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SNAP 8 DRM-1
FUEL ELEMENT
END CLOSURE DEVELOPMENT
(Title Unclassified)

AEC Research and Development Report

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SNAP 8 DRM-1
FUEL ELEMENT
END CLOSURE DEVELOPMENT
(Title Unclassified)

By:

W.F. DENNISON
C.P. MESSINA

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ABSTRACT

Three proposed end plug designs, for use as the final cladding tube closure (hydrogen seal and tube weld) of the SNAP 8 DRM-1 fuel elements, were evaluated. Hydrogen permeation, thermal endurance, shock, and vibration testing results led to the selection and successful utilization of the Reference Design cup-plug in the fabrication of the DRM-1 fuel elements.

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a. DRM-1 Fuel Element

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b. S8ER Fuel Element

Figure 1. Comparison of S8ER and DRM-1 Fuel Elements

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I. INTRODUCTION

The SNAP 8 Developmental Reactor Mockup No. 1 (DRM-1) is a flight prototype system, containing normal uranium fuel elements. This reactor mockup will be used in qualifying the design for flight application. It is designed to provide information pertaining to the interdependence of components under simulated environmental conditions of shock, vibration, temperature, and vacuum. The S8DRM-1 consists of five major assemblies, one of which is the fuel elements.

The basic design of the DRM-1 fuel element consists of a 0.527-in. diameter by 14.000-in. long rod of zirconium-uranium alloy, hydrided to an N_H^* of 6.0, and clad with a 0.010-in. wall Hastelloy N tube. Although zirconium hydride is stable at moderate temperatures, at the reactor operating temperatures (1300 to 1400°F) it readily dissociates to zirconium and hydrogen, producing a nominal 2 atm of hydrogen pressure. The maximum allowable hydrogen loss from a DRM-1 fuel element was set at 1.50 cc(STP)/hr at 1400°F isothermal. To satisfy this requirement, in view of the permeability of metal to hydrogen at elevated temperatures, the inside of the cladding tube was coated with a ceramic (AI 8763D) which has a demonstrated low hydrogen permeation rate. A method of making a seal between the coated tube and a coated "end plug" was required, to complete the glass envelope to meet the DRM-1 design requirements.

The S8DRM-1 fuel element design is quite similar to that of the preceding SNAP 8 Experimental Reactor (S8ER),¹ as shown in Figure 1. The fuel rods are essentially the same size, and the same cladding and coating materials (Hastelloy N and AI 8763D) were used in both cases. Therefore, from the final end seal standpoint, the cladding parameters are the same for both fuel element designs.

This report covers the developmental program undertaken in an effort to improve upon the final end closure design and upon the results obtained with the S8ER configuration. The work was directed at the glass-to-glass seal and the final weld closure.

^{*} N_H = number of hydrogen atoms per cubic centimeter of alloy $\times 10^{-22}$.

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Figure 2. S8ER End Closure
(Figure Unclassified)

Figure 3. Reference Design
End Closure
(Figure Unclassified)

II. DESIGN DEVELOPMENT

Among possible criticisms of the S8ER cup and plug closure (Figure 2) is the fact that the cup and plug are separate components, not interlocked in any way. The cup is free to move, under certain conditions of vacuum or pressure, inside the cladding tube. Such movement, of only a few thousandths of an inch, could result in failure of the glass-glass seal. Another shortcoming is the length added to the fuel element by inserting the cup into the tube, bottom first, leaving the void of the cup to be filled by the end plug. The question of the worth of the grooves on the S8ER cup has also been raised. The grooves are primarily a carryover from the SNAP 10A/2 closure.² With these points in mind, three closure designs were proposed and evaluated.

A. REFERENCE DESIGN

The "Reference Design" was so designated because it appeared to fit the design requirements better than did the other two. This configuration (Figure 3) was achieved by combining the S8ER cup with an end cap, producing a one piece design which would fit into the tube and over the end of the fuel rod. The 3 mil (0.003 in.) interference fit (the cup being 3 mils larger on the OD than the ID of the tube), as used in the S8ER, was maintained in this design. Some advantages of the Reference Design over the S8ER are as follows:

- 1) One piece design, with the cup portion restrained from movement
- 2) More compact, providing for a shorter equivalent element length
- 3) 50% fewer parts to machine, inspect, and handle.

B. ALTERNATE No. 1 CUP

This design, illustrated in Figure 4, differs from the S8ER design only in that the grooves have been removed from the cup. The major advantage here would be that the cup would be easier and cheaper to machine.

