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EVALUATION OF MAGNETIC PULSE FORMING AS A JOINT FABRICATION TECHNIQUE FOR CP-5 FUEL ELEMENTS

by

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and J. Kotora, Jr.

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L. G. Kunc1, R. B. Hagemann,
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Reactor Operations Division

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June 1967

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TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	7
I. INTRODUCTION	7
II. THE FORMING MACHINE	11
A. Principle of Operation	11
B. Application to CP-5 Fuel-element Joints	12
III. TESTING AND EVALUATION	12
A. Sample Construction	12
B. Sample Testing	13
1. "As-received" Samples	13
2. Thermal-cycled Samples	17
3. High-temperature Samples	22
4. Joint-leakage Tests	24
C. Additional Operating Conditions	25
1. Corrosion	25
2. Vibration	26
3. Radiation Damage	27
IV. CONCLUSION	27
REFERENCES	29

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
1.	CP-5 Fuel Element.	8
2.	Typical Welded Joint.	8
3.	Magneform Joint Fabrication	10
4.	Magneform Forming Coil and "Dummy" Fuel Element	10
5.	Completed "Dummy" Fuel Element	11
6.	Basic Circuit for Magnetic Pulse Forming	11
7.	Magneform Test Sample	13
8.	"As-received" Untested Sample	13
9.	Load-deflection Curves for "As-received" Tensile Samples. .	14
10.	Typical "As-received" Tensile-sample Failure.	15
11.	"As-received" Tensile Samples after Test	15
12.	Load-deflection Curves for "As-received" Compression Samples	16
13.	"As-received" Tensile Samples after Test	17
14.	Load-deflection Curves for Thermal-cycled Tensile Samples. .	19
15.	Typical Thermal-cycled Tensile-sample Failure.	19
16.	Typical Thermal-cycled Compression-sample Failure	20
17.	Load-deflection Curves for Thermal-cycled Compression Samples	21
18.	Load-deflection Curves for High-heat Tensile Samples.	22
19.	High-temperature Tensile Samples after Test.	23
20.	Typical High-temperature Tensile-sample Failure.	23
21.	Joint Leak-rate Curve.	25

LIST OF TABLES

<u>No.</u>	<u>Title</u>	<u>Page</u>
I.	"As-received" Tensile-test Results.	14
II.	"As-received" Compression-test Results	16
III.	Physical Measurements before and after Thermal Cycling. . .	18
IV.	Thermal-cycle Tensile-test Results	20
V.	Thermal-cycle Compression-test Results.	21
VI.	High-temperature Tensile-test Results	23
VII.	Physical Measurements before and after High-temperature Test.	24
VIII.	Data on Leak-rate Test of Magneform Joint	25
IX.	Magneform-Weld Comparison.	28

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ABSTRACT

Magnetic pulse forming, a high-energy rate metal-working process, has been investigated and evaluated as a substitute fastening technique for fabricating CP-5 fuel elements. This process produces joints whereby aluminum tubing is magnetically swaged into machined aluminum casting grooves.

A number of samples produced by this technique have been tested to destruction. Test results have compared favorably with the currently used welded joint. Visual and dimensional inspection of the samples revealed a high degree of constructional uniformity. The tensile- and compression-test results have shown consistently high strength. The joints were unaffected by thermal cycling in the temperature range simulating the operating environment of the reactor. Higher temperatures, over 600°F, caused a strength reduction of about 40%, but the joint strength was still more than adequate for the CP-5 reactor application.

Because of the high strength of the joint, the consistency of this strength over many samples, and the economies inherent in the simple fabrication and inspection techniques, the magnetic-pulse-formed joint appears to be a desirable and feasible fastening method for CP-5 fuel-element joints.

I. INTRODUCTION

Over the past 10 years, the CP-5 reactor has been operated with tubular fuel elements. These elements consist of three concentric, aluminum-clad, uranium fuel tubes, fastened together into a fuel subassembly. This subassembly is then welded to structural components to produce the complete fuel assembly as shown in Fig. 1. These structural components

are composed of alloy SG70A-T6 aluminum castings and Series 1100 aluminum tubing. Tubing and castings are fastened together by a circumferential, tungsten, inert-gas weld. A typical joint is shown in Fig. 2. Seven of these welds are necessary for the fabrication of each fuel element.

