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ATOMICS INTERNATIONAL
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NAA-SR-MEMO COVER SHEET

REPORT TITLE **THERMAL ANALYSIS OF DROP-CALORIMETER DETERMINATION OF
SNAP FUEL SPECIFIC HEATS**

AUTHOR
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NAA-SR-MEMO 12324

(This Document Contains _____ Pages.)
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D/737 A. C. Crawford / G. W. Meyers / W. A. Young /		STATEMENT OF PROBLEM <p>Analyze the thermal performance of the drop calorimeter to be used to determine the specific heats of irradiated and non-irradiated SNAP fuel. If possible, propose methods by which the variation in sample composition during a test can be held to less than ± 0.005 H/Zr without sample encapsulation.</p>													
D/742 C. A. Smith 4															
		ABSTRACT: <p>An analytical study of the proposed drop-calorimeter determination of SNAP fuel specific heats is summarized in this report. The partial differential equations describing the transient temperature and hydrogen concentration distributions within a fuel specimen during testing are derived for numerical solution on a digital computer using the Thermal Analyzer Program (TAP-3). Results of the analysis are presented for various initial temperatures and compositions, pressure blowdown rates and calorimeter gas mixtures.</p>													
		<p>A relatively slow blowdown to less than 1 atm hydrogen (by means of a vacuum pump) will permit the desired ± 0.005 H/Zr limits to be held on all delta and epsilon phase fuel specimens at temperatures up to 1700°F without encapsulation. The transient pressure distribution necessary to maintain constant H/Zr in a specimen can be determined from the cooldown curve of the specimen. Because of the long diffusion time constants, particularly below 1300°F, the blowdown need only roughly approximate this ideal pressure transient. Blowdown to a partial vacuum can be avoided by the use of argon-hydrogen mixtures; however, there is the possibility of stratification within the calorimeter. It should be noted that the irradiated fuel samples, of approximately one-fourth the mass of the test samples, will have considerably faster cooldown characteristics necessitating more rapid pressure blowdowns.</p>													

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I. INTRODUCTION

The goal of the SRIP thermophysical properties program is the measurement of the specific heat and thermal diffusivity of irradiated and non-irradiated SNAP fuel as functions of composition, temperature and, in the case of irradiated fuel, of burnup. The thermal conductivity will be calculated from these properties and the density of the fuel.

Specific heats will be measured using a drop calorimeter specifically designed for use with hydrided materials and capable of operation at pressures up to 150 psia. The calorimeter determines the enthalpy change of a material by measuring the heat absorbed in a receiver block from a heated sample of the material dropped into a receptacle within the block. The calorimeter is equipped with environmental control for temperature and pressure. The composition of the fuel will be set by adjusting the hydrogen overpressure in the calorimeter to the desired equilibrium dissociation pressure of the sample. Passage through phase boundaries will be avoided by adjusting the temperature of the copper receiver (1200°F maximum). For compositions in which phase transformations can occur, measurements will first be made with the sample and receiver temperatures below the transformation temperature; the sample and receiver temperature will then be increased above this temperature to obtain specific heats for the high temperature phase.

In the experiment, the sample is heated to a predetermined temperature, T , in a hydrogen atmosphere maintained at the desired equilibrium dissociation pressure. The sample is then dropped (under gravity with electromagnetic braking) into the copper receiver maintained at a lower temperature, T_r . The hydrogen pressure is controlled so that the average H/Zr of the sample does not vary more than ± 0.005 . The heat transfer, $Q(T, T_r)$, from the sample results in a small temperature increase, $\Delta t(T, T_r)$, in the receiver. The specific enthalpy, ΔH , of the specimen is given by

$$\Delta H = H(T) - H(T_r) = \frac{Q(T, T_r)}{m} = C_r \Delta t(T, T_r) \frac{M}{m}$$

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where m is the mass of the specimen, C_r is the specific heat of the receiver and M is the mass of the receiver. From runs at different sample temperatures but identical composition, (H/Zr), the specific enthalpy of the specimen can be determined as a function of temperature:

$$\Delta H = a_0 + a_1 T + a_2 T^2 + a_3 T^3$$

Differentiation with respect to temperature yields the specific heat:

$$C_p = \frac{d\Delta H}{dT} = a_1 + 2a_2 T + 3a_3 T^2$$

The error in the measurement is expected to be approximately $\pm 1\%$ for known standards and not more than $\pm 5\%$ for fuel samples.

