + 2Rr + r^2 - 2R\delta - 2r\delta + \delta^2$$

$$d^2 + (r^2 - c^2) = R^2$$

$$c^2 = d^2 + r^2 - R^2$$

$$c^2 = (E - c)^2 + r^2 - R^2$$

$$\cancel{c^2} = E^2 - 2Ec + \cancel{c^2} + r^2 - R^2$$

$$c = \frac{E^2 + r^2 - R^2}{2E}$$

$$c = \frac{\cancel{R^2} + 2Rr + r^2 - 2R\delta - 2r\delta + \delta^2 + r^2 - \cancel{R^2}}{2(R + r - \delta)}$$

$$c = \frac{Rr + r^2 - R\delta - r\delta + \frac{1}{2}\delta^2}{(R + r - \delta)}$$

$$\theta_2 = 2\cos^{-1}\left(\frac{c}{r}\right)$$

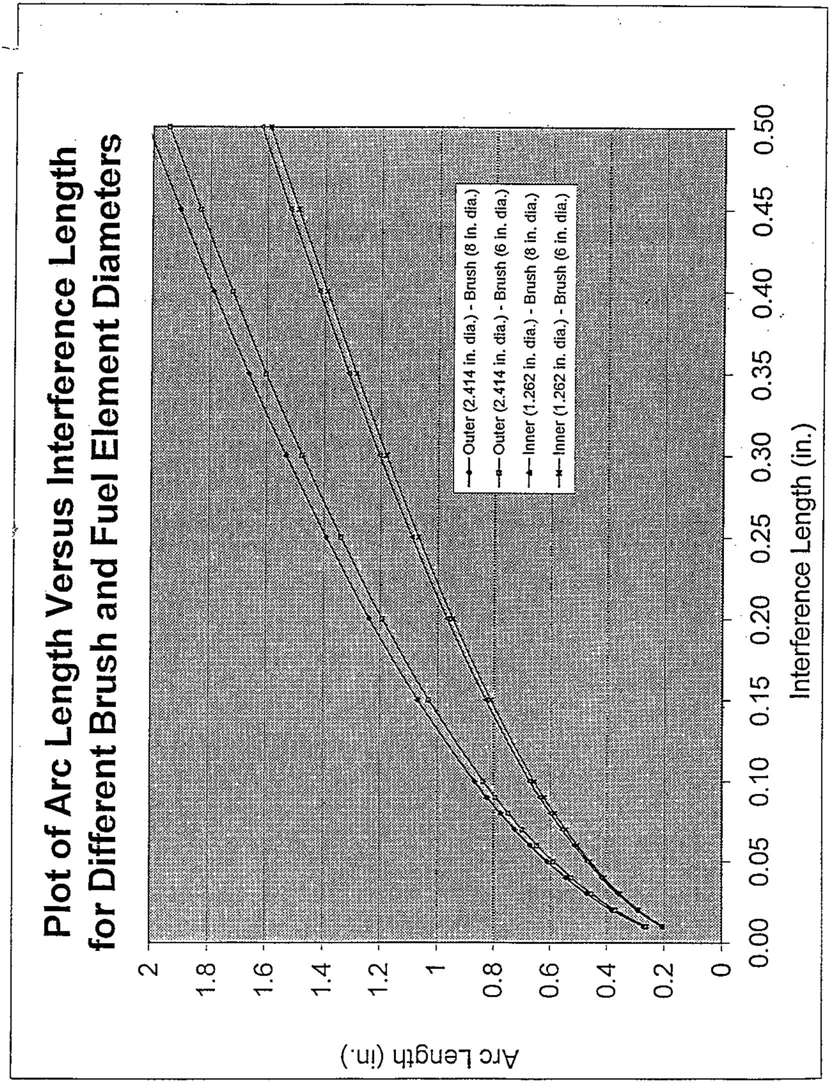
$$S_2 = \theta_2 r$$

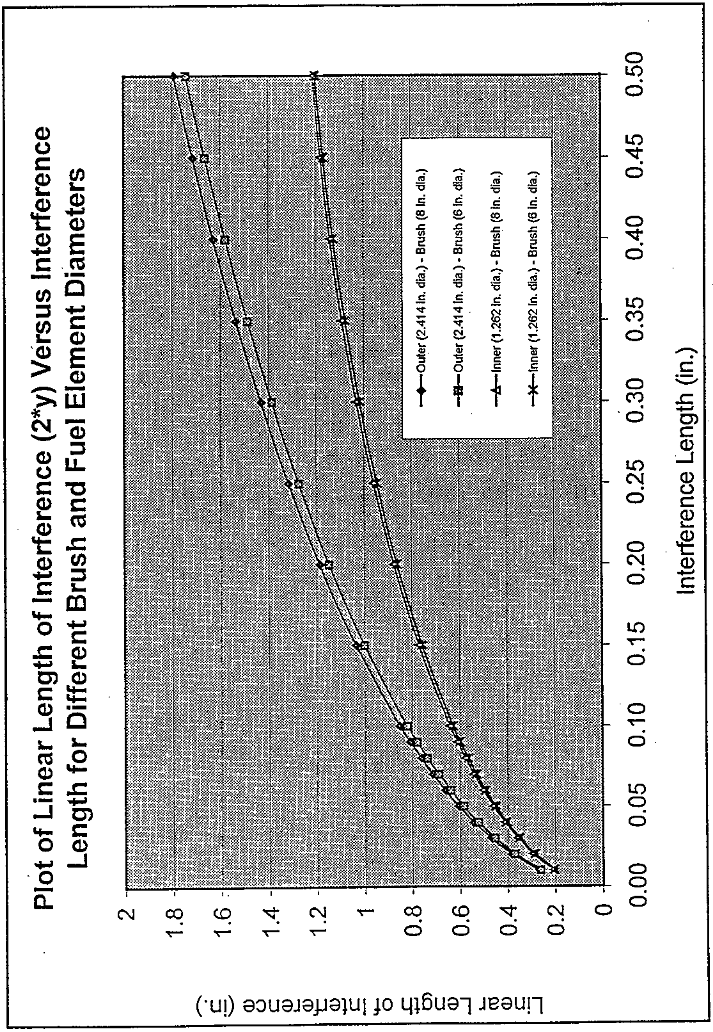
$$S_2 = 2\cos^{-1}\left[\frac{\left(\frac{Rr + r^2 - R\delta - r\delta + \frac{1}{2}\delta^2}{R + r - \delta}\right)}{r}\right] r$$

$$S_2 = 2r\cos^{-1}\left[1 + \frac{\frac{1}{2}\delta^2 - R\delta}{r(R + r - \delta)}\right] \quad \text{(arc length)}$$

$$2y = 2\sqrt{r^2 - c^2} \quad \text{(linear length of interference)}$$

BD-6400-060.1 (07/93)


Plot of Arc Length Versus Interference Length
for Different Brush and Fuel Element Diameters
Outer (2.414 in. dia.) - Brush (8 in. dia.)
Outer (2.414 in. dia.) - Brush (6 in. dia.)
Inner (1.262 in. dia.) - Brush (8 in. dia.)
Inner (1.262 in. dia.) - Brush (6 in. dia.)
Arc Length (in.)
Interference Length (in.)
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50


Plot of Linear Length of Interference (2*y) Versus Interference Length for Different Brush and Fuel Element Diameters
Linear Length of Interference (in.)
Interference Length (in.)
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50
Outer (2.414 in. dia.) - Brush (8 in. dia.)
Outer (2.414 in. dia.) - Brush (6 in. dia.)
Inner (1.262 in. dia.) - Brush (8 in. dia.)
Inner (1.262 in. dia.) - Brush (6 in. dia.)

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