144-576

Fig. 1. CP-5 Fuel Element

Fig. 2. Typical Welded Joint

The welded joint has been a source of trouble for several years. The joint is costly and difficult to produce, and failure of the joint resulted in a complete separation of the element into two sections in 1961 and again in 1963. The failures occurred during routine handling operations. As a result of these failures, an elaborate inspection program was developed to prevent their reoccurrence. Static tensile loading, in conjunction with a dye-penetrant check and radiographic inspection, was used to examine the welds. Eventually, the tensile loading and dye-penetrant check were eliminated, but an improved radiographic inspection was retained. This condition exists today. Each of the seven circumferential welds is given a thorough radiographic inspection. The resultant radiographs are then examined and evaluated by qualified individuals. Defects such as inclusions, porosity, hairline cracking, etc., are eliminated by removing a portion of the weld. The joint is then rewelded and the inspection process repeated.

Numerous problems are associated with the rewelding operation:

1. The high heat applied to the repair area of the tube circumference causes the tube wall to expand and pull away from the casting in that area.
2. The element tends to "bow" and thus becomes slightly curved, necessitating a straightening operation.
3. The reworking and reinspection time needed delays fabrication and increases costs.
4. Evidence suggests that a reworked joint is actually considerably weaker than the original joint.
5. The repairing technique does not ensure that the reworked joint will be free of defects. Thus, the joint may require reworking a second or even a third time.

In early 1965, a Value Engineering study was started. The objective of the study was to evaluate alternate methods of fuel-element fabrication. The magnetic-pulse-swaged joint appeared to offer the most promising solution. Several swaged samples of different joint design were obtained. These prototype samples were examined and tested. The results of these initial tests established the joint design that has been used in all subsequent test samples.

Following production of the prototype samples, a "dummy" fuel element was fabricated. Figures 3 and 4 show the fuel-element fabrication. Figure 5 shows the completed dummy element.

Fig. 3. Magneform Joint Fabrication

Fig. 4. Magneform Forming Coil and "Dummy" Fuel Element

144-944

Fig. 5. Completed "Dummy" Fuel Element

II. THE FORMING MACHINE

The machine used to produce the "dummy" element and test samples was a Magneform Model 1, manufactured by the General Atomics Division of General Dynamics. The fabrication occurred at their Magneform Facility in San Diego, California. The machine is shown in Figs. 3 and 4.

A. Principle of Operation

Discharging a capacitor through a coil over a period of micro-seconds produces magnetic fields having high flux densities. Several years ago, General Atomics conceived a technique of using pulsed magnetic fields created in this manner for the direct forming of metal. Equipment specifically designed for this purpose was developed.¹

Figure 6 shows the basic circuit, consisting of an energy-storage capacitor, a switch, a coil, and a power supply that provides energy to

Fig. 6. Basic Circuit for Magnetic Pulse Forming

charge a capacitor. In operation, current through the coil produces a magnetic field of high intensity between the coil and the workpiece. During the brief impulse, eddy currents in the workpiece restrict the magnetic field to the surface of the workpiece. The interaction of the magnetic field and the eddy currents creates a uniform central force.² This repulsive force between the workpiece and the coil behaves in accordance with Lenz's law. Depending on the shape of the coil, various types of forming operations may be accomplished.

The energy of the Magneform pulse is continuously adjustable to the limits of the machine model. The magnetic pressure applied to the workpiece is dependent upon the amount of current induced in it. Therefore, optimum performance required:

1. Good electrical conductivity of the workpiece.
2. Close contact between the coil and the workpiece.
3. Sufficient insulation between the coil and the workpiece to prevent arcing.

