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ANALYSIS OF SNAPTRAN REACTOR BEHAVIOR

by

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ABSTRACT

The SNAPTRAN program provided nuclear safety information on the rapid transient behavior of zirconium-hydride-uranium fuels. Knowledge of the fission energy source as a function of time in conjunction with knowledge of the fuel temperature yielded a well defined trend from which an evaluation of the specific heat of the fuel was obtained. The specific heat was found to be described by a linear temperature-dependent term plus an Einstein oscillator model temperature-dependent term. The SNAPTRAN reactor temperature coefficient, calculated using this specific heat formulation, varied from -0.10 to -0.18 cents/°F in the range of 100 to 1200°F.

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SUMMARY

The SNAPTRAN program was designed to provide nuclear safety information on the behavior of zirconium-hydride-uranium-fueled reactors subjected to rapid temperature transients caused by large reactivity additions.

The manner in which the fuel acts to self-limit reactor excursions is of paramount interest in evaluating safety aspects of reactor utilization. Normally, the prompt negative temperature (or energy) coefficient of reactivity represents a measure of the self-limiting capability. Because the self-limiting nature of the fuel is manifested by and is directly dependent upon fuel temperature changes, the thermal state of the fuel is important for an evaluation of the temperature coefficient.

Knowledge of the fission energy source as a function of time used in conjunction with knowledge of the fuel temperature yielded a well defined trend from which an evaluation of the specific heat of the fuel was obtained.

The specific heat was found to be represented by a linear temperature-dependent term plus an Einstein oscillator model temperature-dependent term. The SNAPTRAN reactor temperature coefficient, calculated using the specific heat formulation, varied from -0.10 to -0.18 cents/°F in the range of 100 to 1200°F.

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ANALYSIS OF SNAPTRAN REACTOR BEHAVIOR

I. INTRODUCTION

The SNAPTRAN program was designed to provide nuclear safety information applicable to SNAP 10A/2 reactor systems. The program consisted of the SNAPTRAN-1, -2, and -3 test series. Each of these tests investigated the transient behavior of the SNAP 10A/2 fuel under large-transient, power-excursion conditions. The SNAPTRAN-1 tests investigated the nondestructive transient reactor response to large reactivity additions. This series of tests was conducted under conditions approaching but not resulting in fuel damage. A typical SNAP 10A/2 reactor was modified to permit rapid step or pulse reactivity additions of magnitudes much larger than possible with the original SNAP 10A/2 control mechanisms. The SNAPTRAN-2 portion of the program investigated the dynamic behavior of the zirconium-hydride-uranium fuel under the influence of reactivity additions large enough to produce destruction of the core. The reactor used for this portion of the test was the same as that used for the SNAPTRAN-1 test series except for modification of the control mechanisms and circuitry to permit the large reactivity addition required for initiation of the destructive transient. The SNAPTRAN-3 destructive test investigated the transient reactor behavior and the radiological consequences of reactor destruction under conditions simulating accidental water immersion.

Predictions of the response of a reactor to conditions of large, rapid changes in reactivity input depend largely and, in the case of the SNAP 10A/2 reactor, almost completely on a knowledge of the fuel behavior and any associated reactivity feedback effects. This discussion deals with experimental observations of the SNAPTRAN reactor behavior throughout the entire SNAPTRAN program and with the adequacy of theoretical models used to predict this behavior. Thermal and neutronic aspects of the fuel behavior and their effect on reactor response are analyzed. The fuel behavior discussed primarily includes that leading up to but not including reactor destruction; the fuel behavior during destructive tests is treated in reports covering results of the SNAPTRAN destructive tests [1, 2, 3].

To assess the reactivity feedback as a function of thermal changes in the core, a model for the fuel heat capacity was developed from the data obtained during the SNAPTRAN program. Through the use of this model, the temperature as a function of time was then related to the nuclear power and energy. The approach taken to develop the reactivity feedback descriptive model involved evaluation of (a) the nuclear energy and core fuel temperature; (b) the heat capacity of uranium-zirconium-hydride fuel; and (c) the reactivity feedback as a function of total core energy release and fuel temperature.

II. MEASUREMENT OF NUCLEAR ENERGY AND CORE FUEL TEMPERATURE

The data used in developing the heat capacity model were obtained from nuclear measurements of the reactor power using nuclear detectors and from energy and temperature measurements using specialized thermocouple techniques. A detailed description of the measurements and instrumentation is given in an instrumentation report [4].

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1. CORE FUEL TEMPERATURE MEASUREMENTS FROM ENERGY PROBES

Special thermocouple techniques were used for making temperature measurements during the SNAPTRAN program where reactor periods as short as 200 microseconds were encountered. To obtain sufficiently fast response of the thermocouples, Atomics International developed a technique using very small thermocouple wires (1/2-mil Chromel-Alumel) welded to small pieces of fuel [5]. In addition to providing fast response, the use of fine wire reduced the amount of heat conducted out of the fuel particle, thereby permitting the fuel particle to retain essentially all of the nuclear energy released within it during a power transient. Similar techniques have been used by others for making fuel temperature measurements under very rapid transient conditions [6]. These devices are referred to as energy probes throughout this discussion.

The output of the energy probes was used to obtain a core fuel temperature distribution. An appropriate average core fuel temperature rise was then determined by taking a flux-weighted average of the temperature rise distribution. The ratio of the nuclear energy, obtained from the nuclear detectors, to the integrated, core average, temperature rise provided a normalization factor which related the nuclear energy to the average fuel temperature. This normalization factor is then a core-averaged heat capacity expressed in terms of either the total resulting nuclear energy released from the fuel or the total nuclear energy deposited in the core as a function of average core fuel temperature. An advantage is gained in relating the temperature rise to the total nuclear energy released since the energy released per fission and the number of fissions are both well known. Although the energy deposited in the core is difficult to determine precisely, the heat capacity expressed in terms of deposited energy also has an advantage because comparison with out-of-pile work is more easily made [7, 8, 9]. By using the appropriate assumptions regarding flux shape and the relationship between the temperature at a given position and that of the average core fuel temperature, a temperature profile and an evaluation of the transient temperature could be made for the tests regardless of the maximum temperatures reached or the rate at which temperature changes occurred.

Corrections were made for flux differences from one location to another and for material differences in the energy probes and the core fuel. Corrections were also made for the amount of gamma energy absorbed within the fuel of a given probe. For instance, as high as 15 percent contribution from gamma radiation was found to exist in the probe output signal. In the slower transients, because of a time constant of 3 seconds for heat leakage from the fuel piece, the probes required additional correction. For these transients, conventional sheathed-thermocouple techniques were used to determine the average fuel temperature. From these standard techniques, which were not subject to the heat leakage as it occurred in the energy probes, a normalization was made to correct the energy probe data for this nonadiabatic condition. Since the probes were found to be very reliable and reproducible devices, they were used for energy and power as well as temperature determination within the core. Nuclear energy and power results obtained from the probes agreed closely with the energy and power results determined from the nuclear detectors.

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2. TEMPERATURE DETERMINATION CALCULATIONS

The time-dependent, average core temperature, $\bar{T}$ (t), was defined as

$$\bar{T}(t) = \bar{T}_o + \Delta\bar{T}(t) \tag{1}$$

where

$\bar{T}_o$ is the average initial temperature of the core fuel

$\Delta\bar{T}(t)$ is the time-dependent, average temperature rise of the core fuel.

