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EFFECTS OF VIBRATION AND SHOCK
ON
HYDROGEN PERMEATION
OF
SNAP 2/10A DEVELOPMENTAL FUEL ELEMENTS
(Title Unclassified)

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(Title Unclassified)

By

A. J. FITZGERALD

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ABSTRACT

An experimental program was performed to study the hydrogen retention qualities of SNAP 2/10A developmental fuel elements of various designs after these elements had been subjected to simulated launch vibration and shock conditions.

The variance in the N_H^* of the fuel rods and the nonisothermal test temperatures necessitated normalizing the measured permeation rates in order to form a consistent basis of comparison. Previously derived permeation equations were used for the normalization.

Specific results of this experiment are classified. All elements of the developmental designs which were tested had acceptable permeation rates for the SNAP 10A reactor.

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

REF ID: A63110

I. INTRODUCTION

An experimental program was initiated, in August 1961, to determine the ability of fuel elements of various designs for the SNAP 2/10A reactors to withstand the effects of vibration and shock. At that time, the fuel for each element consisted of a 10-in. long by 1-1/4-in. diameter single-piece fuel rod of Zr - 10 wt % U which had been hydrided to a nominal N_H^* of 6.5 before final machining. Beryllium oxide reflectors of the same diameter, each 1-1/2 in. long, were located at each end of the fuel rod. Only normal uranium was used in this program, whereas fully enriched uranium would be used for elements to be used in a reactor. The fuel rod and reflectors were encased in a cladding assembly of chromized Hastelloy-N which had been coated internally with a glass enamel to retard the loss of hydrogen during operation of the reactor. The glass enamel which was used was Solaramic S14-35A, a proprietary ceramic which had been developed by Solar, a subsidiary of International Harvester Company. One end closure was welded to the cladding tube before the ceramic coating was applied, while the ceramic at the other end was "blended" after assembly. The "blending" was done by induction heating of the cladding adjacent to the joint to a temperature at which the ceramic on the cladding tube would fuse to the ceramic on the end cap.

From the reference design described, four other designs were established, and elements of all five designs were fabricated for testing. The elements were subjected to hydrogen permeation tests before and after receiving the vibration and shock inputs in an effort to determine which design would best withstand vibration and shock. Table I gives a description of the element designs. Sketches of each type of element are shown on Figure 1.

The design vibration and shocks were applied to the test fuel elements in the following manner: (a) individual element in air, (b) 7-element cluster in air, and (c) 7-element cluster in H_2O .

The measured permeation rates are normalized to a fuel rod N_H of 6.50 and element isothermal temperatures of 1200 and 900°F. Calculations are made to predict the permeation at 900°F, using the 1200°F data, and those values are compared with the 900°F normalized permeation rates.

A comparison is made of the normalized hydrogen permeation of elements of the five designs, and the best design is determined.

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

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TABLE I

ELEMENT DESIGNATION AND DESCRIPTION

Element Type	Identification Number	BeO End Reflectors	Nominal Length (in.)	Type of Blend	Threaded End Pin	Rounded Edge on Rod
A	P	Yes	13	"A" cap	Yes	No
B	PR	Yes	13	"A" cap	Yes	Yes
C	PC-1-7	No	10	Cup	Yes	Yes
D	PC-8-12	Yes	13	Cup	Yes	Yes
E	PC-14-23	No	10	Cup	No	Yes

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a. Type A

b. Type B

c. Types C and E (PC-17 through PC-23 end pins not threaded. Threads machined from PC-1, -5, -6, -7, -14, and -16 prior to clustering)

d. Type D (Dimensions similar to Type A elements)

Figure 1. Fuel Element Designs (Dimensions typical, not to scale)
(Figure Unclassified)

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Figure 2. Hydrogen Permeation Test Apparatus
(Figure Unclassified)

Figure 3. Typical Furnace Loading Diagram (Not to scale)
(Figure Unclassified)

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II. PROCEDURE

A. GENERAL

The general test procedure consisted of the following steps:

- 1) Element heated in a resistance furnace to permeation test temperature
- 2) Hydrogen permeation measured by a helium-hydrogen mass spectrometer
- 3) Element removed from furnace and placed in vibration and shock fixture
- 4) Vibration and shock performed
- 5) Element returned to furnace for another hydrogen permeation test
- 6) Element disassembled for fuel rod and ceramic coating inspection.

B. HYDROGEN PERMEATION TEST

Figure 2 shows a block diagram of the apparatus used for permeation testing. Figure 3 illustrates the position of the elements and the thermocouples in the furnace.

The permeation test procedure was the same as that used for testing the fuel elements for the SNAP 2 Development Reactor (S2DR). The elements were first heated to 1300°F, to assure that none would rupture during unattended operation at 1200°F.* Also, this procedure decreased the time required to reach stabilization at 1200°F. The elements were then cooled to 1200°F, and held at that temperature until an apparent permeation stabilization had been reached. Usually, 4 hr were required to attain this stabilized condition.

The background rate of the test apparatus was repeatedly checked and always found to be on the order of 0.008 cc(STP)/hr at 1200°F. It was assumed that outgassing of the element occurred rapidly and that the outgassing rate was low in comparison to the stabilized permeation rate of the element.

*One element, PC-3, ruptured upon being heated to 1300°F during the permeation test after vibration and shock.

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C. VIBRATION AND SHOCK

The fuel element holding fixture for vibrating and shocking was a simulated SNAP 2/10A core tank vessel. This core tank fixture was attached to a "shake-table" which received the vibration and shock inputs. Reproducibility of the input to the fuel elements was established by repeatedly subjecting a dummy fuel element, which was instrumented with strain gages, to the specified vibration and shock. The output from the strain gages was recorded on an X-Y plotter, and the resulting graphs indicated excellent reproducibility.