If the resistivity of the workpiece exceeds about $15 \mu\Omega\text{-cm}$, a high-conductivity "driver" material (such as copper or aluminum sheet) should be placed in contact with the workpiece to modify its form.³

B. Application to CP-5 Fuel-element Joints

Discussion with representatives of General Atomics revealed the possibility of using the Magneform machine in CP-5 fuel-element fabrication. Prototype samples using various joint configurations and Magneform machine parameters were fabricated. Testing and examination of the samples were the basis for arriving at the final joint design. The machine parameters were set at various levels during the prototype sample run. After several experimental trials, the best results were yielded by forming the joints at a 4.5-kJ energy level using a 6-in. compression coil with a 3.050-in.-ID x 0.5-in.-wide field shaper.⁴

III. TESTING AND EVALUATION

A. Sample Construction

In August 1965, 40 test samples, made in accordance with the dimensions in Fig. 7, were received from the Magneform machine fabricator (General Atomics, San Diego, California). As shown in this figure, each sample section is composed of two aluminum tubes, magnetically pulse-formed to each end of a CP-5 fuel-element window casting. One joint is prepared for forming by shrink-fitting a 0.065-in.-wall aluminum tube

onto the casting. This simulates all the joints in a fuel element which do not involve the fuel tube. The joint at the other end of the section is formed by slip-fitting a 0.050-in.-wall tube over the casting. As the actual fuel-tube used in the CP-5 reactor fuel element has a thickness of 0.050 in., this joint simulates the fuel tube-to-casting assembly. Figure 8 shows an untested sample section.

Fig. 7. Magneform Test Sample

144-941

Fig. 8. "As-received" Untested Sample

Since each sample consists of two Magneform joints, the failure of a particular sample under load is recorded as the weakest of the two joints.

B. Sample Testing

1. "As-received" Samples

The samples were numbered beginning with No. 100 through 140. As can be seen from the tables in this report, the samples were randomly selected to ensure uniformity in sample strength over the total number of samples.

The first test consisted of obtaining tension and compression failure results for the samples in an "as-received" condition. The results of this test were used to establish a standard of comparison for joint strength. Other samples exposed to high temperature and temperature cycling could then be compared with the "as-received" standard to determine the effect of these test parameters. Fourteen samples were selected for this test. Seven of the samples were tested to destruction in tension, and seven were tested to destruction in compression.

The tensile-testing results exhibited a high degree of uniform joint strength. The average ultimate tensile strength for the seven joints was 5,377 lb. (This corresponds to a stress of 11,400 psi.) Each sample was pulled until total joint separation occurred in one joint. Uniformity of joint strength was remarkable, as can be seen from Table I. The Instron Tensile Machine, used to perform all the tests, plots a graph of load versus deflection as each sample is tested. The machine curves for all seven of the "as-received" tensile samples were placed on one graph to form Fig. 9.

TABLE I. "As-received" Tensile-test Results

Sample No.	Tension Load at Failure, lb	Ultimate Strength, psi	Sample No.	Tension Load at Failure, lb	Ultimate Strength, psi
134	5300	11,200	102	4925	10,400
106	5425	11,450	High	5725	12,100
108	5325	11,250	Low	<u>4925</u>	10,400
118	5725	12,100	Variation	800 lb	
107	5690	12,000		(13.97%)	
133	5250	11,100			

NOTE: Average tensile strength = 5377 lb (11,400 psi).

Fig. 9. Load-deflection Curves for "As-received" Tensile Samples

As expected, the thin-wall tube joint was the one that failed in all seven cases. The design of the joint is such that the sharp edge of the casting causes a ring of aluminum to be sheared from the tubing. As this material is being sheared, the part of the tubing that has been swaged into the casting must expand to allow the tube to slip free. The ring of sheared aluminum remains in the casting groove. This action occurred in all seven tensile samples, as can be seen in Figs. 10 and 11. The resistance to this shearing action gives the joint its high tensile strength.