The time-dependent, average core fuel temperature, $\bar{T}(t)$, was evaluated using a least-squares method. For calculating an average core temperature during the SNAPTRAN-2 and -3 destructive tests and for calculating reactivity coefficients of average core temperature, the temperature rise profile during any test was assumed proportional to the flux shape in the fuel material; and the average was calculated as

$$\Delta\bar{T}(t) = \frac{\sum_{i=1}^{n} \Delta T_i(t)\, f_i}{\sum_{i=1}^{n} f_i^{\,2}} \tag{2}$$

where

$\Delta T_i(t)$ is the time-dependent temperature rise of the ith of n probes

f_i is the flux-weighting factor which is the ratio of the flux (ϕ_i) at the location of the ith probe to the core average flux ($\bar{\phi}_{core}$).

The average core fuel temperatures for the SNAPTRAN-3 and the SNAPTRAN-2 destructive tests are shown in Figure 1.

The temperature data provided by the energy probes were used in conjunction with the core-averaged heat capacity (normalization factor), discussed in Section II-1, to obtain nuclear energy release and power values. Because the nuclear detectors used to provide the core-averaged heat capacity were calibrated during the SNAPTRAN-1 tests, these energy release and power results were consistent throughout all tests.

The total nuclear energy release, $E_i(t)$, necessary to raise the entire fuel volume to the temperature, $T_i(t)$, observed by the ith energy probe at time, t, is given by

$$E_i(t) = \frac{204}{180} \int_{T_o}^{T_i(t)} mc_p(T_i)\, dT_i \tag{3}$$

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where the ratio 204/180 [10] is the ratio of the energy produced per fission (MeV) to the energy deposited per fission (MeV), T_o is the initial temperature of the ith probe, m is the mass of the core fuel, and c_p is the core-averaged specific heat. The product, mc_p, is the core-averaged heat capacity discussed in Section II-1. Since the energy deposited at any point in the fuel may be assumed proportional to the flux-weighting factor at that point, each value of $E_i(t)/f_i$ is an estimate of the total nuclear energy release (as inferred from the ith probe) to time t. The average value of the energy release as a function of time calculated from n energy probes is, therefore,

$$\bar{E}(t) = \frac{1}{n} \sum_{i=1}^{n} E_i(t)/f_i \quad . \tag{4}$$

For SNAPTRAN-3, the nuclear data from the flight-tube scintillator was normalized to the data from the energy probes as shown in Figure 2. The rms deviation is 0.9 percent. The probe data agreed with the nuclear data within 0.2 percent and indicated a peak power of 17.6 GW. The flux factors, f_i, used for SNAPTRAN-3 were developed from calculations made by Atomics International and General Atomics [11].

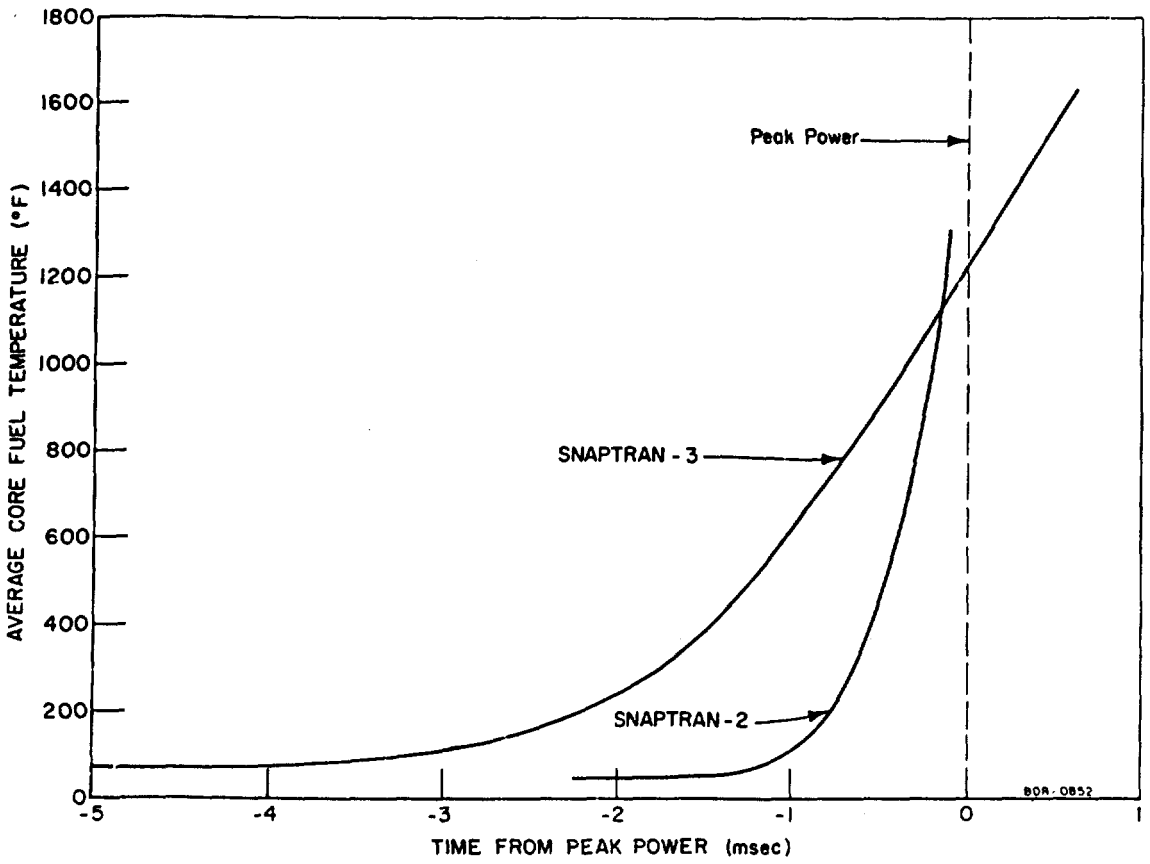

Fig. 1 SNAPTRAN-2 and -3 average core fuel temperature.

For SNAPTRAN-2, a similar analysis was made by normalizing the data from power channel N-26 to the energy release data obtained from EP-154 and -155. The statistical uncertainty between the normalized nuclear data and

