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**ZIRCONIUM HYDRIDE FUEL ELEMENT
PERFORMANCE CHARACTERISTICS**

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ABSTRACT

Design of the U-ZrH fueled SNAP compact reactor requires: (1) prediction of the reactivity decrease over the core lifetime, associated with the loss of hydrogen moderator from the fuel elements, and (2) prediction of the anticipated fuel growth, for the particular reactor operating conditions, to assure integrity of the fuel element cladding. Extensive data were obtained during the course of the SNAP Reactor Development Program regarding the hydrogen-retention characteristics of the ceramic-lined fuel element, and regarding the fuel-growth characteristics of the U-ZrH fuel. The ceramic liner was found to be a very effective and highly durable hydrogen barrier. The fuel growth, observed to consist of a rapid early-life growth, followed by a much slower long-term growth, was found to be temperature, flux, and fluence dependent.

I. INTRODUCTION

The SNAP reactor program has built and operated six U-ZrH_x fueled reactors, one of which (the 10FS-4 system) was operated in earth orbit. As a result of these operations (see Table 1), coupled with a supporting fuels irradiation testing program, an extensive body of data, describing the U-ZrH_x fuel element performance, has been assembled. This report summarizes the results of the SNAP reactor fuel element performance experience, with special emphasis on the irradiation-induced growth behavior of U-ZrH_x fuel and the effectiveness of the ceramic barrier employed to inhibit loss of the hydrogen moderator from the fuel element.

The fuel element design employed in the various SNAP nuclear reactors is comprised of a one-piece cylindrical metal fuel rod, loaded into a hermetically sealed cladding tube. The U-ZrH_x fuel rod is a uniform dispersion of α -uranium (10 wt %, and fully enriched) in a massively hydrided (to an N_H of 6 to 6.5 x 10²² atoms H₂/cc fuel) zirconium structure. The Hastelloy N cladding (Type 304 stainless steel was used in one reactor, the SER) is a thin-walled (0.010 to 0.015 in. thick) tube, closed at each end by TIG or electron beam welded end caps. The entire internal surface area of the cladding tube is coated with a thin (0.002 to 0.003 in. thick) ceramic liner, which serves as a barrier to inhibit the loss of hydrogen from the element during reactor operation.

Evaluation of fuel element performance is based upon two criteria:

- 1) Integrity of the fuel element cladding shall be maintained throughout its design operating lifetime.
- 2) Core reactivity loss, due to hydrogen leakage from the fuel elements, shall be within design specifications.

In meeting these criteria, the single most influential design parameter is operating temperature.

TABLE 1
SNAP REACTORS SUMMARY

	SER	S2DR	10FS-3	10FS-4	S8ER	S8DR	
General							
Power Level (kw)	50	50	40	40	600	600	1000
Coolant Outlet Temperature (°F)	1200	1200	1010	1035	1300	1300	1150
Coolant Inlet Temperature (°F)	1000	1000	890	915	1100	1100	880
Coolant Flow Rate (lb/hr)	4100	4100	4920	4920	48,800	48,800	60,000
Design Life (hr)	NA	NA	8760	8760	~3000	12,000	NA
Operating Time, Design (hr)	1900	2100	10,005	~1000	2400	1670	429
Operating Time, Total (hr)	6035	4800	10,005	~1000	8760	7023	
Total Energy Output (Mwt-hr)	225	273	383	41	5.1×10^3	4.35×10^3	
Fuel Element Design							
Number	61	37	37	37	211	211	
Size, Diameter x Length (in.)	1.0 x 14.0	1.25 x 10.0	1.25 x 10.0	1.25 x 10.0	0.56 x 14.0	0.56 x 16.8	
Cladding Material	347 SS	Hast-N	Hast-N	Hast-N	Hast-N	Hast-N	
Cladding Thickness (mils)	10	13	15	15	10	10	
Hydrogen Barrier Material	Solaramic	Solaramic	Solaramic	Solaramic	AI-D	SCB	
Burnable Poison Material	None	Sm ₂ O ₃	Sm ₂ O ₃	Sm ₂ O ₃	Sm ₂ O ₃	Sm ₂ O ₃	
Burnable Poison Location	NA	Barrier	Barrier	Barrier	Barrier	Barrier	
Hydrogen Gap (mils)	1.0	2.0	4.0	4.0	3.0	7.2	
Element Surface	Smooth	Smooth	Smooth	Smooth	Smooth	Smooth	
N _H	6.0	6.5	6.35	6.35	5.95	6.07	
Number of Fuel Rod Segments	1	1	1	1	1	1	
Internal Atmosphere	He-Air Mixture	He-Air Mixture	0.1 atm He	0.1 atm He	0.1 atm He	Vacuum	
Fuel Element Operations							
Average Power Density (kw/ft)	~1.0	~2.1	1.01	1.01	2.44	2.03	3.4
Peak Power Density (kw/ft)	~1.8	~3.2	~2.0	~2.0	~4.4	~3.7	~6.2
Design Burnup, Average (met. at.%)	NA	~0.01	~0.015	~0.015	0.14	0.13	NA
Design Burnup, Peak (met. at. %)	NA	~0.021	~0.03	~0.03	0.25	0.23	NA
10 k-hr Burnup, Average (met. at. %)	NA	~0.21	~0.015	~0.015	~0.16	0.18	NA
10 k-hr Burnup, Peak (met. at. %)	NA	~0.44	~0.030	~0.030	~0.28	0.33	NA
Average Volume Power Density (kw/ft ³)	~190	~210	~140	~140	1250	1050	1750
Peak Volume Power Density (kw/ft ³)	~340	~370	~250	~250	2300	1900	3200
Peak BOL Fuel Temperature (°F)	~1295	1300	1080	1080	~1550	~1525	~1525
Offset Maximum Radial Average Fuel Temperature (°F)	~1285	1280	1060	1060	~1490	~1475	~1475
Peak Cladding Temperature (°F)	~1265	1265	1020	1020	~1390	~1380	~1150
Heat Transfer Coefficient (Btu/hr-°F-ft ²)	-	-	-	-	1850	1850	1850

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II. SUMMARY AND CONCLUSIONS

Based upon extensive experience with the U-ZrH fuel element performance obtained during the course of the SNAP Reactor Development Program, the following conclusions appear to be in order:

- 1) The hydrogen retention characteristics of the fuel element, as provided by the SCB ceramic liner, are described by the barrier performance parameter, A_D , which exhibits the following properties:
 - a) Generally has magnitude of 0.001 to 0.002 (i.e., 0.1 to 0.2% of the internal surface area of the ceramic liner contains defects)
 - b) Is invariant with time
 - c) Shows no susceptibility to irradiation induced damage
 - d) Is unaffected by imposed short-term loadings which produce stresses in the cladding less than the yield strength
 - e) Is not affected by cyclic loadings, within at least the limits of available test results.
- 2) The hydrogen permeabilities of Hastelloy X, Hastelloy N, and Incoloy 800 have been measured, and found to be almost twice the literature values for Types 316 and 321 stainless steels. The recommended permeation constants for Hastelloy X, Hastelloy N, and Incoloy 800 are:

$$C = 2900 \frac{\text{cc-mm}}{\text{hr-cm}^2\text{-atm}^{1/2}}$$

$$Q = 14750^\circ\text{R} \text{ (16275 cal/mole).}$$

The permeability of the SCB ceramic liner, which provides the prime resistance to hydrogen flow out of the fuel element, has been measured, and found to be about three orders of magnitude lower than the cladding. The recommended permeation constants for the SCB ceramic are:

$$C = 38 \frac{\text{cc}}{\text{hr-cm}^2\text{-atm}}$$

$$Q = 20800^\circ \text{ R (22950 cal/mole)}.$$

- 3) Electron microscopy of the S8DR fuel has indicated that cavity clouds exist, locally, in the region of selected, precipitated uranium (fuel) particles, to the extent that $\sim 10\%$ $\Delta V/V$ swelling occurs locally (independent of the local flux-fluence relationship). Gross swelling is manifested by the concentration of these islands of cavities, and not by the local $\Delta V/V$ in the regions of isolated islands of cavities.
- 4) Growth of U-ZrH fuel is strongly temperature dependent. For a given operating temperature, it appears that the gross fuel growth may be inversely proportional to local fuel power density. Consequently, test irradiation fuel growth obtained at local high-power densities can actually be less than the fuel growth in an S8DR-type reactor operating at similar temperatures, but a lower local power density.

To summarize, the SCB ceramic liner applied to the cladding ID has proved to be a remarkably tough and durable fuel element component. The fuel growth under operating SNAP reactor conditions is strongly temperature dependent. Design of U-ZrH fueled SNAP reactors which operate consistently above the 1300 to 1350°F range demands strong consideration for fuel growth, which could compromise the integrity of the cladding. Lower-temperature reactors, in the range of 1200°F or less, are much less susceptible to fuel growth problems.

III. HYDROGEN PERMEATION

In the operating temperature regime of SNAP reactors (1000 to 1300°F), free hydrogen is evolved from the fuel. The equilibrium pressure of the hydrogen in the fuel element is determined by the operating temperature and fuel hydrogen content, $(H/Zr)_{eff}$, as illustrated in Figure 1.

The escape of the hydrogen moderator from the fuel element must be controlled to a low level, in order to maintain the associated core reactivity decrease (due to hydrogen loss) within design limits. This is accomplished by use of a thin ceramic liner (historically known as "SCB"), applied to the entire inside surfaces of the fuel element cladding and end caps. This section presents an evaluation of the hydrogen-retention characteristics of the SNAP reactor fuel element.

A. THE HYDROGEN PERMEATION PROCESS

1. Physical Model of Hydrogen Permeation

Consider the section of a SNAP fuel element shown in Figure 2. The free hydrogen evolved from the fuel during operation has an equilibrium pressure as described by Figure 1. External to the cladding, the partial pressure of hydrogen in the coolant is essentially zero. The hydrogen pressure differential across the SCB liner - cladding tube composite provides the driving force for hydrogen permeation from the fuel element.

The migration paths for permeation are twofold:

- 1) Through the SCB liner, and then through the cladding tube
- 2) Directly through the cladding tube, in very localized areas, where minute defects in the liner may occur.

The hydrogen permeation by each of these two paths is described by the permeability, Ω , of the components through which the hydrogen must pass.

2. Component Permeabilities

Hydrogen permeates through the SCB liner as diatomic hydrogen, and through the metal cladding tube as monatomic hydrogen.⁽¹⁾ The permeabilities of the SCB and cladding tube are given by the equations:

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Figure 1. Zirconium Hydride Phase Diagram

$$\frac{L}{A_S} = \frac{A_D C_M \sqrt{P} \exp\left(-\frac{Q_M}{T_M}\right)}{t} + C_{SCB} P \exp\left(-\frac{Q_{SCB}}{T_{SCB}}\right) (1 - A_D)$$

MATHEMATICAL DESCRIPTION (SEE SECTION III-A-3)

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Figure 2. Physical Model for Hydrogen Permeation

$$\Omega_{SCB} = C_{SCB} \exp \left(-\frac{Q_{SCB}}{T_{SCB}} \right) \quad \dots (1)$$

$$\Omega_{metal} = C_{metal} \exp \left(-\frac{Q_{metal}}{T_{metal}} \right) , \quad \dots (2)$$

where:

Ω_{SCB} = permeability of SCB (cc of H_2 at STP-mm/hr-cm²-atm)

Ω_{metal} = permeability of metal cladding tube (cc of H_2 at STP-mm/hr-cm²-atm^{1/2})

C_{SCB} = permeation coefficient of SCB (same units as Ω_{SCB})

C_{metal} = permeation coefficient of metal cladding tube (same units as Ω_{metal})

Q_{SCB} = activation energy for hydrogen permeation through SCB (°R)

Q_{metal} = activation energy for hydrogen permeation through metal cladding tube (°R)

T_{SCB} ,
 T_{metal} = temperature of SCB and metal cladding tube, respectively (°R)

The permeation constants, C and Q, were experimentally determined (as described in Section III-B) for typical SNAP fuel element components, and found to be:

$$C_{SCB} = 38 \frac{\text{cc(STP)*}}{\text{hr-cm}^2\text{-atm}}$$

$$Q_{SCB} = 20,800^\circ \text{R}$$

$$C_{metal}^\dagger = 2900 \frac{\text{cc(STP)-mm}}{\text{hr-cm}^2\text{-atm}^{1/2}}$$

$$Q_{metal}^\dagger = 14,750^\circ \text{R}$$

*An SCB thickness dependence is dropped, because of only slight liner thickness variations in typical SNAP fuel elements.

†Applicable to Hastelloy N, Hastelloy X, and Incoloy 800.

3. Analytical Model for Hydrogen Permeation

As noted in Section III-A-1, hydrogen permeation from a SNAP fuel element occurs through two parallel paths — through the SCB-tube composite, and directly through the cladding tube in localized SCB defect areas. Assume that the integrated total defect areas are described by the term A_{defects} , and that the total fuel element internal surface area is A_{surface} . The fractional area, then, that is effectively exposed as bare metal is defined by the term A_D , where

$$A_D = \frac{A_{\text{defects}}}{A_{\text{surface}}} \quad \dots (3)$$

The hydrogen leakage rate from an element is given by

$$L_T = L_D + L_{\text{SCB}} \quad \dots (4)$$

where:

L_T = total leakage rate [cc(SPT)/hr]

L_D = leakage rate through defects [cc(STP)/hr]

L_{SCB} = leakage rate through the SCB-tube composite [cc(STP)/hr].