The fuel elements were vertically loaded into the core tank fixture by inserting the end pins of the fuel elements into the corresponding holes of the upper and lower grid plates. The blend end of each fuel element was inserted into the lower grid plate. A lower grid plate having tapped holes was used for elements with threaded end pins. Dummy fuel elements, having the same dimensions and approximately the same mass as the test elements, were used in conjunction with the test elements (to comprise a full core load of 37 fuel elements) when any element was subjected to vibration and shock.

The fuel elements were subjected to the vibration and shock, either individually or as a cluster of seven elements. In both cases, the elements were located at positions nearest the core tank center (maximum amplification occurs at the core tank center during the longitudinal frequency inputs). The first 7-element cluster, and the individual elements, were vibrated and shocked with the element surrounded by ambient air. For the second 7-element cluster, the core tank was filled with water, prior to vibration and shock inputs. The water was used to simulate NaK, which is used as a heat transfer medium for the SNAP 2/10A reactors.

The fuel elements were subjected to the following vibration inputs:

<u>Axis</u>	<u>Magnitude</u>	<u>Frequency (cps)</u>
Longitudinal	1/2 in. double amplitude	5-12
	3.5 G	12-400
	7.5 G	400-3000
Lateral	1/2 in. double amplitude	
	2.5 G	10-250
	5.0 G	250-400
	7.5 G	400-3000

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The frequency input was varied from low to high frequency at a constant octave sweep of approximately 45 min duration. Inputs were applied with the elements in each of the three mutually perpendicular positions.

The shock inputs were applied twice in each direction in each of the three mutually perpendicular positions. This resulted in each fuel element having received 12 shocks. The shock inputs were as follows: 20 G, 0.002-sec rise with a 0.007-sec dwell square wave.

The vibration and shock inputs described were a best estimate of the levels to which a SNAP 2/10A reactor would be subjected during launch conditions. The present revised reactor component qualification specification describes the vibration and shock levels to be slightly lower than those used in this program.

D. FUEL ROD INSPECTION

Visual, ultrasonic, and penetrant inspections of the fuel rods were performed prior to assembly and after disassembly of the elements.

E. INSPECTION OF CERAMIC COATING

The ceramic coating was inspected visually prior to assembly and after disassembly of the elements.

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TABLE II

N_H , FUEL ROD IDENTIFICATION NUMBERS, AND ELEMENT TEMPERATURE
PROFILES DURING 1200°F PERMEATION TESTS

Element Type	Element Number	Fuel Rod Number	N_H^*	Before Vibration and Shock					After Vibration and Shock				
				Furnace Number	Profile Number	Element Temperature (°F)			Furnace Number	Profile Number	Element Temperature (°F)		
						T_{bl}^*	T_f^*	T_{avg}^*			T_{bl}^*	T_f^*	T_{avg}^*
A	P-2	126-6	6.58	1	B	1202	1231	1222	1	A	1189	1219	1205
	P-3	135-4	6.53	2	A	1200	1218	1189	2	A	1192	1219	1181
	P-5	125-1	6.34	1	B	1210	1215	1204	1	A	1200	1218	1204
	P-6	126-1	6.53	1	A	1193	1221	1207	1	A	1198	1220	1206
	P-7	110-6	6.59	2	B	1207	1208	1180	2	B	1200	1200	1175
B	PR-2	110-8	6.59	2	A	1184	1208	1181	2	A	1202	1202	1182
	PR-4	119-7	6.53	2	B	1208	1208	1182	2	A	1200	1200	1182
	PR-5	120-7	6.48	1	A	1194	1218	1209	1	A	1190	1217	1203
	PR-6	130-2	6.68	1	A	1187	1208	1194	1	B	1198	1232	1223
	PR-7	130-3	6.68	2	B	1202	1202	1179	2	A	1210	1210	1191
	PR-8	125-3	6.12	2	B	1208	1208	1185	2	A	1200	1200	1181
	PR-9	110-9	6.55	1	A	1202	1218	1204	1	A	1189	1219	1203
C	PC-1	120-6	6.82	1	A	1202	1215	1214	1	A	1192	1215	1209
	PC-2	124-3	6.52	2	B	1202	1202	1177	2	B	1212	1212	1194
	PC-3	124-4	6.42	1	A	1190	1220	1210	1	-	-	-	-
	PC-4	124-5	6.35	1	A	1190	1215	1208	1	A	1192	1208	1205
	PC-5	126-3	6.47	2	B	1210	1210	1193	2	B	1208	1208	1191
	PC-6	126-5	6.44	1	A	1190	1209	1205	1	A	1190	1210	1205
	PC-7	135-6	6.54	1	A	1190	1216	1208	1	A	1190	1210	1205
D	PC-8	137-6	6.36	2	B	1200	1200	1181	2	B	1208	1208	1184
	PC-9	107-1	6.26	1	A	1189	1216	1202	1	A	1200	1221	1207
	PC-10	110-5	6.32	2	B	1198	1198	1181	2	B	1202	1202	1172
	PC-11	126-2	6.72	2	B	1202	1202	1178	2	A	1202	1202	1182
	PC-12	110-3	6.29	1	A	1200	1225	1211	1	A	1190	1220	1206
E	PC-1	120-6	6.82	1	B	1192	1203	1203	1	B	1192	1208	1202
	PC-5	126-3	6.47	2	A	1189	1189	1192	2	B	1200	1200	1201
	PC-6	126-5	6.44	1	B	1190	1200	1200	1	B	1192	1202	1198
	PC-7	135-6	6.54	1	B	1190	1205	1202	1	B	1190	1208	1200
	PC-14	124-3	6.52	1	B	1192	1208	1200	1	B	1192	1192	1203
	PC-16	124-5	6.35	2	B	1190	1190	1190	2	B	1192	1192	1190
	PC-17	124-5	6.35	1	A	1200	1200	1200	1	A	1200	1200	1200
	PC-18	135-6	6.54	2	B	1195	1195	1190	2	B	1185	1185	1180
	PC-19	126-3	6.47	1	A	1200	1200	1192	1	B	1210	1210	1202
	PC-20	124-3	6.52	1	A	1200	1200	1192	1	A	1205	1210	1205
	PC-21	120-6	6.82	2	A	1185	1190	1190	2	B	1210	1210	1200
	PC-22	126-2	6.72	1	B	1190	1202	1200	1	A	1200	1200	1200
	PC-23	126-5	6.44	1	A	1200	1200	1197	1	A	1200	1200	1200

*See page 39 for definition of symbols.