144-942

Fig. 10. Typical "As-received" Tensile-sample Failure

144-936

Fig. 11. "As-received" Tensile Samples after Test

The compression strength of the joint was equal to the tensile strength, although the failure mode was different. The average joint strength for the seven compression samples was 5,396 lb. (Once again this corresponds to a stress of approximately 11,400 psi.) Individual sample results

are shown in Table II, and machine curves of the samples are shown in Fig. 12. The compression failure of a sample occurred as a buckling of the aluminum tube. At the ultimate strength, the tube began to buckle, and eventually a convolution was formed. Again, as expected, the thin-wall tube (0.050 in.) failed at the joint in all seven cases. Figure 13 shows the compression samples. Note the center sample No. 112. The test on this sample was continued after the first convolution formed. A second convolution then formed in the thin-wall tube at the joint, and two convolutions then formed at the heavy-wall tube joint. The test was then stopped since it appeared that convolutions would keep forming until the sample had the appearance of a bellows.

TABLE II. "As-received" Compression-test Results

Sample No.	Compression Load at Failure, lb	Ultimate Strength, psi
121	5580	11,800
119	5225	11,100
104	5225	11,100
120	5560	11,750
112	5490	11,600
105	5300	11,200
115	5390	11,400
High	5580	11,800
Low	5225	11,100
Variation	355 lb (6.36%)	

NOTE: Average Compression strength = 5396 lb (11,400 psi).

Fig. 12. Load-deflection Curves for "As-received" Compression Samples

144-937

Fig. 13. "As-received" Tensile Samples after Test

2. Thermal-cycled Samples

The reactor life of a CP-5 fuel element is approximately 9 months. During this time, the element is immersed in D_2O to a depth of 78 in. Six of the seven joints are below the D_2O surface, with the remaining upper joint in a helium atmosphere. During the 9-month life of the element, temperature fluctuations are caused by the alternate operation and shutting down of the reactor. The maximum bulk-water temperature during operation is less than $120^\circ F$. The minimum water temperature during shutdown is limited to greater than $50^\circ F$. In practice, the water temperature rarely drops below $70^\circ F$. The CP-5 Power Log Book reveals that a typical 9-month operating cycle will include approximately 130 shutdowns. Many of these shutdowns are of short duration; therefore the bulk-water temperature does not change more than a few degrees.

Before a Magneform joint could be approved as a replacement for the currently used welded joint in the CP-5 fuel elements, it was felt necessary to evaluate the effects of the thermal cycling imposed upon the joint by the reactor. The thermal cycling might cause the element tube to expand and pull away from the casting, thereby reducing joint strength.

To determine these effects, a thermal-cycle apparatus was constructed. The apparatus consisted of a distilled-water bath, an immersion heater, pump, and heat exchanger, a strip-chart recorder-controller, and an automatic control circuit.

Fourteen test sections were immersed in the water bath and cycled. A total of 428 cycles were achieved; this exceeds the number of cycles imposed upon a fuel element by a factor of three. The temperature range of the cycle test was 100 to $200^\circ F$. The $100^\circ F$ test differential is more severe than the $70^\circ F$ differential that is possible within the reactor. Thus, the thermal-cycle test exceeded reactor conditions in amplitude as well as in number of cycles.

Dimensions of the test samples were measured before and after the thermal-cycle test. The results are recorded in Table III, which indicates that no significant dimensional changes occurred as a result of thermal cycling.

TABLE III. Physical Measurements before and after Thermal Cycling
(dimensions in inches)