Introducing the component permeabilities (Section III-A-2), and noting that hydrogen permeation through a ceramic (SCB) is dependent on the pressure differential to the first power, while permeation through a metal is dependent on the pressure differential to the one-half power,⁽¹⁾ the leakage rate from an element is given by:

$$L_T = \left(A_D \frac{\sqrt{P}}{t} \Omega_{\text{metal}} + (1 - A_D) P \Omega_{\text{SCB}} \right) A_{\text{surface}} \quad \dots (5)$$

where:

A_D = fractional defect area from Equation 3 (dimensionless)

P = differential pressure driving force (atm) ($\approx$ fuel element internal pressure)

t = cladding thickness (mm)

Ω_{metal} = metal permeability from Equation 2 [cc(STP)-mm/hr-cm²-atm^{1/2}]

Ω_{SCB} = SCB liner permeability from Equation 1 [cc(STP)/hr-cm²-atm]

In Equation 5, the first term describes the hydrogen leakage through the SCB defects, while the second term reflects leakage through the SCB - cladding tube composite. Note that, in the second term, only the SCB leakage term appears - no account is taken of the metal leakage (i.e., cladding tube) term, which is in series with the SCB leakage. This is because the resistance to permeation presented by the ceramic liner is of about three orders of magnitude greater than the metal resistance, and hence the metal leakage term is negligible.

Experience has shown that A_D is of the order of 0.001 (0.1%), so that

$$1 - A_D \approx 1$$

Using this simplification, inserting appropriate values for the permeation constants, and dropping the subscript on A_{surface} , the most commonly used form of the hydrogen permeation equation for a SNAP fuel element becomes

$$L_T = \left\{ \left(\frac{A_D \sqrt{P}}{t} \right) (2900) \left[\exp \left(- \frac{14750}{T} \right) \right] + (P)(38) \left[\exp \left(- \frac{20800}{T} \right) \right] \right\} A, \quad \dots (6)$$

where the variables are as defined for Equation 5, with $A_{\text{surface}} = A$.

B. PERMEATION CONSTANTS

1. Metal Permeability

The permeation constants (C and Q in Equation 2) for Hastelloy X, Hastelloy N, Incoloy 800, and Type 304 stainless steel have recently been determined, as part of the SNAP Reactor Development Program. Emphasis was placed on determining the constants for Hastelloy X and Incoloy 800, which were candidate materials for cladding in proposed reactor systems. Determination of the constants for Hastelloy N were included for sake of comparison with prior data,⁽²⁾ obtained in support of the SNAP 8 Reactor Program. The Type 304 stainless steel data were obtained for comparison with existing literature data.

a. Experimental Method

The permeabilities of the metals tested were measured, using a hydrogen-sensitive mass spectrometer connected to a high-vacuum quartz retort fitted into a 3 in. bore by 36 in. long resistance-type tube furnace, as illustrated in Figure 3. The test article (termed a "membrane"), as shown in Figure 4, was a tube section of the metal to be tested, capped at one end, and welded to an SCB-coated tube on the other. The SCB tube section, in turn, was fitted with a 1/8 in. diameter pressure probe, through which hydrogen gas was admitted to the interior of the test membrane.

The test procedure was as follows. The membrane, after being thoroughly liquid honed on the OD and dry blasted with Al_2O_3 on the ID (to remove all surface oxides), was electron beam butt welded to the SCB-coated tube - pressure probe assembly, and installed in the quartz-tube vacuum retort. A hard vacuum ($\sim 10^{-5}$ torr) was established in the retort, using a liquid nitrogen cold-trapped diffusion pump. A similar vacuum was established on the membrane interior, to guard against oxide contamination of the membrane. The vacuum conditions were maintained overnight, prior to initiating the test.

The initial test temperature, usually $\sim 600^\circ\text{F}$, was established on the membrane, using the tube furnace. The hydrogen-detecting mass spectrometer was valved into the vacuum retort system (i.e., on the OD side of the membrane). High-purity hydrogen gas was introduced into the membrane through the pressure probe, and the amount of hydrogen permeating through the membrane was monitored, using the mass spectrometer. When steady-state conditions were reached (usually within 1/2 to 1 hr), the test data [temperature, hydrogen permeation (cc/hr), and imposed pressure] were taken. A new set of temperature-pressure conditions were then established, and the procedure repeated.

Generally, 2 days were required to obtain a full set of data on a given membrane. During the intervening off-hours, the furnace was turned off, and hard vacuum conditions established on the ID and OD of the membrane, to protect against formation of surface oxides, which can have a marked effect upon the permeability of the metal (see Section III-B-1-c).

Figure 3. Permeability Test Apparatus

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Figure 4. Metal Membrane Test Specimen

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TABLE 2
PERMEATION DATA FOR HASTELLOY X AND INCOLOY 800

Hastelloy X			Incoloy 800		
Wall Thickness (in.)	$\frac{1}{T(^{\circ}R)}$	$\Omega_{\text{Hast X}} \left[\frac{\text{cc(STP)-mm}}{\text{hr-cm}^2\text{-atm}^{1/2}} \right]$	Wall Thickness (in.)	$\frac{1}{T(^{\circ}R)}$	$\Omega_{\text{I 800}} \left[\frac{\text{cc(STP)-mm}}{\text{hr-cm}^2\text{-atm}^{1/2}} \right]$
↑ 0.050 ↓	9.434E-4*	0.002402	↑ 0.050 ↓	8.621E-4	0.009005
	8.621E-4	0.00995		7.936E-4	0.03021
	7.936E-4	0.02891		7.936E-4	0.03362
	7.936E-4	0.0271		7.936E-4	0.03028
	7.936E-4	0.0266		6.024E-4	0.457
	8.621E-4	0.0102		6.410E-4	0.2383
	7.353E-4	0.06776		8.621E-4*	0.007838
	6.849E-4	0.141		7.634E-4*	0.03751*
	7.092E-4	0.08798		7.634E-4*	0.0374*
	7.634E-4	0.04013		8.621E-4	0.009827
	7.634E-4	0.03998		7.936E-4	0.02567
	7.634E-4	0.03862		7.936E-4	0.02585
↑ 0.028 ↓	9.434E-4*	0.00152*	↑ 0.028 ↓	7.936E-4	0.0289
	9.434E-4	0.002681		7.936E-4	0.03048
	8.621E-4*	0.006554*		8.621E-4	0.01047
	7.936E-4	0.02465		6.024E-4*	0.3329*
	7.936E-4	0.02658		6.410E-4*	0.1668*
	7.936E-4	0.1898		7.634E-4*	0.03167*
	7.936E-4	0.02258		7.634E-4*	0.03562*
	6.944E-4	0.102		7.634E-4*	0.03292*
	7.353E-4	0.05828		8.621E-4	0.008127
	9.434E-4	0.002603		7.937E-4	0.02105
	8.621E-4	0.007986		7.937E-4	0.02233
	7.936E-4*	0.01683*		7.937E-4	0.02177
↑ 0.016 ↓	7.936E-4*	0.0177*	↑ 0.015 ↓	7.937E-4	0.02351
	7.936E-4	0.02013		8.621E-4	0.007892
	7.936E-4	0.01943		6.024E-4	0.2893*
	7.353E-4	0.05		6.410E-4	0.1622*
	6.849E-4	0.1018		7.634E-4*	0.03406*
	6.849E-4	0.1054		7.634E-4*	0.03807*
				7.634E-4*	0.03486*

*Data points deleted, based on assessment of surface oxide effects.
†E-4 denotes $\times 10^{-4}$

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Upon completion of the test run, the membrane was removed from the retort, and inspected for any surface oxides, as evidenced by discoloration of the metal surfaces (OD and ID). The membrane was then centerless ground to the next required OD (i.e., the wall thickness was reduced), and the entire procedure was repeated.

b. Test Matrix and Data

The test matrix for determining the permeation constants for Hastelloy X and Incoloy 800 was as follows:

<u>Metal</u>	<u>Wall Thicknesses Used (in.)</u>	<u>Range of Test Temperatures (°F)</u>
Hastelloy X	0.016, 0.028, 0.050	600-1000
Incoloy 800	0.015, 0.028, 0.050	700-1200

The data obtained are listed in Table 2.

The Hastelloy N and Type 304 stainless steel permeabilities were measured on single tubes of 0.010-in. wall thickness, over the temperature range of 600 to 1000°F. The data obtained are presented in Table 3.

c. Evaluation of Data

When the test program for measuring permeabilities was initiated, it was observed that contamination of the membrane ID and OD by surface oxides had a significant effect on the apparent permeability of the metal being tested. A typical effect is illustrated in Figure 5.

The effect of surface oxides on the hydrogen permeation rate through a metal has been observed before.⁽¹⁾ The oxide thicknesses encountered early in the test program were, judging from the coloration of the surfaces, of the order of 100 to 1000 Å. Oxide films of these thicknesses were found to decrease the apparent metal permeability by factors of 3 (film on OD) to 10 (film on ID).

Every effort was made to preclude the formation of the oxide films on the metal surfaces during testing. Retort vacuums of 10^{-5} torr and in-leakage levels of 4 μ /hr (or less) were obtained, but surface oxide film formation still occurred, if the test specimen was maintained at test temperatures ($\sim$ 800 to 1000°F) for more than $\sim$ 6 hr. In a further effort to suppress oxidation, test

TABLE 3
PERMEATION DATA FOR HASTELLOY N
AND TYPE 304 STAINLESS STEEL

Wall Thickness (in.)	$\frac{1}{T (^{\circ}R)}$	$\Omega_{\text{Hast-N}} \left[\frac{\text{cc(STP)-mm}}{\text{hr-cm}^2\text{-atm}^{1/2}} \right]$	Metal
0.010	9.434E-4 *	0.001517	Hastelloy N
	8.621E-4	0.006016	
	7.937E-4	0.01414	
	6.849E-4	0.06287	
0.010	8.621E-4	0.00364	Type 304 SS
	7.937E-4	0.008089	
	7.937E-4	0.007661	
	7.937E-4	0.007271	
	8.621E-4	0.007484	
	8.621E-4	0.003560	
	7.937E-4	0.008346	
	7.353E-4	0.01489	
	7.634E-4	0.01131	
	6.897E-4	0.03830	
	10.638E-4	0.000267	
	9.434E-4	0.001298	
	8.197E-4	0.005317	
	7.246E-4	0.01715	

*E-4 denote $\times 10^{-4}$

Figure 5. Effect of OD Surface Oxide on Permeability of Incoloy 800

Figure 6. Permeability of Incoloy 800 — All Current Data

specimens were frequently wrapped with a layer of 1- to 2-mil thick Hastelloy X foil, which acted as a getter for the oxygen in the system.

As a result of the surface oxidation problem — a problem which plagued the test program from the outset — it became necessary to assess the validity of each data point with respect to oxidation effects. The assessment was based upon comparison of apparent permeability at a given test temperature, as indicated by data taken early during a run and then duplicated later in the run. If oxidation effects were occurring, the later datum point would indicate a noticeably lower permeability than the former datum point. The suspect point would then be deleted (see Table 2). Figures 6 through 9 present the results of the Incoloy 800 and Hastelloy X permeability testing program.

The Hastelloy N and Type 304 stainless steel data are presented in Table 3. These data are suspect. The testing was performed after test rig contamination had occurred, as the result of a facility power outage. Due to the press of program curtailment, an attempt was made to obtain permeability data, although the risk of surface oxide contamination of specimens was recognized. The data are presented in Table 3, and the results are illustrated in Figures 10 and 11.

d. Results and Recommended Values

The results of the metal permeability tests are summarized in Table 4. Referring to Figures 7 and 9, it can be seen that the differences in permeability between Hastelloy X and Incoloy 800 are of the order of ~15% in the operating temperature regime of SNAP reactors (1000 to 1300°F). Also note, from Table 4, that the temperature sensitivity (Q term) of Hastelloy N is about the same as for Hastelloy X and Incoloy 800 (within ~6%). The low value of the C term for Hastelloy N is due to oxide effects.

Within the accuracy of the data, it is recommended that the permeability constants for Hastelloy X, Hastelloy N, and Incoloy 800 be taken as

$$C = 2900 \frac{\text{cc-mm}}{\text{hr-cm}^2 \text{-atm}^{1/2}}$$

$$Q = 14,750^\circ\text{R} \text{ (16275 cal/mole).}$$

Figure 7. Permeability of Incoloy 800 – Selected Data

Figure 8. Permeability of Hastelloy X — All Current Data

Figure 9. Permeability of Hastelloy X — Selected Data

Figure 10. Permeability of Hastelloy N – All Current Data

Figure 11. Permeability of Type 304 Stainless Steel — All Current Data

TABLE 4
METAL PERMEABILITY RESULTS

Metal	Permeability		95% Confidence Limits				Literature Values
			Lower		Upper		
	C $\left[\frac{\text{cc(STP)}-\text{mm}}{\text{hr}-\text{cm}^2-\text{atm}^{1/2}} \right]$	Q (°R)	C $\left[\frac{\text{cc(STP)}-\text{mm}}{\text{hr}-\text{cm}^2-\text{atm}^{1/2}} \right]$	Q (°R)	C $\left[\frac{\text{cc(STP)}-\text{mm}}{\text{hr}-\text{cm}^2-\text{atm}^{1/2}} \right]$	Q (°R)	
Hastelloy X	2915	14740	2770	14060	3060	15420	-
Incoloy 800	4715	15120	3895	14100	4475	16140	-
Hastelloy N	1125	14230	*	*	*	*	Reference 2 $C = 190 \left[\frac{\text{cc(STP)}\text{mm}}{\text{hr}-\text{cm}^2-\text{atm}^{1/2}} \right]$ $Q = 12760^\circ\text{R}$
Type 304 SS	125	12195	*	*	*	*	Reference 3 $C = 850 \left[\frac{\text{cc(STP)}\text{mm}}{\text{hr}-\text{cm}^2-\text{atm}^{1/2}} \right]$ $Q = 14590^\circ\text{R}$
Types 316 and 321 SS	-	-	-	-	-	-	Reference 4 $C = 1525 \left[\frac{\text{cc(STP)}\text{mm}}{\text{hr}-\text{cm}^2-\text{atm}^{1/2}} \right]$ $Q = 14570^\circ\text{R}$

*Data are suspect, due to surface oxides; little, if any, meaning is attached to confidence limits on such data.