The major difficulty with this experimental procedure is insuring that the fuel composition is maintained within the ± 0.005 H/Zr limit during the thermal transient. Various experimental alternatives are available which might aid in achieving this goal. These include:

1. Optimal thermal design of the holder (in which the sample rides during the drop).
2. Use of gas mixtures; e.g., argon-hydrogen, to obtain a wider range of hydrogen partial pressures.
3. Blowdown to a vacuum to achieve a pressure decrease of more than one decade and hydrogen pressures below 1 atm.
4. Optimization of the blowdown rate by proper sizing of the vent line.

If the H/Zr limit cannot be met (over some temperature range), it will be necessary to encapsulate the fuel samples (for this range). This adds to the total cost of the experiment and lengthens the test time as separate encapsulated samples are then required for each fuel composition.

This report summarizes an analytical study undertaken to answer these questions. The partial differential equations describing the temperature and hydrogen concentration fields within the fuel sample during the thermal transient are derived for numerical solution on a digital computer using the standard Thermal Analyzer Program (TAP-3). Specific cases run on the model are discussed and general conclusions and recommendations are presented.

II. METHOD OF SOLUTION

Transient behavior of SNAP fuel is described by energy and hydrogen continuity equations. These equations are developed in Reference 1 considering all possible individual energy and mass transfer processes occurring within the fuel and at the fuel surface. These processes are:

1. Heat conduction and storage,
2. Hydrogen transport under the influence of a concentration gradient,
3. Energy transport due to hydrogen enthalpy redistribution,
4. Thermal radiation from the fuel surface to the environment.

The resulting equations are:

$$\rho c_p \frac{\partial T}{\partial t} = \frac{1}{A} \frac{\partial}{\partial r} \left(k A \frac{\partial T}{\partial r} \right) + \bar{c}_p D \frac{\partial N}{\partial r} \frac{\partial T}{\partial r} - H_{diss} \frac{\partial N}{\partial t} \quad (1)$$

$$\frac{\partial N}{\partial t} = \frac{1}{A} \frac{\partial}{\partial r} \left(D A \frac{\partial N}{\partial r} \right) \quad (2)$$

Equation (1) is the energy equation within the fuel material. The first term on the right-hand side of the equation is heat conduction. The second term characterizes the energy transport due to hydrogen enthalpy redistribution and can be shown to be negligible (Ref. 2). The last term is an energy change due to endothermic hydrogen dissociation. Equation (2)

represents a hydrogen balance within the fuel material. The equation neglects the redistribution of hydrogen under the influence of a temperature gradient (thermal diffusion).

The appropriate boundary conditions are:

$$q_{in} = k \left(\frac{2T}{2r} \right)_{r=R} \quad (3)$$

$$\text{and } N_r = P = N_s \quad (4)$$

where N_s is the hydrogen concentration at the surface of the fuel specimen, defined by the calorimeter hydrogen partial pressure and the specimen surface temperature.

Beginning at the time of sample release, the energy and mass transfer equations (1 through 4) are solved simultaneously by finite difference methods using the Thermal Analyzer Program (TAP-3). The general method of solution is well described in Reference 1.

Figure 1 illustrates the one-dimensional model adopted. The cylindrical fuel slug is divided into five radial increments of equal thickness. Nodes 1 - 5 represent the average increment temperatures, respectively, from the fuel center to the outside. Nodes 11 - 15 represent the average increment hydrogen concentrations. Nodes 6 and 16 represent the surface temperature and surface concentration, respectively.