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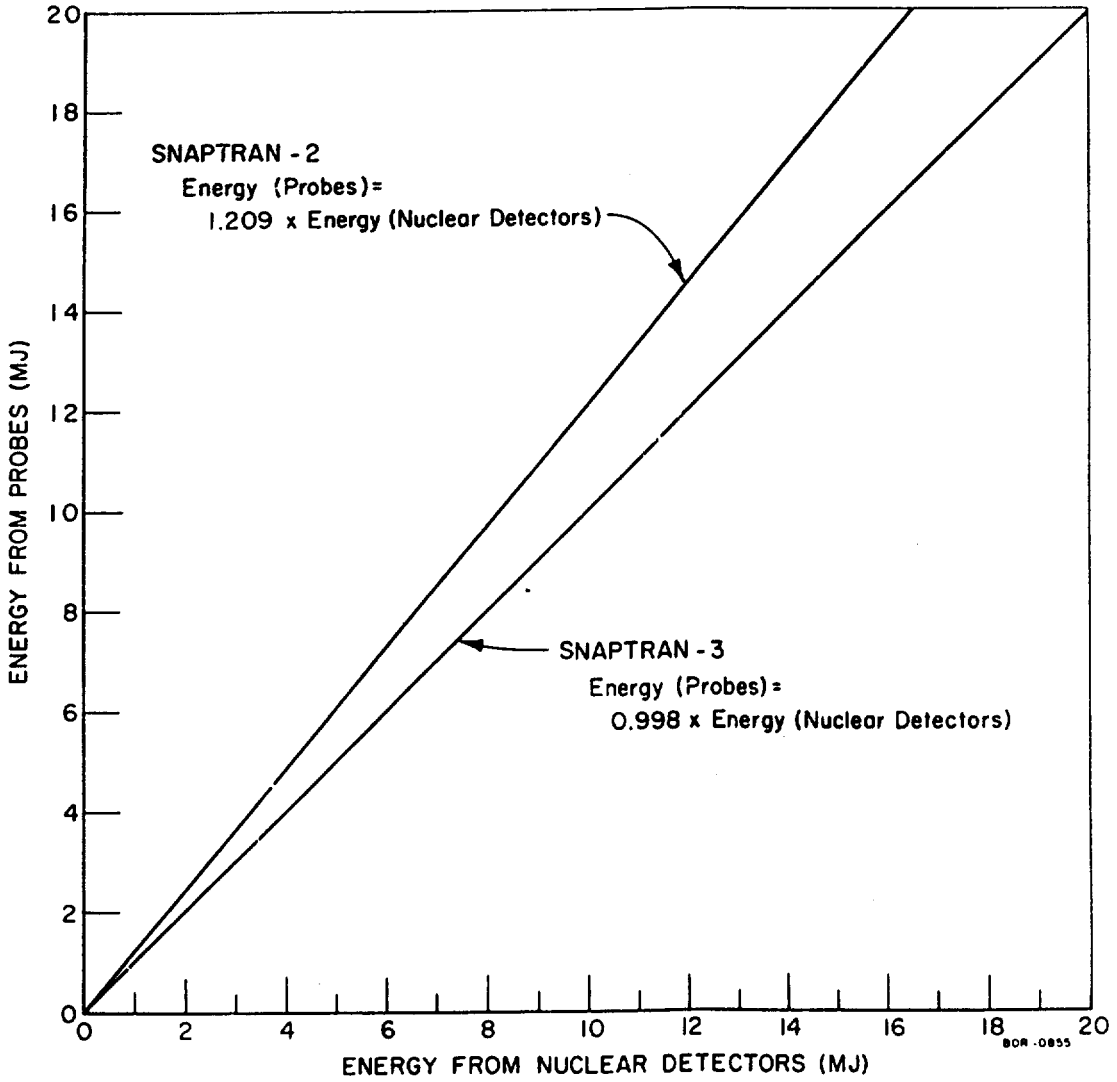

Fig. 2 Nuclear energy measured by nuclear detectors and energy probes.

the energy probe data was only 0.4 percent, but the resulting value of peak power was 89.6 GW, some 20 percent higher than the power indicated from nuclear detectors.

3. ACCURACY OF TEMPERATURE MEASUREMENTS

The uncertainties in the calculation of absolute power from energy probe temperature data are listed in Table I.

III. HEAT CAPACITY OF SNAPTRAN FUEL

The involvement of the SNAPTRAN fuel heat capacity in the analysis of the reactor dynamic behavior stems from the utilization of the temperature or energy coefficient of reactivity in predicting the power excursion behavior of a SNAP 10A/2 reactor.

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TABLE I

UNCERTAINTIES ASSOCIATED WITH ABSOLUTE POWER CALCULATIONS

Uncertainty	SNAPTRAN-2 (percent)	SNAPTRAN-3 (percent)
Power Calibration (Nuclear Detectors)	± 12	± 12
Heat Capacity Versus Temperature Fit to Data	± 5	± 5
Flux Factor Averaging	± 5	± 5
Relative Flux Factor Absolute Value	± 10	± 10
Data Channel Scatter (one data point)	± 5	± 3
Power Channel Data Matching Continuity	± 5	± 3
Overall Absolute Power Uncertainty	± 17	± 15

The energy coefficient of reactivity is normally sufficient to provide reactivity feedback correlation in most dynamic reactor prediction models. Since the specific heat of the reactor fuel material is usually well known, an accurate theoretical model can be developed to represent the effect of temperature on the nuclear state and, hence, on power as a function of time. In the SNAPTRAN reactor, however, where the feedback is dependent to a large degree on the thermal state of the reactor, the energy release from fission must be related to the thermal state of the reactor at any given time during an excursion.

In the case of the SNAPTRAN fuel (a zirconium-hydride compound consisting of 1.8 atoms of hydrogen per zirconium atom), only limited data were available over the 0 to 2000°F temperature range encountered in SNAPTRAN testing.

Data have been published by Douglas [12], Flotow and Osborne [13], and Turnbull [14] for various ranges of temperature and degrees of hydriding, but the samples investigated did not include uranium. Because of the lack of data, the effect of uranium presence on the specific heat of zirconium-hydride was determined for temperatures of interest by extrapolating the low-temperature work (0 to 750°F) done by Taylor [7].

The specific heat of zirconium-hydride is related to the quantum-mechanical nature of the hydrogen atom in zirconium-hydride. The vibrational energy of the hydrogen atom which contributes to the total heat capacity of the zirconium-hydrided fuel directly bears on the feedback effects, and these effects are related to the instantaneous thermal state of the SNAPTRAN reactor fuel. The reduction in temperature rise per unit energy deposited due to energy used in the hydrogen atom vibration is manifested in negative reactivity feedback. This negative feedback results from spectrum hardening which, in turn, is a manifestation of thermally induced changes in the neutron scattering process. The partitioning in zirconium-hydride of some of the output energy acts as a moderating agent and helps to control the energy-producing system. This viewpoint is supported by Roberts [15] in his thermalization theory for zirconium-hydride.

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1. THEORETICAL MODELS

Several models describing the heat capacity of zirconium-hydride with uranium were evaluated. A simple linear form was used to extrapolate the data of Taylor [7] beyond 700°F. The model was

$$C = A + B\Delta T \tag{5}$$

where

C = heat capacity

T = temperature

A,B = arbitrary constants.

Although the scatter in the data acquired by Taylor [7] in the range of ambient to 700°F causes some degree of uncertainty in the absolute value of the heat capacity, C, the data acquired from the SNAPTRAN program provided a high degree of certainty in the shape of the heat capacity curve as a function of temperature. The probes were found to be extremely reliable in providing a reproduction of the trend of fuel temperature as a function of time. Only the calibration factors for the probes were subject to uncertainty. The calibration factor relating nuclear energy to fuel temperature is based on knowledge concerning the heat capacity and the positional weighting factor relating a given probe output to the temperature averaged over the core.

Because of the capability of the probes, when used in conjunction with the nuclear detectors to define the trend of the nuclear energy to temperature ratio as a function of temperature, the development of a theoretically justifiable model to describe the zirconium-hydride heat capacity was possible. The model chosen was based on the Einstein oscillator model [16].