The measured values of C and Q for stainless steel (Table 4) were obviously distorted by oxide effects, as indicated by the discrepancy between the measured values and existing literature data. In passing, note that the recommended C for Hastelloy X, Hastelloy N, and Incoloy 800 is about twice the value for Types 316 and 321 stainless steels, with the temperature dependence (Q) being very nearly the same.

2. SCB Ceramic Permeability

Two different methods were used to measure the hydrogen permeability of the SCB ceramic liner. The first method, used in the initial test program (1964), consisted of selecting 10 SCB-coated Hastelloy N cladding tubes from among a lot of 40 coated tubes. These 10 tubes exhibited no observable coating defects, and appeared to have a high-quality ceramic liner, as judged from the results of extensive inspection (by boroscope) of the tube ID. Each of the 10 membranes were then subjected to a permeation test at 1400°F, at 2 atm internal hydrogen pressure, and 3 of the membranes exhibiting the lowest measured leakages were selected for additional testing. Of the 3 membranes, one appeared to have the highest quality ceramic liner, based upon the results of permeation testing of the 3 membranes over a range of pressures and temperatures; and this one membrane was subjected to extensive permeability testing, to determine the permeation constants (C_{SCB} and Q_{SCB} in Equation 1) for the SCB ceramic.

The second method (in 1973) consisted of fabricating 4 SCB-coated Hastelloy X cladding tubes, each tube having a different liner thickness (ranging from 1 to 6 mils in thickness). These tubes were to be permeation tested at temperatures from 1000 to 1500°F, at internal hydrogen pressures as high as 100 atm. It was assumed that the ceramic liner in each tube had some level of area defects, A_D , which could be determined by permeation testing at a given temperature with several different internal hydrogen pressures. Using this technique, and by appropriately manipulating Equation 5, the A_D term for a given tube can be calculated as follows:

$$A_D = \frac{RL_1 - L_2}{R - \sqrt{R}} \cdot \frac{t_m}{A\Omega_{HastX}\sqrt{P_1}}, \quad \dots (7)$$

where:

$R = P_2/P_1$ = ratio of test pressures at same temperature (dimensionless)

L_1, L_2 = measured hydrogen permeation rates (cc/hr) at test pressures, P_1 and P_2 (atm), respectively

t_m = Hastelloy X tube thickness (mm)

A = internal surface area of test membrane (cm^2)

$\Omega_{\text{Hast X}} = C_{\text{Hast X}} \exp(-Q_{\text{Hast X}}/T)$ = permeability of Hastelloy X at test temperature, T ($^{\circ}\text{R}$) ($\text{cc-mm/hr-cm}^2\text{-atm}^{1/2}$)

Since A_D , the ceramic liner area defect term, should be a constant for a given tube, the ceramic permeability can then be calculated for that tube for any set of pressure-temperature test conditions by the relationship

$$\Omega_{\text{SCB}} = \frac{(L_{\text{SCB}})(t_{\text{SCB}})}{(A)(P)}, \quad \dots (8)$$

where:

L_{SCB} = hydrogen permeation through liner (= total permeation minus permeation through bare metal, as determined by A_D term)

t_{SCB} = liner thickness (mm)

P = internal hydrogen pressure (atm).

The underlying assumption inherent in the second approach to measuring the permeability of the SCB liner is that the first-power pressure dependence of hydrogen permeation through a ceramic material is independent of pressure. Wüstner's experiments with permeation of hydrogen through silica, at pressures up to 800 atm (see Reference 1, page 175), appear to support this assumption. Similarly, Smithells and Ransley (see Reference 1, page 175) work appears to substantiate the postulate that the square-root dependence of hydrogen permeation through metals is obeyed, at least up to pressures of 112 atm.

a. Results of First Method

As discussed previously, a single SCB-coated Hastelloy N cladding tube was selected by process of elimination, and was tested to determine the permeability of the ceramic liner. Note that, since one tube was used, no physical verification of an inverse ceramic thickness effect on permeation rate could be made. For

Figure 12. Permeability of SCB Ceramic

this reason, the units of SCB permeability ($\text{cc/hr-cm}^2\text{-atm}$) do not contain a thickness term. The results are illustrated in Figure 12.

b. Results of Second Method

Due to program closeout, only one tube was permeation tested, and only limited data were obtained. These data gave anomalous results, indicating, in fact, a negative ceramic leakage. The press of time precluded additional testing. The method is still felt to be valid, and is recommended for consideration by others who might be faced with measuring the permeability of a ceramic-metal composite.

3. Recommended Values

Based on a review of the permeability results for Hastelloy X, Incoloy 800, and Hastelloy N (see Figures 7, 9, and 10, respectively), it is recommended that the permeation constants for all three metals be taken as:

$$C = 2900 \frac{\text{cc-mm}}{\text{hr-cm}^2\text{-atm}^{1/2}}$$

$$Q = 14,750^\circ\text{R} \text{ (16,275 cal/mole)}.$$

The reasoning is as follows. While the C and Q values for Hastelloy X and Incoloy 800 appear quite different in Table 4, an overlay of Figures 7 and 9 will indicate that the actual differences in permeability are: (1) nil at 600°F , and (2) $\sim 20\%$ at 1200°F . The spread of the data (95% confidence limits) is of the order of 50% at 1200°F . The use of different permeation constants for Hastelloy X and Incoloy 800 does not seem justified, under these circumstances. The more consistent data on Hastelloy X favor the use of the derived Hastelloy X constants.

The Hastelloy N data were known to be somewhat influenced by surface oxides. The temperature dependence is, however, very similar ($14,230^\circ\text{R}$). Due to the metallurgical similarities between Hastelloys X and N, it is believed that similar permeabilities probably exist. For these reasons, it is recommended that the permeation constants for Hastelloy N be taken as being the same as for Hastelloy X.

Figure 13. Recommended Permeability of Hastelloy X, Hastelloy N, and Incoloy 800

To summarize, the recommended permeability of Hastelloy X, Hastelloy N, and Incoloy 800 are as shown in Figure 13. It is interesting to note that the temperature dependence of permeability (Q) is almost identical to that for Types 316 and 321 stainless steels, with the overall magnitude (C) being almost twice the steel values:

$$\left(2900 \frac{\text{cc-mm}}{\text{hr-cm}^2\text{-atm}^{1/2}} \text{ vs } 1525 \frac{\text{cc-mm}}{\text{hr-cm}^2\text{-atm}^{1/2}} \right) .$$

The recommended permeation constants for the SCB ceramic liner, based on the results of the first method, are:

$$C = 38 \frac{\text{cc}}{\text{hr-cm}^2\text{-atm}}$$

$$Q = 20,8000 (^{\circ}\text{R}) (22,950 \text{ cal/mole}).$$

No inverse liner thickness effect was verified for the ceramic, since only one membrane (with one ceramic thickness) was tested, and the second method, looking for a thickness effect, was unsuccessful. This has no effect in analyzing SNAP fuel element performance, since the thickness tested (~ 3 mils) is, indeed, the thickness employed in the fuel elements.

C. FUEL ELEMENT HYDROGEN PERMEATION PERFORMANCE

The hydrogen retention characteristics of a SNAP fuel element are described by the timewise variation of the area defect term, A_D , sometimes known as the barrier performance parameter. Long-term (of the order of 10,000 hr or longer) ex-reactor permeation tests of fuel elements, periodically interrupted for thermal cycling, have been performed to determine the long-term timewise trend of A_D . Additional short-term load tests, cyclic load tests, and uniaxial tensile tests have been performed, to further characterize the barrier performance. The details and results of these tests are presented in the following sections.

1. Thermal Aging - Thermal Cycling Tests

Production SNAP (S8DR-type) fuel elements were subjected to long-term thermal aging at test temperatures of 1300 to 1400°F. Total test times ranged

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Figure 14. Ex-Reactor Fuel Element Thermal Cycle

up to 10,000 hr. Periodically (every 2000 hr), the elements were removed from the thermal aging permeation test furnaces and subjected to simulated reactor thermal transients (see Figure 14).

The elements tested were randomly selected from developmental lots (termed pre-production elements) and the S8DR reactor production run (production elements and Phase V elements). The Phase V elements were thermally aged at 1300°F; the remaining elements were tested at 1400°F. It is apparent, from Figure 15, that thermal aging - thermal cycling had no discernible effects on the hydrogen permeation performance of the fuel elements, as illustrated by the long-term timewise trend of the barrier performance parameter, A_D .

2. Thermal-Mechanical Loading Tests

a. Load Relaxation Tests

An SCB-coated, 0.032-in. wall, Hastelloy-clad fuel element, and an SCB-coated, 0.020-in. wall, Incoloy 800-clad fuel element, were subjected to a 0.050 in. lateral deflection near the axial midpoint for periods of 250 to 300 hr at a test temperature of 1200°F. The test setup is shown in Figure 16.

Measurements of the load required to produce the 0.050 in. constant deflection were made periodically during the test period, as were fuel element permeation rates. The load-stress relaxation characteristics are discussed in Reference 5. There was no noticeable increase in the hydrogen permeation rate of either element, indicating that the barrier hydrogen retention characteristics were unaffected by the imposed loading.

b. Cyclic Loading Tests

Two SCB-coated, 0.028-in. wall, Hastelloy X-clad fuel elements were subjected to lateral cyclic loadings. One element was tested at 1100°F, the other at 1200°F. The lateral loads, reversed every 3 min for a total of 1391 cycles, produced 0.050 in. deflections either side of the neutral point. The test setup is illustrated in Figure 17.

The hydrogen permeation rate of the elements was monitored continuously during the tests. There was no apparent increase in the permeation rates, indicating that the barrier hydrogen retention characteristics were unaffected by the imposed cyclic loadings on the fuel elements.

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Figure 15. Effects of Thermal Aging and Thermal Transients on Ex-Reactor Fuel Element Hydrogen Permeation Performance

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Figure 16. Load Relaxation Test Rig

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Figure 17. Cyclic Loading Test Rig

3. Short-Term Uniaxial Tensile Tests

Short-term uniaxial tensile tests have been conducted on 3 SCB-coated, 0.010-in. wall, Hastelloy N-clad fuel elements, and on 13 SCB-coated, 0.010 to 0.028-in. wall, Hastelloy X-clad fuel elements. The Hastelloy N elements were tested at 1300, 1400, and 1500°F, respectively. The Hastelloy X elements were tested, variously, in the 1100 to 1300°F range. The applied axial loadings were applied at a strain rate of 0.002 in./in.-min, similar to a standard tensile test loading. Fuel element permeation rates were monitored continuously during application of the tensile loadings. The results showed that, under short-term tensile loadings, the hydrogen barrier performance degraded (defined as a two-fold, or greater, increase in measured permeation rate) only when the cladding tube reached the yield point, and suffered measurable, permanent deformation.

4. S8DR Experience

The post-test examination of the S8DR reactor core⁽⁶⁾ included measurements of hydrogen permeation rates and overall hydrogen loss (by comparison of pre- vs post-reactor operation hydrogen content in the fuel) from selected fuel elements, chosen from the 211 elements in the core. A direct end point comparison of hydrogen permeation rates for these fuel elements was possible, since pre-test permeation rates were available.

An assessment of the average timewise variation of the barrier performance parameter, A_D , for the S8DR fuel elements was made possible by considering the measured core reactivity decrease (due to hydrogen loss), as calculated from the reactor operating history. Details of the analytical approach may be found in Reference 6.

Figure 18 presents the current assessment (revised with respect to the conclusions presented in Reference 6) of the timewise variation of A_D for the zero-to-low cladding strain fuel elements from the S8DR reactor. As illustrated, A_D appears to have taken an early-life increase from the measured pre-test value to the final post-test value in the timespan of ~1000 hr, remaining constant thereafter. Originally,⁽⁶⁾ this early-life adjustment to the measured post-test value was thought to be the result of early-life reactor core fuel element thermal instabilities, causing local cyclic loadings on the cladding-barrier composite of

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Figure 18. Assessed Timewise Variation of A_D for S8DR Reactor Fuel Elements

the elements. Recent investigations indicate, however, that the early-life apparent increase in A_D was a manifestation of surface oxide removal by the hot NaK coolant. Similar apparent increases in A_D have been produced by 1000° F static NaK soakings of S8DR-type elements, for periods of 500 to 1000 hr. These results, coupled with the results of the cyclic loading tests (see Section III-C-2-b), which showed no effects of such loadings on A_D , have combined to produce the reassessment of barrier performance in S8DR. The conclusion now is that the barrier performance of the S8DR zero-to-low cladding strains elements was essentially identical to the ex-pile thermal aging - thermal cycling test elements (i.e., that A_D , the barrier performance parameter, is invariant with time, and exhibits no apparent ill effects as a result of exposure to irradiation).

D. RECOMMENDED DESIGN CRITERIA

Based on the results of the component permeability testing program, the recommended permeation constants for the Hastelloy X, Hastelloy N, and/or Incoloy 800 cladding materials, and for the SCB ceramic liner, are as follows:

Metal Constants:

$$C = 2900 \frac{\text{cc-mm}}{\text{hr-cm}^2\text{-atm}^{1/2}}$$

$$Q = 14,750^\circ \text{R} \text{ (16,250 cal/mole).}$$

SCB Ceramic Constants:

$$C = 38 \frac{\text{cc}}{\text{hr-cm}^2\text{-atm}}$$

$$Q = 20,800^\circ \text{F} \text{ (22,950 cal/mole).}$$

Extensive permeation testing of SNAP fuel elements has indicated that the magnitude of the barrier performance parameter, A_D , runs from 0.0010 to 0.0020. The recommended value of A_D for fuel element hydrogen permeation analyses is 0.0015.

