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ENVIRONMENTAL TESTING

SNAP 10A

FUEL ELEMENTS

(Title Unclassified)

AEC Research and Development Report

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ENVIRONMENTAL TESTING

SNAP 10A

FUEL ELEMENTS

(Title Unclassified)

By

J. L. ISAACS

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ABSTRACT

The hydrogen barrier in fuel elements for SNAP 10A reactors has shown good hydrogen retention properties at temperatures over 300°F higher than the maximum design fuel temperature of the reactor (1085°F). In fact, a temperature excursion to 1475°F did not severely damage the hydrogen barrier of any of the 24 fuel elements involved. Thus, the fuel elements have demonstrated a large margin of safety for operation in a SNAP 10A reactor.

One hundred and twenty SNAP 10A fuel elements containing normal uranium were subjected to a series of high-level inputs in order to determine the reliability of SNAP 10A fuel elements as a function of the severity of the environment. Fuel elements were subjected to environmental inputs up to 2-1/2 times more severe than the qualification level inputs. All fuel elements completed the program without having a hydrogen (moderator) loss rate exceeding the defined failure limit of 2.0 cc (STP)/hr at 1200°F, which is equivalent to 0.0375 cc (STP)/hr at SNAP 10A operating conditions.

Failure is a misnomer because, even if several elements in the reactor had permeation rates exceeding the defined failure limit, the system could still complete its mission successfully. In fact, if all elements in the reactor "failed" (as defined previously), the reactor would still produce the desired power for most of the mission life. Although some of the environmental inputs damaged the fuel elements slightly, the maximum permeation was never more than three-fourths of the failure limit.

Ten elements which successfully completed the program were given some additional tests. Foremost among these was a 1400°F endurance test. This temperature, which is more than 300°F higher than the reactor temperature, caused only slight damage to the elements. In fact, one element showed better performance after 200 hr at 1400°F. However, this element later failed (as defined previously) after a thermal cycle from 1400 to 1450°F,

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ABSTRACT

followed by another thermal cycle from 1400°F to room temperature and back to 1400°F.

Operation of a SNAP 10A reactor was simulated by a computer code, FUSAK. It was found that the reactor would have lost 3.2¢ of reactivity if the actual reactor elements performed identically to the elements in this program. This represents a 10.75°F drop in reactor operating temperature.

Two methods were used to determine fuel element reliability. The first (demonstrated reliability) was limited by the number of elements tested and the fact that no elements failed. This method gave a conservative estimate of 99.52%. The other method had no restrictions, and it gave a much more realistic estimate of 99.979% for one element to successfully withstand all inputs. For a core load of 37 fuel elements, this corresponds to a reliability of 99.926%, as compared to the reliability goal of 99.5%.

Suggestions for future work are given; and all fuel elements in this program have been stored, in the event future testing is desired.

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Figure 1. SNAP 10A Flight System
(Figure Unclassified)

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I. INTRODUCTION

In early 1955, the Atomic Energy Commission initiated the Systems for Nuclear Auxiliary Power (SNAP) program for development of nuclear power systems suitable for use in space. Since nuclear systems can provide the compact, long-duration energy necessary for exploration of the distant parts of the solar system, SNAP reactors will be the forerunners of the advanced nuclear power plants needed for future missions. The first power system flight tested under the SNAP programs was the SNAP 10A system (Figure 1).

The SNAP 10A reactor is an outgrowth of the SNAP Experimental Reactor (SER) and the SNAP 2 Developmental Reactor (S2DR) programs. Under these programs, reactors were successfully operated between 1959 and 1962. Information obtained from these and other related programs was used in the design of the ground-tested SNAP 10A FS-3 (Flight System-3), which became critical in January 1965, and the FS-4 system, which was launched in April 1965. The latter system operated successfully in space for 43 days before shutdown.

The SNAP 10A system is primarily intended for use as a low power source for space vehicles. It was statically controlled (no external control necessary), and was to produce 39.5 kwt for 1 yr. Already under development are more advanced reactors which will provide power many hundred times that of the SNAP 10A.

Heat generated in the SNAP 10A reactor (Figure 2) is transmitted to the thermoelectric convertor by a circulating liquid-metal coolant. The convertor was to produce a minimum electrical power of 525 w.^(1, 2)

A. FUEL ELEMENTS

The heart of the SNAP 10A reactor is the 37 fuel-element core. The fuel elements consist of a zirconium - 10 wt % uranium rod, protected by a ceramic coated Hastelloy N cladding assembly. The rod was hydrided to an N_H of 6.35 (6.35×10^{22} atoms of H/cc) so that the fuel element also contains the moderator.

As shown in Figure 3, the fuel elements are 1.25 in. in diameter and 12.45 in. long. The cladding assembly consists of a ceramic coated 15-mil wall tube and two coated end assemblies. The ceramic coating is Solaramic S-14-35-SM enamel supplied by Solar, a division of International Harvester.

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Figure 2. SNAP 10A Reactor and Shield
(Figure Unclassified)

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Figure 3. SNAP 10A Fuel Element
(Figure Unclassified)

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Elements are assembled by first welding the blind end cap to the tube, and internally coating the entire assembly. The hydrided fuel rod is then placed into the assembly, and the coated closure cup is placed over it. The ceramic on the cup is then fused to the ceramic on the tube to provide a continuous ceramic envelope around the fuel rod. Finally, the closure cap is welded into place to complete the fuel element.

The primary reason for internally coating the SNAP 10A cladding assembly with ceramic is to minimize the hydrogen loss from the fuel rods. The operating life of the SNAP 10A reactor is largely dependent on the presence of the hydrogen (neutron moderator) in the core; so, if the barrier is absent or even damaged, it would shorten the expected useful life of the SNAP 10A reactor.

B. PERFORMANCE TESTING

Since the ceramic barrier is structurally the weakest part of the fuel element, it is necessary to subject elements to any input which could damage the barrier in order to determine the true reliability of the SNAP 10A core. By subjecting fuel elements to a series of simulated inputs during performance testing, it was possible to determine what effect each input had on the fuel element.

The condition of the fuel element can be determined by isothermally heating the element in an evacuated chamber and monitoring the hydrogen loss rate. If the test input should affect the fuel element, the hydrogen loss rate will increase, indicating a damaged ceramic barrier and a less efficient fuel element. It is possible to either damage the ceramic slightly, causing some increase in loss rate, but not enough hydrogen loss to jeopardize the operation of the reactor; or to damage the element enough to deleteriously affect reactor operation. The largest hydrogen loss rate that will not exceed the design limits for reactor operation is called the fuel element acceptance limit. Elements exceeding this rate did not begin this test program.

Fuel elements in the SNAP 10A reactor are subjected to 5 different phases of reactor operation. They are:

- 1) Handling and delivery
- 2) Prelaunch checkout
- 3) Launch

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4) Reactor startup

5) Reactor operation

Any of these could adversely affect the fuel elements and jeopardize the reactor. Therefore, elements designed for use in the SNAP 10A reactor should demonstrate a high degree of reliability to withstand all five phases of operation.

Each phase of operation (with the exception of radiation in Phase 5) can be simulated in the laboratory by one or more performance test inputs. Each input is designed to subject the fuel element to an environment which is at least as severe as that found in the reactor. The environmental tests are described in the following sections.

1. Handling and Delivery

Groups of fuel elements are shipped between two points, loaded and unloaded in a reactor core, and subjected to normal handling during testing. If the fuel elements can withstand the launch simulation test, they should not be affected by this input.

2. Prelaunch Checkout

Prelaunch conditions are simulated by the thermal soak input, where the elements are slowly heated to the reactor operating temperature, dwell at this temperature for several hours, and are slowly cooled to ambient temperature.

3. Launch

Launching is simulated by the vibration and shock input, where the elements are subjected to vibration and shock at levels greater than possible during launch.

4. Reactor Startup

Reactor startup is simulated by ramp heating, where the elements are rapidly heated to the reactor operating temperature.

5. Reactor Operation

It is too expensive to test many elements in an operating nuclear reactor, so this phase was split into two operations. One operation, which can be easily applied to many fuel elements, determines the effect of long term testing at the reactor operating temperature, while the second operation subjects a limited

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number of elements to a nuclear environment. Because of the expense involved, only a few elements receive the latter operation.

Elements discussed in this report have been subjected to Operational Phases 1, 2, 3, 4, and the nonnuclear portion of 5. The results of nuclear testing are reported in References 3 and 4.