C. ALTERNATE No. 2 CUP

Figure 5 illustrates this configuration. A thin walled cup is again used to make the glass-glass seal, but it is also designed to be welded to the cladding tube for mechanical stability. An end plug fills the void of the cup, and is

Figure 4. Alternate No. 1 Cup
(Figure Unclassified)

Figure 5. Alternate No. 2 Cup
(Figure Unclassified)

welded to the top edge of the cup rather than the tube. This provides for mechanical integrity. The advantage of this design would be in maintaining the basic S8ER configuration, while adding mechanical integrity to the cup. The obvious disadvantage is the added welding step.

D. SAMPLE PREPARATION

Twenty-five samples of each design were fabricated, and assembled with 7-in. lengths of coated tubing. The glass-glass seals were made by localized induction heating, programmed with the equipment developed for the S8ER,¹ at 1850°F for 2 min. Grooves were placed on the outer wall of 12 of the Reference Design cups, to evaluate the worth of this variation. The assembly sequence of was as follows:

- 1) Reference Design:
 - a) Shrink plug into tube
 - b) Weld plug to tube
 - c) Make glass-glass seal
- 2) Alternate No. 1 Cup:
 - a) Shrink cup into tube
 - b) Make glass-glass seal
 - c) Insert void plug into cup and weld to tube
- 3) Alternate No. 2 Cup:
 - a) Shrink cup into tube
 - b) Weld cup to tube
 - c) Make glass-glass seal
 - d) Insert void plug into cup and weld

A considerable amount of difficulty was encountered in making the cup-to-tube weld of the Alternate No. 2 design. The fabrication yield with this design was low.

Figure 6. End Seal Sample Testing System
(Figure Unclassified)

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III. TESTING

After fabrication, the test samples were permeation tested at 1300°F and 2 atm (abs) of H₂ pressure to determine the leakage of the glass-glass seal. The test furnace arrangement is illustrated in Figure 6. The testing procedure consisted of loading the sample into the furnace retort, evacuating the retort, and then bringing the sample up to temperature. The background hydrogen of the sample and system was then measured, after which the sample was pressurized with hydrogen. The hydrogen leakage was measured and monitored until equilibrium was reached, at which time the rate was recorded in cc(STP)/hr. Localized heating of the end seal was used for two reasons. The first was to measure the hydrogen leakage from the end seal alone, with as little contribution as possible from the cladding tube. The second was that the pressure probe and probe cap, unprotected by the ceramic hydrogen barrier, had to remain at a temperature low enough that the hydrogen permeation through the bare metal was insignificant. With the test equipment used, approximately 20 cm² of surface area of the end seal and cladding tube were at a temperature of 1000°F or greater, and hydrogen was permeating at a significant rate.

The permeation test results are presented in Tables 1, 2, 3, and 4, and are summarized in Table 5. These data indicate that the grooveless Reference Design is the best closure from the permeation standpoint, although the number of samples in this group was smaller than those of the other groups. Therefore, 14 additional samples of the grooveless variety were fabricated and tested. The results of this group, presented in Table 6, showed a 100% yield with an average leak rate of 0.03 cc/hr, when tested at 1400°F and 2 atm H₂ pressure. This group was erroneously tested at 100°F higher (1400°F) than the original group (1300°F), but showed leak rates of an equivalent magnitude. So, in taking the liberty of tabulating the two groups of data as one (1300 and 1400°F), we have an overall average of 0.06 cc/hr for 27 samples. Twenty-six of these were acceptable, for a 96% yield having an average leak rate of 0.02 cc/hr.

Some of the Reference Design and Alternate No. 2 cup samples were retested at 1300°F, followed by runs at 1400 and 1500°F, to look into the thermal stability of the glass-glass seal. The results of these tests are presented in Table 7; and they indicate that, for relatively short periods (<100 hr), the seals are thermally stable, even above the design temperature, with no appreciable difference between the two designs.

TABLE 1
END SEAL TESTS, REFERENCE
DESIGN
(Grooved)

Sample Number	Permeation Rate (cc/hr at 1300°F and 2 atm)
A-1	0.97
A-2	0.00
A-3	0.01
A-4	0.70
A-7	1.40
A-8	0.69
A-14	0.59
A-15	0.00
A-17	0.94
A-20	0.00
A-21	0.00
A-22	0.60

Overall average of the 12 samples =
0.49 cc/hr

Average of the 5* good samples =
0.00

(42% Yield)

*A good sample being defined as one which leaks
<0.1 cc/hr at 1300°F and 2 atm H₂

TABLE 2
END SEAL TESTS, REFERENCE
DESIGN
(Grooveless)