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III. RESULTS

A. MEASURED HYDROGEN PERMEATION RATES

The temperature profiles of the furnaces used for permeation tests are shown on Figure 4. The measured fuel element temperatures during the 1200°F (nominal) permeation tests are tabulated in Table II. This table also shows the identification number and N_H of each fuel rod. Table III shows the measured fuel element temperatures during the 900°F (nominal) permeation tests.

The measured hydrogen permeation rate of each element tested in this investigation is given in Tables IV, V, and VI. The temperatures mentioned below refer to nominal test temperatures.

- 1) Table IV lists the measured permeation rates at 1200 and 900°F of element Types A, B, C, and D which were individually subjected to the vibration and shocks in air. Permeation rates at 1200°F were measured for all 24 elements. Some of the elements were not tested at 900°F.
- 2) Table V lists the measured permeation rates at 1200°F of Type E elements which were grouped in a 7-element cluster while being vibrated and shocked in air. Element Number 15 was a dummy element, used to complete the cluster. No permeation tests at 900°F were performed on these elements. Note that Elements PC-1, PC-5, PC-6, and PC-7 had been previously subjected to individual element vibration and shock (cf. Table IV).
- 3) Table VI lists the measured permeation rates at 1200°F of additional Type E elements which were also grouped in a 7-element cluster while being vibrated and shocked. Unlike the first cluster, however, this cluster was submerged in water during the vibrating and shocking. No permeation tests at 900°F were performed on the elements from this second cluster.

B. NORMALIZED HYDROGEN PERMEATION RATES

The permeation rates which were measured were normalized to $N_H = 6.5$ and $T = 1200$ or 900°F .^{*} The normalized hydrogen permeation rate of each

^{*}See pages 27-29 for normalization procedure.

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a. Furnace 1, Profile A

b. Furnace 1, Profile B

Figure 4. Element Temperature Profile
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c. Furnace 2, Profile A

d. Furnace 2, Profile B

Figure 4 (Continued). Element Temperature Profile
(Figure Unclassified)

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TABLE III
FUEL ELEMENT TEMPERATURE PROFILES DURING
900°F PERMEATION TESTS

Element Type	Element Number	Before Vibration and Shock (°F)			After Vibration and Shock (°F)		
		T _{bl} *	T _f *	T _{avg} *	T _{bl} *	T _f *	T _{avg} *
A	P-2	890	903	889	-	-	-
	P-3	-	-	-	898	913	913
	P-5	-	-	-	898	913	899
	P-6	903	928	912	910	928	914
	P-7	910	910	892	910	901	882
B	PR-2	-	-	-	912	939	915
	PR-4	-	-	-	910	903	890
	PR-5	-	-	-	900	923	909
	PR-6	890	912	897	900	929	920
	PR-7	910	910	892	902	891	880
	PR-8	915	915	885	-	-	-
	PR-9	890	912	897	905	925	911
C	PC-1	895	910	908	-	-	-
	PC-2	910	910	883	-	-	-
	PC-3	895	918	906	-	-	-
	PC-4	895	910	908	-	-	-
	PC-5	905	905	897	-	-	-
	PC-6	-	-	-	-	-	-
	PC-7	902	918	915	-	-	-
D	PC-8	910	910	892	915	906	886
	PC-9	895	932	918	890	913	898
	PC-10	895	895	885	910	901	882
	PC-11	916	916	885	-	-	-
	PC-12	898	916	901	-	-	-

*See page 39 for definition of symbols.

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TABLE IV

CHANGE IN MEASURED HYDROGEN PERMEATION RATE AT
1200 AND 900° F DUE TO VIBRATION AND
SHOCK OF SINGLE ELEMENTS IN AIR

Element Type	Element Number	Permeation Rate Before Vibration and Shock [cc(STP)/hr]		Permeation Rate After Vibration and Shock [cc(STP)/hr]	
		1200° F	900° F	1200° F	900° F
A	P-2	2.27	0.030	1.88	-
	P-3	1.15	-	1.56	0.021
	P-5	1.75	-	1.72	0.010
	P-6	1.17	0.025	1.04	0.009
	P-7	0.96	0.017	1.18	0.019
B	PR-2	1.10	-	1.21	0.023
	PR-4	0.81	-	0.70	0.024
	PR-5	0.83	-	0.97	0.024
	PR-6	0.87	0.010	3.05	0.041
	PR-7	0.81	0.021	1.04	0.071
	PR-8	0.26	0.004	0.23	-
	PR-9	0.93	0.027	2.22	0.033
C	PC-1	1.32	0.019	0.87	-
	PC-2	1.42	0.023	2.49	-
	PC-3	0.40	0.009	Ruptured	-
	PC-4	1.34	0.033	1.63	-
	PC-5	0.31	0.057	0.43	-
	PC-6	0.32	-	0.66	-
	PC-7	0.50	0.013	0.27	-
D	PC-8	0.33	0.027	0.27	0.008
	PC-9	0.59	0.024	1.24	0.018
	PC-10	0.45	0.062	0.34	0.009
	PC-11	1.12	0.018	1.10	-
	PC-12	0.37	0.003	0.43	-

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TABLE V

CHANGE IN MEASURED HYDROGEN PERMEATION RATE
AT 1200°F DUE TO VIBRATION AND SHOCK
OF A 7-ELEMENT CLUSTER IN AIR

Element Type	Element Number	Permeation Rate [cc(STP)/hr]	
		Before Vibration and Shock	After Vibration and Shock
E	PC-1	0.87	1.39
	PC-5	0.34	0.35
	PC-6	0.43	0.36
	PC-7	0.66	0.70
	PC-14	0.57	0.52
	PC-15	Dummy Element	-
	PC-16	0.92	1.13

TABLE VI

CHANGE IN MEASURED HYDROGEN PERMEATION RATE
AT 1200°F DUE TO VIBRATION AND SHOCK
OF A 7-ELEMENT CLUSTER IN WATER

Element Type	Element Number	Permeation Rate [cc(STP)/hr]	
		Before Vibration and Shock	After Vibration and Shock
E	PC-17	0.33	0.43
	PC-18	0.22	0.21
	PC-19	0.71	0.81
	PC-20	0.13	0.13
	PC-21	0.23	0.31
	PC-22	0.48	0.35
	PC-23	1.28	1.29

element tested in this investigation is given in Tables VII, VIII, and IX. The arrangement of these tables is identical to the arrangement of the tables of measured permeation rate data (Tables IV, V, and VI).