Sample No.	Before Cycling				After Cycling			
	A	A'	B	B'	T.C.A	T.C.A'	T.C.B	T.C.B'
110	2.988	2.916	2.990	2.919	2.988	2.916	2.993	2.919
	2.990	2.916	2.990	2.919	2.990	2.916	2.993	2.919
123	2.987	2.916	2.992	2.919	2.987	2.916	2.994	2.919
	2.983	2.916	2.993	2.919	2.984	2.916	2.995	2.919
113	2.987	2.916	2.991	2.919	2.987	2.916	2.993	2.919
	2.984	2.916	2.990	2.919	2.984	2.916	2.991	2.919
137	2.988	2.916	2.997	2.919	2.989	2.916	2.997	2.919
	2.988	2.916	2.995	2.919	2.988	2.916	2.995	2.919
111	2.985	2.916	2.993	2.919	2.985	2.916	2.993	2.919
	2.985	2.916	2.991	2.919	2.985	2.916	2.991	2.919
109	2.984	2.916	2.995	2.919	2.984	2.916	2.995	2.919
	2.987	2.916	2.993	2.919	2.987	2.916	2.993	2.919
138	2.988	2.916	2.996	2.919	2.988	2.916	2.995	2.919
	2.988	2.916	2.997	2.919	2.989	2.916	2.997	2.919
136	2.987	2.916	2.995	2.919	2.987	2.916	2.994	2.919
	2.988	2.916	2.996	2.919	2.989	2.916	2.995	2.919
124	2.987	2.916	2.995	2.919	2.988	2.916	2.995	2.919
	2.989	2.916	2.996	2.919	2.990	2.916	2.996	2.919
140	2.987	2.916	2.996	2.919	2.987	2.916	2.996	2.919
	2.989	2.916	2.997	2.919	2.990	2.916	2.997	2.919
139	2.988	2.916	2.998	2.919	2.989	2.916	2.997	2.919
	2.988	2.916	2.996	2.919	2.988	2.916	2.996	2.919
122	2.987	2.916	2.990	2.919	2.988	2.916	2.994	2.919
	2.987	2.916	2.989	2.919	2.987	2.916	2.993	2.919
125	2.982	2.911	2.995	2.919	2.982	2.911	2.995	2.919
	2.983	2.911	2.994	2.919	2.983	2.911	2.994	2.919
135	2.986	2.916	2.998	2.919	2.990	2.916	2.998	2.919
	2.987	2.916	2.994	2.919	2.990	2.916	2.996	2.919

Seven of the thermal-cycle samples were then tensile-tested until complete joint separation occurred. Figure 14 is a graph of the tensile-strength curves for the thermal-cycled tensile samples. The thermal-cycle tensile-sample failures were similar to the "as-received" tensile samples. In each sample, a ring of aluminum was sheared from the tube wall and remained in the casting groove (see Fig. 15). Also, in each sample, the

0.050-in. tube wall failed at the joint. Joint strength was very high, averaging 5,469 lb or 11,950 psi before failure. Individual sample results are listed in Table IV.

Fig. 14. Load-deflection Curves for Thermal-cycled Tensile Samples

144-940

Fig. 15. Typical Thermal-cycled Tensile-sample Failure

TABLE IV. Thermal-cycle Tensile-test Results*

Sample No.	Tensile Load at Failure, lb	Ultimate Strength, psi
110	5525	11,700
123	5580	11,800
113	5410	11,400
109	5880	12,400
136	5825	12,300
125	5610	11,850
135	5690	12,000
High	5880	12,400
Low	5410	11,400
Variation	470 lb (8%)	

NOTE: Average tensile strength = 5649 lb (11,950 psi).

*Samples cycled 428 times between 100 and 200°F.

Cycling occurred with samples immersed in water bath.

The remaining seven thermal-cycle samples were compression-tested. These samples failed in a manner identical to that of the "as-received" samples. In all seven samples, a convolution formed at the 0.050-in. tube wall at the joint (see Fig. 16). The average joint strength was 5,359 lb compression, which is equal to that of the "as-received" samples. Individual sample test results are shown in Table V, and machine curves of the thermal cycled compression samples are shown in Fig. 17.

144-939

Fig. 16. Typical Thermal-cycled Compression-sample Failure

TABLE V. Thermal-cycle Compression-test Results*

Sample No.	Compression Load at Failure, lb	Ultimate Strength, psi
137	5375	11,350
111	5500	11,600
138	5410	11,400
124	5210	11,000
140	5190	10,950
139	5380	11,350
122	5450	11,500
High	5500	11,600
Low	5190	10,950
Variation	310 lb (5.6%)	

NOTE: Average compression strength = 5359 lb (11,300 psi).

*Samples cycled 428 times between 100 and 200°F.

Cycling occurred with samples immersed in water bath.

Fig. 17. Load-deflection Curves for Thermal-cycled Compression Samples

The results of the thermal-cycle testing indicate that, within the temperature range typical of the reactor operation, there were no adverse effects upon the Magneform joint strength.