To fit theoretical functions to SNAPTRAN experimental data, a treatment of the differences in available data due to different experimental techniques and differences in concentration of the various elements within the fuel was necessary. Data are available, but vary widely over the ranges of material composition and temperature covered. Therefore, in an attempt to normalize the shape of the heat capacity curve of zirconium-hydride as derived from SNAPTRAN experiments to other curves derived from out-of-pile work, the differences in elemental concentration must be taken into account. Correlation of the data of Taylor [7], Beck [8], Tomasch [9], and Finch [17] with the SNAPTRAN data was possible due to the similarity in concentration of the various elements tested. A mathematical model was needed to augment this data correlation and to extend the knowledge of the heat capacity into the fuel temperature range of 1000 to 2000°F. Theoretical justification for the mathematical model was sought particularly in light of the discussion concerning semi-empirical and theoretical models presented by J. D. Young et al [18]. A theoretical model, however, was considered reliable only in the event that this model agreed with the available experimental data. For example, the calculated temperature coefficient for the SNAPTRAN-3 test turned out to be only one third of that which was actually measured. Since the calculation of the coefficient depended fundamentally on the heat capacity evaluation for relating nuclear energy and fuel temperature, the discrepancy in the calculated versus the experimentally

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observed coefficient suggested that the formulation of the heat capacity, which up to that time had been semi-empirical[19], should be examined in light that new data exist and that perhaps a theoretical model would yield more promising results.

To determine the adequacy of the theoretical model, investigation of the nuclear energy and fuel temperature was undertaken with attention given primarily to the heat capacity as a function of temperature and, secondly, to the normalization of the function to available data. Precise heat capacity data were not available at the time of the SNAPTRAN tests, although a considerable amount of research had been done on SNAP 10A/2 fuel and related zirconium-hydride compounds. The nuclear energy released by the fuel during step transients provided an energy source with a high deposition rate. The temperature response of the energy probes to the deposition of nuclear energy was then used to calculate the specific heat, with the assumption that the temperature rise of the fuel sample in the probe was representative of the temperature rise in the adjacent core fuel.

Probe temperature and nuclear energy release are related by

$$\frac{dT_i}{dt} = \frac{r\ f_i\ P(t)}{m\ c_p(T_i)} \tag{6}$$

and

$$\frac{dE}{dT_i} = P(t)/\frac{dT_i}{dt} = \frac{m\ c_p(T_i)}{r\ f_i} \tag{7}$$

where T_i is the temperature of the ith energy probe, t is time, P(t) is reactor power as a function of time, m is the core fuel mass, $c_p(T_i)$ is the fuel specific heat as a function of temperature, r is the ratio of deposited-to-total nuclear energy, and f_i is the flux-weighting factor appropriate to the probe location considered. Calculations of probe temperature and energy release were made for the step tests of the SNAPTRAN-1 series. From these temperature and energy data, relative values of the flux-weighting factors were determined and fitted to a calculated flux shape [9] to determine the point-to-average flux ratios, f_i. Figure 3 illustrates the temperature dependence of c_p apart from an overall multiplication factor. The shaded area represents the uncertainty in the shape of the curve.

The overall multiplication factor for the quantity (mc_p/r) was determined by fitting the energy release obtained from the energy probes to the energy release determined from the nuclear detectors for the step tests of the SNAPTRAN-1 series. The integral of the curve shown in Figure 3 was applied, apart from an unknown constant, to data from each probe to estimate the energy release. Using the energy release obtained from the nuclear detectors, the unknown constant of normalization was obtained and applied to give the data shown in Figure 4. Values of c_p were calculated as a function of temperature by use of the mass of the core fuel material and a deposited-to-total nuclear energy ratio of 180/204 MeV.

The fuel material specific heat is shown in Figure 4 in calories per gram of fuel material per degree centigrade. The uncertainties shown at each calculated

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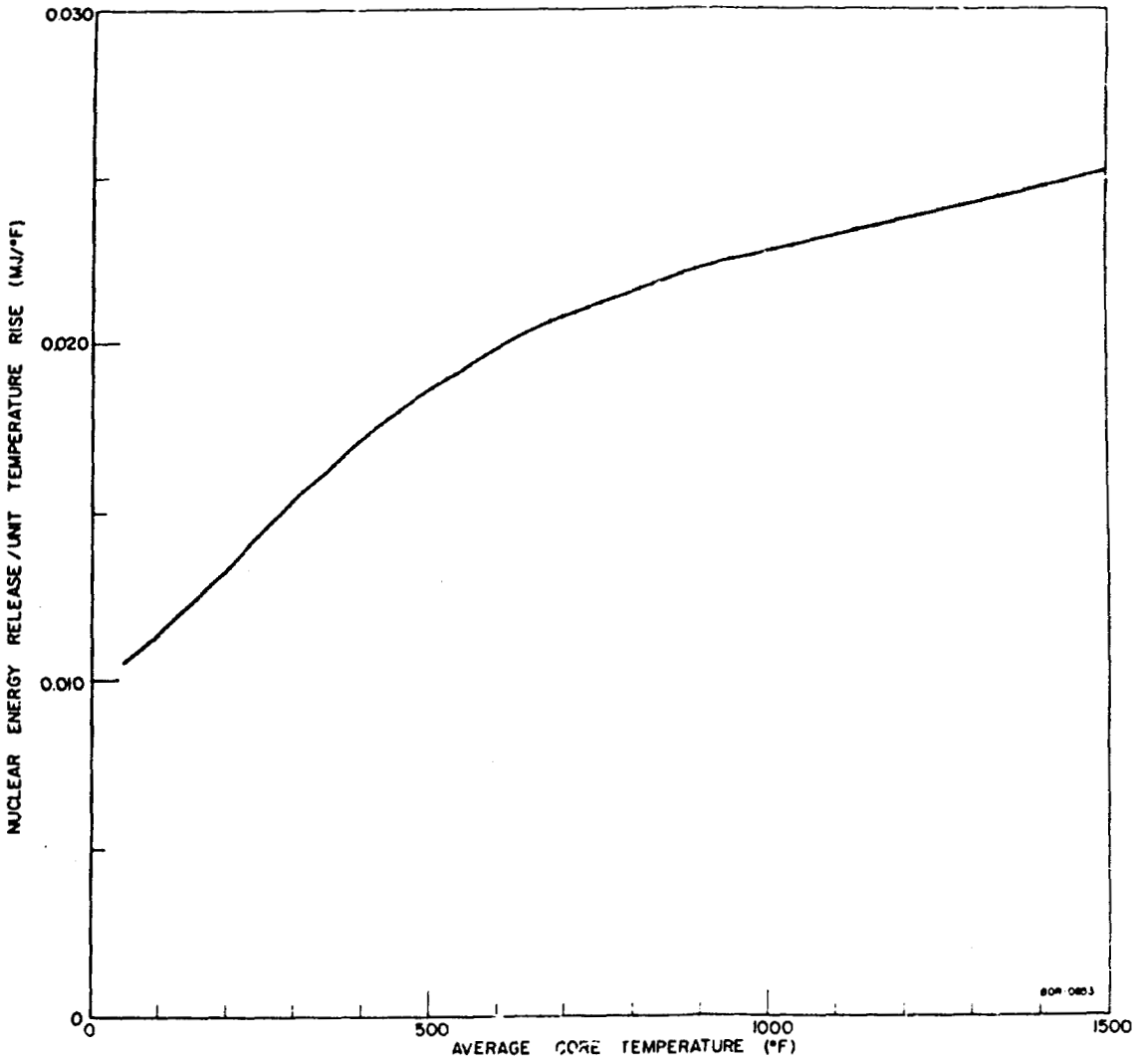

Fig. 3 Nuclear energy per unit temperature rise.

point indicate the uncertainty in the temperature dependence, estimated to be about ± 5 percent up to 550°C and increasing to about ± 10 percent at 800°C. The dashed-line envelope drawn in Figure 4 corresponds to the ± 12 percent uncertainty in the power calibration of the nuclear detectors in the SNAPTRAN-1 test series. Since energy release measurements from energy probes were normalized to fit the data from the nuclear detectors, the power calibration remains the most significant uncertainty in the specific heat determination.