Sample Number	Permeation Rate (cc/hr at 1300°F and 2 atm)
A-5	0.03
A-6	0.00
A-9	0.02
A-10	0.01
A-11	0.01
A-12	0.04
A-13	0.07
A-16	1.02
A-18	0.03
A-19	0.06
A-23	0.01
A-24	0.00
A-25	0.00

Overall average of the 13
samples = 0.10 cc/hr

Average of the 12* good
samples = 0.02 cc/hr

(92% Yield)

*A good sample being defined as one which leaks
<0.1 cc/hr at 1300°F and 2 atm H₂

TABLE 3
END SEAL TESTS, ALTERNATE
No. 1 CUP
(Grooveless S8ER Cup)

Sample Number	Permeation Rate (cc/hr at 1300°F and 2 atm)
D-1	0.00
D-2	0.00
D-3	No Test
D-4	3.8
D-5	0.02
D-6	0.00
D-7	0.03
D-8	0.00
D-9	0.00
D-10	0.00
D-11	0.00
D-12	0.00
D-13	0.00
D-14	0.00
D-15	0.00
D-16	0.00
D-17	0.00
D-18	0.02
D-19	0.07
D-20	0.09
D-21	0.31
D-22	0.05
D-23	0.04
D-24	0.01
D-25	0.02

Overall average of the 24 samples
with rates = 0.19 cc/hr
Average of the 22 good* samples =
0.02 cc/hr
(88% Yield)

*A good sample being defined as one which leaks
<0.1 cc/hr at 1300°F and 2 atm H₂

TABLE 4
END SEAL TESTS, ALTERNATE
No. 2 CUP
(Welded Cup)

Sample Number	Permeation Rate (cc/hr at 1300°F and 2 atm)
B-1	Off Scale
B-2	0.04
B-3	0.41
B-4	1.09
B-5	No Test
B-6	No Test
B-7	0.82
B-8	No Test
B-9	0.04
B-10	0.07
B-11	Off Scale
B-12	0.06
B-13	No Test
B-14	No Test
B-15	No Test
B-16	0.76
B-17	0.01
B-18	0.82
B-19	0.00
B-20	1.59
B-21	0.66
B-22	0.32
B-23	0.72
B-24	1.00
B-25	4.00

Overall average of the 17 samples
with finite rates = 0.73 cc/hr
Average of the 6 good* samples =
0.04 cc/hr
(24% Yield)

*A good sample being defined as one which leaks
<0.1 cc/hr at 1300°F and 2 atm H₂

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TABLE 5
SUMMARY OF END SEAL SCREENING TEST

End Seal Design	Number Samples Tested	Overall Average Leakage (cc/hr at 1300°F and 2 atm)	Yield* (%)	Average Leakage of Acceptable Samples (cc/hr at 1300°F and 2 atm)
Reference Design (Grooved)	12	0.49	42 (5/12)	0.00
Reference Design (Grooveless)	13	0.10	92 (12/13)	0.02
Alternate No. 1 Cup (Welded)	19	0.73	24 (6/25)	0.04
Alternate No. 2 Cup	24	0.19	88 (22/25)	0.02

*Based upon samples leaking at or less than 0.1 cc/hr at 1300°F and 2 atm H₂

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TABLE 6
REFERENCE DESIGN END SEALS, CONFIRMATION GROUP

Sample Number	Permeation Rate (cc/hr at 1400°F and 2 atm)	Sample Number	Permeation Rate (cc/hr at 1400°F and 2 atm)
A-31	0.02	A-38	0.00
A-32	0.00	A-39	0.00
A-33	0.01	A-40	0.00
A-34	0.10	A-41	0.00
A-35	0.06	A-42	0.00
A-36	0.11	A-43	0.04
A-37	0.01	A-44	0.09
Overall average of the 14 samples = 0.03 cc/hr			
100% Yield			

TABLE 7
END SEAL PERMEATION RATES AT
ELEVATED TEMPERATURES

Sample Number	Permeation Rate (cc/hr)			
	1300°F 2 atm	Repeat 1300°F 2 atm	1400°F 2 atm	1500°F 2 atm
Reference Design				
A-11	0.01	0.01	0.06	0.07
A-12	0.04	0.01	0.03	0.06
A-13	0.07	0.00	0.02	0.07
A-15	0.00	0.00	0.01	0.13
A-19	0.06	0.02	0.02	0.04
A-20	0.00	0.00	0.04	0.09
A-21	0.00	0.01	0.11	0.15
A-23	0.01	0.00	0.09	0.16
Average	0.02	0.01	0.05	0.10
Alternate No. 2 (Grooveless Cup)				
D-2	0.00	0.00	0.06	0.21
D-22	0.05	0.00	0.00	0.21
D-24	0.01	0.00	0.01	0.14
D-25	0.02	0.02	0.03	0.07
Average	0.02	0.01	0.03	0.09