3. High-temperature Samples

CP-5 fuel elements are not subjected to high temperatures during normal operation. However, there is a possibility (although extremely remote) that some unusual condition could cause the element temperature to rise above normal operating limits. Loss of coolant flow, or in the worst case, loss of coolant, would cause temperatures to rise. If temperature were to reach the melting point of aluminum ($\sim 1,220^{\circ}\text{F}$), the joint construction would be of little consequence since the element would melt. However, below the melting point, fuel-element temperatures are of interest since the joint would be required to remain intact.

To expose the samples to high temperatures (600°F and up), the samples were heated in a high-temperature oven. Five samples were selected for the test. Two were heated to 600°F for 1 hr, two were heated to 800°F for the same duration, and one was heated to 940°F (the maximum temperature of the oven) for 1 hr. All samples were heated in an air medium and allowed to cool before removal from the oven.

The five samples were then tensile-tested until separation occurred. Figure 18 shows machine curves of the heated samples, and Table VI gives individual results. The average tensile strength for the heated samples was 2,817 lb. In all five cases, the thin-wall tube at the joint was the area that failed as predicted. Figures 19 and 20 show tensile-tested, high-temperature samples. In all cases, a small amount of aluminum has been sheared off by the sharp edge of the casting groove, but there is an absence of the complete ring of aluminum that was present in the "as-received" and thermal-cycled samples. Dimensional measurements, made before and after heating of the samples, are shown in Table VII. No appreciable changes in dimension were noted.

Fig 18. Load-deflection Curves for High-heat Tensile Samples

TABLE VI. High-temperature Tensile-test Results

Sample No.	Test Temp, °F	Tensile Load at Failure, lb	Ultimate Strength, psi
116	600	2850	6,020
112	600	2850	6,020
103	800	2975	6,300
129	800	2660	5,630
117	940	2750	5,820
	High	2975	6,300
	Low	2660	5,630
	Variation	315 lb (10.6%)	

NOTE: Average tensile strength = 2817 lb (5,950 psi).

144-938

Fig. 19. High-temperature Tensile Samples after Test

144-943

Fig. 20. Typical High-temperature Tensile-sample Failure

TABLE VII. Physical Measurements before and after High-temperature Test
(dimensions in inches)

Sample No.	Before Heating				Test Temp, °F	After Heating			
	Diameter A	Diameter A'	Diameter B	Diameter B'		Diameter A	Diameter A'	Diameter B	Diameter B'
116	2.987	2.916	2.989	2.919	600	2.989	2.916	2.990	2.919
	2.988	2.916	2.992	2.919		2.990	2.916	2.993	2.919
128	2.983	2.910	2.991	2.919	600	2.983	2.910	2.992	2.919
	2.987	2.910	2.993	2.919		2.987	2.910	2.994	2.919
103	2.983	2.916	2.994	2.919	800	2.985	2.916	2.994	2.919
	2.987	2.916	2.992	2.919		2.987	2.916	2.993	2.919
129	2.988	2.916	2.997	2.919	800	2.989	2.916	2.999	2.916
	2.988	2.916	2.997	2.919		2.988	2.916	2.998	2.916
117	2.980	2.916	2.996	2.919	940	2.981	2.916	2.996	2.919
	2.984	2.916	2.996	2.919		2.985	2.916	2.996	2.919

Although joint strength was noticeably reduced because of high temperature, these temperatures do not occur during normal operation of the reactor. Joint strength was still many times greater than the strength needed to support the 100-lb structural load that rests upon the element when it is in the reactor.

4. Joint-leakage Tests

Should a major loss of coolant occur in the CP-5 reactor, the reactor's emergency cooling system would function to fill the fuel elements with emergency coolant. When the water level reached the height of the element windows (~46 in.), it would then overflow around the outside of the elements. If the Magneform joint is to be used for CP-5 element construction, it should be able to meet the requirement of being watertight if subjected to the above conditions.

Two tests were performed to determine the watertight characteristics of the Magneform joint. The first test consisted of sealing the bottom of the full-scale dummy, CP-5, fuel element that had been assembled by the magnetic swaging process. The dummy element was filled with water to the level of the element windows and allowed to stand for 2 weeks in this condition. This put five of the element joints under static water pressure, the bottom joint being under 46 in. H₂O or 1.7 psi. No joint leakage was noted during the 2-week test period.