Fuel elements used in the nonnuclear simulations contain normal uranium, rather than the enriched uranium used for elements in the actual reactor. Otherwise, the elements are identical to the reactor elements. Normal uranium is used because it reduces the possibility of nuclear accidents and simplifies the experimental procedure without affecting the test results.

C. PREVIOUS WORK

In order to design a fuel element which could demonstrate a high degree of reliability to withstand all phases of SNAP 10A reactor operation, an experimental program was initiated in 1961. Using the experience gained in the SER and S2DR programs, five fuel element designs were proposed. During developmental testing, each design was subjected to vibration and shock (the most severe environmental input) to determine the best design.⁽⁵⁾ The present SNAP 10A design (Figure 3) was chosen at this time. Further developmental tests were made to determine the effects of vibration and shock and of endurance testing.^(6, 7) No element was severely damaged during these tests.⁽⁸⁾

The second portion of the test program (Qualification Testing)^(9, 10) began in 1962. These tests were designed to establish the reliability of fuel elements of the SNAP 10A design to successfully withstand all phases of reactor operation. Sixty-six elements completed the following series of nonnuclear performance test inputs without damage:

- 1) Thermal soak
- 2) Vibration and shock
- 3) Ramp heat
- 4) Thermal endurance

After completing all inputs, the fuel elements were cut open and the condition of their ceramic barriers was checked. No adverse effects were found.

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D. ENVIRONMENTAL TEST PROGRAM

The third portion of the test program has been designated Environmental Testing. This testing was designed to establish the reliability of the fuel element design as a function of the input level. Fuel elements were subjected to vibration and shock, ramp heat, and thermal endurance inputs at levels up to 2-1/2 times higher than the level in the Qualification Program.⁽¹⁰⁾ In addition, several special tests were performed. This report covers the Environmental Testing Program.

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II. PROGRAM DESCRIPTION

One hundred and twenty normal SNAP 10A fuel elements were assembled between February 1963 and June 1964 for testing in the Environmental Test Program. All elements contained normal uranium rather than enriched uranium, but otherwise met all specifications for use in the SNAP 10A reactor.

A. TEST PROGRAM

Fuel elements in the Environmental Test Program received the same 4 test inputs as the elements in the Qualification Program:

- 1) Thermal soak
- 2) Vibration and shock
- 3) Ramp heat
- 4) Thermal endurance

However, for this program, the level of one or more of these inputs was increased. Figure 4 shows the planned sequence of inputs for each of the 4 test phases. The purpose and test procedure for each phase is described in the following sections.

1. Phase I (High Vibration and Shock)

This phase was designed to establish the maximum vibration and shock input that the elements could withstand. A group of 5 fuel elements was subjected to vibration and shock at 200% of the SNAP 10A qualification level without failure, so a second group of 5 different elements received a 250% input. Since the permeation of no element exceeded the defined failure limit, the 20 remaining Phase I elements received the 250% level.

2. Phase II (High Ramp Heat)

The second phase was to establish the maximum ramp heat input that an element could complete without failure. Each ramp heat input consisted of five heating-cooling cycles. All elements received a gradient ramp heat input to 600° F at 600° F/min without failure. A group of 5 elements then successfully completed a gradient ramp heat input to 1050° F at the same rate, so a second group of 5 received a similar gradient ramp heat input to 1200° F. No element failed, so all 20 remaining elements received the same gradient ramp heat input to 1200° F.

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*L1200 DENOTES A PERMEATION TEST AT 1200°F
 †100% DENOTES THE SNAP 10A QUALIFICATION LEVEL INPUT⁽¹⁰⁾
 §10 ELEMENTS RECEIVED AN ISOTHERMAL RAMP HEAT RATHER THAN THE
 GRADIENT RAMP HEAT (see text).

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Figure 4. SNAP 10A Fuel Element Environmental Test Sequence (nonnuclear)
 (Figure Unclassified)

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3. Phase III (Interaction)

In order to determine the maximum combination of high-level vibration and shock and high-level ramp heat that an element can withstand, a group of 5 elements received a 250% vibration and shock input followed by 1200°F ramp heat. Since no element failed, all remaining elements received the same combination.

4. Phase IV (Control)

This phase established the response of fuel elements to a series of reference level inputs. Normally, this function would be provided by the Qualification Test Program, but certain changes in the test requirements (See Section IV) made it necessary to add this phase. The results of this phase were used to determine the extent of damage done in the other 3 phases.

5. Endurance Test

After completing the 3 pre-endurance inputs, all fuel elements were placed on endurance test. Twelve elements from each phase were placed on test at 1200°F; another 12 elements per phase were tested at 1300°F; and the remaining 6 elements per phase were tested at 1350°F. By this method, it was possible to determine the effect of the high temperature tests regardless of prior testing.

B. TEST INPUTS

Before beginning the Environmental Test Program, it was necessary for every fuel element to successfully complete an acceptance test sequence. The same procedure is followed for reactor elements.

1. Acceptance Permeation Tests

Two permeation tests were performed on all SNAP 10A fuel elements after assembly. The first test was to determine whether an element had a permeation rate below the acceptance limit of 0.8 cc(STP)/hr when the element was at 1200°F (isothermal). The second test was to determine whether the acceptance vibration test, described in the following section, damaged the barrier.

2. Acceptance Vibration Test

Every element was subjected to an acceptance vibration test. This test was necessary to cull elements which were sensitive to vibration. The vibration inputs are listed in Table 1.

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TABLE 1
ACCEPTANCE VIBRATION
LEVELS*

Magnitude	Frequency (cps)
3/16 in. DA	5 - 13
3.4 g	13 - 400
5 g	400 - 3000

*Vibration levels were the same for each of three mutually perpendicular axes. The vibration inputs were applied at a constant octave sweep rate, requiring 5 min on each axis.

3. Environmental Tests

Although the severity of the test inputs varied for each phase, the test sequence remained the same. The inputs are described briefly in the following sections.

a. Thermal Soak

Three slow temperature cycles, consisting of heating at 300°F/hr to 1200°F, dwelling at 1200°F for 10 hours, and cooling at 300°F/hr to ambient temperature, constituted the thermal soak test.

b. Vibration and Shock

The vibration and shock reference levels are presented in Table 2. Fuel elements in Phases II and IV were subjected to the reference level inputs, while the elements in Phases I and III received either 200 or 250% of the reference level.

c. Ramp Heating

The ramp heating input was at a gradient temperature condition. The heating rate was 600°F/min for 1 min at the blind end and 300°F/min over the same time interval for the closure end, which caused an axial temperature gradient of about 300°F. Radially, the mean volume temperature of the blind end cap was $50 \pm 25^\circ\text{F}$ cooler than the adjacent cladding at the peak temperature. Twenty elements in Phase I and all elements in Phases II and IV received this input.

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TABLE 2
VIBRATION AND SHOCK LEVELS

Vibration Reference Levels

Vibration inputs were applied along each of three mutually perpendicular axes in a single sweep at a constant octave sweep rate and proceeding from low to high frequency in a period of 25 min. Vibration reference levels were as follows:

Frequency (cps)	Magnitude
5 to 20	1/8 in. , 0 to peak
20 to 400	5 g peak
400 to 3000	7.5 g peak

Shock Reference Levels

Shock inputs were two half-sine pulse shocks applied in each direction along each of three mutually perpendicular axes (for a total of twelve shocks for the elements). Each shock pulse had a time duration of 6 ± 1 msec. Shock loads were as follows:

Axis	Magnitude (g)
Longitudinal (centerline of fuel element. Positive direction is toward top end of fuel element)	20
Lateral	10
Normal	10

Note: For inputs at 200 or 250% of the reference level, only the magnitude is multiplied by the appropriate number, leaving the frequency and direction the same.

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The high level gradient ramp heat input had the same rate, but for longer times, so that the peak temperature was increased to either 1050 or 1200°F. Fuel elements in Phases II and III received this test. This was a second ramp heat test for the elements in Phase II.

Ten Phase I fuel elements received an isothermal ramp heat input rather than a gradient input, because they were tested before the revised test specification was adopted. The isothermal input was the same input that fuel elements in the Qualification Program received,⁽¹⁰⁾ but to 1200°F instead of to 1100°F.

4. Thermal Endurance

The fuel elements from each phase were subdivided into 3 groups and placed on endurance test for a period of 6 mo to 1 yr. The groups were:

- 1) 12 elements at 1200°F
- 2) 12 elements at 1300°F
- 3) 6 elements at 1350°F

5. Postendurance Testing

After completion of the endurance test, all fuel elements were given a 1200°F permeation test and a dimensional check. This completed the test sequence for 110 of the 120 elements in this program. The remaining 10 fuel elements received some combination of the following inputs:

- 1) High-level gradient ramp heat
- 2) Permeation vs temperature study
- 3) Additional 1200°F endurance testing
- 4) High temperature endurance testing (1400°F)

The test equipment and procedures for all inputs except the gradient ramp heat input are discussed in Appendix 1 of Reference 9. The gradient ramp heat input is discussed in the Appendix of this report.