The ceramic barrier has proved to be a remarkably tough and durable liner. Thermal aging-cycling tests, and thermal-mechanical loading tests, including

cyclic loads, have shown the barrier to be highly resistant to damage by conditions which might be encountered in reactor operation. The S8DR experience has indicated that the barrier is resistant to irradiation damage. The conclusion is that A_D is invariant with time, and it is recommended that the A_D value of 0.0015 be applied as a constant over the life of a reactor core design.

IV. U-ZrH FUEL GROWTH CHARACTERISTICS

A. THEORETICAL MODEL

U-ZrH fuel exhibits high growth rate during initial operation, with a subsequent transition to a much lower growth rate after the initial, so-called "offset," growth period. This phenomenon was first noted when fuel growth data from test irradiations were plotted against burnup, and the growth rate then extrapolated back to zero burnup. The offset growth characteristic was then physically verified by observation of the fuel-to-cladding ΔT (from which the fuel-to-cladding gap closure can be deduced) during operation of the NAA-120-4 Irradiation Experiment.⁽⁷⁾

The long-term (low - growth) rate is associated with solid fission product accumulation in the fuel matrix. The early-life rapid, offset, growth rate, occurring during the first 0.1 met. at. % burnup period, is deduced to be the vacancy-condensation-type growth phenomenon. The reasoning is as follows.

Electron microscopy of S8DR fuel indicated that the offset growth was associated with prismatic cavities in the fuel matrix, the cavities being up to 1500 Å in diameter and occurring at densities of up to 10^{15} cavities/cc. Inordinately low surface tensions (~ 200 ergs/cm² vs ~ 1500 ergs/cm², for zirconium metal) would be required to associate the cavities with fission-gas-stabilized bubbles. In addition, postirradiation annealing of S8ER fuel failed to produce the additional growth which would be associated with fission gas stabilization in the fuel.

The evidence, a saturating type of early-life growth, preclusion of fission gas stabilization, and similarity of the growth phenomenon to observed growth characteristics in U_3Si ⁽⁸⁾ and fast neutron irradiated stainless steel,⁽⁹⁾ strongly suggests that U-ZrH fuel undergoes a vacancy-condensation type of growth. Because cavities have been observed in material exhibiting metallographic evidence of twin ϵ -phase banding, the nucleation of vacancy clusters is thought to be associated with the U-ZrH δ - ϵ phase transformation in some currently unexplained manner — probably related to nucleation, in a similar transformation occurring in U_3Si .

The theoretical model for U-ZrH fuel was developed in conjunction with a semi-empirical model, used to fit the irradiation test data, of the form:

$$\frac{\Delta V}{V} = A_g + B \quad , \quad \dots(9)$$

where:

$\Delta V/V$ = fuel growth (%)

A_g = offset growth, a function of burnup rate (i.e., flux) burnup (fluence), operating temperature, and time

B = linear growth associated with solid fission product accumulation (fluence dependent)

The value of B can be derived by considering the crystal atomic volumes of the fission products, and averaging the volumes over the fission yields. Values of B between 2 and 3 times the met. at. % burnup are obtained, the major uncertainty being in the assumptions of how cesium is bound in the lattice. Correlation with the test data indicates a value for B of ~ 3 is reasonable.

The value of A was expected to be flux and fluence (burnup rate and burnup, respectively) dependent, similar to the early correlations of swelling in nickel and nickel-based alloys. These flux-fluence relationships were expected during the early (offset) growth period. Inverse flux dependence would be expected after "saturation" of the offset growth, if recombination of point defects along a fission track was significant. Consider, for example, the simple balance equation for point defects (vacancies and interstitials created by displacement pressures along a fission product recoil track or by recoil resulting from neutron collision processes).

$$\frac{dn_v}{dt} = a\phi - bn_v^2 - cN \sum n_v - dMn_v \quad , \quad \dots(10)$$

where:

n_v = number density of defects

$a\phi$ = rate of production of defects

bn_v^2 = rate of recombination of vacancies with interstitials

$cN\sum n_v$ = loss of N cavities of capture area

dMn_v = loss to grain boundaries, loops, etc.

If n_v is small [i.e., ϕ (flux) is small], most defects produced end up in cavities or other sinks. If n_v is large (i.e., ϕ is large), a substantial portion of the defects can be lost to recombination processes. For a fixed fluence (ϕt), therefore, a larger number of vacancies can migrate to cavities to cause growth for small values of flux than for large values of flux. One obtains, therefore, the probability that U-ZrH fuel operated at a constant temperature can have larger growth for smaller burnup than fuel with greater burnup, hence indicating a multiple (two) valued functional form, when plotted as growth vs temperature—the S8DR experience. This possibility would be most noticeable in the time period immediately following offset growth saturation (0.1 met. at. %).

The detailed theoretical model was, therefore, based on the following assumptions:

- 1) Early life saturation of vacancies
- 2) Classical diffusion of defects to spherical cavities and circular prismatic loops
- 3) Preferential capture of interstitials at loops, leading to a supersaturation of vacancies
- 4) Annealing of loops (as reported for nickel), or decrease in the loop preference for interstitials, with a concurrent increase in the number of loops per unit volume of fuel.

These assumptions were based on the following observations. The first assumption was based on the NAA-120-4 observation that the initial growth showed very nearly linear behavior with burnup — a behavior associated with single cavities. No significant nucleation appeared to occur after the short initial operating time. Different cavity sizes would result from agglomeration of cavities intersected by fission product tracks.

The second assumption allowed description of the diffusion into cavities, by means of a cavity cross section proportional to cavity radius.

The third assumption is common to most irradiation swelling correlations. It is based on investigations which indicate that interstitial loops have a slight preference for interstitial capture. The model proposed in Reference 10 was employed to define a preference factor, δ , relating the effective loops cross section for interstitials to that for vacancies.

The fourth assumption leads to the saturation concept. Since there are no data on loop kinetics in U-ZrH fuel, both assumptions are equally valid. Acceptable parameter values can be selected for the annealing time constant, or the decrease in preference with loop density increase. Results for both models can be made to be in qualitative agreement with the NAA-120-4 results.

The developed theoretical model has predicted a strong temperature dependence for the offset growth magnitude. If stronger loop annealing time constants were employed, then the annealing model would predict growth behavior similar to that observed in the fast neutron irradiation of stainless steels and U_3Si . This resulted from the rapid annealing of loops at high temperatures.

Unfortunately, investigations aimed at determining the magnitude of recombination required for a strong inverse dependence of growth on burnup (in the range of 0.05 to 0.30 met. at. %) have not been completed.

B. FUEL GROWTH DATA

1. Sources of Data

There are two sources of fuel growth data applicable to the U-ZrH_x SNAP fuel element design. These sources are: (1) special irradiation experiments, and (2) the S8DR reactor.

The five special irradiation experiments (termed the NAA 115-1, 115-2, 117-1, 120-4, and 121)^(7,11-14) were performed during the middle-to-late 1960's in the Hanford production reactors. Each experiment consisted of several individual fuel specimens, arranged end to end in the horizontal irradiation facility tube. The operating temperatures of the specimens were monitored by thermocouples, and controlled throughout life, using a flowing, variable-mixture, binary gas (helium-argon) to provide a controlled radial-thermal resistance external to the clad fuel specimens. The operating power densities, and hence

burnup rate and total burnup, were controlled by special flux depressors-shapers located in the vicinity of the fuel specimens.

The operating variables were carbon content, hydrogen content, operating temperature, burnup, and power density. In the 115-1, 115-2, and 117-1 assemblies, the fuel specimens were 4-in. long cylindrical rods (~ 0.530 in. OD). The 121 fuel specimens were full size (~ 17 in. long) S8DR-type fuel elements. The 120-4 samples were thin-walled (~ 0.080 in. thick), 2-1/2-in. long, hollow cylinders, mechanically centralized in the cladding tubes.

The second source of applicable fuel growth data is the S8DR core fuel elements. Extensive post-test examination of 12 selected elements from the core yielded 75 fuel-growth data points, over a range of burnup, power density, and operating temperatures.

Other irradiation experiments, in addition to those previously mentioned, were performed by the SNAP Program during the late 50's and early 60's. These early fuels irradiations were performed under conditions of temperatures, fuel compositions, and heat ratings outside the operating envelope of the final SNAP 8 system. For this reason, the fuel growth data from these tests are excluded from consideration in the overall $U-ZrH_x$ fuel swelling correlation.

2. Fuel Growth Data

The fuel growth data obtained from applicable irradiation experiments and the S8DR core fuel elements are presented in Table 5. Only selected data points are used in establishing the fuel swelling correlation (see Section IV-D for discussion of this selection process).

Presented in Table 6 are the salient features of those early irradiation experiments which are not used in the fuel swelling correlation. These data are presented for sake of completeness only, and will not be discussed further.

3. Assessment of Uncertainties

The assessed uncertainties on the data used to determine $\Delta V/V$ are as follows:

- 1) Density measurements, ± 0.001 gm/cc
- 2) Hydrogen content, $(H/Zr)_{eff} \pm 0.02$.

TABLE 5
APPLICABLE FUEL GROWTH DATA
(Sheet 1 of 8)

Test Designation	Fuel Sample ID	Pre-Test Data					Calculated Operating Temperatures (°F)			Post-Test Data										Remarks			
		U Content (wt %)	C Content (wt %)	(H/Zr) _{eff}	Density (gm/cc)	Fuel rod OD (in.)	Beginning of Life (BOL)	Offset Time (~2000 hr)	End of Life (EOL)	Calculated Burnup (met. at. %)	(H/Zr) _{eff}	Density (gm/cc)	Fuel Rod OD (in.)	$\Delta V/V$ (%)		$\Delta D/D$ (%)		Isotropy Ratio ($\Delta V/V$)/($\Delta D/D$)		Fuel Phase	Cladding Condition	Fuel Rod Condition	Maximum Diametral Strain in Cladding (%)
														Corrected	Uncorrected	Corrected	Uncorrected	Based on Corrected Values	Based on Uncorrected Values				
NAA-115-1 Irradiation Experiment	IS-1A	9.89	0.08	1.68	6.050	0.5275	-	-	-	0.39	1.47	NA	NA	-	-	-	-	-	-	-	C*	C*	0
	IS-2	10.11	0.09	1.59	6.099	0.5276	1450	1390	1370	0.41	1.47	5.980	0.5299	2.641	1.990	0.696	0.436	3.79	4.56	δ	I	C	0
	IS-3A	10.02	0.04	1.66	6.061	0.5275	1445	1385	1370	0.41	1.58	5.855	0.5321	3.749	3.518	0.964	0.872	3.89	4.03	δ, δ+ε	I	I	0.17
	IS-4	9.98	0.40	1.71	6.100	0.5275	1465	1395	1375	0.41	1.64	5.856	0.5330	4.314	4.167	1.101	1.042	3.92	4.00	δ, δ+ε	I	I	0
	IS-5A	10.07	0.04	1.64	6.061	0.5277	1510	1440	1410	0.41	1.64	5.827	0.5332	4.016	4.016	1.042	1.042	3.85	3.85	δ	I	I	0
	IS-6	9.99	0.10	1.69	6.071	0.5336	1440	1415	1410	0.43	1.55	5.977	0.5365	2.032	1.573	0.726	0.543	2.80	2.90	δ, δ+ε	I	I	0.25
	IS-7	10.05	0.11	1.84	6.053	0.5275	1550	1450	1425	0.41	1.49	5.880	0.5314	4.068	2.942	1.188	0.739	3.42	3.98	ε, δ+ε	I	I	0.28
	IS-8	10.05	0.11	1.82	6.062	0.5337	1440	1440	1460	0.42	1.46	6.017	0.5324	2.002	0.747	0.257	-0.243	7.79	-3.08	ε, δ+ε	I	C	0.26
	IS-9	9.89	0.08	1.68	6.068	0.5275	1530	1510	1500	0.43	1.60	5.968	0.5304	1.856	1.676	0.622	0.550	2.98	3.05	δ, δ+ε	I	I	0.24
	IS-10	10.04	0.12	1.69	6.073	0.5275	1460	1420	1420	0.42	1.65	5.984	0.5300	1.578	1.487	0.510	0.474	3.09	3.14	δ, δ+ε	C	I	0.40
	IS-11	10.04	0.12	1.67	6.073	0.5274	1360	1350	1350	0.39	1.65	5.967	0.5293	1.826	1.776	0.380	0.360	4.80	4.93	δ, δ+ε	I	I	0.33
	IS-12	10.04	0.13	1.69	6.072	0.5276	1270	1250	1250	0.37	1.65	5.976	0.5299	1.697	1.606	0.472	0.436	3.60	3.68	δ, δ+ε	I	I	0

*C = cracked, I = intact

TABLE 5
APPLICABLE FUEL GROWTH DATA
(Sheet 2 of 8)

