726927

For Distribution at the Winter Meeting of the American Nuclear Society
Washington, D. C., November 15-18, 1965

R

SNAPTRAN-2 DESTRUCTIVE TEST PREDICTIONS

R. E. Prael* and R. P. Rose**

Phillips Petroleum Company
Atomic Energy Division
Idaho Falls, Idaho

Introduction

The SNAPTRAN program being conducted by Phillips at the NRTS has thus far included the SNAPTRAN-3 water immersion destructive test and the SNAPTRAN-1 reactor kinetics test series. The SNAPTRAN-2 destructive test is currently in preparation. The kinetics data from SNAPTRAN-1 are generally applicable to the SNAPTRAN-2 destructive test predictions since these two reactors are quite similar. The treatment of disassembly behavior for SNAPTRAN-2 will have significant differences, however, from that observed in SNAPTRAN-3 destructive test.

The analysis to be described was undertaken to estimate the results of the SNAPTRAN-2 destructive test. Among the most important of these results are limits on energy release and maximum power. Other significant features studied include the effect of operational variables such as reactivity insertion rates, the time sequence of mechanical events during disassembly as related to the power curve, and the rate and characteristics of the disassembly. The conclusions reached have been used in the hazards evaluation, in estimations of requirements for instrumentation and photography, and as a test of extrapolation from non-destructive testing data. It is expected that these calculations will greatly aid in interpreting the results of the SNAPTRAN-2 test.

Descriptive Model

A cross-section of the reactor is shown in Figure #1. The core consists of 37 uranium-zirconium hydride fuel elements in a hexagonal array. A beryllium reflector surrounds the reactor, with control exercised by rotation of the four beyllium drums as shown. The diameter of the core is about 9 inches and its length about 12 inches. The destructive transient is initiated by rotating the control drums to the full-in position. Note that the drums are labeled step drums and pulse drums. First, the step drums are rotated together, then the pulse drums are rotated together.

* Associate Member, American Nuclear Society
** Member, American Nuclear Society

Disassembly occurs in a SNAPTRAN-type reactor by release of hydrogen from the fuel matrix after a certain fuel temperature threshold is reached, and by subsequent acceleration of various core and reflector components in an outward direction as a result of hydrogen pressure buildup. A schematic of the disassembly model is shown in Figure #2. Cylindrical geometry is assumed. In our simplified model, only a portion of the core, labeled "destructive zone" on the figure, is assumed to contribute hydrogen to the pressure pulse. The volume and shape of this region is one of the variable parameters studied in this analysis.

The pressure pulse is initiated when the core hot-spot reaches the threshold temperature which is 1900°F for this type of fuel. Radial action by the pressure is restricted until the temperature at the boundary of the destructive zone reaches the threshold temperature. The pressure is assumed to act radially on the mass of the reflector and outer ring of fuel elements and axially on the inner fuel elements and grid plates.

Mathematical Model

The space-independent reactor kinetics equations as shown in Figure #3 are used to compute reactor power. In Figure #4, the time dependent reactivity is described as the sum of initial subcritical reactivity level, the reactivity insertion as a function of time, the feedback effects of increasing average core temperature, and the reactivity effect of core disassembly. A constant temperature coefficient with respect to average core temperature is assumed, as shown in eq. (5), with an upper limit for temperature feedback provided as a variable parameter. Such a limit is believed necessary to account for uncertainties in reactivity effects after the hydrogen has been transformed to the free state. The reactivity effect of disassembly is considered linear in both axial and radial displacements as shown in eq. (6). Since only small displacements are necessary to shut down the power burst, this approximation is considered reasonable.

The drum reactivity insertion is shown in Figure #5. The step drums are rotated into the reflector in approximately 100 msec to bring the reactor to a delayed critical level. The pulse drums are rotated into the reflector in about 18 msec to put the reactor on a minimum period of around 200 μsec.

In Figure #6, the general equation used to compute the average core temperature, $\bar{T}$, the hot-spot temperature, $\hat{T}$, the average temperature in the destructive zone, T_z, and the temperature at the zone boundary, T_b. In each case, the appropriate value of the volume-weighting factor f is employed. The core heat capacity is assumed to be linearly dependent on fuel temperature over the range where thermal feedback is important.