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III. RESULTS AND CONCLUSIONS

All 120 fuel elements completed the program without a failure. Thus, it is concluded that SNAP 10A design fuel elements are capable of withstanding environments (nonnuclear) many times more severe than any experienced during reactor operation.

Due to the size of this program, it is inapt to present a complete data compilation. However, any data pertinent to the discussion will be included in this report. A compilation of all data can be found in Reference 11.

A. SUMMARY OF TEST RESULTS

Figure 5 and Tables 3, 4, and 5 summarize the data from the Environmental Test Program.

1. Failure Criterion

The failure rate [2.0 cc(STP)/hr at 1200°F] was chosen to be 2.5 times the acceptance limit for SNAP 10A reactor fuel elements. The acceptance limit is 0.8 cc(STP)/hr at 1200°F, which is based on the design value for the maximum hydrogen loss from the SNAP 10A reactor (0.05%). This loss equals 0.015 cc (STP)/hr for one year at the reactor operating temperature, which is again equivalent to 0.8 cc(STP)/hr at 1200°F.

Failure, per se, is a misnomer. The permeation rate of several fuel elements in a reactor could grossly exceed the defined failure limit without compromising the mission.⁽¹⁹⁾ In fact, if the permeation of all elements in a reactor reached the failure limit, the reactor would still produce the desired power for most of the mission life. The failure limit used in this program is therefore very conservative.

Nevertheless, if any fuel element had a permeation rate which exceeded the failure limit, it would have been removed from the program as a "failed" element. As stated previously, no element had a permeation rate greater than the defined failure rate during this program.

2. Program Termination

During the spring of 1965, it was decided that further testing would not contribute sufficiently to an extension of the technology. Therefore, on July 1, 1965,

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Figure 5. SNAP 10A Fuel Element Performance (Pre-Endurance)

TABLE 3
FUEL ELEMENT DATA BY PHASE

Phase	Number of Elements	Composition, (wt %)			Effective H/Zr	Average 1200°F Permeation Rate [cc(STP)/hr]								
		H	C	U		Before Thermal Soak	After Thermal Soak	After 100% Vibration and Shock	After 200% Vibration and Shock	After 250% Vibration and Shock	After Isothermal Ramp Heat	After 600°F Ramp Heat	After 1050°F Ramp Heat	After 1200°F Ramp Heat
I	5	1.801	0.22	10.01	1.885	0.29	0.29	-	0.26	-	0.22	-	-	-
I	5	1.800	0.19	10.02	1.877	0.16	0.13	-	-	0.13	0.15	-	-	-
I	3	1.746	0.18	10.18	1.822	0.21	0.27	-	0.52	-	-	0.48	-	-
I	17	1.792	0.18	10.14	1.869	0.30	0.22	-	-	0.48	-	0.50	-	-
II	5	1.796	0.17	10.00	1.870	0.20	0.18	0.30	-	-	-	0.16	0.23	-
II	25	1.785	0.17	10.07	1.861	0.27	0.26	0.29	-	-	-	0.32	-	0.36
III	30	1.754	0.18	10.22	1.831	0.39	0.37	-	-	0.64	-	-	-	0.62
IV	30	1.754	0.17	10.20	1.830	0.38	0.39	0.42	-	-	-	0.47	-	-

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TABLE 4
FUEL ELEMENT DATA BY INPUT

Test Input	Number of Elements	Permeation Rate [cc(STP)/hr at 1200°F]					Statistically Significant ("t" Test)
		Before Test	Range	After Test	Range	ΔL	
Acceptance	120	0.35	0.10 - 0.81	0.32	0.08 - 0.76	-0.03	Yes
Thermal Soak	120	0.32	0.08 - 0.76	0.31	0.06 - 0.81	-0.01	No
Vibration and Shock (%)							
100	60	0.32	0.09 - 0.81	0.36	0.07 - 0.83	+0.04	Yes
200	8	0.28	0.08 - 0.42	0.36	0.16 - 0.80	+0.08	No
250	52	0.31	0.06 - 0.76	0.54	0.08 - 1.38	+0.23	Yes
Ramp Heat Isothermal	10	0.20	0.08 - 0.37	0.19	0.09 - 0.33	-0.01	No
Gradient (°F)							
600 Pk	60	0.36	0.07 - 0.83	0.38	0.08 - 0.94	+0.02	No
600 Pk*	20	0.48	0.11 - 1.24	0.50	0.15 - 1.27	+0.02	No
1050 Pk†	5	0.16	0.08 - 0.23	0.23	0.11 - 0.46	+0.07	No
1200 Pk†	25	0.32	0.11 - 0.94	0.36	0.09 - 0.87	+0.04	No
1200 Pk*	30	0.64	0.21 - 1.38	0.62	0.24 - 1.53	-0.02	No

*After High Level Vibration and Shock
†After 600°F Ramp Heat

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TABLE 5
FUEL ELEMENT ENDURANCE DATA
Average 1200°F Permeation Rate [cc(STP)/hr]

Phase	Temper- ature (° F)	Months on Test											
		6			9			10-1/2			12		
		Number of Elements	Before	After	Number of Elements	Before	After	Number of Elements	Before	After	Number of Elements	Before	After
I	1200	-	-	-	-	-	-	2	0.46	0.31	10	0.19	0.14
I	1300	6	0.50	0.35	-	-	-	-	-	-	6	0.64	0.26
I	1350	6	-	-	3	0.22	0.33	3	0.53	0.25	-	-	-
II	1200	3	0.33	0.29	3	0.32	0.27	3	0.23	0.14	3	0.16	0.16
II	1300	6	0.44	0.23	6	0.29	0.36	-	-	-	-	-	-
II	1350	-	-	-	6	0.42	0.41	-	-	-	-	-	-
III	1200	12	0.68	0.35	-	-	-	-	-	-	-	-	-
III	1300	12	0.57	0.30	-	-	-	-	-	-	-	-	-
III	1350	6	0.62	0.31	-	-	-	-	-	-	-	-	-
IV	1200	12	0.43	0.30	-	-	-	-	-	-	-	-	-
IV	1300	12	0.54	0.33	-	-	-	-	-	-	-	-	-
IV	1350	6	0.44	0.30	-	-	-	-	-	-	-	-	-

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all testing was terminated and the elements were stored pending further action. Further work suggested for these elements is presented in Section VII.

In order to make the decision to terminate the program, two assumptions were made. They were:

- 1) Fuel elements which have not been damaged by 6 to 10-1/2 mo on endurance test would not be damaged by continuing the test to 1 yr.
- 2) A comparison can be made between an element which has 6 mo on endurance test and one that has 1 yr on test (i. e. , analytical evaluations can be made regardless of the time at temperature).

Although both assumptions appear valid, and all calculations were made based on these two points, further work should be done to confirm them.

B. PRE-ENDURANCE TESTING

Each element was subjected to inputs according to the test plan given in Figure 4. The effects of each pre-endurance input are given in the following paragraphs.

1. Thermal Soak

All elements successfully completed this input without any effect. A statistical "t" test, as presented in Table 4, confirmed this result. However, a significant decrease in the average permeation rate was found between the acceptance test and the pre-thermal soak permeation test. Since there was no input between these tests, it is concluded that this decrease was due to outgassing of the external surface of the fuel element.

2. Vibration and Shock

Since the average permeation rate increased significantly after both low and high vibration and shock inputs (100, 200, and 250% of the SNAP 10A qualification level), these inputs were damaging to the fuel elements. This conclusion was confirmed by a "t" test on the data before and after the input. The results, as given in Table 4, show that the increase in permeation rate for the 100 and 250% was statistically significant at the 95% confidence level. Vibration and shock at the 200% level gave the same trend, but was not significant, due to the small sample size.

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A statistical study was performed to determine whether a relationship exists between the fuel element position in the vibration and shock test fixture and the change in permeation rate caused by the input. A linear relationship had previously been found for SNAP 2 fuel elements⁽¹²⁾ (these elements have the same dimensions as the SNAP 10A fuel elements, but they have AI-8763D ceramic barrier), so a similar relationship was thought to exist for SNAP 10A fuel elements.

This study showed that a linear relationship does exist for elements which received the 250% vibration and shock input, but no similar relationship could be found for fuel elements which received the 100% input. There were not enough elements subjected to the 200% input to statistically make any conclusions.