The normalized hydrogen permeation rates at 1200°F are summarized in Table X. The percentage increase of the average permeation rates for each type of element is also shown in this table.

C. FUEL ROD INTEGRITY

Figure 5 shows Fuel Rods No. 124-3 and 120-6 after having been vibrated and shocked. The surface condition of these rods is typical of all of the fuel rods tested, and did not appear to be affected by the vibrating and shocking. Fuel Rod No. 124-3 was used to assemble Element PC-2, and was subjected to the individual element vibration and shock. Fuel Rod No. 120-6 was used to assemble Elements PC-1 and PC-21; therefore, it was subjected to the individual element vibration and shock as well as the 7-element cluster vibration and shock. The ultrasonic and visual testing indicated that the vibrations and shocks had little, if any, effect on fuel rod crack propagation.

D. CERAMIC INTEGRITY

Figures 6 and 7 show typical conditions of the ceramic on the claddings and end caps after element disassembly. Figure 6a shows the midsection of a cladding tube. Figure 6b shows sections of a cladding tube at both ends. Figure 7 shows "H" caps, separated from the tube at the weld.

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TABLE VII

CHANGE IN NORMALIZED HYDROGEN PERMEATION RATE AT
1200 AND 900°F DUE TO VIBRATION AND
SHOCK OF SINGLE ELEMENTS IN AIR

Element Type	Element Number	Permeation Rate Before Vibration and Shock [cc(STP)/hr]		Permeation Rate After Vibration and Shock [cc(STP)/hr]	
		1200°F	900°F	1200°F	900°F
A	P-2	1.46	0.027	1.41	-
	P-3	1.03	-	1.44	0.019
	P-5	2.50	-	2.48	0.015
	P-6	1.04	0.027	0.91	0.006
	P-7	0.73	0.012	0.98	0.014
B	PR-2	0.92	-	0.98	0.012
	PR-4	0.68	-	0.64	0.020
	PR-5	0.83	-	1.00	0.022
	PR-6	0.49	0.006	1.44	0.019
	PR-7	0.27	0.008	0.31	0.032
	PR-8	0.70	0.003	0.74	-
	PR-9	0.72	0.024	2.40	0.023
C	PC-1	0.43	0.008	0.26	-
	PC-2	1.41	0.020	2.20	-
	PC-3	0.49	0.010	Ruptured during testing	-
	PC-4	2.09	0.050	2.63	-
	PC-5	0.32	0.054	0.45	-
	PC-6	0.39	-	0.79	-
	PC-7	0.40	0.010	0.21	-
D	PC-8	0.53	0.034	0.40	0.010
	PC-9	1.14	0.161	2.19	0.033
	PC-10	0.78	0.109	0.56	0.014
	PC-11	0.58	0.008	0.57	-
	PC-12	0.59	0.005	0.74	-

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TABLE VIII

CHANGE IN NORMALIZED HYDROGEN PERMEATION RATE
AT 1200°F DUE TO VIBRATION AND SHOCK
OF A 7-ELEMENT CLUSTER IN AIR

Element Type	Element Number	Permeation Rate [cc(STP)/hr]	
		Before Vibration and Shock	After Vibration and Shock
E	PC-1	0.31	0.52
	PC-5	0.44	0.39
	PC-6	0.56	0.46
	PC-7	0.53	0.59
	PC-14	0.44	0.56
	PC-15	Dummy Element	-
	PC-16	0.93	1.22

TABLE IX

CHANGE IN NORMALIZED HYDROGEN PERMEATION RATE
AT 1200°F DUE TO VIBRATION AND SHOCK
OF A 7-ELEMENT CLUSTER IN WATER

Element Type	Element Number	Permeation Rate [cc(STP)/hr]	
		Before Vibration and Shock	After Vibration and Shock
E	PC-17	0.57	0.73
	PC-18	0.24	0.26
	PC-19	0.80	0.81
	PC-20	0.14	0.11
	PC-21	0.07	0.07
	PC-22	0.25	0.16
	PC-23	1.57	1.58

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TABLE X

EFFECT OF VIBRATION AND SHOCK ON NORMALIZED HYDROGEN
PERMEATION RATE OF FUEL ELEMENTS AT 1200°F

Element Type	Number of Elements	Before Vibration and Shock		After Vibration and Shock		Increase in Average Rates (%)
		Range of Permeation Rates [cc(STP)/hr]	Average Permeation Rate [cc(STP)/hr]	Range of Permeation Rates [cc(STP)/hr]	Average Permeation Rate [cc(STP)/hr]	
A	5	0.73 to 2.50	1.35	0.91 to 2.48	1.44	7
B	7	0.27 to 0.92	0.66	0.31 to 2.40	1.07	62
C	7	0.32 to 2.09	0.79	0.21 to 2.63	1.09	38
D	5	0.53 to 1.14	0.72	0.40 to 2.19	0.89	24
E	13	0.07 to 1.57	0.54	0.07 to 1.58	0.57	6

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Figure 5. Typical Fuel Rod Surface Conditions

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a. Midsection of Cladding Tube

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b. Sections of Both Ends of a Cladding Tube

Figure 6. Ceramic Defects after Element Disassembly

7550-51545B

Figure 7. End Cap Ceramic Condition after Element Disassembly

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IV. DISCUSSION OF RESULTS

A. NORMALIZATION OF HYDROGEN PERMEATION RATES

As shown in Tables II and III, the N_H of the fuel rods varied from 6.12 to 6.82, and the temperature of the elements during permeation tests was not isothermal. Since hydrogen permeation is a function of temperature and pressure (in addition to other variables), and since the dissociation pressure of the fuel is a function of temperature and N_H , a direct comparison of the measured permeation rates of the elements listed in Tables IV, V, and VI is unjustified. Therefore, the measured permeation rates were normalized to a fuel rod N_H of 6.50 and element isothermal temperatures of 1200 and 900°F.