Three Reference Design samples were then subjected to thermal cycling, thermal soaking, and ramp heating. These tests are detailed and tabulated in Table 8. It can be seen that the cycling and soaking did little if any damage to the seals. On the other hand, the ramp heating appears to have catastrophically affected the coating in Sample 43, and caused a significant increase in Sample 44. Seal failure alone should have caused a 1 to 2 cc/hr leakage. Later developmental testing of 12 prototype S8DRM-1 fuel elements³ using the reference design seal has shown that thermal soaking did not affect the seals. Ramp heating of the same elements caused an average increase of 0.02 cc/hr,⁴ while thermal cycling raised the average permeation rate to 0.12 cc/hr.⁴

TABLE 8
THERMAL TESTING, DRM-1 END SEALS

Test	Sample No. 42	Sample No. 43	Sample No. 44
Original Rate, 1400°F and 2 atm	0.00	0.04	0.09
After 50 Thermal Cycles (1200 to 1300°F at 50°F/min) Permeation rate at 1300°F and 2 atm	0.06	0.11	0.12
After 5 Thermal Soaks (400 to 1300°F at 300°F/min, Dwell 10 hr at 1300°F, Cooled to 400°F at 300°F/min) Permeation Rate at 1300°F and 2 atm	0.00	0.02	0.11
Ramp Heating			
No. 42 No Test — Mechanical Failure	—		
No. 43 1 cycle, 300°F/min to 1300°F 11 cycles, 800°F/min to 1300°F		— 14.0	
No. 44 1 cycle, 550°F/min to 1300°F 1 cycle, 1225°F/min to 1300°F 1 cycle, 1225°F/min to 1300°F			0.20 0.60 0.80

To obtain data on the longevity of the seal provided by the Reference Design, eight samples were placed on thermal endurance tests. Four were tested at 1300°F and 2 atm H₂ pressure, and four at 1400°F and 1 atm H₂. The 2 atm at 1300°F was intended to provide a higher and more accurately measurable permeation rate at that temperature. An S8ER type seal was placed with each group,

for comparative purposes. A plot of the data from these two groups is given in Figure 7.

The S8ER seal in the 1400°F group was removed from test at the 75-hr point, because its leak rate had increased to 1.0 cc/hr, from an initial 0.2 cc/hr. The four Reference Designs at 1400°F continued on test until 1910 hr had been accrued, and their leakage had become significantly higher. The individual rates of these four samples were then determined. Two remained unchanged, with essentially zero leakage; while the other two had rates of 2.0 and 2.5 cc/hr.

The group at 1300°F has performed quite satisfactorily; and, at this writing (5000 hr accrued), is still on test, with an average permeation rate of 0.1 cc/hr at 1300°F and 2 atm H₂.

The cause of the failure of the 1400°F samples (1 S8ER and 2 Reference Design) cannot be isolated, but is undoubtedly due to either thermal or mechanical stresses, or a combination of the two.

The mechanical strength of the glass-glass seal of the Reference Design was evaluated by subjecting 12 prototype fuel elements to shock and vibration.⁴ The elements were subjected to inputs simulating vehicle startup and launch, in accordance with Specification NR7568-06.⁵ The average hydrogen loss rate of the 12 elements was 0.04 cc/hr at 1300°F, before and after vibration and shock. Radiographic examination revealed no damage to the fuel rods.

In view of the overall test data, the grooveless Reference Design end closure was specified for use with the DRM-1 fuel elements.

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Figure 7. Thermal Endurance, DRM-1 End Seals

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IV. WELD DEVELOPMENT

As noted previously, the Reference Design closure had several apparent advantages over the S8ER closure, with respect to improving the integrity of the glass-glass seal. This was not the case, however, from the final weld closure standpoint. It was apparent that achieving good weld integrity would be difficult, because:

- a) The high-temperature assembly operation could oxidize the cup-plug weld lip
- 2) The problem of weld preparation operations, immediately prior to welding.

For the same reasons, we anticipated that difficulty would be encountered in statistically qualifying the closure weld for production, based upon the depth of weld penetration. The welding development program, therefore, was aimed at minimizing and overcoming these two problems.