For the second test, a fuel-element nose casting, Magneformed to a 6-in. length of ~3-in. ID by 0.065-in. wall tubing was fabricated. Aluminum flanges with Teflon gaskets were made for each end of the test section and were held in place by a tie rod. Thus, a small pressure vessel was formed. The vessel was then filled with water and hydrostatically tested. Table VIII shows the results of the test. From the results of this test, leak rates for various pressure readings were calculated and are shown in Fig. 21. Before the leak-rate measurements, the joint had already been pressurized to 300 psi to determine the approximate pressure range that the joint could withstand. It seems reasonable to assume that the leak rate, at lower pressures, would

have been smaller if the initial pressure test had not been carried out. This test may have expanded the tubing sufficiently to cause a higher leak rate.

TABLE VIII. Data on Leak-rate Test of Magneform Joint

Date	Time	Test Pressure, psi
2/6/67	11:16	300
	11:19	245
	11:30	210
	11:45	190
	12:00	177
	13:00	137
	14:00	116
	15:00	103
	16:00	92
2/7/67	17:00	90
	09:50	44

Fig. 21. Joint Leak-rate Curve

We can conclude from these two tests that the Magneform joint will remain watertight under CP-5 reactor operating conditions.

C. Additional Operating Conditions

In addition to the thermal cycling previously discussed, the reactor environment imposes other conditions upon the fuel element. The following general discussion is presented as a line of reasoning to show that these other conditions do not have an appreciable effect on the fuel-element joints, and in any case the effect will not be worsened by a changeover from the welded to the swaged joint. An exacting investigation of corrosion, vibration, and radiation effects on fuel-element joints is beyond the scope of this report.

1. Corrosion

There is no reason to expect a great amount of corrosion in

the 9-month period which is the usual life of an element. The element is immersed in high-purity D_2O coolant, which is maintained at a more or less neutral pH of 7.0 ± 0.5 to resist corrosion. The low operating temperature ($<120^\circ F$) also acts to retard corrosion. All reactor piping and wetted components are of stainless steel or aluminum, which minimizes galvanic coupling problems. The condition existing at the crack between the casting and the tube in a Magneform joint is duplicated by the crack between these same components on the inside of a welded joint. Past operating history shows that fuel-element corrosion has never been a problem in the CP-5 reactor D_2O system.

In a Magneform joint, the outer tubing is undoubtedly subjected to hoop stresses. The magnitude and effect of these stresses were not evaluated. Fortunately, pure aluminum such as the 1100 series is quite resistant to stress-corrosion cracking.⁵ Thus, even though hoop stress exists, stress-corrosion cracking should not be a problem.

Figure 15 shows a tensile-tested, thermal-cycled sample in which some corrosion is apparent. The other six tensile samples from this test group showed a similar amount of local corrosion and pitting. However, the tensile-test results show that the corrosion had no effect on joint strength.

Note that the tank used for the water bath in the thermal-cycle test was carbon steel. This contributed greatly to the amount of corrosion products formed during the test. In addition, the temperatures reached during the test helped to accelerate corrosion. Thus, a more corrosive environment was produced during this test than that which is present in the reactor.

2. Vibration

Because of the complex geometry of the fuel element, fluid velocity and vibration cannot be determined accurately. However, the following line of reasoning may provide some insight into the problem of vibration.

A CP-5 fuel element is cooled by a flow of D_2O which enters the bottom of the element and flows upward through the fuel section. This coolant exits at the fuel-element coolant-discharge windows, which are about 4 ft above the bottom of the element. The coolant flow rate is approximately 100 gpm, and since the inside diameter of the element is about 3 in., the coolant velocity is 5 ft/sec. Introduction of an air-cooled thimble facility into the center of a fuel element reduces the internal cross-sectional area of the fuel element from about 7 sq in. to about $4\frac{1}{2}$ sq in. This area occurs as an annulus. However, for a rough approximation, the area can be considered as that of a $2\frac{1}{2}$ -in.-diam pipe. The 100-gpm flow would attain a velocity of approximately 6.7 ft/sec through this annulus. This velocity is

still relatively low and suggests that vibration due to the coolant flow is probably not significant. Mechanical vibration due to pulsation of the coolant pump is damped by the heat exchanger, approximately 40 ft of piping, and flexible bellows in the line. The location of fuel elements in a water-filled tank adds considerable viscous damping to the system and minimizes vibration.