Forty-seven fuel elements were subjected to the 250% vibration and shock input. Of these, 38 were located along the X or normal axis of the test fixture (Positions 1 through 4, Figure 6), and the other nine elements were located in a row parallel and adjacent to the X axis (Positions 5 through 8, Figure 6).

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Figure 6. Vibration and Shock Core
Tank Loadings
(Figure Unclassified)

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Two studies were made on the 250% data. The first examined only those elements which were along the X axis during the test input. This yielded the following equation:

$$\Delta L = 0.0132 + 0.1366 (X) \quad \dots (1)$$

where

ΔL = the change in 1200°F permeation rate [cc(STP)/hr]

X = the distance (in.) from the centerline of the core tank to the centerline of the fuel element along the X axis

For the other study, the data of all 47 fuel elements were examined. The distance (X) remains the distance along the X axis. Thus, the distance for all elements is measured from a line normal to the X axis and passing through the element centerline. This equation is:

$$\Delta L = 0.0182 + 0.1286 (X) \quad \dots (2)$$

Both equations were found to have significant correlation coefficients, and slopes significantly greater than zero. Additional statistical tests showed that no difference exists, at the 0.05 significance level, between the slopes and intercepts of both equations. Therefore, either equation can be used to describe the relationship.

3. Ramp Heat

Although all elements were ramp heated, only the first 10 elements in Phase I were ramp heated isothermally. The average 1200°F permeation rate for these elements decreased 0.01 cc(STP)/hr. The remaining 110 elements received one or two gradient ramp heat inputs* to a peak temperature of either 600, 1050, or 1200°F. The results show that the average element had a permeation increase of 0.02 cc(STP)/hr after the low level (600°F) input, and an increase of only 0.01 cc(STP)/hr after a high level (1050 or 1200°F) input. Since these changes are within experimental accuracy, we conclude that the ramp heat input will not damage the fuel element. The data are shown in Tables 3 and 4.

*Each ramp heat input included 5 thermal cycles, each of which simulated 1 reactor startup.

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4. 10FS-1 Fuel Elements

Thirteen fuel elements in the Environmental Test Program received their acceptance vibration input while loaded into the 10FS-1 reactor, rather than in a separate vibration and shock test fixture (See Section II-B). These elements were loaded with 24 fuel element mockups into the 10FS-1 core during the system acceptance vibration test. The elements were then given a final acceptance permeation test.

As shown in Table 6, no element was severely damaged by the test. Only one element (N-158) showed a significantly increased permeation rate after the input. However, this rate was still below the SNAP 10A acceptance limit of 0.8 cc(STP)/hr, so the element received further testing. After completing all Phase II inputs and 9 mo at 1300°F, the permeation rate of Element N-158 was still below the acceptance limit.

5. Pre-Endurance Conclusions

Using data from this program and from the SNAP 10A Qualification Test Program, the following conclusions were drawn:

1) Thermal Cycling, simulating prelaunch checkout, and Ramp Heating, which simulates reactor startup, will not damage the SNAP 10A fuel element.

2) Launch, simulated by Vibration and Shock, may cause slight damage to the barrier of the fuel elements. However, this damage will in no way jeopardize the design objectives of the present SNAP 10A reactor.

3) Since elements located around the periphery of the core are more susceptible to damage than those located nearer the center, any damage (as suggested in Section III-B-2) should affect outer elements only. However, these elements have far less reactivity worth than central elements. Therefore, there should be no noticeable reactivity loss due to any operation through launch and reactor starting.

C. ENDURANCE TESTING

The elements in each phase were placed into 3 groups by use of a random numbers table. Two groups of 12 elements from each phase were then placed on endurance test at 1200 and 1300°F, respectively. The remaining 6 elements

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TABLE 6
PERMEATION DATA OF 10FS-1 FUEL ELEMENTS

Element Number	1200° F Permeation Rate [cc(STP)/hr]					
	Pre-10FS-1	Post-10FS-1	Pre-Thermal Soak	Post-Thermal Soak	Post-Vibration and Shock	Post-Ramp Heat
N-140	0.22	0.20	0.19	0.21	0.30	0.23
N-142	0.35	0.24	0.29	0.23	0.29	0.46
N-143	0.10	0.12	0.10	0.09	0.28	0.11
N-152	0.24	0.14	0.13	0.13	0.30	0.23
N-156	0.25	0.40	0.29	0.26	0.33	0.22
N-158	0.31	0.69	0.53	0.61	0.70	0.60
N-162	0.15	0.15	0.14	0.09	0.08	0.09
N-163	0.25	0.27	0.23	0.30	0.25	0.15
N-164	0.28	0.21	0.20	0.18	0.19	0.27
N-166	0.17	0.13	0.25	0.57	0.83	0.78
N-167	0.29	0.22	0.16	0.16	0.23	0.29
N-168	0.18	0.18	0.12	0.12	0.14	0.15
N-170	0.12	0.22	0.09	0.41	0.52	1.15
Average	0.22	0.24	0.21	0.26	0.34	0.36
Average of 60 Phase I and II Elements	0.28	0.26	0.26	0.23	0.34	0.37

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were placed on 1350°F test. All elements completed at least 6 mo on test before the program was terminated.

All elements were loaded into vacuum retorts, either singly or as clusters of either 2 or 3 elements, and the hydrogen loss rate from each retort was periodically monitored. By fitting all data to an equation of the following form:

$$L = K_1 \exp(-K_2 t) \quad \dots (3)$$

where

L = endurance permeation rate [cc(STP)/hr]

t = hours on endurance test

the total hydrogen loss for one year on test can be found. These curves are presented in Figure 7.

1. Temperature Excursions

Twice during this program, groups of elements were subjected to endurance temperatures more than 100°F higher than the nominal test temperature. Both were short term tests, but only one was planned. These tests are described in the following paragraphs.

a. 10 Elements From 1200 to 1300°F

Before changing the specification for the Environmental Test Program to include endurance tests at 1300 and 1350°F, 10 elements on test at 1200°F were subjected to one day at 1300°F. The data, as presented in Table 7, showed that 1300°F did not damage these elements. No tests were made at temperatures around 1350°F. However, when the first group of 3 elements to be tested at 1350°F were loaded into an endurance furnace, they were kept at 1200 and at 1300°F for several days before being taken to 1350°F. No adverse effects were seen.

b. 24 Elements From 1300 to 1475°F

On December 23, 1964, the control unit for one of the thermal endurance furnaces failed. This furnace contained 24 fuel elements from this program and had been operating at 1300°F for more than 6000 hr. When the failure was

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Figure 7. SNAP 10A Fuel Element Performance (Endurance)

discovered, the furnace temperature had reached 1475°F (Figure 8). Attempts to restore control to the furnace failed, so the furnace was turned off.

As shown in Table 8, up to 48 atm of internal pressure can be generated within a SNAP 10A fuel element at 1475°F. These pressures could have damaged the elements, so all elements were given a dimensional check and a permeation test. No changes in the external dimensions of the fuel elements were found.

Generally, the individual permeation rates were found to be only about 10% higher than the estimated rates just prior to the excursion. Therefore, all elements were reloaded into the repaired endurance furnace to continue on test.

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TABLE 7
EFFECT OF SHORT TERM 1300°F TEST

Element Number	Hours on Endurance Test			
	1752 hr L_{1200}^*	1896 hr L_{1300}	1920 hr L_{1200}	2592 hr L_{1200}
N-88, 101, 104	0.37	1.30	0.39	0.39
N-97	0.08	0.34	0.08	0.06
N-105	0.15	0.63	0.13	0.13
N-137, 146, 159	0.33	1.32	0.34	0.30
N-155	0.05	0.32	0.06	0.06
N-165	0.22	0.72	0.20	0.18
Average	0.20	0.77	0.20	0.19

* L_{1200} denoted a permeation rate at 1200°F [cc(STP)/hr].