The method used to normalize the results is discussed below. It was assumed that all of the hydrogen permeation from a fuel element could be divided into the permeation through the cladding and the permeation through the blend. Equations 1 through 3, which follow, were used to adjust the measured permeation rates to the normal conditions of temperature and hydrogen concentration.

$$\varphi_{cl} = \frac{KP(T_{avg})^{5/2} \exp(-28160/T_{avg})}{8.43 \times 10^{13} P \exp(-28160/T_{avg}) + (T_{avg})^{5/2}} \dots (1)^1$$

where

φ_{cl} = permeation rate through the cladding [cc(STP)/hr]

K = a constant = 1.69×10^6 , based on permeation tests of fuel elements for the S2DR

P = pressure [atm(absolute)]

T_{avg} = average element temperature (°R)

$$\varphi_{bl} = K_{bl} \sqrt{P} \exp(-12760/T_{bl}) \dots (2)^2$$

where

φ_{bl} = permeation rate through the blend [cc(STP)/hr]

K_{bl} = a constant calculated for each element, based on the measured values of permeation and temperature

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P = pressure [atm (absolute)]

T_{bl} = blend temperature ($^{\circ}R$)

$$\phi_T = \phi_{cl} + \phi_{bl} \quad \dots (3)$$

where

ϕ_T = total permeation rate [cc(STP)/hr]

The dissociation pressure of the hydrided fuel was calculated from the equation

$$\text{Log } P(\text{atm}) = 8.36 H/Zr - 6.23 - 15066/T_f \quad \dots (4)^3$$

A sample calculation is given in the Appendix.

The normalized hydrogen permeation through the cladding of Element PC-21 was more than the measured permeation of that element. Therefore, it was assumed that there was insignificant permeation through the blend. The measured permeation was normalized by use of Equations 1 and 4 only.

The use of the three permeation relationships tacitly assumes that there are no ceramic defects at any place other than at the blend. If such a defect did exist, the cladding permeation calculated by Equation 1 would be very small in comparison with the permeation through the defect. In fact, the permeation would be a function similar to the permeation through a blend. Therefore, at isothermal conditions, the permeation through a cladding defect would be included as part of the blend permeation by calculation of the constant, K_{bl} , in Equation 2. On the other hand, if the temperatures of the blend and the defects are not the same, the error involved in the permeation calculation would be dependent upon the difference between the temperature of the cladding and the temperature of the blend.

B. EXTRAPOLATION OF 1200°F DATA TO 900°F

In order to see whether 1200°F permeation data could be used to predict 900°F permeation rates, calculations were made (using the 1200°F permeation) to predict 900°F normalized permeation rates. The method of calculating the predicted values was as follows:

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- 1) ϕ_{cl} was calculated using Equation 1, the dissociation pressure, and the measured values of the element temperatures during the 1200°F testing.
- 2) ϕ_{bl} was calculated using Equation 3, the measured value of ϕ_T , and the calculated value of ϕ_{cl} .
- 3) K_{bl} was calculated using the value of ϕ_{bl} , $T = 1200^\circ\text{F}$, and $N_H = 6.50$.
- 4) ϕ_{bl} was normalized to 1200°F and the dissociation pressure corresponding to $N_H = 6.50$.
- 5) ϕ_{cl} was calculated for 900°F.
- 6) ϕ_{bl} was calculated using K_{bl} , $T = 900^\circ\text{F}$, and the dissociation pressure for $N_H = 6.50$.
- 7) ϕ_{cl} was added to ϕ_{bl} to give ϕ_T at 900°F, predicted from 1200°F data.

The difference between the normalization of 900°F permeation measurements and the prediction of normalized 900°F permeation (calculated from the 1200°F measurements) was in the values of K_{bl} . For the predicted permeation values, K_{bl} was calculated using the 900°F permeation measurement. A sample calculation, illustrating this procedure, is given in the Appendix.

Table XI lists the results of these calculations, and compares the predicted normalized permeation with the actual normalized permeation. The average difference between the normalized permeation at 900°F and the predicted normalized permeation at 900°F (based on 1200°F data) is 0.007 cc(STP)/hr. There are three probable sources of error in these calculations:

- 1) Dissociation pressure at 900°F, and the uncertainty of the H/Zr of each element.
- 2) A defect in the cladding, together with a significant difference in blend and cladding temperatures.
- 3) Permeation dependency on pressure and temperature is different in the 900°F range and the 1200°F range.