The solid line in Figure 4 is a least-squares fit of the Einstein oscillator model to experimental data available for materials similar in composition to the SNAPTRAN fuel. The data used in the least-squares fit were adjusted to correspond to the fuel composition. Then dependence of the specific heat, c_p, on the temperature is expressed by

$$c_p = A \left[1 + \left(\frac{\theta_E}{T} \right)^2 \frac{e^{\theta_E/T}}{\left(e^{\theta_E/T} - 1 \right)^2} \right] + BT \tag{8}$$

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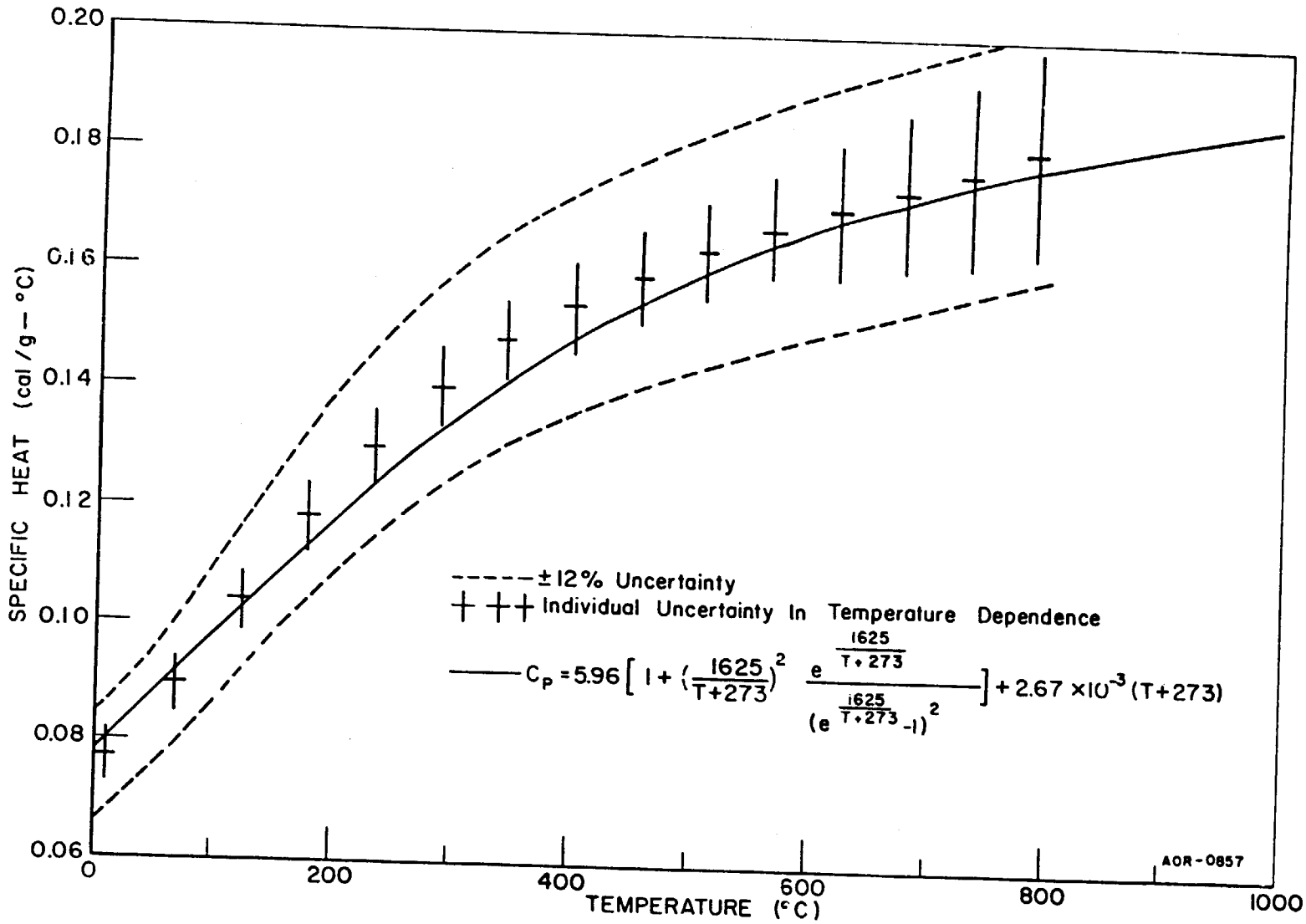

Fig. 4 Specific heat of SNAPTRAN fuel (10.0 wt% U-235 in zirconium-hydride 1.8).

where

T = °K (degrees Kelvin)

c_p = specific heat in cal/mole - °K

A = 5.96 cal/mole - °K

$B = 2.67 \times 10^{-3}$ cal/mole -°K^2

θ_E = 1625 °K.

The quantity, θ_E, is the Einstein temperature assumed to be 1625 °K, corresponding to an oscillator energy of 0.14 eV, a value determined from neutron scattering experiments [20]. The specific heat determined for SNAPTRAN differs from the data summarized by the solid line in Figure 4 by an rms deviation of 6.5 percent which is well within the experimental uncertainties. To show the temperature dependence of the SNAPTRAN data to that of the oscillator model, the SNAPTRAN data may be normalized by a factor of 0.94 determined by a least-squares fit. The rms deviation due to differences in shape is then found to be about 2 percent, well within the ± 5 percent uncertainty in shape.

Specific heat calculations for various probes in the SNAPTRAN-2 and -3 tests are shown in Figure 5 together with the values calculated from the SNAPTRAN-1 test. The data from SNAPTRAN-2 and -3 indicate a larger contribution from the linear dependent term than the SNAPTRAN-1 data. The deviation from linearity may be due, in part, to variations in the flux shape which was assumed constant in the calculations.

IV. CALCULATION OF REACTIVITY EFFECTS IN THE SNAPTRAN TESTS

To ensure consistency in the calculations of the reactivity effects during transient tests of the SNAPTRAN program, calculations were made from the time-dependent reactivity data from nuclear detectors and the average core temperature calculations described in Section II-2. The corresponding energy coefficient calculations were made with nuclear data normalized to the energy release data indicated by energy probes. The results of the SNAPTRAN-1 tests are, therefore, comparable with those of the SNAPTRAN-2 and -3 destructive tests.

For each of the step tests of the SNAPTRAN-1 series, calculations of the energy coefficient of reactivity, $d\rho/dE$, were made as a function of nuclear energy release over the total range of energy. Semiquantitative conclusions were drawn from these data. For each test, the energy coefficient decreased with increasing energy deposition, up to about a 30 percent decrease as compared to the coefficient for a test with an initial inverse period of about 700 sec^{-1}. The values of the energy coefficient calculated at peak power did not vary as significantly from test to test with increasing energy deposition and, consequently, increasing average core temperature.