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Figure 8. Temperatures During Endurance Failure (12-23-64)
(Figure Unclassified)

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TABLE 8
DATA OF ELEMENTS FROM FURNACE WITH CONTROL FAILURE

Retort Number	Element Number	Phase	Internal Pressure at 1475° F (atm)	Hours at Temperature Before Failure	Permeation Rate [cc(STP)/hr at 1300° F]				
					Pre-Endurance	Post-Incident (~)	Post-Incident*	After 1 Month on Endurance	After 2 Months on Endurance
1	N-214	IV	18.2†	672	2.0	1.6	1.4	5.3	5.0
	N-249		27.5†		2.0	1.6	1.5		
	N-293		18.2†		<u>2.2</u>	<u>1.7</u>	<u>1.9</u>		
					6.2	4.9	4.8		
2	N-163	I	15.5	6096	0.71	0.52	0.84	2.4	2.7
	N-167		34.0		1.2	0.73	0.73		
	N-175		43.0		<u>1.1</u>	<u>0.69</u>	<u>0.52</u>		
					3.0	1.9	2.1		
3	N-158	II	32.0†	3072	2.3	0.98	2.1	3.2	3.0
	N-186		28.0†		0.80	0.46	0.67		
	N-187		48.0†		<u>0.83</u>	<u>0.50</u>	<u>0.87</u>		
					3.9	1.9	3.6		
4	N-164	II	43.0†	2136	1.1	1.1	1.1		
	N-181		14.2†		1.2	1.4	1.5		
	N-223		12.0†		<u>1.0</u>	<u>1.2</u>	<u>1.4</u>		
					3.3	3.7	4.0		
5	N-222	IV	21.0†	1872	0.98	1.0	1.6	3.5	3.2
	N-234		18.2†		0.88	0.94	0.88		
	N-238		15.5†		<u>0.98</u>	<u>1.5</u>	<u>0.70</u>		
					2.8	2.4	3.2		
6	N-232	III	18.2†	1536	2.0	1.0	1.6	3.7	3.9
	N-237		17.0†		1.8	0.92	1.3		
	N-243		22.0†		<u>1.5</u>	<u>0.80</u>	<u>0.85</u>		
					5.3	2.7	3.8		
7	N-246	III	18.2†	672	1.6	0.80	1.2	1.0	0.91
8	N-247	III	23.5†	672	1.4	1.2	1.2	1.3	1.2
9	N-170	I	4.0	6096	4.5	1.3	1.7	1.6	1.1
10	N-182	I	13.0	6096	2.4	1.2	1.3	1.4	1.4
11	N-178	I	15.5	6096	4.0	1.1	1.6	1.3	1.2
12	N-256	III	17.0†	<u>672</u>	<u>1.2</u>	<u>1.3</u>	<u>0.49</u>	<u>1.5</u>	<u>1.4</u>
Average				2770	1.65	1.06	1.16	1.28	1.22

*Individual permeation tests

†Average pressure based on initial fuel composition – adjustment made only for the elements on 6100 hr test

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Although some of the rates decreased slightly, the average element endurance permeation rate stayed constant. It has therefore been concluded that a short time at temperatures up to 1475°F will cause slight damage to the fuel element, but will not cause catastrophic degradation. Further tests at temperatures near 1400°F are discussed in the postendurance testing section.

2. Endurance Conclusions

Using data obtained from endurance testing, we make the following conclusions:

- 1) Extended time at temperature, which simulates nonnuclear operation of a reactor, will not damage the fuel elements.
- 2) Temperatures far greater than the 900 to 1050°F operating temperatures of the SNAP 10A reactor will not cause severe element damage.

D. POSTENDURANCE TESTING

A series of additional tests was made on the 10 Phase I fuel elements which completed one year of endurance test. These elements previously received the following inputs: thermal soak, high-level vibration and shock, isothermal ramp heat, and one year of 1200°F endurance. All elements received a dimensional check and a permeation test after endurance. No significant change in dimensions was found. Permeation data are summarized in Table 9.

Five of these elements were ramp heated 5 times to 1200°F (gradient), permeation tested, and placed back on endurance test at 1200°F to determine the "restart" capability of the fuel elements. The post-ramp heat permeation test, as presented in Table 9, and all endurance permeation tests for over 1000 hr showed no change due to these additional ramp heats. Therefore, it appears that these elements could be used in a reactor which is restarted. These 5 elements were then transferred to a 1400°F furnace to determine whether SNAP 10A fuel elements can withstand extended 1400°F operation.

The other 5 fuel elements were given a series of permeation tests at 1100, 1200, 1300, 1350°F and at the average SNAP 10A reactor axial temperature profile (Figure 9). The data were used to determine the constants in the following equation, which shows the effect of temperature on permeation.

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TABLE 9
POSTENDURANCE DATA

Element Number	Vibration and Shock Level (%)	Retort Number	Hydrogen Permeation at 1200°F [cc(STP)/hr]					
			Retort Rates			Individual Rates		
			0 Hours	5000 Hours	1 Year	Pre- Endur- ance	Post- Endur- ance	Post - Ramp Heat
N-137	250	2501	0.35	0.30	0.28	0.12	0.13	0.14
N-146						0.09	0.07	0.07
N-159						0.14	0.12	-
N-88	200	2502	0.82	0.51	0.56	0.25	0.16	0.19
N-101						0.23	0.19	0.21
N-104						0.33	0.17	-
N-105	200	2507	0.18	0.13	0.13	0.18	0.18	0.18
N-155	250	2508	0.15	0.06	0.06	0.15	0.05	-
N-97	200	2509	0.13	0.09	0.10	0.13	0.13	-
N-165	250	2512	0.28	0.20	0.18	0.28	0.22	-
	Average		0.19	0.14	0.13	0.19	0.14	

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Figure 9. Average Profile, SNAP 10A
Centerline Element⁽¹³⁾
(Figure Unclassified)

$$\ln (\text{permeation rate}) = 25.858 - \frac{46100}{\text{temperature } (^{\circ}\text{R})} \quad \dots (4)$$

Three of these five elements were then ramp heated and placed back on endurance test at 1200°F to determine whether a combination of thermal cycling and ramp heating will cause element failure. Since no adverse effect was found after 500 hr at 1200°F, these three elements were also transferred to a 1400°F furnace. The other two elements went directly on test at 1400°F.

All ten of these elements were at 1400°F for at least 2500 hr. Eight of the ten completed over 3200 hr with only slight barrier damage. The other two elements (N-88 and N-101) began 1400°F test in a single retort. After 200 hr at 1400°F, the hydrogen flow from the retort increased about 40%. The elements

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were unloaded and then permeation tested in individual retorts at 1200°F. The 1200°F permeation of N-88 had increased from 0.24 to 0.86 cc(STP)/hr, while that of N-101 had decreased from 0.24 to 0.11 cc(STP)/hr. The temperature of these 2 elements, still in individual retorts, was increased to 1400°F. After 1200 additional hours at 1400°F, the temperature of these elements was cycled to 1200°F and the permeation rates again measured. The permeation of N-88 was unchanged, but the permeation of N-101 increased to 0.17 cc(STP)/hr. The elements were again heated to 1400°F and remained there until they had accumulated about 1650 hr at this temperature.

The temperature of N-101 was then increased to 1450°F for 6 days, while N-88 remained at 1400°F. When N-101 was again tested at 1400°F, its permeation rate had doubled, indicating significant damage. Both elements were then cycled from 1400°F to room temperature and back to 1400°F. The permeation rate for N-88 showed no effect, but the rate for N-101 increased by about a factor of 7, indicating severe barrier damage.

From these data, we conclude that 1400°F, per se, causes increased permeation rates, even though the internal hydrogen pressure decreases. This indicates a less efficient hydrogen barrier. In addition, it appears that extended time at 1450°F, combined with 1400°F testing and thermal cycling, can cause catastrophic damage. Further testing at these temperatures could better define the failure threshold and the causes of failure.

The data of all of these elements are discussed further in Section IV-D-1-b.

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IV. DISCUSSION

A. PROGRAM REVISIONS

The Environmental Test Program is designed to determine the effect of high level inputs on SNAP 10A fuel elements. The original test specification called for 3 test phases of 30 elements each. The phases were to determine the effect of high level vibration and shock, ramp heat, and a combination of these inputs, respectively. The first 10 fuel elements were tested according to this specification.

During an analytical study of startup temperature transients in the SNAP 10A reactor, it was found that fuel elements experience severe temperature gradients in the latter stages of startup.⁽¹³⁾ Since both the Qualification and Environmental Test Programs were well underway by this time, it was impossible to start over again with a different simulation of reactor startup. All qualification elements and 10 environmental elements had already received the ramp heat input before this discovery, so it was necessary to revise the environmental test specification to include this new information before the remaining 110 elements were ramp heated. Each specification change is discussed in the following sections. The program was delayed several months by these changes.

1. Gradient Ramp Heat Input

The gradient ramp heat input more closely represents the severe thermal transients and stresses found during startup than the isothermal input. Therefore, the remaining 110 elements received a gradient ramp heat input.