C. HYDROGEN PERMEATION AT 900°F

Of particular interest to the SNAP 10A program is the hydrogen permeation rate at 900°F, as given in Table XI. The measurements at this temperature

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TABLE XI

NORMALIZED vs PREDICTED NORMALIZED
HYDROGEN PERMEATION AT 900°F

Element Type	Element Number	Permeation Before Vibration and Shock [cc(STP)/hr]		Permeation After Vibration and Shock [cc(STP)/hr]	
		Based on 900°F Data	Predicted from 1200°F Data	Based on 900°F Data	Predicted from 1200°F Data
A	P-2	0.027	0.025	-	0.024
	P-3	-	0.017	0.019	0.025
	P-5	-	0.044	0.015	0.044
	P-6	0.027	0.017	0.006	0.015
	P-7	0.012	0.012	0.014	0.016
B	PR-2	-	0.015	0.012	0.016
	PR-4	-	0.011	0.020	0.010
	PR-5	-	0.013	0.022	0.016
	PR-6	0.006	0.007	0.019	0.025
	PR-7	0.008	0.003	0.003	0.004
	PR-8	0.001	0.011	-	0.012
	PR-9	0.024	0.011	0.023	0.042
C	PC-1	0.008	0.006	-	0.003
	PC-2	0.020	0.024	-	0.038
	PC-3	0.010	0.007	-	-
	PC-4	0.050	0.036	-	0.046
	PC-5	0.005	0.004	-	0.006
	PC-6	-	0.005	-	0.013
	PC-7	0.010	0.005	-	0.002
D	PC-8	0.034	0.008	0.010	0.006
	PC-9	0.004	0.019	0.033	0.038
	PC-10	0.011	0.012	0.014	0.009
	PC-11	0.008	0.009	-	0.008
	PC-12	0.005	0.009	-	0.012

indicate that each type of element is apparently permeation acceptable for the requirements of the SNAP 10A reactor. Permeation rates are less than 0.04 cc(STP)/hr for 30 of the 31 tests performed at this temperature. Because of the time required to approach equilibrium conditions while testing at 900°F, not all elements were tested at this temperature.

D. ROUNDED vs SHARP EDGE FUEL ROD

In order to compare the effect of fuel rod edge on the permeation of fuel elements, the initial permeation rates of element Types A and B only were considered. These elements were essentially alike (nominally 13 in. long, with BeO end reflectors, threaded end pins, and without a blend cup), except that the Type A elements contained fuel rods and reflectors with sharp or "square" edges, while the fuel rods and reflectors of the Type B elements had rounded edges. The other elements (Types C, D, and E) all contained cups at the blend end. The average initial permeation (cf. Table X) of the Type A elements was 1.35 cc(STP)/hr, while the average initial permeation of the Type B elements was 0.66 cc(STP)/hr. These average rates indicate that the sharp edge fuel rods and reflectors may have damaged the hydrogen barrier during element assembly.

E. CUP vs "A" CAP TYPE BLENDS

In order to arrive at any plausible distinction between these two blends as to their relative ability to act as hydrogen barriers, only the element permeation rates prior to vibration and shock were considered. Obviously, the other design factors (3-piece or 1-piece elements, sharp or rounded edge fuel rods, etc.) enter into the effect of vibration and shock on the element permeation. The average normalized permeation of the "A" cap type blend elements (Types A and B) was 0.95 cc(STP)/hr at 1200°F, prior to vibration and shock. The average normalized permeation of the elements having a cup type blend (Types C, D, and E) was 0.65 cc(STP)/hr at 1200°F, prior to vibration and shock testing.

Perhaps a more definite distinction can be made by comparing the normalized hydrogen permeation of element Types C, D, and E, prior to vibration and shock, to the hydrogen permeation of the fuel elements made for the S2DR core. Except for the threaded end pin, the S2DR element design is the same as the Type A element design. The average hydrogen permeation at 1200°F for the elements of

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the S2DR core was 0.7 cc(STP)/hr,⁴ excluding the four thermocoupled elements. The yield to produce the 0.7 cc(STP)/hr average was approximately 40%. That is, out of the total number of elements fabricated for the core, 60% were rejected because of excessive hydrogen permeation at 1200°F. Comparably, the yield for elements with a cup type blend (Types C, D, and E) to produce a 0.7 cc(STP)/hr average normalized hydrogen permeation at 1200°F was 78%.

Again, caution must be used in the interpretation of these results. There is no definite proof that the cup type blend effected the increased yield. Both the increased yield and the apparently improved permeation of the elements could have been caused by either altering the blend design or altering the fuel rod design, or both.

F. CONDITION OF FUEL RODS AFTER ELEMENT DISASSEMBLY

Figure 5 shows the typical condition of fuel rod surfaces after vibration and shock and hydrogen permeation testing. Only 5 rods, of the 36 examined, showed any increased fuel rod surface crack propagation due to vibration and shock, and these showed only slight increases. No correlation was found between hydrogen permeation and fuel rod surface condition, either before or after vibration and shock.

G. CERAMIC CONDITION AFTER ELEMENT DISASSEMBLY

Figures 6 and 7 show typical ceramic coating conditions after element disassembly. Considerable damage was generally found at the cladding end sections, with lesser amounts of damage at other sections of the tubes. The damage existed in the forms of abrasion, scratches, and pitting. There was no apparent correlation between element hydrogen permeation and the condition of the ceramic coating of the tubes. It is probable that the ceramic damage occurred as a result of element disassembly.

It is significant to note that, for the majority of the elements, considerable force was required to remove the fuel rods from the cladding assembly upon element disassembly. This indicates that an interference fit existed between the fuel rod and the ceramic coating. Since the elements were assembled by exerting a slight "push" on the fuel rods, some dimensional change apparently occurred to an element component during permeation testing. If such a change did occur during initial permeation tests, it could have significant effect on the

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fuel element during vibration and shock. The inference that the fuel rod did not move within the cladding during vibration and shock is substantiated by the fact that no ceramic damage was noted at the "H" cap faces. This is shown in Figure 7.

H. THREADED vs NONTHREADED END PINS

In order to reduce the effects of vibration and shock on the elements, a threaded end pin at the "H" cap end of the element was designed to fasten the element to the grid plate assembly during vibration and shocking. However, this method of attachment would quite probably increase the time required for re-entry burnup. Therefore, it became desirable to determine whether the nonthreaded end pins would be an acceptable element component design, using permeation rates as a basis of comparison.

Observing the results tabulated in Table VIII (Type E), it appears that the nonthreaded end pin design is acceptable.