Node 7 represents the wall of the moly sample holder and node 8 the surface of the copper receiver block. The fuel surface temperature is coupled to the container wall by radiation and conduction, as is the container wall to the receiver surface. To obtain the transient solutions, nodes 1 - 7 and 11 - 16 are set at appropriate initial values and the

receiver surface temperature and the fuel surface hydrogen concentration are varied as functions of time.

The finite difference forms of the governing fuel equations are:

(1) Energy Balance

$$T_i(t + \Delta t) = T_i(t) + \frac{\Delta t}{C_i} \left[Y_{i-1,i} (T_{i-1} - T_i) + Y_{i+1,i} (T_{i+1} - T_i) + Q_i \right] \quad (5)$$

where $Y = \frac{kA}{\Delta r} \quad (6)$

$$Q_i = H_{diss} \left(\frac{N_t - N_{t-\Delta t}}{\Delta t} \right)_i \Delta V_i \quad (7)$$

$$C_i = \rho C_p \Delta V_i \quad (8)$$

(2) Hydrogen Mass Balance

$$N_i(t + \Delta t) = N_i(t) + \frac{\Delta t}{\Delta V_i} \left[Y_{i-1,i} (N_{i-1} - N_i) + Y_{i+1,i} (N_{i+1} - N_i) \right] \quad (9)$$

where $Y = \frac{DA}{\Delta r} \quad (10)$

Because of the explicit appearance of the time step (Δt) in equation (9), a constant 0.2 sec time increment was pre-selected. This is less than any of the nodal time constants in the problem. Mass diffusion constants are 10 sec or greater; thermal time constants are between 0.25 and 0.4 sec.

The hydrogen concentration N in lb/in^3 is related to H/Zr by the equation (Ref. 1, p. 58):

$$N = \frac{0.9 \rho (H/Zr)}{91.22 + (H/Zr)} = \frac{0.198 (H/Zr)}{91.22 + (H/Zr)} \quad (11)$$

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since $\rho = 0.22 \text{ lb/in}^3$ for SNAP fuel.

Fuel specific heat, in the delta phase, is expressed as a function of H/Zr and temperature (Ref. 1, p. 38):

$$C_p \text{ [Btu/lb-}^\circ\text{F]} = 0.1 (H/Zr - 1.073) + 0.711(10^{-4}) T \text{ [}^\circ\text{F]} \quad (12)$$

or, alternately

$$C_p = \frac{9.122 N}{0.198 - N} - 0.1073 + 0.711(10^{-4}) T \quad (13)$$

A fuel thermal conductivity of 13 Btu/hr-ft- $^\circ\text{F}$ is assumed, independent of H/Zr. Assumed surface emissivities are 0.4 for fuel and moly and 0.6 for the oxidized copper receiver.

Heats of dissociation of hydrogen in SNAP fuel are taken from Figure 15 of Reference 1 and are replotted in Figure 2 of this report. The values are largely based on measurements by Johnson and Raymond. The curve is reported to be accurate within ~6% except for the beta phase values which are accurate to within ~15%.

The equilibrium hydrogen concentration, or equivalently the H/Zr, of SNAP fuel is a function of both pressure and temperature. The assumed standard isochore map is that of Johnson (Ref. 3) replotted in Figure 3. However, to avoid the complication of a bivariant table in the TAP program, the approximate equation given in Reference 4 is employed:

$$P = \left[\frac{(H/Zr)}{1.97 - (H/Zr)} \right]^3 \exp \left(13.6 - \frac{19800}{T} \right) \quad (14)$$

where P = Hydrogen pressure, atm
 T = Temperature, $^\circ\text{K}$

Experimental values of the diffusion coefficient of hydrogen through delta-phase zirconium hydride (Ref. 5) are shown in Figure 4. The exponential approximation used in this study is indicated as well as the earlier approximation of Reference 4. A maximum slope has been assumed for conservativeness; e.g., the diffusion is accelerated at temperature above 1300°F, thus making it more difficult to hold the required H/Zr limit.