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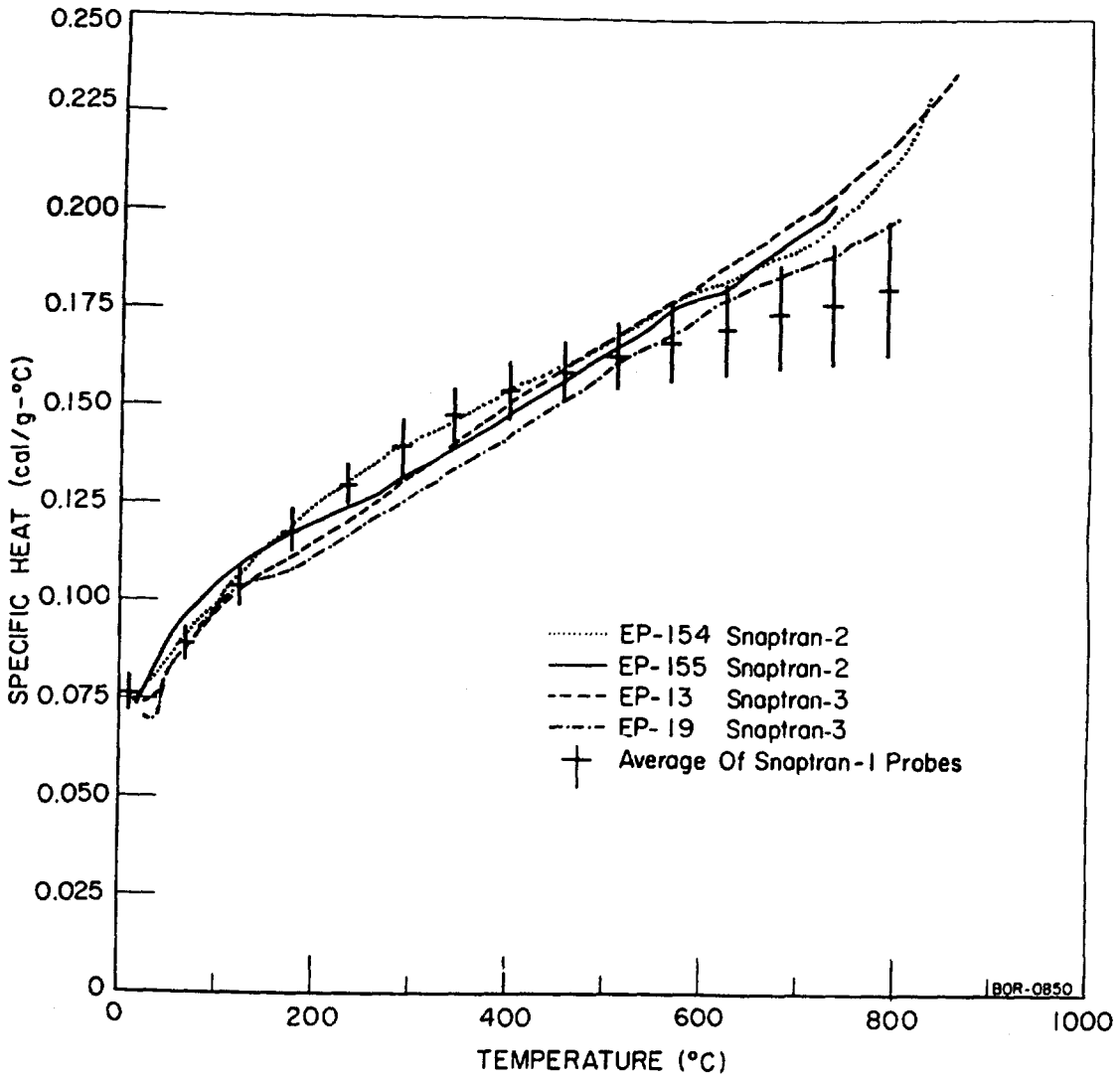

Fig. 5 Specific heat from energy probes for SNAPTRAN-2 and -3.

In an effort to clarify the temperature dependence and the possible existence of a rate dependence for the energy coefficient, two sets of calculations were made for the SNAPTRAN-1 step tests. In the first case, the average energy coefficient ($\Delta\rho/\Delta E$) to peak power ($\hat{P}$),

$$\frac{\Delta\rho}{\Delta E} = \frac{\alpha_o \ \ell/\beta_{eff}}{E_{\hat{P}}} \tag{9}$$

with $E_{\hat{P}}$ the energy release at peak power, ℓ/β_{eff} the reduced prompt neutron lifetime, and α_o the initial inverse period, was calculated and considered as a function of the average core temperature midway from ambient to peak power. In the second case, the instantaneous energy coefficient at peak power,

$$\left.\frac{d\rho}{dE}\right|_{\hat{P}} = \frac{\ell}{\beta \ P(t)} \left.\frac{d^2 \ln P(t)}{dt^2}\right|_{\hat{P}} \tag{10}$$

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was calculated and treated as a function of average core temperature at peak power. Determination of the average energy coefficient were made for the double-drum pulse tests by determining the shift in control drum position at maximum power (the ρ = 1 dollar point) and by fitting the resulting reactivity compensation to a linear function of energy release. These calculations were made for the two destructive tests for feedback reactivity to the time of disassembly.

The results of the energy coefficient calculations are shown in Figure 6. The least-squares-fitted straight line for energy coefficient at peak power is also shown. The general trend of the data indicates that energy coefficients averaged to peak power are significantly higher than instantaneous energy coefficients measured at peak power.

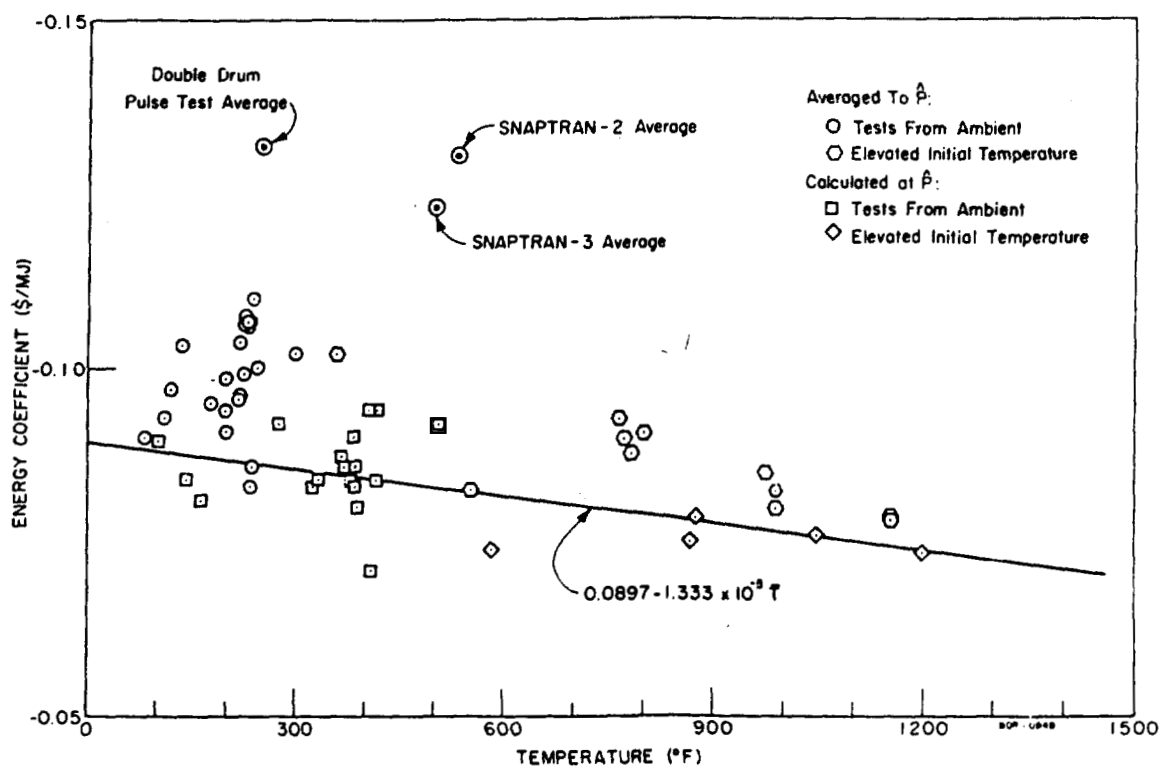

Fig. 6 SNAPTRAN energy coefficient versus temperature.