The remaining 20 elements in Phase I, and all elements in Phases II and IV, were ramp heated at 600°F/min to 600°F with about a 300°F axial gradient and a difference of 50°F between the mean volume temperature of the blind end cap and the adjacent cladding. The elements in Phase III received the same input but with a peak temperature of 1200°F. After the 600°F ramp heat, all elements in Phase II received another ramp heat to either 1050 or 1200°F.

2. Phase II Low-Level Ramp Heat

Since no qualification test elements received the gradient input, it was necessary to obtain the greatest amount of information on the qualification level

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ramp heat input from this program. Therefore, it was hypothesized that it would not affect the elements in Phase II to receive a low level input before the high level input. In this manner, 90 elements received the input rather than 60. It was confirmed later that, in fact, this change did not affect the results.

3. Phase IV

When the new ramp heat input was added to the specification, it was necessary to also add a "control" phase (Phase IV). Normally, the qualification elements serve as control elements (i. e., elements used to determine the effect of qualification level inputs). But with the different ramp heat input, the qualification elements were no longer representative. Thus, 30 elements had to be added to this program as control elements.

4. High Temperature Endurance Test

At the same time that specification changes were made to better simulate reactor startup, another unrelated change was made. High temperature (1300 and 1350°F) endurance tests were added to determine the temperature capability of the Solaramic coating.

B. VIBRATION AND SHOCK

1. Similarity to Past Work

The increased permeation rates caused by vibration and shock are presented in Table 4. These changes compare favorably with work done in earlier programs.

All elements in the Qualification Program⁽⁹⁾ received the same vibration and shock inputs as did the 60 elements in Phases II and IV of this program. The input increased the permeation for the 60 environmental elements by 0.04 cc(STP)/hr at 1200°F, which is equivalent to about 0.01 cc(STP)/hr at 1100°F. The latter number is essentially the same as the 0.007 cc(STP)/hr increase at 1100°F seen during the Qualification Test Program. No qualification elements received the 200 or 250% inputs.

During developmental test, 2 elements were subjected to 250% vibration and shock inputs.⁽⁶⁾ The average permeation decrease of 0.02 cc(STP)/hr at 1100°F for the 250% input in the developmental tests appears to be inconsistent with the average 1200°F increase of 0.23 cc(STP)/hr seen for the 250% elements

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in this program. However, the 2 developmental elements were tested in Positions 7 and 8 of the core tank (Figure 6). Equations 1 and 2 show that, for these positions, the predicted 1200° F permeation increase would be about 0.08 cc (STP)/hr. This is equivalent to about 0.02 cc(STP)/hr at 1100° F, so the difference in response of the developmental elements is attributed to the small sample size. In fact, one of the developmental elements showed a permeation increase of 0.01 cc(STP)/hr at 1100° F.

2. Contact During Vibration and Shock

Six elements which received a 100% vibration and shock input and 6 elements which were subjected to a 200% input were found to be contacting each other during the test. Visual observation after test showed that some elements from both of the aforementioned groups had experienced polishing and/or galling of the external surface due to contact with other elements. This was especially obvious in the area where the blind end cap was welded to the tube. At this point, a small "buildup" existed. The entire top of this enlargement had been contacting the neighboring element, as evidenced by the oxidized layer being abraded all around the weld area. Areas of less damage were seen along several elements.

Immediately after this was noticed, the test fixture grid plate holes and dummy element end pins were checked against the test specification and were found to be within tolerance. Therefore, the only explanation seemed to be that the enlargements caused by the weld "buildup" altered the internal clearances and thereby affected the element response during the input. This could conceivably cause the contact.

All fuel elements were permeation tested, but no damage, beyond that seen from other elements after vibration and shock, was found. All elements were given a dimensional check, especially in the area of the blind end weld, but all were within specified tolerances. However, the diameter of each "galled" element at the blind end weld was greater than 1.255 in. which, while within specification, is larger than the 1.250 in. average diameter. The blind weld diameters and core tank positions are shown in Figure 10. Figure 11 shows the abraded area on five of the elements.

Since all dimensions were within specified tolerance, an analysis was made of the dimensions allowed by the specifications. It was found that due to a

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Figure 10. Core Tank Position for Twelve Fuel Elements (Figure Unclassified)

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Figure 11. Elements "Galled" During Vibration and Shock (Figure Unclassified)

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"buildup" of tolerances, interference could occur (cf. Table 10). Therefore, these vibration and shock inputs did simulate possible flight conditions.

TABLE 10
DIMENSIONS AND TOLERANCES ON FUEL ELEMENTS
AND GRID PLATES

	Inches
(1) Distance between hole center lines	1.260
(2) Holes drilled within 0.0015 in. of true position	0.003
(3) Shortest distance between hole centers, (1) - (2)	1.257
(4) Hole diameter	0.1875
(5) Pin diameter	0.1800
(6) Tolerance of hole diameter	± 0.001
(7) Shortest possible distance between hole edges, (3) + (5) - (4) - (6)	1.2475
(8) Maximum envelope diameter of fuel element	1.260
(9) Possible interference, (8) - (7)	0.0125

C. GRADIENT RAMP HEAT

An explanation of the ramp heat input and calculations is presented in the Appendix.

When the gradient ramp heat input was added to the program, the temperature differential between the mean volume temperature of the blind end cap and the adjacent cladding temperature was to be $75 \pm 25^\circ\text{F}$ when the peak cladding temperature was 600°F . However, the test equipment could not consistently meet this limit because this temperature differential varied from element to element. The specified temperature differential was lowered to 50°F , and the average value for the 80 elements which received this input was 42°F . However, some elements which were ramp heated to a peak cladding temperature of 1050 or 1200°F had a temperature differential of over 150°F , and were not damaged.

After the specification change, about 100 elements were ramp heated. Although the differential temperature of some elements was outside the specified

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limits, it was decided not to retest these elements because no significant damage had been seen for any elements which exceeded the upper limit. The average, maximum, and minimum differentials are given in Table 11. A complete listing of the temperatures for each element is given in Reference 11.

TABLE 11
BLIND END TEMPERATURE DIFFERENTIALS

Level	Number of Elements	Temperature Differentials (°F)		
		Average	Maximum	Minimum
Low (600° F)	80	42	112	7
High (1050 or 1200° F)	60*	90	192	43

*Includes 30 elements which were previously tested at 600°F.

D. THEORETICAL ANALYSES

Two different methods were employed to examine the performance of fuel elements during this program. The first, an analysis of K_{BLD} , was used to evaluate the fuel element "quality" after each permeation test,⁽¹⁴⁾ and the second, a computation using the digital computer program FUSAK, determined the performance of the elements in a simulated SNAP 10A reactor.⁽¹⁵⁾ Both methods were developed by M. E. Nathan.

1. K_{BLD}

After each test input, elements are permeation tested to determine what damage, if any, occurred. Increased permeation would denote a damage element. However, if the test input was a one-year endurance test, the fuel element may have lost enough hydrogen to significantly decrease the internal pressure⁽¹⁶⁾ (i. e., the driving force causing hydrogen loss). In this case the permeation rate could be lower even though the element was damaged. Thus, the K_{BLD} method is needed to correct for this.

a. Development of K_{BLD}

Hydrogen can be lost from a SNAP 10A element by: (1) permeation through the ceramic coated tube (L_{CL}) and (2) leakage through defects in the ceramic

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barrier and the closure (L_{BLD}). Thus the total hydrogen loss from the element (L) becomes:

$$L = L_{CL} + L_{BLD} \quad \dots (5)$$

Nathan and Watrous⁽¹⁴⁾ found that:

$$L_{CL} = K_{CL} f_1(P, T) \quad \dots (6)$$

and

$$L_{BLD} = K_{BLD} f_2(P, T) \quad \dots (7)$$

where:

P = fuel element internal pressure

T = test temperature

K_{CL} = constant

K_{BLD} = factor denoting fuel element quality

Combining Equations 5, 6, and 7 and solving for K_{BLD} gives:

$$K_{BLD} = \frac{L - K_{CL} f_1(P, T)}{f_2(P, T)} \quad \dots (8)$$

Equation 8 has an infinite number of solutions, each depending on a value for K_{CL} . No method is presently available which can analytically or experimentally determine what portion of the total loss rate comes through the ceramic barrier by the permeation process. Even the best fuel element might have some defects, but it was assumed to have none in order to obtain a unique solution. Thus, the best element is that element which minimizes K_{CL} with $K_{BLD} = 0$. The best SNAP 10A fuel element made to date is N-146, which happens to be one of the Environmental Test elements. K_{CL} for N-146 was found to be 5.65×10^5 , and this value has been used for all SNAP 10A fuel element calculations involving K_{BLD} since June 22, 1964.