In Figure #7, eq. (8), the expression is shown that describes the release of hydrogen from the fuel. W is the weight of hydrogen released in the destructive zone. At T_1 (about 1900°F), approximately 1% of the hydrogen is freed from the Zr lattice. This quantity of hydrogen is sufficient to cause disintegration along dislocations in the fuel. When the temperature reaches T_2 (about 2600°F), sufficient pressure is generated within the fuel matrix to cause a lattice disintegration. At this temperature it is assumed that essentially all the hydrogen behaves as a free gas. An exponential is used to interpolate between these two temperatures.

The volume available to the hydrogen is calculated with eq. (9). It is the volume of the destructive zone including the expansion, minus the volume of the fuel material. The pressure of the gas is approximated with the perfect gas law as shown in eq. (11), where T_g is the temperature of the hydrogen. The two displacements are calculated with eqs. (11), which are just expressions of acceleration = force/mass. In the case of the axial displacement, corrections have been made to the effective area on which the pressure acts to account for drag effects.

The computation of the gas temperature, T_g, is described in Figure #8. Equilibrium thermodynamics is used to write an energy balance which equates the change in internal energy plus expansion work to the internal energy of a quantity of gas entering at temperature T_Z. The incremental energy changes are expressed in conventional fashion in terms of mole number N in eqs. (13) and (14). Combining these expressions, applying the perfect gas law, and setting the logarithmic derivative of N equal to the logarithmic derivative of W leads to the differential equation for T_g shown in eq. (15).

Selection of Model Parameters

The results of non-nuclear testing of fuel materials have been used for the estimation of fuel properties, particularly hydrogen release and the core heat capacity (approximately 0.01 Mwsec/°F at 68°F). The SNAPTRAN-1 kinetics testing series established a prompt neutron generation time of 6.5 ± 0.3 msec, as well as a prompt temperature coefficient of about 0.13¢/°F, constant when used in conjunction with the heat capacity described previously. The SNAPTRAN-3 destructive test provided an estimate of the worth of reflector removal of about 8 dollars/inch, and, in addition, an approximate verification of the linearity of the heat capacity. The destruct threshold temperature of approximately 1900°F is estimated from non-nuclear testing as well as extrapolation from SNAPTRAN-3 results.

Results and Conclusions

The calculations described have been made using the best-estimate input parameters and reasonable variations in these parameters to place bounds on the calculational results and to study the effects of individual uncertainties. A typical case is shown in Figure #9 based on parameters near the best-estimate values. The input reactivity, corresponding to that shown in Figure #4, is 4.85 dollars. Other parameters are generally the same as the values mentioned previously. The minimum period for this case is 220 μsec. The peak power is 120 Gw with an total nuclear energy release of 68 Mwsec. In Figure #10, the disassembly behavior is shown. Disassembly begins about 250 μsec before peak power. Pressure rises rapidly to a maximum of the order of 140,000 psi. Axial and radial displacements are shown in inches. Fuel is accelerated axially to a velocity around 800 ft/sec, and the reflector is accelerated radially to a velocity of about 300 ft/sec.

By variation of input parameters, it is found that the energy release is highly sensitive to the degree of thermal feedback attained before the disassembly begins. Although the temperature coefficient is quite well known from the SNAPTRAN-1 testing, even small variations in the temperature coefficient and heat capacity indicate that the uncertainties in the upper limit on energy from this effect may be as large as 20 Mwsec. It is also found that variations of destructive zone volume and geometry and the drag effects, or lack of such effects, produce an uncertainty of the order of 5 Mwsec. The uncertainty in worth of disassembly leads to a variation of about 5 Mwsec. Although these variations may lead to a large range of disassembly velocities, the net effect on energy release is quite small. The most recent calculations, made for an insertion of 5.05 dollars corresponding to planned test conditions, indicate that the range in energy release, considering all parameters, is from 60 to 120 Mwsec for a $5.05 destructive test.

In conclusion, it is found that the test conditions indicate an expected energy release of about 68 Mwsec. The major source of uncertainty is the phenomenon of temperature feedback which is well known compared to the other parameters. The destructive test itself will be very important in extending our knowledge of these effects at high temperatures. Although the model is quite simplified and uncertainties in some parameters quite large, the use of such simple disassembly model appears justified by the lack of sensitivity to parameters concerned with the disassembly. The mathematical model, as postulated, should describe the SNAPTRAN-2 test adequately for the objectives which were established.