Test Designation	Fuel Sample ID	Pre-Test Data					Calculated Operating Temperatures (°F)			Post-Test Data										Remarks			
		U Content (wt %)	C Content (wt %)	(H/Zr) ^{eff}	Density (gm/cc)	Fuel Rod OD (in.)	Beginning of Life (BOL)	Offset Time (~2000 hr)	End of Life (EOL)	Calculated Burnup (met. at, %)	(H/Zr) ^{eff}	Density (gm/cc)	Fuel Rod OD (in.)	$\Delta V/V$ (%)		$\Delta D/D$ (%)		Isotropy Ratio ($\Delta V/V$)/($\Delta D/D$)		Fuel Phase	Cladding Condition	Fuel Rod Condition	Maximum Diametral Strain in Cladding (%)
														Corrected	Uncorrected	Corrected	Uncorrected	Based on Corrected Values	Based on Corrected Values				
NAA-115-2 Irradiation Experiment	IS-21	9.84	0.14	1.74	6.039	0.5295	1405	1375	1355	0.31	1.64	5.887	0.5383	2.879	2.582	1.780	1.662	1.62	1.55	$\delta, \delta + \epsilon$	I	C	0
	IS-22	9.84	0.12	1.59	6.073	0.5292	1450	1410	1390	0.31	1.49	5.966	0.5358	2.342	1.793	1.465	1.247	1.60	1.44	δ	C	C	0.36
	IS-23	9.83	0.02	1.74	6.043	0.5288	1440	1405	1390	0.33	1.56	5.876	0.5350	3.368	2.842	1.381	1.172	2.44	2.42	$\delta, \delta + \epsilon$	I	C	0.18
	IS-24	9.84	0.43	1.78	6.139	0.5291	1430	1380	1360	0.33	1.64	5.928	0.5363	3.851	3.559	1.479	1.361	2.60	2.62	$\delta, \delta + \epsilon$	I	C	0.36
	IS-25	9.83	0.02	1.74	6.043	0.5292	1400	1350	1325	0.32	1.74	5.881	0.5348	2.755	2.755	1.058	1.058	2.60	2.60	$\delta, \delta + \epsilon$	I	I	0
	IS-26	9.84	0.13	1.70	6.074	0.5344	1380	1360	1360	0.32	1.60	6.004	0.5369	1.363	1.166	0.547	0.468	2.49	2.49	$\delta, \delta + \epsilon$	I	I	0.36
	IS-27	9.82	0.13	1.77	6.071	0.5292	1410	1340	1320	0.33	1.70	5.789	0.5379	5.019	4.871	1.703	1.644	3.05	2.96	$\epsilon, \delta + \epsilon$	I	I	0.41
	IS-28	9.82	0.11	1.85	6.066	0.5342	1370	1370	1370	0.31	1.54	5.994	0.5383	2.067	1.201	1.114	0.768	1.86	1.56	$\epsilon, \delta + \epsilon$	I	C	0.89
	IS-29	9.84	0.13	1.68	6.076	0.5292	1510	1460	1450	0.31	1.50	5.989	0.5337	2.171	1.453	1.367	0.850	1.59	1.71	$\delta, \delta + \epsilon$	C	C	0
	IS-30	9.84	0.13	1.71	6.074	0.5292	1410	1390	1390	0.31	1.56	6.006	0.5319	1.591	1.132	0.693	0.510	2.30	2.22	$\delta, \delta + \epsilon$	C	C	0
	IS-31	9.84	0.13	1.69	6.074	0.5292	1325	1265	1245	0.31	1.68	5.977	0.5371	1.639	1.623	1.500	1.493	1.09	1.09	$\delta, \delta + \epsilon$	C	C	0.36
	IS-32	9.84	0.13	1.70	6.076	0.5291	1220	1200	1180	0.30	1.55	5.978	0.5329	2.130	1.639	0.914	0.718	2.33	2.28	$\delta, \delta + \epsilon$	I	C	0

TABLE 5
APPLICABLE FUEL GROWTH DATA
(Sheet 3 of 8)

		Pre-Test Data					Calculated Operating Temperatures (°F)			Post-Test Data										Remarks			
Test Designation	Fuel Sample ID	U Content (wt %)	C Content (wt %)	(H/Zr) ^{eff}	Density (gm/cc)	Fuel Rod OD (in.)	Beginning of Life (EOL)	Offset Time (~2000 hr)	End of Life (EOL)	Calculated Burnup (met. at. %)	(H/Zr) ^{eff}	Density (gm/cc)	Fuel Rod OD (in.)	$\Delta V/V$ (%)		$\Delta D/D$ (%)		Isotropy Ratio $(\Delta V/V)/(\Delta D/D)$		Fuel Phase	Cladding Condition	Fuel Rod Condition	Maximum Diametral Strain in Cladding (%)
														Corrected	Uncorrected	Corrected	Uncorrected	Based on Corrected Values	Based on Uncorrected Values				
NAA-17-1 Irradiation Experiment	M-1	9.99	0.10	1.69	6.069	0.5338	1300	1300	1310	0.60	1.68	5.906	0.5408	2.776	2.760	1.319	1.312	2.10	2.10	$\delta, \delta + \epsilon$	I	C	0.89
	M-2	9.99	0.10	1.69	6.071	0.5336	1315	1320	1340	0.60	1.57	5.953	0.5380	2.343	1.982	0.969	0.825	2.42	2.40	$\delta, \delta + \epsilon$	I	I	0.77
	M-3	10.16	0.05	1.70	6.068	0.5336	1310	1310	1330	0.60	1.62	5.885	0.5366	3.290	3.110	0.634	0.562	5.19	5.53	$\delta, \delta + \epsilon$	I	C	0.80
	M-5	10.10	0.05	1.55	6.107	0.5340	1270	1290	1300	0.59	1.58	5.961	0.5389	2.285	2.449	0.852	0.918	2.68	2.67	δ	C	I	0.84
	M-6	10.11	0.09	1.60	6.099	0.5339	1310	1310	1330	0.59	1.45	5.953	0.5391	3.265	2.453	1.299	0.974	2.51	2.52	δ	C	I	1.82
	M-7	9.89	0.40	1.64	6.109	0.5337	1320	1310	1320	0.59	1.66	5.961	0.5395	2.434	2.483	1.067	1.087	2.28	2.28	δ	I	C	0.68
	M-9	10.10	0.05	1.70	6.040	0.5338	1240	1240	1230	0.40	1.64	5.948	0.5378	1.679	1.547	0.802	0.749	2.09	2.07	$\delta, \delta + \epsilon$	I	I	0.52
	M-10	9.99	0.10	1.69	6.063	0.5336	1280	1275	1275	0.40	1.62	5.930	0.5387	2.391	2.243	1.017	0.958	2.35	2.34	$\delta, \delta + \epsilon$	I	I	0.41
	M-11	9.89	0.40	1.70	6.088	0.5330	1230	1230	1250	0.40	1.68	5.948	0.5391	2.403	2.354	1.164	1.144	2.06	2.06	$\delta, \delta + \epsilon$	I	I	0.71
	M-12	9.99	0.10	1.67	6.065	0.5336	1220	1210	1210	0.29	1.64	5.997	0.5357	1.200	1.134	0.420	0.394	2.86	2.88	$\delta, \delta + \epsilon$	I	I	0.43
	M-13	10.11	0.10	1.60	6.095	0.5335	1380	1375	1375	0.27	1.55	6.035	0.5350	1.272	0.994	0.392	0.281	3.25	3.54	δ	I	I	0.21
	M-14	9.89	0.40	1.70	6.102	0.5336	1390	1400	1420	0.27	1.42	6.057	0.5336	1.925	0.743	0.472	0.0	4.08	NA	$\delta, \delta + \epsilon, \beta$	I	I	0
	M-15	10.05	0.11	1.83	6.055	0.5337	1220	1220	1240	0.29	1.69	5.829	0.5473	4.189	3.877	2.673	2.548	1.57	1.52	$\epsilon, \delta + \epsilon$	C	I	3.05
	M-16	9.89	0.40	1.85	6.075	0.5336	1190	1200	1215	0.29	1.62	6.016	0.5354	1.472	0.981	0.533	0.337	2.76	2.91	$\epsilon, \delta + \epsilon$	I	I	0.64
	M-17	9.90	0.05	1.81	6.044	0.5336	1145	1145	1165	0.52	1.68	5.972	0.5364	1.486	1.207	0.637	0.525	2.33	2.30	$\epsilon, \delta + \epsilon$	C	I	0.59
	M-18	10.05	0.11	1.79	6.044	0.5340	1145	1145	1175	0.52	1.67	5.852	0.5416	3.553	3.281	1.531	1.423	2.32	2.31	$\epsilon, \delta + \epsilon$	I	I	0.92

TABLE 5
APPLICABLE FUEL GROWTH DATA
(Sheet 4 of 8)

		Pre-Test Data					Calculated Operating Temperatures (° F)			Post-Test Data										Remarks			
Test Designation	Fuel Sample ID	U Content (wt %)	C Content (wt %)	(H/Zr) ^{eff}	Density (gm/cc)	Fuel Rod OD (in.)	Beginning of Life (BOL)	Offset Time (~2000 hr)	End of Life (EOL)	Calculated Burnup (met. at. %)	(H/Zr) ^{eff}	Density (gm/cc)	Fuel Rod OD (in.)	ΔV/V (%)		ΔD/D (%)		Isotropy Ratio (ΔV/V)/ (ΔD/D)		Fuel Phase	Cladding Condition	Fuel Rod Condition	Maximum Diametral Strain in Cladding (%)
														Corrected	Uncorrected	Corrected	Uncorrected	Based on Corrected Values	Based on Uncorrected Values				
NAA-120-4 Irradiation Experiment	F-1	10.52	0.13	1.85	6.026	~0.4 in. OD x ~0.25 in. ID (Annular Fuel Geometry)	1300	1300	1300	0.83	1.74	5.618	NA	7.437	7.227	NA	NA	NA	NA	ε, δ + ε	I	I	0
	F-2	10.08	0.14	1.72	6.048		1300	1300	1300	0.82	1.73	5.777	NA	4.691	4.691	NA	NA	NA	NA	δ, δ + ε	I	I	0
	F-3	10.08	0.14	1.72	6.046		1300	1300	1300	0.83	1.71	5.801	NA	4.223	4.223	NA	NA	NA	NA	δ, δ + ε	I	I	0
	F-4	10.10	0.14	1.86	6.028		1300	1300	1300	0.86	1.81	5.725	NA	5.385	5.293	NA	NA	NA	NA	ε	I	C	0.3
	F-5	10.52	0.13	1.86	6.052		1300	1300	1300	0.85	1.85	5.677	NA	6.662	6.606	NA	NA	NA	NA	ε	I	I	0
	H-1	10.05	0.12	1.70	6.047		1500	1500	1500	0.83	1.66	5.525	NA	9.567	9.448	NA	NA	NA	NA	δ, δ + ε	I	I	0
	H-2	10.56	0.12	1.71	6.069		1500	1500	1500	0.86	1.59	5.376	NA	13.244	12.891	NA	NA	NA	NA	δ, δ + ε	I	C	0
	H-3	10.52	0.13	1.70	6.071		1500	1500	1500	0.84	1.70	5.516	NA	10.062	10.062	NA	NA	NA	NA	δ, δ + ε	I	I	0
	H-4	9.98	0.15	1.85	6.050		1500	1500	1500	0.87	1.74	5.592	NA	8.404	8.190	NA	NA	NA	NA	ε, δ + ε	I	I	0
	H-5	9.98	0.15	1.85	6.052		1500	1500	1500	0.89	1.79	5.581	NA	8.517	8.439	NA	NA	NA	NA	ε, δ + ε	I	C	0
	M-1	10.52	0.13	1.71	6.070		1600	1600	1500	0.82	1.49	4.812	NA	27.763	26.143	NA	NA	NA	NA	δ, δ + ε	I	C	0
	M-2	10.08	0.14	1.72	6.045		1600	1600	1500	0.81	1.44	4.953	NA	23.317	22.047	NA	NA	NA	NA	δ, β	I	C	0
	M-3	10.05	0.12	1.70	6.044		1600	1600	1500	0.82	1.26	4.985	NA	25.603	21.244	NA	NA	NA	NA	δ, β	I	C	0.2
	M-4	10.05	0.12	1.85	6.025		1600	1600	1500	0.85	1.69	5.315	NA	13.679	13.358	NA	NA	NA	NA	ε, δ + ε	I	I	0
	M-5	9.98	0.15	1.84	6.022		1600	1600	1500	0.85	1.71	5.192	NA	16.300	15.986	NA	NA	NA	NA	ε, δ + ε	I	I	0

TABLE 5
APPLICABLE FUEL GROWTH DATA
(Sheet 5 of 8)