Using Equation 8 and the assumed value for K_{CL} , it is possible to obtain K_{BLD} values for every element after every permeation test. If K_{BLD} increases

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between tests, the fuel element has been damaged, but if K_{BLD} remains constant or decreases, the element has not been damaged by the input.

b. Calculated Results

A K_{BLD} analysis was made on every element in this program. K_{BLD} values were calculated after every pre- or postendurance input, and at least once every 1000 hr during endurance. A complete listing of K_{BLD} values is given in Reference 11.

The quality of the fuel elements produced in the SNAP 10A program was not constant. Figure 12 shows that the K_{BLD} of 266 SNAP 10A elements (186 with normal uranium and 80 with enriched uranium) varied with the date of initial acceptance permeation test, D, according to the following equation:

$$K_{BLD} = 277.9 - 0.0237D + (3.46 \times 10^{-3})D^2 \quad \dots (9)$$

Most environmental test elements were accepted during 1963 and early 1964.

For analysis, each test phase was subdivided into at least 3 groups:

- 1) Elements on endurance at 1200°F which received a gradient ramp heat input
- 2) Elements on endurance at 1300°F
- 3) Elements on endurance at 1350°F

Due to the restriction in 1), the Phase I elements had a fourth group containing those elements which were given an isothermal ramp heat input.

Figures 13 through 16 present curves of the average K_{BLD} vs time for each test phase. On each figure, the first 200 to 500 hr at temperature occurred during the pre-endurance portion of the program (the end of this period is denoted by a ●). Generally, the K_{BLD} values increase during pre-endurance test and decrease during endurance test. Figure 17 shows the average K_{BLD} curve for all 120 elements in the program, and it indicates the same trend.

Table 12 presents a complete summary of the effect of endurance testing on the elements. It shows the higher endurance temperatures cause a greater percentage of damaged elements, regardless of the prior testing on the elements.

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Figure 12. K_{BLD} vs Date of First Acceptance Test

In order to indicate the high temperature capability of SNAP 10A fuel elements, 10 elements were at 1400°F for over 2500 hr as part of postendurance testing. As shown in Figure 18, 8 elements were slightly damaged at this temperature. A ninth element, N-101, actually performed well during the first 1300 hr at temperature, but it was loaded in a double test retort with the damaged element (N-88) so the average K_{BLD} shows an increase. The data given in Table 13 confirm this conclusion. Later, Element N-101 was tested at 1450°F for 6 days, and then cycled to room temperature and back to 1400°F. The K_{BLD} increase after this event (about 400%) indicates severe degradation of the ceramic barrier. Therefore, N-101 became the first and only "failure" in the SNAP 10A fuel element performance test program.

c. Conclusions

Using a K_{BLD} analysis, all pre-endurance conclusions were confirmed and some new conclusions about endurance were made. They are:

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Figure 13. K_{BLD} vs Time for Phase I Elements

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Figure 14. K_{BLD} vs Time for Phase II Elements

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Figure 15. K_{BLD} vs Time for Phase III Elements

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Figure 16. K_{BLD} vs Time for Phase IV Elements

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Figure 17. K_{BLD} vs Time for All Elements

TABLE 12

PRE- AND POSTENDURANCE K_{BLD} VALUES BY PHASE

Phase	Number of Elements	Endurance Temperature (°F)	Average K_{BLD} Based on 1200° F Permeation Test		Percentage of Elements With Increased K_{BLD}
			Before Endurance	After Endurance	
I (High Level Vibration and Shock)	12	1200	329.5	266.2	33
	12	1300	1003.0	944.9	58
	6	1350	612.1	1008.5	83
II (High Ramp Heat)	12	1200	506.4	431.1	17
	12	1300	566.8	772.7	67
	6	1350	715.5	1609.5	100
III (Interaction)	12	1200	1607.1	945.6	8
	12	1300	1269.8	986.8	25
	6	1350	1417.6	1476.8	67
IV (Reference Pre-endurance)	12	1200	926.0	754.8	0
	12	1300	1211.6	1070.9	8
	6	1350	1074.1	1173.1	67
All	48	1200	842.2	599.4	15
	48	1300	1012.8	943.8	40
	24	1350	954.8	1342.0	79
	120	-	933.0	885.7	38

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Figure 18. K_{BLD} vs Time for Ten Elements at 1400°F

TABLE 13
K_{BLD} VALUES FOR TWO ELEMENTS

Test Input	K _{BLD} Temperature (°F)	K _{BLD}	
		N-88	N-101
Pre- 1400°F	1200	256	260
After 200 hr at 1400°F	1200	1431	64
After 1100 more hours at 1400°F	1200	1706	311

- 1) Pre-endurance testing generally damages the elements slightly.
- 2) High-level vibration and shock causes the greatest pre-endurance damage.
- 3) Fuel elements endurance tested at 1200°F perform better than those tested at temperatures above 1200°F because:
 - a) K_{BLD} decreases during 1200°F endurance.
 - b) K_{BLD} generally remains constant or increases for elements at 1300 or 1350°F.
 - c) 1350°F endurance testing damages a greater percentage of elements than 1300°F.
 - d) Elements performed better at 1350 than at 1400°F, and a combination of 1400 and 1450°F testing caused the only element "failure".

2. FUSAK⁽¹⁵⁾

a. Introduction

A fuel element loaded into a SNAP 10A reactor will undergo many changes during the lifetime of the reactor. Some of these are:

- 1) The ceramic barrier may be affected by pre-launch checkout, launch, and reactor startup.
- 2) Irradiation or aging may also affect the barrier.

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3) The fuel rod will experience density and thermal conductivity changes due to irradiation swelling and hydrogen loss.

4) The hydrogen will redistribute within the fuel rod due to the reactor temperature gradient.

These are just a few of the many complex changes taking place. It is possible to determine the individual effect of all of these changes.

A computer code (FUSAK) is available which can predict fuel element performances in the SNAP 10A reactor by computing the net effect of the aforementioned changes. This code, then, will predict the percent hydrogen loss for an element as a function of time in the reactor.

b. Results

In order to predict the performance of fuel elements in the reactor, it is necessary to know the reactor power, coolant inlet temperature, and pump flow rate as a function of time. These quantities were determined for the FS-3 reactor,⁽¹⁷⁾ and are presented in Figure 19.

A prediction of the performance of the environmental test elements in the FS-3 reactor was made. Based on the K_{BLD} vs time curve for environmental elements at the nominal temperature (1200°F), the total hydrogen loss was found to be 0.0473% (Figure 20). This translates to a reactivity loss of 3.2¢⁽¹⁸⁾ and a temperature loss of about 11°F.

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Figure 19. Operation Data for FUSAK Calculation

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Figure 20. Hydrogen Loss From Simulated SNAP 10A Reactor Operation

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V. RELIABILITY

One of the primary objectives of the Environmental Test Program was the determination of the reliability of SNAP 10A fuel elements to withstand the environmental inputs. Three methods were used to estimate the reliability. They were:

- 1) An estimation of the assessed reliability based on a distributional analysis of the permeation data
- 2) The conventional method of estimating the demonstrated reliability
- 3) A modified conventional method of estimating demonstrated reliability where adjustments are made for inputs in excess of the Qualification Level.

Each method is discussed in the following sections.

A. ASSESSED RELIABILITY

This method provides the most realistic estimates of the fuel element reliability. Since this method is based only on a distributional analysis of the fuel element permeation data, it is not restricted by the number of elements tested or by the fact that no elements failed during testing. Both of these points limit the other two methods.

As shown in Table 14, the probability of 37 fuel elements (a core load) completing all prelaunch inputs, launch, and one year of operation is 99.93% at the 50% confidence level. This is greater than the reliability goal of 99.5%.⁽¹⁹⁾ All reliability values are based on the ability of the fuel elements to withstand the inputs without exceeding the defined failure limit.