I. ACCURACY OF HYDROGEN PERMEATION MEASUREMENTS

This experiment utilized a CEC mass spectrometer type helium leak detector (Model 24-210B), modified to detect hydrogen in the range of 0 to 10 cc(STP)/hr at a pressure of approximately 0.001μ Hg. This type of instrument was the same as that used for the permeation testing of the fuel elements for the S2DR reactor. As such, it represents an improvement over the equipment used to measure the hydrogen permeation of earlier SNAP fuel elements, which utilized the collection of gas in a known volume for a measured period of time. The most obvious improvements obtained by using the mass spectrometer method, rather than the gas collection method, are: (1) the tremendous saving in time and personnel required for permeation testing, and (2) the fact that only the hydrogen gas is measured.

However, the method used to determine the permeation rate of the fuel elements in this experiment had the following unfavorable characteristics:

- 1) The method used was actually a comparative method of measurement which required a known standard hydrogen leak.
- 2) Filament wear or "aging" caused the sensitivity of the instrument to vary.

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A discussion of these characteristics follows.

- 1) A typical standard hydrogen leak, used to calibrate the CEC mass spectrometer, consisted of a glass tube filled with hydrogen gas at 1 atm pressure, sealed at one end with a glass capillary at the opposite end to restrict the hydrogen flow. The leak rate through the capillary varied from standard leak to standard leak, and was in the range of 5×10^{-4} to 5×10^{-3} cc(STP)/hr. The standard leaks were initially calibrated by the manufacturer, and these calibrations were later checked by AI personnel. On the basis of reproducibility, two of the standard leaks were selected to be used for calibrating the mass spectrometer used to measure the hydrogen permeation from the fuel elements.

It was assumed that the leak rate of each standard leak was essentially constant, because of the low leak rate. Using two standard leaks to calibrate the mass spectrometer, a cross check was possible, to ascertain whether the standard leaks were constant. No apparent change in the leak rates of the two bottles was observed during the time required for the completion of the vibrations, shocks, and permeation measurements.

- 2) The standard leaks were on the order of 5×10^{-4} cc(STP)/hr, while the element leak rates were on the order of 0.2 to 2 cc(STP)/hr. This required extrapolation from the low range of the spectrometer (the range of the standard leaks) to the high range of the spectrometer (the range of element permeation). It was necessary to assume that the spectrometer output was linear throughout its entire range.
- 3) The filament of the spectrometer ionizes a fraction of the hydrogen gas flowing through the spectrometer. Over a period of time, various deposits will form on this filament. This affects the amount of ionization and therefore causes a change in the sensitivity of the instrument. This change in sensitivity meant that the calibration of the instrument would vary with time. The spectrometer was calibrated daily when used during these experiments. When the sensitivity of the spectrometer began to change radically, the filament was replaced.

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The unfavorable characteristics of the method used to determine the permeation rate of the elements obviously affected the accuracy of the measurements. In order to obtain an idea of the reproducibility of the measured permeation values, a simple test series was performed.

The method consisted of repeatedly measuring the permeation of elements tested in various furnaces. For this test series, four additional furnaces (A, B, C, and D, which were part of another hydrogen permeation test system) were used. The results of this test series are shown in Table XII. Again, the data were normalized, because element temperature profiles varied from test to test. A statistical analysis was made of these data, and Figure 8 shows the best estimate of the deviation as a function of the normalized permeation rate. For permeation rates greater than 0.6 cc(STP)/hr, the deviations among several permeation measurements of the same fuel element would be expected to be less than 10%.

Figure 8. Estimated Deviation of Permeation Measurements
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TABLE XII

REPRODUCIBILITY OF HYDROGEN PERMEATION MEASUREMENTS

Element Number	Before Vibration and Shock					
	Furnace Number	T _{bl} * (°F)	T _{avg} * (°F)	T _f * (°F)	φ _m * [cc(STP)/hr]	φ _n * [cc(STP)/hr]
P-5	1	1200	1218	1204	1.75	2.78
P-5	2	1216	1201	1184	1.58	2.67
P-5	1	1210	1204	1215	1.75	2.50
P-3	1	1210	1228	1219	2.24	1.87
P-3	2	1190	1193	1175	1.39	1.73
P-3	2	1200	1218	1198	1.15	1.03
PR-7	1	1190	1213	1199	0.62	0.15
PR-7	2	1200	1198	1182	0.64	0.22
PR-7	2	1202	1202	1179	0.81	0.27
PC-7	1	1190	1210	1205	0.66	0.61
PC-7	2	1218	1218	1197	0.55	0.44
PC-7	1	1190	1216	1208	0.50	0.40
PC-22	1	1202	1203	1205	0.44	0.25
PC-22	1	1190	1202	1205	0.48	0.28
PC-22	1	1190	1202	1200	0.48	0.25
PC-23	2	1200	1204	1208	1.28	1.48
PC-23	2	1190	1196	1202	1.46	1.85
PC-23	1	1200	1200	1197	1.28	1.57
After Vibration and Shock						
PC-20	B	1195	1200	1200	0.22	0.22
PC-20	D	1198	1200	1198	0.20	0.21
PC-20	C	1200	1200	1200	0.22	0.22
PC-20	A	1202	1200	1205	0.25	0.24
PC-20	1	1205	1210	1205	0.13	0.11
PC-18	B	1198	1200	1198	0.28	0.29
PC-18	A	1200	1198	1202	0.35	0.35
PC-18	C	1198	1200	1202	0.30	0.30
PC-18	D	1200	1198	1198	0.38	0.39
PC-18	2	1185	1185	1180	0.21	0.26
PC-22	A	1200	1200	1198	0.36	0.18
PC-22	D	1200	1200	1198	0.34	0.16
PC-22	1	1200	1200	1200	0.35	0.16
PC-23	B	1198	1200	1200	1.29	1.59
PC-23	A	1200	1198	1198	1.21	1.50
PC-23	1	1200	1200	1200	1.29	1.58

*See page 39 for definition of symbols.