The average energy coefficient as a function of initial inverse period is shown in Figure 7. In Figure 7, the temperature dependence indicated in Figure 6 was taken into account by dividing the period-dependent energy coefficient function by the normalized function $(1 - 1.49 \times 10^{-4}\ \overline{T})$. For the double-drum pulse tests, the initial period was approximated by $1/2\ \alpha_{max}$. The period dependency is quite noticeable on the plot. As an approximation to the form of the data, the line

$$0.088 + 3 \times 10^{-5}\ \alpha_o \tag{11}$$

is plotted also. This expression appears to be a good approximation to the data up to about α_o = 1600 sec^{-1}.

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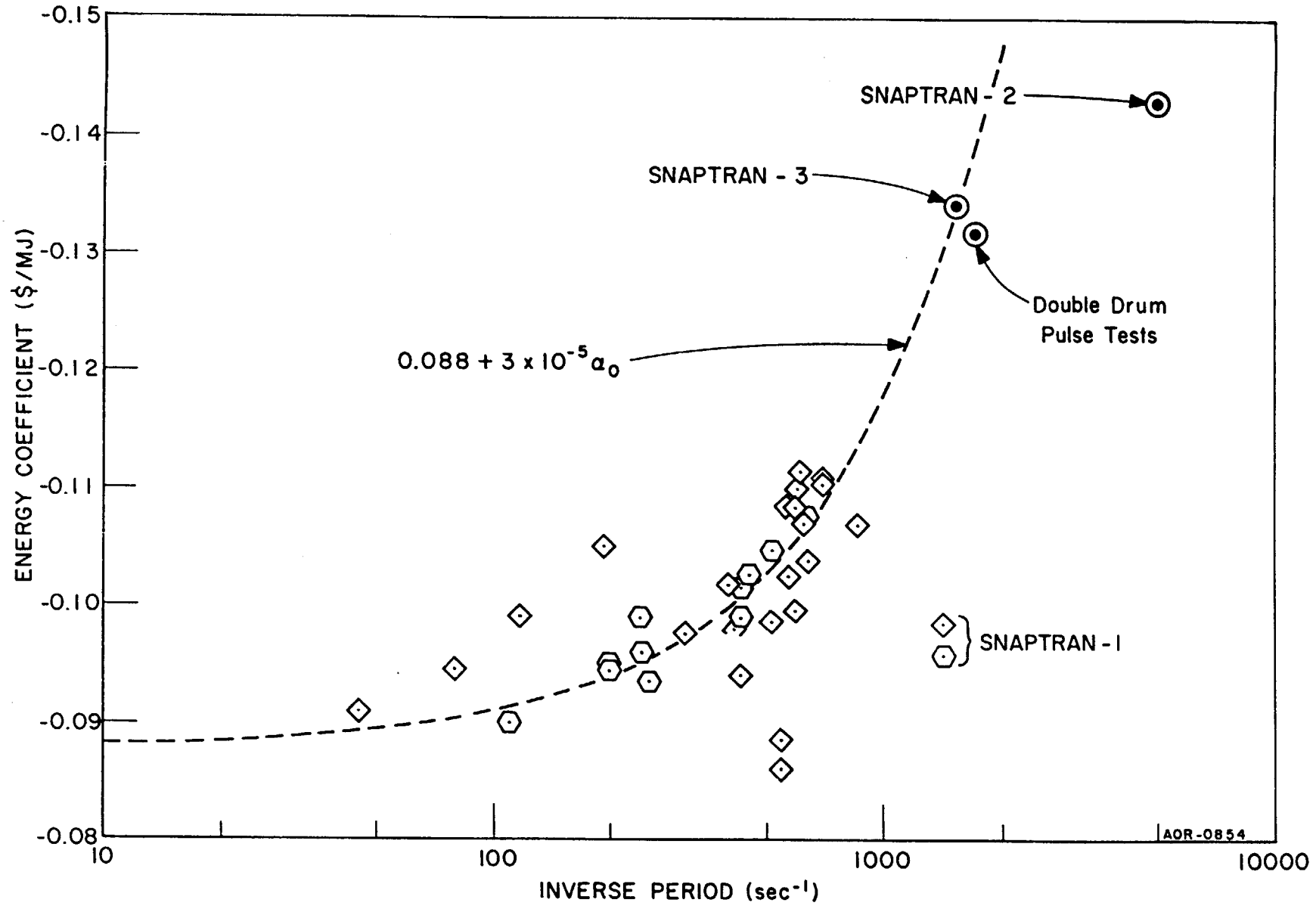

Fig. 7 SNAPTRAN energy coefficient versus inverse period.

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In Figure 8, the temperature coefficient averaged to peak power is shown. The averaged temperature coefficient divided by $(1 + 3.41 \times 10^{-4}\ \alpha_0)$, which is a normalization of the inverse period dependence indicated by the expression $(0.088 + 3 \times 10^{-5}\ \ _0)$, is shown in Figure 9. The data are closely described by the expression for the dashed-line curve,

$$\alpha_T(\bar{T}) = (0.0897 - 1.333 \times 10^{-5}\ \bar{T})\ \frac{mc_p(\bar{T})}{r} \tag{12}$$

where $\frac{mc_p\ (\bar{T})}{r}$ is the ratio of nuclear energy release to unit temperature rise shown in Figure 3. The disassembly in the SNAPTRAN-2 test started before peak power and caused the SNAPTRAN-2 value of the coefficient to fall far below the trends seen throughout the testing in SNAPTRAN-1 and -3.

V. CONCLUSIONS FROM ANALYSIS OF SNAPTRAN KINETICS TESTS

Some of the most extensive data available on the specific heat of zirconium-hydride were obtained from the SNAPTRAN experiments. By properly normalizing the observed data, the specific heat for zirconium-hydride with uranium was defined with a high degree of accuracy. The fuel temperature was then correlated to the nuclear energy and used to define a well-behaved trend in the negative temperature coefficient. Through the use of the model developed from correlations of nuclear energy with the negative temperature coefficient, accurate and reliable predictions of the excursion behavior of zirconium-hydride reactors are possible.