Looking at the problem in another way brings out the fact that the present welded joint is subjected to the same vibration that a Magneform joint would be expected to withstand. A small jagged inclusion, void, or other area of stress concentration in the weld would be highly susceptible to crack initiation and propagation if vibration were indeed a problem, since the vibrational stress would be superimposed over the static stress. If the vibrating component is relatively large, any failures that might occur would be of a brittle nature.⁶ The fact that weld cracking does not occur suggests that vibration is not an important consideration.

3. Radiation Damage

Neutron and gamma radiation increases the hardness, brittleness, and tensile strength of aluminum. The general effect is somewhat analogous to cold-working of the material.⁷

Past operating history of the CP-5 reactor fuel element reveals that radiation damage has not been a problem. Element failures to this date have occurred because of the fastening method and cannot be directly attributed to radiation damage. The materials used to form the element are the same regardless of the process used, e.g., Magneform or welding. Thus the use of the Magneform should not cause the element to be any more susceptible than the welded joint to radiation damage.

IV. CONCLUSION

By direct comparison with the presently used welded joint, the magnetically swaged joint exhibits several definite advantages:

A. Magneform swaging is entirely a machine operation. Once the parameters of the machine have been set and the joint has been positioned and aligned through adequate fixturing, the only remaining action required is the release of the energy, actuated by a switch.

By contrast, welding requires a good deal of highly specialized skill by a craftsman. The strength of the joint is dependent on the skill of the craftsman, the temperature of the weld area, the speed of rotation, casting impurities, etc. A qualified and competent welder may produce many satisfactory welds. However, some welds will be unsatisfactory.

B. By the elimination of several variables such as mentioned above and using the Magneform machine, a more uniform output is realized. Although high strength and cost are both important, they are secondary to reliability. A CP-5 fuel-element joint must hold the element together during its insertion, use, and withdrawal. Consistency of joint strength is the greatest asset of the swaged joints. This has been demonstrated by the testing results recorded in this report.

C. Not only do the Magneform joints exhibit similar tensile strength and more reliability than welded joints, they are also less costly.

Data gathered for the last 18 fuel elements produced has revealed that an average of 40 man-hr per element were used in weld preparation, welding, radiographic inspection, reworking, and reinspection. These efforts can be drastically reduced, and in time eliminated.

D. The Magneform joint is formed without the application of intense heat. Therefore, the expansion, shrinkage, and bowing problems common to the welding process are eliminated.

Table IX compares the Magneform joint with the welded joint.

TABLE IX. Magneform-Weld Comparison

Conditions	CP-5 Welded Joints	Magneform Joints
Load at failure, lb	5,680*	5,377
Ultimate tensile stress, psi	12,000*	11,400
Variation in tensile samples, %	17.8	13.97
Weakest joint in fuel assembly	Fuel tube	Fuel tube
Corrosion properties: 7.0 $\pm$ 0.5 pH high-purity D ₂ O	Good	Good
Resistance to vibration damage	Good	Good
Ultimate compression stress, psi	Not known	11,400
Thermal cycling (100-200°F)	Not known	No effect
High temperature	Not known	38% strength reduction
Strength uniformity	Fair	Excellent
Fabrication, inspection, and rework Time: Man-hr/element	40 hr avg/element	~8 hr/element
Joint consistency	Depends on welder skill	Uniform due to repeatability of machine operation
Inspection	Radiography and dye check	Visual
Possibility of handling damage	High	Low; less handling involved
Cost savings per fuel assembly		~\$250 less than for a welded assembly

*Calculated from strip samples. Actual production run-samples were weaker and exhibited much greater variability.

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