B. DEMONSTRATED RELIABILITY

Table 15 gives the demonstrated reliability of SNAP 10A fuel elements to withstand various environmental inputs. The values are based on testing 120 environmental elements and 66 qualification elements. No adjustment has been made to account for the environmental inputs being more severe than the qualification inputs. In addition, the assumption was again made that the permeation rate of one fuel element exceeding the defined "failure" limit will stop the reactor. This assumption is not correct because as many as three catastrophic failures would drop the reactor temperature by only 11°F at the end of one year.⁽¹⁹⁾

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TABLE 14
 ASSESSED RELIABILITY
 (50% Confidence Level)

Input	Reliability	
	One Fuel Element	37 Element Core
Thermal Soak	> 0.99999	> 0.99963
Vibration and Shock (100%)	> 0.99999	> 0.99963
Ramp Heating	0.99979	0.99926
All Pre-Endurance Inputs	0.99979	0.99926
Endurance:		
90 days	> 0.99999	> 0.99963
1 year (estimated)	> 0.99999	> 0.99963
All Inputs	0.99979	0.99926

TABLE 15
 DEMONSTRATED RELIABILITY
 (50% Confidence Level)

Input	No. of Qualification Elements	No. of Environmental Elements	Reliability	
			One Element	37 Element Core
Thermal Shock	66	120	0.9984	0.9425
Vibration and Shock	66	120	0.9963	0.8711
Ramp Heat	66	120	0.9994	0.9766
All Pre-Endurance Inputs	66	120	0.9963	0.8711
Thermal Endurance:				
90 days	66	120	0.9988	0.9573
6 months	66	120	0.9976	0.9154
1 year	66	78*	0.9952	0.8376
All Inputs	66	120	0.9952	0.8376

*This number based on a total of 685,532 endurance hours completed by 120 elements during the program;
 $\frac{685,532}{8760} = 78$ elements for 1 yr.

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The values determined by this method are restricted by the number of tests performed and the fact that no failures occurred during testing. In fact, the estimates are very conservative, as shown by the following example. Since 186 elements completed a 100% vibration and shock input without failure, the demonstrated reliability for 37 fuel elements is 87.11% at the 50% confidence level. If, for example, 550 elements were tested without failure, the reliability would be about 94%. This means the demonstrated reliability is limited by the financial outlay for testing.

C. MODIFIED DEMONSTRATED RELIABILITY

The reliabilities presented in Table 15 are based on the assumption that all elements received only qualification level inputs. However, it is possible to modify these numbers to account for the more severe environmental inputs. Vibration and shock at the higher levels (200 or 250% of SNAP 10A qualification level) has been studied, and an estimate made of the severity of these inputs in relation to the low level inputs.

Investigation showed that 100% vibration and shock caused an average equivalent increase in leak rate of 0.044 cc(STP)/hr at 1200°F, while elements receiving the 250% input had a corresponding increase of 0.235 cc(STP)/hr. Statistical evaluation shows that these changes are noticeably different at the 0.05 significance level, so 250% vibration and shock is more "damaging" than 100% vibration and shock. Although the test results of the 200% vibration and shock could not be evaluated in the same manner because of the small sample size, the data are consistent.

Since there was a significant difference between the change in permeation rates of elements subjected to 100 and 250% vibration and shock, a ratio was used to determine, in general, how much more damaging the 250% input was to the fuel elements than was the 100% input. This ratio shows that on the average we would expect the 250% input to be 5.34 times as damaging as the 100% input. The 95% confidence limits on this ratio are 2.48 and 8.20.

Thus, it is concluded that all SNAP 10A elements have received an equivalent of 411 tests at the vibration and shock reference level (100%). This gives a modified reliability for vibration and shock of 0.9983 for one element and 0.9389

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for 37 elements. Examination of Table 15 shows that this is the minimum demonstrated reliability for all pre-endurance inputs.

D. CONCLUSIONS

The first method (assessed reliability) gives not only the highest estimates of reliability, but also the most realistic estimates. The values calculated by the other methods are limited by the number of elements tested.

A complete discussion of each method of reliability analysis, along with other related statistical and reliability data, can be found in Reference 20.

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VI. SUMMARY

All 120 normal SNAP 10A fuel elements completed the test program without a failure. In summary, the conclusions made in this report are repeated below:

- 1) No input caused severe barrier degradation during the test program.
- 2) Pre-launch checkout and reactor startup do not damage fuel elements, but launch may cause some damage. However, this input will not cause enough damage to jeopardize the design objectives of the reactor.
- 3) Fuel element damage due to extended operation at elevated temperatures is a function of the temperature. However, the damage noted for elements at 1300°F would not jeopardize 1 yr of reactor operation.
- 4) No fuel element failed at a temperature below 1400°F.
- 5) Based on assessed reliability estimation, the fuel elements have a probability of 99.999% to successfully withstand all inputs.

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VII. FUTURE WORK

Throughout the Developmental, Qualification, and Environmental Test Programs, fuel elements were subjected to temperatures up to 300°F higher than the maximum design fuel temperature of the reactor (1085°F) without severe barrier damage. In fact, a temperature excursion to 1475°F did not severely damage the barrier. Thus, the ultimate temperature capability of the Solaramic coating is still not known.

A test program to determine the ultimate capability using the 120 fuel elements from the Environmental Test Program should be undertaken. In this program, the fuel elements would be subjected to endurance temperatures exceeding 1400°F until failure. As an added feature, the data obtained in this program would allow more advanced reliability determinations to be made on the performance of the SNAP 10A fuel element.

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APPENDIX GRADIENT RAMP HEATING

A. GRADIENT RAMP HEATING INPUT

The isothermal ramp heat input given to the qualification elements and the first 10 elements in this program was not a representative input because of temperature gradients during startup. Therefore, the gradient ramp heat input replaced the isothermal input.

1. Description of Gradient Ramp Heat Input (Design Level)

The revised ramp heat input consists of five cycles of gradient ramp heating. The gradient temperature along the fuel rod is approximately linear. The cladding adjacent to the blind end of the element is heated at a controlled rate of $600 \pm 10^\circ\text{F}/\text{min.}$ to a maximum temperature of $600 \pm 15^\circ\text{F.}$ The cooling rate is $50^\circ\text{F}/\text{min.}$, or less, to at least 150°F between each ramp heat.

The induction heating unit was profiled such that:

- 1) The cladding adjacent to the blind end is heated at a rate of approximately $300^\circ\text{F}/\text{min.}$, while the cladding at the blind end is being heated to 600°F.
- 2) An approximately linear temperature gradient will exist across the the fuel element from end to end during the test.
- 3) The mean volume temperature of the blind end cap at peak temperature is $50 \pm 25^\circ\text{F}$ cooler than the adjacent cladding.
- 4) The mean volume temperature of the blind end cap at peak temperature is $25 \pm 25^\circ\text{F}$ cooler than the adjacent cladding.

2. Calculation Method

All fuel elements which were subjected to this test had three thermocouples attached to the closure end cap and three thermocouples attached to the blind end cap for monitoring temperatures. For control, a thermocouple was attached to the cladding adjacent to the weld at the blind end.

The mean volume temperature of the end caps is calculated in the following manner (refer to Figure 21):

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Figure 21. Volumetric Regions of the End Caps During Ramp Heating (Figure Unclassified)

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1) Three thermocouples are placed on the end cap of the fuel element as indicated below:

- a) TC_3 , on the outer edge of the fuel cap at radius r_3 .
- b) TC_1 , adjacent to the end pin at radius r_1 .
- c) TC_2 , located midway between r_1 and r_3 at radius r_2 .

2) The end cap will be divided into four annular regions such that

$$\sum_{i=1}^4 V_i = V_T$$

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where V_i is the volume of i^{th} annulus and V_T is the total volume of the end cap. The division of the end cap will be dependent upon r_i (for $i = 1, 2, 3$) such that

- a) The maximum radius of the first region is r_1 .
- b) The maximum radius of the second region is r_2 .
- c) The maximum radius of the third region is $r_3 - 0.075$ in.
- d) The maximum radius of the fourth region is r_3 .

3) The temperature registered by the thermocouple is plotted as a function of r , as shown in Figure 21. It is assumed that the temperature between r_i and $r_i + 1$ is a linear function of r . It is also assumed that the temperature from r_1 to the center is a constant such that the temperature of the cap from $0 \leq r \leq r_1$ is equal to the temperature at r_1 .

4) The mean volume temperature is computed from

$$\bar{T} = \frac{\sum_{i=1}^4 T_i V_i}{V_T}$$

where $\bar{T}$ is the mean volume temperature and T_i is the arithmetic mean temperature of the i^{th} region obtained from the plot of temperature of the end cap vs r .

5) Figure 22 presents the actual temperatures during ramp heating of Element N-269. Using the technique just discussed, the mean volume temperature of the end cap was 1118°F at the point of maximum temperature differential. The cladding temperature was 1210°F , so the calculated temperature differential was 92°F .

3. Equipment

The same equipment was used for both the isothermal and the gradient ramp heat inputs. It is described in the Appendix of Reference 9. It was necessary to make only minor modifications to the equipment.

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Figure 22. Gradient Ramp
Heating for N-0269
(10-17-64)
(Figure Unclassified)

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