The non-irradiated fuel specimens are right circular cylinders, 2 cm (0.787 inches) in diameter and 7 cm (2.756 inches) long. The moly sample holder is 1 inch in diameter with approximately 20 mils wall thickness. The diameter of the cavity in the copper receiver block is 1.5 inches. The five compositions to be tested and the temperature ranges for each are listed below; the lower temperatures given for the high H/Zr ratios are a consequence of the 10 atm pressure limitation.

<u>Hydrogen Content</u> <u>(effective H/Zr)</u>	<u>Temperature Range (°F)</u>
1.2	RT - 1700
1.58	RT - 1700
1.65	RT - 1700
1.70	RT - 1645
1.81	RT - 1430

III. RESULTS OF ANALYSIS

A. Initial Temperature Below 1400°F

As shown in Figure 4, the diffusion coefficient which governs the rate of hydrogen movement is extremely dependent upon temperature. In going from 1700 - 1400°F, the diffusion coefficient decreases by more than a decade (9×10^{-4} to 7×10^{-5} cm²/sec). A consequence of this temperature sensitivity is that at temperatures below 1400°F hydrogen redistribution during a calorimeter drop test is very slight. At these temperatures, the time constant for redistribution is on the order of an hour compared to the fuel sample thermal time constant of ~2 minutes.

This conclusion is substantiated by Figures 5 and 6. The analytical case summarized in Figure 5 is for a sample initially at 1400°F and 1.82 H/Zr (corresponding to 7 atm hydrogen pressure). The sample is released into the receiver block maintained at 70°F. The pressure is held constant at the initial 7 atm. When the sample temperature reaches 1000°F (at 57 sec), the equilibrium H/Zr exceeds 1.95. However, the average H/Zr of the fuel sample never increases above 1.823. In fact, there is no noticeable change in H/Zr at all below 1200°F.

Figure 6 is for a sample with an initial H/Zr of 1.835 cooled from 1410 to 1200°F. Because of the receiver's elevated temperature, the radiative heat transfer is reduced and the sample is cooled slower than in the previous case. Therefore, there is more re-hydriding. If the pressure is maintained at 10 atm, the average H/Zr increases to 1.840 before the sample cools to 1300°F, and the limit of 0.005 change in H/Zr is eventually exceeded. (It should be noted that the equilibrium H/Zr corresponding to 10 atm is ~1.88 at 1300°F and ~1.94 at 1200°F.)

These large concentration potentials can be greatly reduced or, in some cases, even reversed by reducing the calorimeter pressure during the test. For example, if the pressure is dropped to 1 atm, the equilibrium H/Zr is ~1.77 at 1300°F and ~1.84 at 1200°F. The dotted curve in Figure 6 indicates the H/Zr variation with time when the pressure is reduced from 10 atm to 1 atm between 5 and 10 sec after the sample is dropped into the receiver block. In this case, the sample average H/Zr changes less than 0.002.

B. Elevated Temperatures

A series of cases, covering a hydride range of 1.58 to 1.70 H/Zr, was run at the maximum initial temperature level (1640 to 1700°F depending on the sample H/Zr). In each case, the calorimeter pressure was selected to yield the desired equilibrium H/Zr at the initial temperature; this

pressure was then maintained throughout the cooldown transient. Both extremes of receiver temperature (70 and 1200°F) were investigated. The results are summarized in Figures 7 through 9. In no case does the average H/Zr of the fuel specimen remain within the required ± 0.005 H/Zr limits.

The large variations in H/Zr are the consequence of the constant pressure levels assumed. Inspection of the isochores in Figure 3 shows that as the surface temperature of a sample decreases (at constant pressure), the corresponding equilibrium hydrogen concentration increases. The concentration difference between the sample and its surrounding atmosphere provides a driving potential for rehydridation of the fuel. A countering factor is the rapid decrease in the diffusion coefficient with temperature which lengthens the time to reach equilibrium as the temperature drops. The result of these two effects, as shown in Figures 7 through 9, is to change the time dependence of the sample average H/Zr as the receiver temperature is varied. With a low receiver temperature, more hydriding occurs in the first 25 sec because the more severe drop in sample temperature produces a larger driving potential. Then as the temperature falls below 1400°F, the diffusion time constant markedly increases and the rate of hydriding decreases. Thus there is a crossing of the hydrogen concentration curves for the extreme cases of minimum and maximum receiver temperature.