The oxidation resistance of Hastelloy N at shrink-fit assembly temperatures (1800°F) is reported to be good.⁶ However, it was anticipated that, during assembly exposure to air, along with the introduction of impurities from outgassing of the ceramic hydrogen barrier and the fuel rod, some metal oxidation would result. Precautions were taken to minimize this by conducting the assembly process in a vacuum of 10^{-1} torr. In addition, the thickness of the closure weld lip was increased from 0.020 to 0.040 in. This increase was to permit the use of a higher energy input during the welding operation, if the surface oxides in the weld zone did present difficulties.

Test closure welds were made, using process parameters developed for the S8ER closure design during an earlier electron beam welding and heating study.⁷ An excess amount of weld spatter was observed, which indicated an expulsion of foreign matter from the weld interface region. As a result of this condition, none of the closures could be completed successfully.

A comprehensive precleaning operation was then incorporated into the assembly process. Surface oxides were removed by liquid honing the entire cladding tube. Ultrasonic cleaning was employed to remove the contaminants from the interface region. The possibility of entrapped moisture in the weld region was precluded by drying in an oven at 350°F for 30 min.

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Closure weld tests were repeated, employing the cleaning operations prior to welding. In addition, the diameter of the beam during welding was increased from 0.010 to 0.020 in. This change would reduce the heat concentration, and yet increase the weld energy input, thereby enhancing the possibility of floating molten oxides to the surface of the weld puddle. Adjustments were made in welding parameters to achieve full penetration. No difficulties were encountered from contaminants, and successful closures were obtained. Each circumferential weld was made in one pass, with no discontinuities occurring from expulsion of foreign matter. Transverse sections through the welds were metallographically examined, to observe weld quality and penetration characteristics. A representative test closure weld is shown in Figure 8. As can be seen, the weld is uniform and defect free. In addition, full penetration has been achieved.

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Figure 8. Representative Test
Closure Weld
(Figure Unclassified)

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V. WELD QUALIFICATION

Standard nondestructive test methods cannot be effectively used as a measure of closure weld quality. The electron beam closure weld is made in a vacuum, and therefore the standard helium leak check cannot be used. In addition, the weld is not receptive to radiographic inspection techniques, due to the joint configuration. It was thus necessary to resort to destructive tests for weld qualification for S8DRM-1 fuel elements. A 20 sample preproduction run was made, to demonstrate that the welding technique could statistically provide, with 90% confidence, that at least 95% of the welds have a minimum penetration of 67% of the nominal tubing wall thickness. Metallographic examination was used for this purpose. Data from sections showed an average of 0.0102 in. penetration, with a standard deviation of 0.001 in. These data indicated that the confidence statement was easily met, and the welding parameters listed in Table 9 were approved for use in production.

TABLE 9
ELECTRON BEAM CLOSURE
WELDING PARAMETERS

Accelerating voltage (kv)	90 ± 3
Beam current (ma)	1.1 ± 0.2
Focus current (amp)	0.51 ± 0.02
Rotation speed (rpm)	20 ± 2

Until nondestructive inspection techniques can be developed to provide a quantitative measure of weld quality, a periodic surveillance of production welds is required, to demonstrate conformance to fabrication requirements. This will be accomplished by randomly selecting one fuel element, from each 40 produced, for destructive testing.

VI. PRODUCTION UTILIZATION

The grooveless Reference Design end closure was used in the fabrication of 25 fuel elements for the SNAP 8 DRM-1 core loading. During fabrication, a change was made in the ceramic hydrogen barrier, which will be covered in another report. Consequently, 12 elements contained AI 8763D coating, and 13 contained the newer SCB-1 coating. The average permeation rate of the 25 elements was 0.29 cc/hr/element, when tested isothermally at 1400°F. The range of the leak rates was from 0.12 to 0.52 cc/hr, well within the specification of 1.50 cc/hr/element or less, when tested at 1400°F isothermal. A completed element and its various components are shown in Figure 9.

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Figure 9. DRM-1 Fuel Element Components
(Figure Unclassified)

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VII. CONCLUSIONS

Three end closure designs were fabricated and tested for use in SNAP 8 DRM-1 fuel elements. The lowest hydrogen leak rates were obtained with the grooveless Reference Design. This, coupled with other test data (shock, vibration, thermal endurance, etc.) and the fact that it is a one piece configuration, led to the "Reference Design" being designated as the closure for the DRM-1 fuel elements. The 25 required fuel elements were successfully fabricated with an average permeation rate of 0.29 cc/hr at 1400°F, far better than the 1.50 cc/hr maximum specification limit.

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