		Pre-Test Data					Calculated Operating Temperatures (°F)			Post-Test Data										Remarks			
Test Designation	Fuel Sample ID	U Content (wt %)	C Content (wt %)	(H/Zr) _{eff}	Density (gm/cc)	Fuel Rod OD (in.)	Beginning of Life (EOL)	Offset Time (~2000 hr)	End of Life (EOL)	Calculated Burnup (met. at. %)	(H/Zr) _{eff}	Density (gm/cc)	Fuel Rod OD (in.)	$\Delta V/V$ (%)		$\Delta D/D$ (%)		Isotropy Ratio ($\Delta V/V$)/($\Delta D/D$)		Fuel Phase	Cladding Condition	Fuel Rod Condition	Maximum Diametral Strain in Cladding (%)
														Corrected	Uncorrected	Corrected	Uncorrected	Based on Corrected Values	Based on Uncorrected Values				
NAA-121 Irradiation Experiment	121-1-1	10.58	0.15	1.723	6.090	0.5300	1150	1140	1130	0.16	1.78	6.040	0.5334	0.71	0.83	0.36	0.40	1.96	2.08	ε + δ	I	I	0
	121-1-2	10.58	0.15	1.723	6.090	0.5300	1310	1295	1280	0.22	1.70	6.024	0.5332	1.16	1.10	0.42	0.40	2.76	2.75	δ	I	I	0
	121-1-3	10.58	0.15	1.723	6.090	0.5300	1360	1330	1310	0.28	1.70	5.976	0.5349	1.96	1.90	0.64	0.62	3.06	3.06	δ	I	I	0
	121-1-4	10.58	0.15	1.723	6.090	0.5300	1400	1360	1340	0.28	1.67	5.952	0.5333	2.45	2.32	0.89	0.85	2.75	2.73	δ	I	I	0
	121-1-5	10.58	0.15	1.723	6.090	0.5300	1400	1370	1360	0.22	1.63	5.970	0.5320	2.24	2.01	0.76	0.68	2.95	2.96	δ	I	I	0
	121-1-6	10.58	0.15	1.723	6.090	0.5300	1390	1345	1340	0.17	1.67	5.995	0.5325	1.72	1.59	0.65	0.61	2.65	2.61	δ	I	I	0
	121-2-1	10.58	0.15	1.725	6.090	0.5300	1045	1030	1020	0.16	1.86	6.032	0.5321	0.66	0.96	0.34	0.44	1.94	2.18	ε	I	C	0
	121-2-2	10.58	0.15	1.725	6.090	0.5300	1265	1250	1240	0.22	1.75	6.028	0.5328	0.98	1.03	0.40	0.42	2.45	2.45	δ	I	C	0
	121-2-3	10.58	0.15	1.725	6.090	0.5300	1380	1350	1325	0.30	1.69	5.995	0.5346	1.66	1.58	0.66	0.63	2.52	2.51	δ	I	C	0
	121-2-4	10.58	0.15	1.725	6.090	0.5300	1415	1370	1345	0.30	1.66	5.957	0.5333	2.38	2.23	0.91	0.96	2.62	2.32	δ	I	C	0
	121-2-5	10.58	0.15	1.725	6.090	0.5300	1390	1370	1360	0.23	1.64	6.007	0.5322	1.56	1.38	0.58	0.52	2.69	2.65	δ	I	C	0
	121-2-6	10.58	0.15	1.725	6.090	0.5300	1350	1340	1335	0.18	1.67	6.033	0.5322	1.08	0.95	0.43	0.39	2.51	2.44	δ	I	C	0
	121-3-1	10.37	0.16	1.734	6.089	0.5300	1150	1120	1110	0.18	1.81	6.015	0.5332	1.07	1.23	0.63	0.68	1.70	1.81	ε + δ	I	C	0
	121-3-2	10.37	0.16	1.734	6.089	0.5300	1300	1270	1250	0.26	1.72	5.996	0.5349	1.58	1.55	0.65	0.64	2.43	2.42	δ	I	C	0
	121-3-3	10.37	0.16	1.734	6.089	0.5300	1390	1330	1320	0.31	1.71	5.951	0.5357	2.37	2.32	0.96	0.94	2.47	2.47	δ	I	C	0
	121-3-4	10.37	0.16	1.734	6.089	0.5300	1420	1355	1335	0.30	1.68	5.926	0.5348	2.87	2.75	1.08	1.04	2.66	2.64	δ	I	C	0
	121-3-5	10.37	0.16	1.734	6.089	0.5300	1405	1360	1345	0.22	1.63	5.927	0.5333	2.96	2.73	0.92	0.84	3.22	3.25	δ	I	C	0
	121-3-6	10.37	0.16	1.734	6.089	0.5300	1400	1375	1365	0.18	1.65	5.957	0.5340	2.40	2.22	0.77	0.71	3.12	3.13	δ	I	C	0

TABLE 5
APPLICABLE FUEL GROWTH DATA
(Sheet 6 of 8)

Test Designation	Fuel Sample ID	Pre-Test Data					Calculated Operating Temperature (°F)			Post-Test Data										Remarks			
		U Content (wt %)	Carbon Content (wt %)	(H/Zr) eff	Density (gm/cc)	Fuel Rod OD (in.)	Beginning of Life (BOL)	Offset Time (~2000 hr)	End of Life (EOL)	Calculated Burnup (metal at. %)	(H/Zr) eff	Density (gm/cc)	Fuel Rod OD (in.)	$\Delta V/V$ (%)		$\Delta D/D$ (%)		Isotropy Ratio $(\Delta V/V)/(\Delta D/D)$		Fuel Phase	Cladding Condition	Fuel Rod Condition	Maximum Cladding Strain in Element (%)
														Corrected	Uncorrected	Corrected	Uncorrected	Based on Corrected Values	Based on Uncorrected Values				
S8DR	2-06-1	10.55	0.15	1.749	6.082	0.5292	1385	1355	1280	0.170	1.710	6.001	0.5318	1.432	1.350	0.524	0.491	2.73	2.75	δ	I	I	0.16
	-2	10.55	0.15	1.749	6.082	0.5292	1460	1410	1325	0.129	1.677	5.898	0.5349	3.267	3.120	1.136	1.077	2.88	2.90	δ	I	I	0.16
	-3	10.55	0.15	1.749	6.082	0.5292	1430	1395	1310	0.097	1.695	5.914	0.5345	2.956	2.841	1.048	1.002	2.82	2.84	δ	I	I	0.16
	-4	10.55	0.15	1.749	6.082	0.5292	1390	1375	1285	0.060	1.724	5.974	0.5324	1.857	1.808	0.625	0.605	2.97	2.99	δ	I	I	0.16
	3-09-1	10.33	0.12	1.724	6.080	0.5290	1210	1200	1115	0.091	1.797	6.021	0.5314	0.829	0.978	0.395	0.454	2.10	2.15	ε	I	C	0.18
	-2	10.33	0.12	1.724	6.080	0.5290	1330	1305	1235	0.154	1.703	5.998	0.5319	1.418	1.367	0.568	0.548	2.50	2.49	δ	I	C	0.18
	-3	10.33	0.12	1.724	6.080	0.5290	1380	1330	1265	0.168	1.679	5.951	0.5334	2.271	2.168	0.871	0.832	2.61	2.61	δ	I	C	0.18
	-4	10.33	0.12	1.724	6.080	0.5290	1410	1350	1285	0.172	1.661	5.901	0.5349	3.173	3.033	1.168	1.115	2.72	2.72	δ	I	C	0.18
	-5	10.33	0.12	1.724	6.080	0.5290	1440	1365	1300	0.167	1.542	5.854	0.5363	4.038	3.861	1.445	1.380	2.79	2.80	δ	I	C	0.18
	-6	10.33	0.12	1.724	6.080	0.5290	1450	1375	1305	0.151	1.643	5.808	0.5374	4.882	4.683	1.660	1.588	2.94	2.95	δ	I	C	0.18
	-7	10.33	0.12	1.724	6.080	0.5290	1450	1380	1310	0.131	1.644	5.802	0.5375	4.991	4.791	1.672	1.607	2.99	2.98	δ	I	C	0.18
	-8	10.33	0.12	1.724	6.080	0.5290	1435	1380	1300	0.095	1.652	5.807	0.5374	4.882	4.701	1.647	1.588	2.96	3.07	δ	I	C	0.18
	-9	10.33	0.12	1.724	6.080	0.5290	1405	1375	1290	0.058	1.665	5.866	0.5364	3.790	3.648	1.451	1.399	2.61	2.71	δ	I	C	0.18
	4-08-1	10.69	0.14	1.741	6.075	0.5288	1445	1410	1335	0.164	1.670	6.001	0.5320	1.376	1.228	0.664	0.605	2.07	2.03	δ	I	I	0
	-2	10.69	0.14	1.741	6.075	0.5288	1495	1445	1370	0.163	1.642	5.959	0.5329	2.160	1.940	0.860	0.775	2.51	2.50	δ	I	I	0
	-3	10.69	0.14	1.741	6.075	0.5288	1485	1445	1365	0.124	1.650	5.935	0.5332	2.556	2.357	0.930	0.832	2.75	2.83	δ	I	I	0
	-4	10.69	0.14	1.741	6.075	0.5288	1450	1425	1340	0.091	1.672	5.964	0.5330	2.009	1.858	0.834	0.794	2.41	2.34	δ	I	I	0

TABLE 5
APPLICABLE FUEL GROWTH DATA
(Sheet 7 of 8)

Test Designation	Fuel Sample ID	Pre-Test Data					Calculated Operating Temperature (°F)			Post-Test Data										Remarks			
		U Content (wt %)	Carbon Content (wt %)	(H/Zr) ^{eff}	Density (gm/cc)	Fuel Rod OD (in.)	Beginning of Life (BOL)	Offset Time (~2000 hr)	End of Life (EOL)	Calculated Burnup (metal at, %)	(H/Zr) ^{eff}	Density (gm/cc)	Fuel Rod OD (in.)	ΔV/V (%)		ΔD/D (%)		Isotropy Ratio (ΔV/V)/(ΔD/D)		Fuel Phase	Cladding Condition	Fuel Rod Condition	Maximum Cladding Strain in Element (%)
														Corrected	Uncorrected	Corrected	Uncorrected	Based on Corrected Values	Based on Uncorrected Values				
S8DR	5-05-1	10.49	0.18	1.745	6.087	0.5285	1305	1330	1250	0.136	1.770	6.024	0.5308	0.996	1.046	0.433	0.453	2.25	2.31	δ	I	I	0
	-2	10.49	0.18	1.745	6.087	0.5285	1405	1365	1285	0.151	1.712	6.009	0.5318	1.380	1.298	0.657	0.624	2.10	2.08	δ	I	I	0
	-3	10.49	0.18	1.745	6.087	0.5285	1450	1390	1315	0.157	1.680	5.954	0.5333	2.381	2.233	0.967	0.908	2.46	2.46	δ	I	I	0
	-4	10.49	0.18	1.745	6.087	0.5285	1480	1400	1325	0.154	1.663	5.886	0.5352	3.595	3.415	1.340	1.268	2.68	2.69	δ	I	I	0
	-5	10.49	0.18	1.745	6.087	0.5285	1495	1410	1335	0.143	1.663	5.829	0.5368	4.606	4.426	1.642	1.570	2.81	2.82	δ	I	I	0
	-6	10.49	0.18	1.745	6.087	0.5285	1500	1415	1340	0.123	1.663	5.787	0.5378	5.364	5.184	1.832	1.760	2.93	2.95	δ	I	I	0
	-7	10.49	0.18	1.745	6.087	0.5285	1485	1410	1335	0.097	1.663	5.768	0.5383	5.710	5.531	1.926	1.854	2.96	2.99	δ	I	I	0
	-8	10.49	0.18	1.745	6.087	0.5285	1455	1400	1325	0.065	1.668	5.779	0.5382	5.510	5.330	1.907	1.835	2.89	2.90	δ	I	I	0
	6-01-1	10.70	0.14	1.761	6.088	0.5291	1225	1215	1120	0.042	1.828	6.047	0.5317	0.545	0.678	0.431	0.491	1.26	1.38	ε + δ	C	I	0.84
	-2	10.70	0.14	1.761	6.088	0.5291	1285	1270	1180	0.074	1.794	6.036	0.5312	0.795	0.861	0.369	0.397	2.15	2.17	ε	C	I	0.84
	-3	10.70	0.14	1.761	6.088	0.5291	1340	1325	1240	0.127	1.754	6.033	0.5304	0.945	0.912	0.258	0.246	3.66	3.17	δ	C	I	0.84
	-4	10.70	0.14	1.761	6.088	0.5291	1390	1365	1280	0.141	1.726	6.020	0.5313	1.214	1.130	0.448	0.416	2.71	2.72	δ	C	I	0.84
	-5	10.70	0.14	1.761	6.088	0.5291	1430	1390	1310	0.146	1.708	5.971	0.5330	2.079	1.959	0.785	0.737	2.65	2.66	δ	C	I	0.84
	-6	10.70	0.14	1.761	6.088	0.5291	1480	1425	1350	0.129	1.683	5.799	0.5381	5.183	4.984	1.773	1.701	2.92	2.93	δ	C	I	0.84
	-7	10.70	0.14	1.761	6.088	0.5291	1480	1425	1350	0.107	1.680	5.761	0.5393	5.878	5.676	2.000	1.928	2.94	2.94	δ	C	I	0.84
	-8	10.70	0.14	1.761	6.088	0.5291	1460	1410	1330	0.080	1.690	5.732	0.5401	6.396	6.211	2.143	2.079	2.98	2.99	δ	C	I	0.84
	-9	10.70	0.14	1.761	6.088	0.5291	1420	1385	1305	0.049	1.705	5.775	0.5386	5.566	5.420	1.848	1.796	3.01	3.02	δ	C	I	0.84
	6-02-1	10.60	0.15	1.742	6.085	0.5291	1200	1190	1135	0.067	1.730	6.058	0.5320	0.479	0.446	0.693	0.548	0.69	0.81	ε + δ	I	C	0.21
	-2	10.60	0.15	1.742	6.085	0.5291	1255	1245	1210	0.093	1.665	6.060	0.5306	0.579	0.413	0.487	0.284	1.19	1.45	ε + δ	I	C	0.21
	-3	10.60	0.15	1.742	6.085	0.5291	1405	1385	1320	0.049	1.565	5.883	0.5355	3.964	3.434	1.544	1.210	2.57	2.84	δ	I	C	0.21

TABLE 5
APPLICABLE FUEL GROWTH DATA
(Sheet 8 of 8)