C. Controlled Blowdown to Vacuum

From the previous discussion, it is apparent that the calorimeter pressure should be controlled so as to insure a constant sample H/Zr. If this is too difficult to achieve, a semicontrolled blowdown in which the final pressure is selected to give, at 1400°F, an H/Zr identical to the initial H/Zr may be satisfactory. For example, with a 1.70 H/Zr specimen, the blowdown should be to a final pressure of 1 atm as this corresponds to 1.70 H/Zr at 1400°F. Samples with H/Zr greater than 1.70 can easily be employed as they require final hydrogen pressures above 1 atm. However,

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samples with H/Zr of less than 1.70 require final pressures less than 1 atm for proper equilibration at 1400°F. These weak vacuums can be achieved by a small vacuum pump attached to the test equipment.

A major consideration for blowdown is the time-variation of the calorimeter pressure. If, during part of the blowdown, the pressure is too far from equilibrium with the sample, the sample's average hydrogen concentration may vary more than the specified 0.005 H/Zr. An ideal pressure blowdown curve can be generated for each sample composition and receiver temperature from the calculated surface temperature transient and the isochore map relating temperature to pressure at a given fuel composition. Such pressure curves are plotted in Figure 10 for 1.70 H/Zr and in Figure 11 for 1.58 H/Zr. Because of the more rapid sample cooldown, the pressure reduction must be faster for the lower receiver temperatures.

These ideal blowdown rates can be compared to experimentally measured rates. Figure 12 is a plot of the actual calorimeter blowdown through a 3/8 inch vent line. This curve is hereafter referred to as the reference blowdown. Inspection of Figure 10 indicates that for 1.70 H/Zr the reference blowdown is intermediate in speed between the ideal curves for maximum and minimum receiver temperatures, but matches the 70°F receiver curve much more closely. This is also implied in Figures 13 and 14. The H/Zr limits are held for the minimum receiver temperature but not the maximum receiver temperature.

Similar curves are plotted in Figures 15 and 16 illustrating the test behavior of fuel specimens with 1.65 and 1.58 H/Zr, respectively. The results fall well within the 0.005 H/Zr limits for the rapid cooldowns associated with a 70°F receiver block. However, with the block at its maximum temperature of 1200°F, the limits are not held.

The equilibrium H/Zr defined by the instantaneous pressure and the sample surface temperature is also plotted in Figures 15 and 16 for the

reference blowdown rate. Initially, there is a large decrease in the equilibrium H/Zr as the pressure drops more rapidly than the temperature. When the pressure approaches its asymptote, the equilibrium H/Zr increases and passes through its initial value at a temperature near 1400°F. The equilibrium H/Zr continues to increase as the temperature decreases below 1400°F. However, only a slight increase in the sample average H/Zr occurs below 1400°F because of the very small diffusion coefficient.

Prior to determining the ideal pressure blowdowns, an investigation of the effects of variations in the blowdown rate was made. The results are summarized in Figure 17. For a test condition of ~ 1.70 initial H/Zr at 1645°F and 10 atm hydrogen pressure with receiver at 1200°F and blowdown to 1 atm hydrogen, the following rates were duplicated:

1. Reference (Figure 12)
2. Blowdown four times faster than reference
3. Blowdown two times slower than reference
4. Reference blowdown delayed 5 sec. from time of drop.

Comparison of Figure 17 with Figure 10 indicates that all of the above rates are excessively fast; initially, the pressure decreases too rapidly producing low equilibrium H/Zr at the sample surface and dehydration of the sample. However, the latter two cases listed above did reduce dehydration to the point where the H/Zr limits were met.