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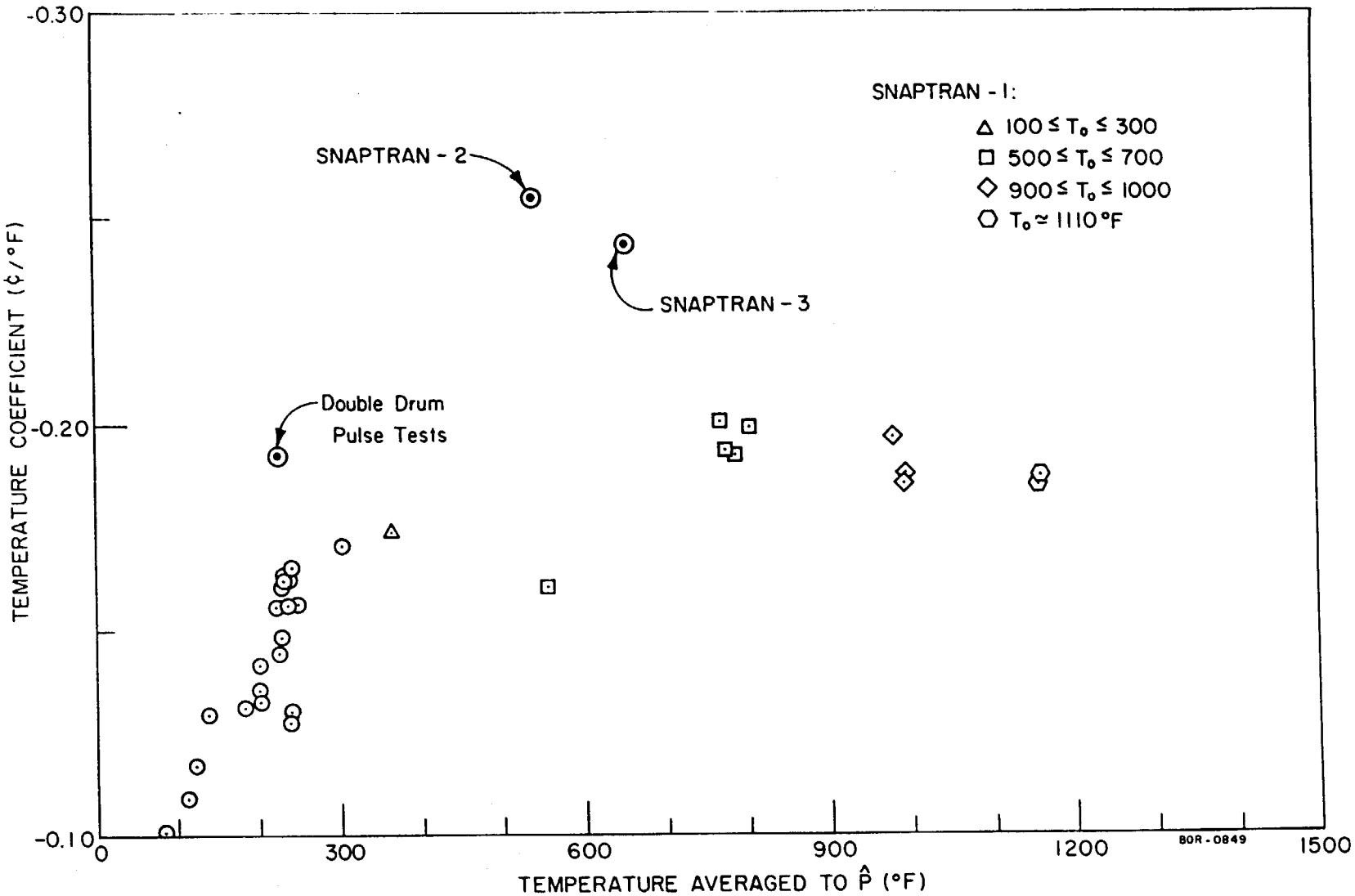

Fig. 8 SNAPTRAN temperature coefficient versus core fuel temperature.

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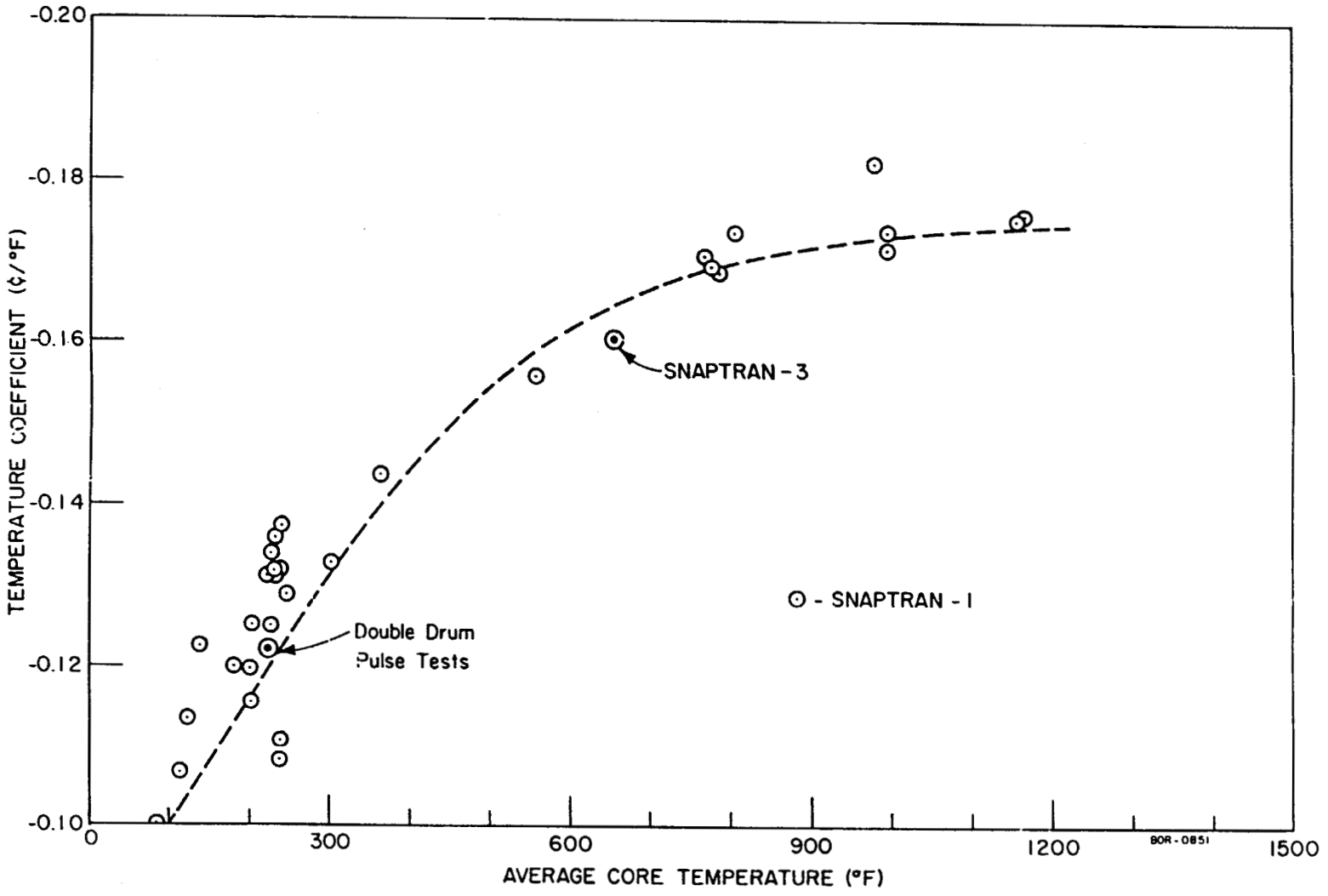

Fig. 9 SNAPTRAN temperature coefficient with correction made for period dependency.

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