Test Designation	Fuel Sample ID	Pre-Test Data					Calculated Operating Temperature (°F)			Post-Test Data										Remarks			
		U Content (wt %)	Carbon Content (wt %)	(H/Zr) ^{eff}	Density (gm/cc)	Fuel Rod OD (in.)	Beginning of Life (BOL)	Offset Time (~2000 hr)	End of Life (EOL)	Calculated Burnup (metal at. %)	(H/Zr) ^{eff}	Density (gm/cc)	Fuel Rod OD (in.)	$\Delta V/V$ (%)		$\Delta D/D$ (%)		Isotropy Ratio ($\Delta V/V$)/($\Delta D/D$)		Fuel Phase	Cladding Condition	Fuel Rod Condition	Maximum Cladding Strain in Element (%)
														Corrected	Uncorrected	Corrected	Uncorrected	Based on Corrected Values	Based on Uncorrected Values				
S8DR	7-02-1	10.76	0.14	1.722	6.096	0.5288	1235	1215	1150	0.081	1.752	6.054	0.5316	0.628	0.694	0.504	0.530	1.25	1.31	€	I	C	0.1
	2	10.76	0.14	1.722	6.096	0.5288	1285	1275	1210	0.104	1.695	6.056	0.5303	0.710	0.661	0.303	0.283	2.34	2.34	€	I	C	0.1
	3	10.76	0.14	1.722	6.096	0.5288	1445	1375	1335	0.132	1.588	5.847	0.5362	4.585	4.259	1.530	1.399	3.00	3.04	€	I	C	0.1
	4	10.76	0.14	1.722	6.096	0.5288	1455	1420	1365	0.075	1.563	5.965	0.5328	2.653	2.196	0.939	0.756	2.82	2.90	€	I	C	0.1
	7-16-1	10.63	0.12	1.762	6.086	0.5292	1200	1185	1110	0.066	1.810	6.046	0.5317	0.568	0.667	0.471	0.472	1.21	1.41	€	I	I	0
	2	10.63	0.12	1.762	6.086	0.5292	1265	1240	1175	0.099	1.762	6.034	0.5373	0.862	0.862	0.567	0.586	1.52	1.47	€	I	I	0
	3	10.63	0.12	1.762	6.086	0.5292	1305	1285	1220	0.115	1.726	6.023	0.5312	1.121	1.039	0.468	0.378	2.40	2.75	€	I	I	0
	4	10.63	0.12	1.762	6.086	0.5292	1380	1355	1290	0.133	1.659	6.006	0.5320	1.563	1.334	0.659	0.529	2.37	2.52	€	I	I	0
	5	10.63	0.12	1.762	6.086	0.5292	1420	1380	1310	0.133	1.630	5.945	0.5335	2.673	2.379	0.969	0.813	2.76	2.93	€	I	I	0
	6	10.63	0.12	1.762	6.086	0.5292	1435	1385	1310	0.121	1.620	5.898	0.5353	3.495	3.184	1.316	1.153	2.66	2.76	€	I	I	0
	7	10.63	0.12	1.762	6.086	0.5292	1435	1385	1300	0.102	1.614	5.850	0.5364	4.366	4.040	1.568	1.361	2.78	2.97	€	I	I	0
	7-31-1	10.56	0.14	1.755	6.088	0.5290	1195	1175	1110	0.072	1.785	6.049	0.5316	0.578	0.645	0.463	0.491	1.25	1.31	€	I	I	0.84
	2	10.56	0.14	1.755	6.088	0.5290	1235	1220	1165	0.097	1.740	6.040	0.5315	0.828	0.795	0.484	0.473	1.71	1.68	€ + €	I	I	0.84
	3	10.56	0.14	1.755	6.088	0.5290	1300	1280	1235	0.120	1.685	6.033	0.5313	1.062	0.912	0.499	0.435	2.13	2.10	€	I	I	0.84
	4	10.56	0.14	1.755	6.088	0.5290	1360	1330	1285	0.132	1.650	5.973	0.5334	2.165	1.925	0.924	0.832	2.34	2.31	€	I	I	0.84
	5	10.56	0.14	1.755	6.088	0.5290	1395	1345	1300	0.136	1.620	5.890	0.5355	3.679	3.362	1.349	1.229	2.73	2.74	€	I	I	0.84
	6	10.56	0.14	1.755	6.088	0.5290	1410	1365	1315	0.131	1.590	5.814	0.5383	5.147	4.713	1.914	1.758	2.69	2.68	€	I	I	0.84
	7	10.56	0.14	1.755	6.088	0.5290	1430	1380	1285	0.118	1.600	5.741	0.5407	6.434	6.044	2.352	2.212	2.74	2.73	€	I	I	0.84
	8	10.56	0.14	1.755	6.088	0.5290	1440	1400	1290	0.099	1.600	5.730	0.5403	6.639	6.248	2.256	2.136	2.94	2.93	€	I	I	0.84
	9	10.56	0.14	1.755	6.088	0.5290	1435	1410	1300	0.075	1.600	5.749	0.5392	6.825	5.897	2.068	1.928	3.30	3.06	€	I	I	0.84
	10	10.56	0.14	1.755	6.088	0.5290	1380	1380	1275	0.042	1.625	5.866	0.5362	4.086	3.784	1.473	1.361	2.77	2.78	€	I	I	0.84
	9-20-1	10.54	0.13	1.729	6.089	0.5292	1210	1210	1120	0.037	1.809	6.053	0.5306	0.407	0.588	0.193	0.265	2.11	2.22	€	I	I	0
	2	10.54	0.13	1.729	6.089	0.5292	1220	1210	1125	0.065	1.804	6.049	0.5308	0.497	0.661	0.217	0.302	2.29	2.19	€	I	I	0
	3	10.54	0.13	1.729	6.089	0.5292	1330	1315	1235	0.097	1.724	6.051	0.5308	0.623	0.623	0.227	0.302	2.74	2.06	€	I	I	0
	4	10.54	0.13	1.729	6.089	0.5292	1375	1355	1275	0.106	1.693	6.030	0.5316	1.051	0.985	0.479	0.454	2.19	2.17	€	I	I	0
	5	10.54	0.13	1.729	6.089	0.5292	1425	1393	1315	0.111	1.665	5.982	0.5329	1.920	1.789	0.732	0.699	2.62	2.56	€	I	I	0
	6	10.54	0.13	1.729	6.089	0.5292	1455	1416	1335	0.097	1.645	5.928	0.5343	2.896	2.716	0.998	0.964	2.90	2.82	€	I	I	0
	7	10.54	0.13	1.729	6.089	0.5292	1455	1420	1340	0.086	1.643	5.920	0.5344	3.031	2.851	1.054	0.983	2.86	2.90	€	I	I	0
	8	10.54	0.13	1.729	6.089	0.5292	1425	1415	1320	0.063	1.660	5.946	0.5337	2.549	2.402	0.853	0.850	2.99	2.83	€	I	I	0
	9-40-1	10.52	0.14	1.735	6.088	0.5291	1210	1210	1130	0.037	1.796	6.056	0.5310	0.405	0.537	0.268	0.359	1.51	1.50	€	I	I	0
	2	10.52	0.14	1.735	6.088	0.5291	1235	1225	1140	0.065	1.790	6.053	0.5309	0.465	0.580	0.237	0.340	1.96	1.71	€	I	I	0
	3	10.52	0.14	1.735	6.088	0.5291	1345	1325	1255	0.097	1.703	6.045	0.5312	0.784	0.718	0.385	0.397	2.04	1.81	€	I	I	0
	4	10.52	0.14	1.735	6.088	0.5291	1385	1355	1285	0.105	1.678	6.019	0.5317	1.260	1.145	0.499	0.491	2.53	2.33	€	I	I	0
	5	10.52	0.14	1.735	6.088	0.5291	1450	1395	1325	0.109	1.645	5.959	0.5335	2.355	2.158	0.873	0.862	2.70	2.50	€	I	I	0
	6	10.52	0.14	1.735	6.088	0.5291	1430	1380	1305	0.088	1.665	5.962	0.5331	2.261	2.113	0.853	0.756	2.65	2.79	€	I	I	0
	7	10.52	0.14	1.735	6.088	0.5291	1370	1335	1255	0.063	1.705	6.036	0.5318	0.925	0.860	0.423	0.510	2.19	1.69	€	I	I	0

TABLE 6
OTHER FUEL GROWTH DATA

Test Designation	Sample Identification	Power Density* (kw/kg)	Burnup (met. at. %)	Fuel Temperature (°F)	$\Delta V/V$ (%)
NAA-43-5	1	83	1.6	770	7.1
	2	83	1.6	770	7.1
NAA-43-6	1	117	2.2	730	7.3
	2	117	2.2	730	7.3
NAA-53	1	170	0.68	1260	1.3
	2	130	0.52	1420	3.6
	3	130	0.97	1400	8.8
NAA-75-1	1	307	0.68	1000	3.8
	2	485	2.15	1000	7.1
NAA-75-2	1	401	0.50	1050	4.9
	2	503	1.26	900	4.1

*Typical SNAP-8 reactor power density ≈ 14 kw/kg.

Using these uncertainties, a first-order error analysis indicates an uncertainty of $\pm 10\%$ on $\Delta V/V$. Burnup determinations are based upon mass spectrometry measurements, performed by Idaho Nuclear, with a quoted uncertainty of $\pm 15\%$.

The assessed uncertainty applied to the calculated operating fuel temperatures is $\pm 50^\circ\text{F}$. This uncertainty applies equally to both the irradiation experiment temperature conditions and to the S8DR core fuel element operating temperatures.

C. ELECTRON MICROSCOPY OF S8DR FUEL

Limited transmission electron microscopy (TEM) was conducted on selected portions of S8DR Fuel Element 3-09, in order to confirm that the fuel swelling mechanism for U-ZrH fuel is indeed associated with the condensation of excess vacancies into voids within the fuel structure.

Optical microscopy of wafers cut from selected axial positions on the fuel rod from Element 3-09 failed to reveal any void formations which would account for the observed macroscopic fuel growth, as determined by density change

(Archimedes immersion method) and substantiated by fuel rod diametral growth (precision profilometry method) (Figure 19).

The TEM samples were selected from three axial positions along the fuel rod (Figure 19), to provide observations of the microstructure of the fuel which operated at: (1) similar power density (hence, burnup), but at different operating temperatures, and (2) slightly different power densities and temperatures (see Figure 20). Unirradiated material, examined to provide a reference for comparison, indicated the microstructure to consist of zirconium hydride with a very fine uranium precipitate. The uranium particles were spherical in shape, averaging $\sim 1 \mu$ in diameter, and were relatively uniformly distributed, $\sim 40 \mu$ apart, although isolated regions were found where three or four uranium particles were grouped within $\sim 10 \mu$ of each other.

The fuel wafers cut from Element 3-09 were first mechanically thinned to ~ 5 mils thickness, and subsequently electrochemically reduced in a thickness to $\sim 1000 \text{ \AA}$, for the TEM examination. Initial observations, using the 100-kv machine at Atomics International, showed a significant number of voids in the $1000 \text{ \AA}$ range (i.e., of about the same diameter as the wafer thickness). Follow-up examinations were made on the 650-kv electron microscope at the Oak Ridge National Laboratory, using wafers of $\sim 2500 \text{ \AA}$ thickness.

These examinations revealed voids in all three specimens (Figure 21), illustrating a typical observation, wherein clouds of voids were observed in the vicinity of uranium fuel particles, with regions far from the particles retaining a microstructure similar to unirradiated material. The damage apparently occurred in the ZrH matrix, due to fission fragments, as proposed by Roberts.

Figures 22 through 24 present the results of extensive void-size counts, conducted on numerous TEM plates taken of the three fuel wafers. The following general observations were made:

- 1) At the two high-temperature locations, the distribution of voids was relatively uniform, on a macroscopic basis; however, areas immediately adjacent to grain boundaries and uranium particles did not show voids.
- 2) The void sizes increased and the number of voids decreased, moving from the low-temperature specimen to the highest operating-temperature specimen examined.

72-N3-53-2A

Figure 19. S8DR Fuel Element 3-09,
Post-Test Observations

*FUEL LENGTH $\approx$ 16.8 in. (42.7 cm)

72-N3-53-5A

Figure 20. S8DR Fuel Element 3-09,
BOL Operating Conditions

Figure 21. Typical TEM Observation of Voids in Irradiated Fuel From Element 3-09

72-N3-53-6A

Figure 22. S8DR Fuel Element 3-09 Void Size Distribution - Z/L = 0.30

72-N3-53-7A

Figure 23. S8DR Fuel Element 3-09 Void Size Distribution — $Z/L = 0.60$

72-N3-53-8A

Figure 24. S8DR Fuel Element 3-09 Void Size Distribution — $Z/L = 0.69$

- 3) The low-temperature specimen showed nine uniform macroscopic distributions of the voids (i.e. some areas examined showed no voids, while other areas examined showed a large number of voids). No apparent reason for this difference could be seen in the microstructure.

Table 7 summarizes the results of the TEM work. It is interesting to note that the local fuel growth observed by TEM ranges from 2.2 to 4.6 times the observed macroscopic growth, again illustrating the localized nature of the fuel growth damage in U-ZrU fuel.

TABLE 7
SUMMARY OF TEM EXAMINATION RESULTS

Sample Location (Z/L)	Temperature (°C)	Burnup (fissions/cc x 10 ¹⁹)	N (voids/cc x 10 ¹⁴)	Average Void Diameter (Å)
0.30	715	5.5	8.8	434
0.60	782	5.8	5.4	584
0.69	787	5.3	4.2	661

Sample Location (Z/L)	($\Delta V/V$) _{local} (%)	($\Delta V/V$) _{macro} (%)	($\Delta V/V$) _{local} / ($\Delta V/V$) _{macro}
0.30	6.5	1.4	4.6
0.60	9.7	3.9	2.5
0.69	10.4	4.7	2.2

D. CORRELATION OF DATA

1. Test Irradiations Data Selection

Forty of the 73 fuel growth data points obtained from the SNAP fuels irradiation tests were selected as being applicable for use in establishing a fuel swelling correlation. The criteria used in the selection process were:

- 1) Applicability of fuel composition to the SNAP 8 reference reactor system
- 2) Operation of the fuel in the region of the phase diagram (Figure 1), so that the fuel was neither in pure δ or pure ϵ throughout its operating lifetime. This excludes low and high hydrogen content fuel from the correlation

- 3) Exclusion of test fuel which exhibited a large change in hydrogen content from beginning of life (BOL) to end of life (EOL)
- 4) Exclusion of test fuel which operated with defected cladding.