D. Argon-Hydrogen Gas Mixtures

An alternative to blowdown to a vacuum is the use of mixtures of argon and hydrogen. The equilibrium H/Zr at a specified fuel temperature is set by the hydrogen pressure surrounding the fuel sample. The presence of other gases is inconsequential; the important parameter is the hydrogen partial pressure. With a properly adjusted mixture, the required final hydrogen pressure (of less than 1 atm) is compatible with a total pressure of 1 atm.

As an illustration, consider a 1.65 H/Zr fuel specimen. The test begins with the sample at 1645°F and 10 atm pressure with 5 atm hydrogen partial pressure. The sample is dropped into the cold receiver block. Simultaneously, the calorimeter is vented, reducing the total pressure to 1 atm and the hydrogen partial pressure to 0.5 atm corresponding to 1.65 H/Zr (identical to the initial value) at 1400°F. This scheme permits initial temperatures as high as 1645°F, being limited by the maximum pressure reduction of 10 to 1.

The major uncertainty with this scheme is the possibility of gas separation and stratification within the calorimeter which would completely invalidate the test results. For this reason, blowdown to a vacuum (with a pure hydrogen atmosphere) is considered more attractive.

E. Thermal Optimization of Sample Holder

One other possible way to decrease the change in sample hydrogen concentration would be to cool the sample faster. A maximum rate of cool-down occurs when the sample is allowed to radiate directly to the receiver cavity walls; i.e., when the sample holder is not used (or when it is reduced to the minimum structure required for support). The resulting gains have been analytically determined and are summarized in Figures 7 and 8.

Figure 7 shows the transient behavior of a fuel sample of 1.71 H/Zr dropped, with and without a holder, into a 70°F receiver. The cooldown is considerably faster for the drop without a holder, and the hydrogen concentration change is only about one-half that for the drop with a holder. However, as the receiver temperature is increased, the relative advantages of direct radiation to the receiver block disappear. This is shown graphically in Figure 8. A 1.66 H/Zr sample is dropped into a 1200°F receiver.

The cooldown transient is not significantly accelerated without a holder and there is only a small improvement in the hydrogen concentration variation.

It is therefore concluded that the potential gains associated with a thermally optimized sample holder are minor. Much more substantial gains will result from careful tailoring of the pressure environment. In addition, a redesign to permit direct radiation would jeopardize the containment of a fractured sample.

F. Asymmetry Effects

Consideration should be given to possible temperature and concentration gradients produced by eccentricity within the experimental assembly. Severe thermal gradients produce stresses within the fuel specimen which may lead to fractures and loss of physical integrity. Large circumferential concentration gradients may invalidate test results.

Two limiting cases of asymmetry have been investigated analytically:

1. Fuel sample offcenter, touching holder on one side; and
2. Fuel sample and holder offcenter in same direction.

The latter case provides an upper limit for asymmetry effects as it presumes that the fuel and the holder are maximally eccentric in the same direction producing two line contacts: fuel to holder and holder to cavity wall. Three one-dimensional TAP networks, of the type used for the previously discussed symmetric cases, were interconnected to provide a two-dimensional model including appropriate asymmetric boundary conditions. The specific test considered was of a 1.71 H/Zr sample at 1645°F dropped into a 700°F receiver with the hydrogen pressure maintained constant at 10 atm.

Comparisons of the average temperature and concentration for the asymmetric cases and the corresponding symmetric case are shown in Figure 18.

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Asymmetry results in a lower average thermal resistance between the fuel and the receiver and, therefore, a more rapid thermal response. The faster cooling, in turn, results in a smaller change in the average hydrogen concentration.

Quite large circumferential gradients are produced by asymmetry, particularly in the case of combined sample and holder eccentricity. Instantaneous surface gradients of temperature and concentration are plotted in Figure 19. Maximums occur about 10 sec after initiation of the transient. The combined asymmetry case is more than twice as severe as the fuel asymmetry only case. Because of thermal stresses, these temperature variations may not be tolerable. If this is the case, some efforts will have to be made to insure reasonable centering, particularly of the holder within the receiver cavity.