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J. SUMMARY OF THE EFFECT OF VIBRATION AND SHOCK ON ELEMENT HYDROGEN PERMEATION

Table X best summarizes the effect of vibration and shock on the hydrogen permeation of SNAP 2/10A fuel elements tested. Fuel element Types A and E showed the least percentage increase in average normalized hydrogen permeation at 1200°F. There is a significant difference between the average rates of the Type A and Type E elements, the latter being the lower. In fact, only 2 of the 13 Type E elements had a permeation rate significantly higher than the 0.8 cc(STP)/hr which was the acceptable limit for fuel elements for the S2DR core.

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V. CONCLUSIONS

The results of this experiment show that the Type E elements were the best of the element designs tested, not only from the standpoint of initial element hydrogen permeation, but, more important, from the standpoint that this design best withstands vibration and shock.

There is indication that the cup type blend is preferable to the "A" cap type blend, and that the rounded fuel rod edge is preferable to the sharp fuel rod edge.

Fuel rod surface crack propagation did not increase significantly, as a result of the design vibrations and shocks.

No correlation could be found between hydrogen permeation and the following:

- a) Threaded vs nonthreaded end pins
- b) Fuel rod surface cracks
- c) Three-piece vs one-piece elements
- d) Condition of ceramic coating after element disassembly.

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LIST OF SYMBOLS

K_{bl} = blend constant

N_H = number of hydrogen atoms $\times 10^{-22}$ per cc of fuel

ϕ_m = measured hydrogen permeation at furnace conditions [cc(STP)/hr]

ϕ_{cal} = calculated hydrogen permeation at given conditions [cc(STP)/hr]

ϕ_n = normalized hydrogen permeation at stated conditions [cc(STP)/hr]

ϕ_{bl} = hydrogen permeation rate through the blend [cc(STP)/hr]

ϕ_{cl} = hydrogen permeation rate through the cladding [cc(STP)/hr]

ϕ_T = total hydrogen permeation rate [cc(STP)/hr]

P = pressure [atm(absolute)]

T_{avg} = average element temperature ($^{\circ}R$)

T_{bl} = blend temperature ($^{\circ}R$)

T_f = fuel rod temperature ($^{\circ}R$)

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APPENDIX SAMPLE CALCULATIONS

I. Normalization of hydrogen permeation rate for an $N_H = 6.50$ and an isothermal 1200°F

A. DATA: TAKEN FROM TABLES II AND IV, ELEMENT P-3

$$\phi_m = 1.56 \text{ (after vibration and shock)}$$

$$T_{bl} = 1192^\circ\text{F} = 1652^\circ\text{R}$$

$$T_f = 1219^\circ\text{F} = 1679^\circ\text{R}$$

$$T_{avg} = 1181^\circ\text{F} = 1641^\circ\text{R}$$

$$N_H = 6.53$$

B. EQUATIONS

$$(1) \log P = 8.36 \text{ H/Zr} - 6.23 - 15066/T_f$$

$$(2) \phi_{c1} = \frac{KP(T_{avg})^{5/2} \exp(-28160/T_{avg})}{8.43 \times 10^{13} P \exp(-28160/T_{avg}) + (T_{avg})^{5/2}}$$

$$(3) \phi_{bl} = K_{bl} \sqrt{P} \exp(-12760/T_{bl})$$

$$(4) \phi_T = \phi_{c1} + \phi_{bl}$$

C. SOLUTION FOR $N_H = 6.53$, $\text{H/Zr} = 1.85$

$$(1) \log P = 8.36(1.85) - 6.23 - (15066/1679) = 0.2628$$

$$P = 1.83 \text{ atm}$$

$$(2) \phi_{c1} = \frac{(1.69 \times 10^6)^* (1.83)(1641)^{5/2} \exp(-28160/1641)}{8.43 \times 10^{13} (1.83) \exp(-128160/1641) + (1641)^{5/2}} = 0.104 \text{ cc(STP)/hr}$$

$$(3) \phi_{bl} = 1.56 - 0.104 = 1.46 \text{ cc(STP)/hr}$$

$$(4) K_{bl} = \frac{1.46 \exp(12760/1652)}{\sqrt{1.83}} = 2.435 \times 10^3$$

*This constant was previously derived from data obtained from permeation testing of elements for the S2DR reactor.

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D. NORMALIZATION FOR $N_H = 6.5$, $H/Zr = 1.85$

$$T_{bl} = T_{avg} = 1660^\circ R$$

$$(1) \log P = 8.36(1.85) - 6.23 - (15066/1660) = 0.1601$$

$$P = 1.445 \text{ atm}$$

$$(2) \phi_{c1} = \frac{1.69 \times 10^6 (1.445)(1660)^{5/2} \exp(-28160/1660)}{8.43 \times 10^{13} (1.445) \exp(-28160/1660) + (1660)^{5/2}} = 0.100 \text{ cc(STP)/hr}$$

$$(3) \phi_{b1} = 2.435 \times 10^3 \sqrt{1.445} \exp(-12760/1660) = 1.343 \text{ cc(STP)/hr}$$

$$\phi_n = 0.100 + 1.343 = 1.44 \text{ cc(STP)/hr}$$

II. Calculations to predict normalized permeation at 900°F from the 1200°F permeation measurements (Element P-3)

$$T_{bl} = T_{avg} = 1360^\circ R$$

$$(1) \log P = 8.36(1.85) - 6.23 - (15066/1360) = -1.842$$

$$P = 0.0144 \text{ atm}$$

$$(2) \phi_{c1} = \frac{(1.69 \times 10^6)(0.0144)(1360)^{5/2} \exp(-28160/1360)}{8.43 \times 10^{13}(0.0144) \exp(-28160/1360) + (1360)^{5/2}} = 0.0000 \text{ cc(STP)/hr}$$

$$(3) \phi_{b1} = (2.435 \times 10^3) \sqrt{0.0144} \exp(-12760/1360) = 0.0246 \text{ cc(STP)/hr}$$

$$(4) \phi_n = 0.0000 + 0.0246 = 0.025 \text{ cc(STP)/hr}$$

Normalized permeation at 900°F based on 900°F data = 0.019 cc(STP)/hr.

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