The test specimens selected for use in the fuel growth correlation were (refer to Table 5):

NAA-115-1 samples	IS3A [*] , IS4 [*] , IS5 [*] , IS-12
NAA-115-2 samples	IS21, IS23 [*] , IS24 [*] , IS25 [*] , IS28
NAA-117-1 samples	M1, M2, M3 [*] , M6, M7 [*] , M9 [*] , M10, M11 [*] , M12, M16 [*]
NAA-120-4 samples	E2, E3, H1, H3, H4, H5
NAA-121-1 samples	2, 3, 4, 5, 6
NAA-121-2 samples	2, 3, 4, 5, 6
NAA-121-3 samples	2, 3, 4, 5, 6

2. S8DR Data Selection

All fuel growth data from S8DR were considered in the later correlations, except those samples which operated entirely in the ϵ phase or which started in the ϵ phase and later passed into the δ operating phase. Additionally, the fuel growth in Elements 4-08, 9-20, and 9-40 were observed to be somewhat lower than the main body of data, and were deleted for sake of conservatism.

3. Correlation Forms

Two forms of correlations were employed. The original form, the Bonser-Swenson correlation, was of the form:

$$\left(\frac{\Delta V}{V} - Ab\right) = C \exp(-Q/T) \quad , \quad \dots(11)$$

where:

$\Delta V/V$ = volumetric fuel growth (%)

b = burnup (met. at. %)

*Those samples marked with asterisks contained either low carbon (<0.05 wt%) or high carbon (>0.30 wt%). They were used in the original correlation (the so-called "Bonzer-Swenson" correlation), and were subsequently deleted from consideration in the later correlations.

A, C = empirical constants determined by best fit of data

Q = activation energy for vacancy diffusion ($^{\circ}R$) — also determined by best fit of data

T = absolute operating temperature ($^{\circ}R$) of fuel at the time offset fuel growth has been completed

The Bonser-Swenson correlation considered only the test fuel irradiation data from the NAA-115-1, 115-2, 117-1, and 120-4 (the NAA-121 data not being available at the time). The resulting form was

$$\left(\frac{\Delta V}{V} - 3.21b\right) = 5.76 \times 10^6 \exp[-27000/T (^{\circ}R)]$$

Subsequently, Roberts developed the theoretical model presented in Section IV-A, and proposed the correlation form:

$$\left(\frac{\Delta V}{V} - A_1 b\right) = A_2 \exp\left(-\left\{2.3\dot{b} \exp\left[\frac{A_3}{2}\left(\frac{1860}{T} - 1\right)\right] + A_3\left(\frac{1860}{T} - 1\right)\right\}\right), \dots (12)$$

where:

$\dot{b}$ = burnup rate, expressed as burnup/10,000 hr operation

T = absolute operating temperature ($^{\circ}R$) of fuel at the time offset fuel growth has been completed

A_1, A_2, A_3 = empirical constants determined by best fit of data

The Bonser-Swenson form, and the Roberts form, were tested against the data set containing the selected irradiation data and S8DR data (see Figure 25). The Roberts form was found to correlate somewhat better with the data than the Bonser-Swenson form, the resulting correlation being:

$$\left(\frac{\Delta V}{V} - 3b\right) = 0.055 \exp\left(-\left\{2.3\dot{b} \exp\left[\frac{21.5}{2}\left(\frac{1860}{T} - 1\right)\right] + 21.5\left(\frac{1860}{T} - 1\right)\right\}\right). \dots (13)$$

Figures 26 and 27 illustrate the temperature and burnup rate dependencies expressed by the correlation. Table 8 shows the agreement of calculated fuel growth to observed fuel growth for the applicable data.

6531-51235

Figure 25. U-ZrH Fuel Growth Data Used for Correlation

6531-51236

Figure 26. Effect of Fuel Operating Temperature (At offset) on Fuel Growth for a Constant Burnup Rate

6531-51237

Figure 27. Effect of Burnup Rate on Fuel Growth for a Constant Offset Temperature

TABLE 8
COMPARISON OF CALCULATED FUEL GROWTH TO OBSERVED
FUEL GROWTH, USING ROBERTS CORRELATION
(Sheet 1 of 2)

Sample Identification	Calculated Offset Temperature (°F)	$[1/T (°R)] \times 10^4$	Fuel Growth (%)		Difference (Observed - Calculated) (%)
			Observed	Calculated	
M-12	1205	6.01	0.330	0.046	+0.284
121-22	1250	5.85	0.320	0.248	+0.072
121-32	1270	5.78	0.800	0.312	+0.488
702-2	1275	5.76	0.398	0.607	-0.209
731-3	1280	5.75	0.702	0.595	+0.107
716-3	1285	5.73	0.776	0.675	+0.101
1S12	1290	5.71	0.587	0.292	+0.295
121-12	1295	5.70	0.500	0.633	-0.133
E-3	1300	5.68	1.733	0.053	+1.680
E-2	1300	5.68	2.231	0.055	+2.176
M-1	1300	5.68	0.976	0.139	+0.837
309-2	1305	5.67	0.956	0.765	+0.191
M-10	1315	5.63	1.191	0.460	+0.731
601-3	1325	5.60	0.564	1.262	-0.698
121-33	1330	5.59	1.440	0.874	+0.566
121-13	1330	5.59	1.120	0.971	+0.149
731-4	1330	5.59	1.769	1.337	+0.432
505-1	1330	5.59	0.588	1.311	-0.723
309-3	1330	5.59	1.809	1.198	+0.611
121-26	1340	5.56	0.540	1.620	-1.080
121-16	1345	5.54	1.210	1.811	-0.601
731-5	1345	5.54	3.271	1.676	+1.595
121-23	1350	5.52	0.760	1.309	-0.549
309-4	1350	5.52	2.657	1.549	+1.108
121-34	1355	5.51	1.940	1.388	+0.552
M-2	1355	5.51	0.543	0.581	-0.038
716-4	1355	5.51	1.218	2.150	-0.932
206-1	1355	5.51	0.922	1.698	-0.776
121-35	1360	5.49	2.300	1.971	+0.329
121-14	1360	5.49	1.610	1.655	-0.045
1S21	1360	5.49	1.949	1.516	+0.433
M-6	1365	5.48	1.495	0.750	+0.745
1S28	1365	5.48	1.137	1.654	-0.517
731-6	1365	5.48	4.754	2.341	+2.413
601-4	1365	5.48	0.791	2.248	-1.457
505-2	1365	5.48	0.927	2.159	-1.232
309-5	1365	5.48	3.537	2.024	+1.513

TABLE 8
COMPARISON OF CALCULATED FUEL GROWTH TO OBSERVED
FUEL GROWTH, USING ROBERTS CORRELATION
(Sheet 2 of 2)

Sample Identification	Calculated Offset Temperature (°F)	$[1/T (^{\circ}R)] \times 10^4$	Fuel Growth (%)		Difference (Observed - Calculated) (%)
			Observed	Calculated	
121-25	1370	5.46	0.870	2.244	-1.374
121-24	1370	5.46	1.480	1.852	-0.372
121-15	1370	5.46	1.580	2.307	-0.727
121-36	1375	5.45	1.860	0.037	+1.823
702-3	1375	5.45	4.189	2.709	+1.480
309-9	1375	5.45	3.616	3.590	+0.026
309-6	1375	5.45	4.429	2.520	+1.909
206-4	1375	5.45	1.677	3.563	-1.886
731-10	1380	5.43	3.960	4.067	-0.107
731-7	1380	5.43	6.080	3.072	+3.008
716-5	1380	5.43	2.274	2.906	-0.632
309-8	1380	5.43	4.537	3.344	+1.193
309-7	1380	5.43	4.598	2.928	+1.670
716-7	1385	5.42	4.060	3.495	+0.565
716-6	1385	5.42	3.132	3.264	-0.132
602-3	1385	5.42	3.817	4.226	-0.409
601-9	1385	5.42	5.419	4.226	+1.193
601-5	1390	5.41	1.641	3.213	-1.572
505-3	1390	5.41	1.910	3.092	-1.182
206-3	1395	5.39	2.665	4.078	-1.413
731-8	1400	5.38	6.342	4.334	+2.008
505-8	1400	5.38	5.315	4.846	+0.469
505-4	1400	5.38	3.133	3.617	-0.484
731-9	1410	5.35	6.600	5.334	+1.266
601-8	1410	5.35	6.156	5.252	+0.904
505-7	1410	5.35	5.419	4.982	+0.437
505-5	1410	5.35	4.177	4.319	-0.142
206-2	1410	5.35	2.840	4.511	-1.671
505-6	1415	5.33	4.995	4.918	+0.077
702-4	1420	5.32	2.428	6.054	-3.626
601-7	1425	5.31	5.557	5.883	-0.326
601-6	1425	5.31	4.796	5.525	-0.729
H-5	1500	5.10	5.847	5.506	+0.341
H-4	1500	5.10	5.794	5.655	+0.139
H-3	1500	5.10	7.542	5.885	+1.657
H-1	1500	5.10	7.077	5.963	+1.114

E. RECOMMENDED DESIGN APPROACH

The prediction of U-ZrH fuel growth in a SNAP 8 fuel element, operating at or near the SNAP 8 performance levels, should be made using the Robert's correlation given previously. The prediction is of necessity a trial and error type of calculation, involving assumption of an offset fuel temperature with subsequent determination of the predicted fuel growth (and hence, fuel-to-cladding gap closure). The amount of gap closure is then used to calculate the offset temperature, which is compared to the assumed offset temperature. The calculation is repeated until the assumed and calculated temperatures are in agreement.

It should be noted that use of the correlation provides a prediction of the nominal anticipated fuel growth. The upper limits on the fuel swelling are generally required for sizing of the fuel-to-cladding gap, to assure that the fuel does not come in contact with the ceramic liner. The upper limit margin which should be applied is an additional 3% $\Delta V/V$ volumetric fuel growth, over and above the nominal prediction of the correlation. This upper limit value is based upon the maximum deviation between observed growth and the growth calculated by the correlation (see Table 8), which is related to S8DR Element 7-31, the largest fuel-growth element in the S8DR core.

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NOMENCLATURE LIST

<p>A = internal surface area of test membrane (cm^2)</p> <p>A_g = offset growth, a function of burnup rate (i.e., flux), burnup (fluence), operating temperature, and time</p> <p>A_D = fractional area effectively exposed as bare metal (dimensionless)</p> <p>A_{defects} = integrated total defect areas (cm^2)</p> <p>A_{surface} = total fuel element internal surface area (cm^2)</p> <p>$a\phi$ = rate of production of defects</p> <p>B = linear growth associated with solid fission product accumulation (fluence dependent)</p> <p>b = burnup (met. at. %)</p> <p>$\dot{b}$ = burnup rate, expressed as burnup/10,000 hr operation</p> <p>bn_v^2 = rate of recombination of vacancies with interstitials</p> <p>C_{metal} = permeation coefficient of metal cladding tube [$\text{cc(STP)}\text{-mm/hr-cm}^2\text{-atm}^{1/2}$]</p> <p>$C_{\text{SCB}}$ = permeation coefficient of SCB [$\text{cc(STP)}/\text{hr-cm}^2\text{-atm}$]</p> <p>$cN\sum n_v$ = loss of N cavities of capture area</p> <p>dMn_v = loss to grain boundaries, loops, etc.</p> <p>$\bar{D}$ = average void diameter (A)</p> <p>$\Delta D/D$ = diametral fuel growth (%)</p> <p>L_1, L_2 = measured hydrogen permeation rates (cc/hr) at test pressures P_1 and P_2 (atm)</p> <p>L_D = leakage rate through defects [$\text{cc(STP)}/\text{hr}$]</p> <p>L_{SCB} = leakage rate through SCB-tube composite [$\text{cc(STP)}/\text{hr}$] (total permeation minus permeation through bare metal, as determined by A_D term)</p> <p>L_T = total leakage rate [$\text{cc(STP)}/\text{hr}$]</p> <p>n_v = number density of defects</p> <p>N = number of voids/cc of fuel</p>	<p>P = differential pressure driving force (atm), also = internal hydrogen pressure (atm)</p> <p>Q = activation energy for vacancy diffusion (determined by best fit of data) ($^\circ\text{R}$)</p> <p>Q_{metal} = activation energy for hydrogen permeation through metal cladding tube ($^\circ\text{R}$)</p> <p>Q_{SCB} = activation energy for hydrogen permeation through SCB ($^\circ\text{R}$)</p> <p>R = ratio of test pressures at same temperature (P_2/P_1) (dimensionless)</p> <p>T = absolute operating temperature of fuel at the time offset fuel growth has been completed ($^\circ\text{R}$)</p> <p>T_{metal} = temperature of metal cladding tube ($^\circ\text{R}$)</p> <p>T_{SCB} = temperature of SCB ($^\circ\text{R}$)</p> <p>t = cladding thickness (mm)</p> <p>t_{SCB} = SCB thickness (mm)</p> <p>$\Delta V/V$ = volumetric fuel growth (%)</p> <p>δ = preference factor, relating the effective loop cross section for interstitials to that for vacancies</p> <p>ϕ = flux ($\text{n/cm}^2\text{-sec}$)</p> <p>ϕt = fluence (n/cm^2)</p> <p>$\Omega_{\text{Hast X}} = C_{\text{Hast X}} \exp(-Q_{\text{Hast X}}/T)$ = permeability of Hastelloy X at test temperature, T ($^\circ\text{R}$) [$\text{cc(STP)}\text{-mm/hr-cm}^2\text{-atm}^{1/2}$]</p> <p>$\Omega_{\text{metal}}$ = permeability of metal cladding tube [$\text{cc(STP)}\text{-mm/hr-cm}^2\text{-atm}^{1/2}$]</p> <p>$\Omega_{\text{SCB}}$ = permeability of SCB [$\text{cc(STP)}/\text{hr-cm}^2\text{-atm}$]</p>
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