At first inspection, the surface variation of concentration appears to be intolerable; a maximum surface-to-surface (180° rotation) difference of 0.15 H/Zr exists for the combined asymmetry case while the required limit is 0.005 H/Zr variation. However, Figure 20 shows the variation to be confined to a narrow annulus at the edge of the fuel specimen. At 10 sec time, approximately 65% ($r/R = 0.8$) of the fuel volume is still at the initial hydrogen concentration. Significant variations of H/Zr occur only in the outermost 20% ($r/R = 0.9$) of the fuel volume. Thus, although the surface variation is great, its overall effect is small.

IV. CONCLUSIONS AND RECOMMENDATIONS

1. Changes in average H/Zr are very small for fuel specimen temperatures below approximately 1400°F regardless of the hydrogen pressure within the calorimeter. This is a direct consequence of the small diffusion coefficients and, correspondingly, the long diffusion time constants. The major problem in this temperature range may well be the time required to establish an equilibrium hydrogen concentration prior to a drop test.

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2. For specimen temperatures above 1400°F, a near-constant surface N_H (or H/Zr) must be maintained by controlling the pressure reduction during cooldown. A minimum requirement is the selection of a pressure reduction yielding an equilibrium H/Zr at 1400°F equal to the initial H/Zr.

3. A relatively slow pumpdown (to less than 1 atm hydrogen in some cases) will permit the desired ± 0.005 H/Zr limits to be met on all delta and epsilon phase fuel specimens at temperatures up to 1700°F without sample encapsulation. The transient pressure distribution necessary to maintain constant H/Zr in a sample is defined by the sample's surface temperature history and the isochore map for SNAP fuel. Because of the long diffusion time constants, particularly below 1400°F, the blowdown need only roughly approximate this ideal pressure transient.

To achieve these weak vacuums (approximately 0.1 atm hydrogen minimum pressure), a small vacuum pump should be installed on the vent line of the calorimeter.

4. The irradiated fuel samples to be tested later in this program have about one-fourth the mass of the non-irradiated samples discussed in this report. Correspondingly, the irradiated samples will have considerably faster cooldown characteristics necessitating more rapid pressure pumpdowns. It is suggested that, prior to specific heat measurements in the hot cell, a new set of optimized blowdown curves be generated based on these samples' masses and dimensions.

5. One possible alternative control technique is the use of argon-hydrogen gas mixtures. By adjusting the ratio of the two gases, hydrogen partial pressures from 1 atm to below 0.1 atm can be established concurrent with a total pressure of 1 atm, or correspondingly, from 10 atm to below 1 atm total pressure. A significant uncertainty associated with gas

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mixtures is the possibility of gas stratification within the calorimeter. Thus, this technique is not recommended as an alternative to the use of weak vacuums.

6. The present container design is more than adequate. Some improvements in the cooldown transient could be achieved by removing almost all of the drop-container mass and allowing the fuel sample to radiate directly to the receiver block. However, these potential gains are small and the containment of a fractured sample would be jeopardized. Much more substantial gains will result from careful tailoring of the pressure environment.

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V. REFERENCES

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		MODEL NO.

FIGURE 1
NODAL MODEL

- Finite Capacity Node
- Zero Capacity Node

Unclassified		
Classification	RD/DI	Group
		Date: 1/31/67
Authorized Disposition & Signature

FIGURE 2
HYDROGEN HEAT OF DISSOCIATION
IN SNAP FUEL MATERIAL

2/1/67

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KE SEMI-LOGARITHMIC 359-73
KEUFFEL & ESSER CO. MADE IN U.S.A.
3 CYCLES X 140 DIVISIONS

UNCLASSIFIED

Classification

RD/D

Group

Date 1/5/67

Authorized Classifier Signature

FIGURE 3

DISSOCIATION PRESSURE
SOCHORES

FOR ZIRCONIUM HYDRIDE

(Redrawn from NAA-SR-9295)

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FIGURE 4

HYDROGEN DIFFUSION COEFFICIENT

359-91
SEMI-LOGARITHMIC
KEUFFEL & ESSER CO. MADE IN U.S.A.
5 CYCLES X 70 DIVISIONS

UNCLASSIFIED
Classification
Date 11/31/71
Authorized Classifier Signature

2/1/67

FIGURE 5

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DROP-CALORIMETER TEST

1400 → 70 °F

Initial H/Zr ~ 1.82

DNAM
11/11/66

Unclassified
5/5/01
Group
Authorized Classifier Signature

2/1/67

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FIGURE 6

DROP-CALORIMETER TEST

1410 → 1200 °F

Signature: *[Signature]*
 Date: 1/11/67
 Authorized Classifier Signature: *[Signature]*

PLM
11/1/66

2/1/67

FIGURE 7

DROP - CALORIMETER TEST Page 25 of 38

H/Z - 1.71

Press. Constant at 10 atm

PMN
11/29/66

Unclassified
Classification R570

Date: 1/1/67
Authorized Classifier Signature

2/1/67

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FIGURES

DROP-CALORIMETER TEST

H/Zr ~ 1.66

Pressure Const. at 8 atm

DMM
11/29/66

Under Sec

Classification 40/3 Group

Authorized Classifier Signature

Date: 1/31/67

2/1/67

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FIGURE 9

DROP-CALORIMETER TEST

H/Zr ~ 1.59

Pressure Constant at 4 atm

1700 to 70°F

Avg H/Zr

2/1/67

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FIGURE 10
IDEAL PRESSURE BLOWDOWNS
 $H/Zr = 1.70$

Classification	RD/01 Group
Date: 2/1/67	
Authorized Classifier Signature

Classification (S/N) Group

Authorized Classification Signature

DEAL PRESSURE BLOW DOWNS

$$H/Z_r = 1.58$$

KE **SEMI-LOGARITHMIC** **359-63**
KEUFFEL & ESSER CO. **MADE IN U.S.A.**
2 CYCLES X 140 DIVISIONS

2/1/67

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FIGURE 12

REFERENCE CALORIMETER BLOWDOWN
THROUGH 3/8 INCH VENT LINE

Classification: Unclassified
Date: 1/21/67
Authorized Classifier Signature: [Signature]

2/1/67

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FIGURE 13

1 1/2" X 10 INCHES
MADE IN U.S.A.
KEUFFEL & ESSER CO.

FWMM
11/21/66

Unclassified
Classification
Date: 1/31/67
Authorized Classifier Signature

FIGURE 14

DROP-CALORIMETER TEST

H/Zr = 1.70 645 to 1200°F P = 10 to 1 atm.

PMM

1/23/66

FIGURE 15

2/1/67

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DROP-CALORIMETER TEST

 H/Zr in = 1.65 640 to 70°F $P = 5.0 \rightarrow 0.5$ atm H_2

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FIGURE 16

DROP-CALORIMETER TEST

$H/Z_{cr} = 1.58$ 1640 to 70°F

$P = 2.2 \rightarrow 0.22 \text{ atm } H_2$

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FIGURE 17

EFFECT OF BLOWDOWN VARIATIONS

H/Z initial = 1.7078 1645 to 1200°F P_{s10} to 1 atm N_2

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FIGURE 18

ASYMMETRY LIMITS

$H/2r \sim 1.71$

1645 to 70°F

$P = 10$ atm

TEMPERATURE VARIATION

$H/2r$ VARIATION

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FIGURE 19

ASYMMETRY LIMITS

H/Zr = 1.71

1645 to 709F

Psio atm

Classification	Group
Unclassified (Signature)	Date 12/12/66 Authorized Official Signature

PMW
12/12/66

KE 10' X 10 TO 1/2 INCH 46 1323
7 X 10 INCHES
MADE IN U.S.A.
KEUFFEL & ESSER CO.

2/1/67

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FIGURE 20

CIRCUMFERENTIAL CONCENTRATION
VARIATIONS - ASYMMETRIC CASES

$H/Z_r = 1.71$

1645 to 70°F

$P = 10$ atm

Unlabeled

Classification _____

RD/DT _____

Group _____

Date: 2/1/67

Authorized Observer Signature _____

PMW
12/17/66