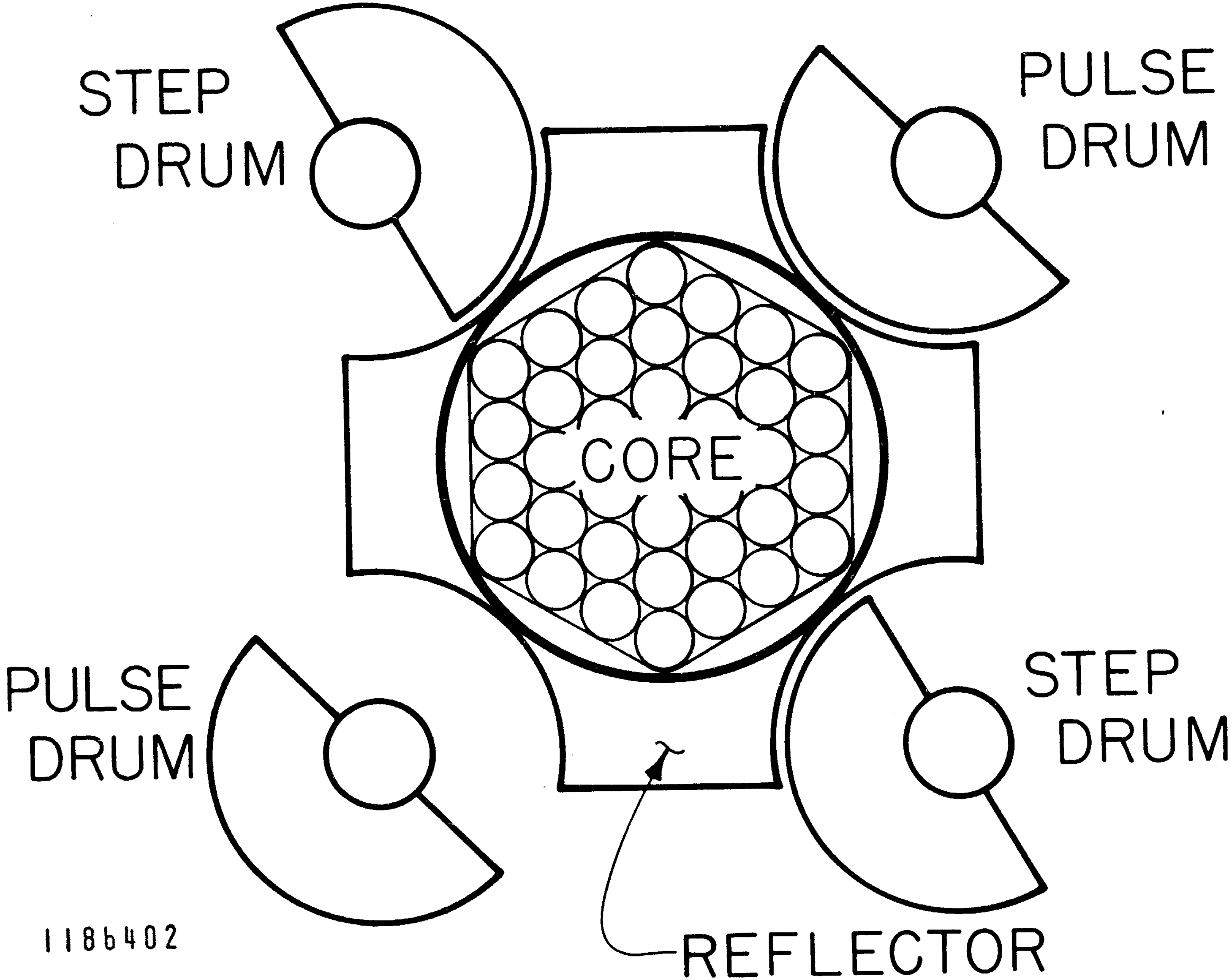
General References

G. F. Brockett et al, SNAPTRAN 2/10A-3 Destructive Test Results, IDO-17019 (January, 1965)

J. M. Waage (ed.), Safety Analysis Report SNAPTRAN 2/10A-1 and -2 Safety Tests, IDO-17076 (October 1965)

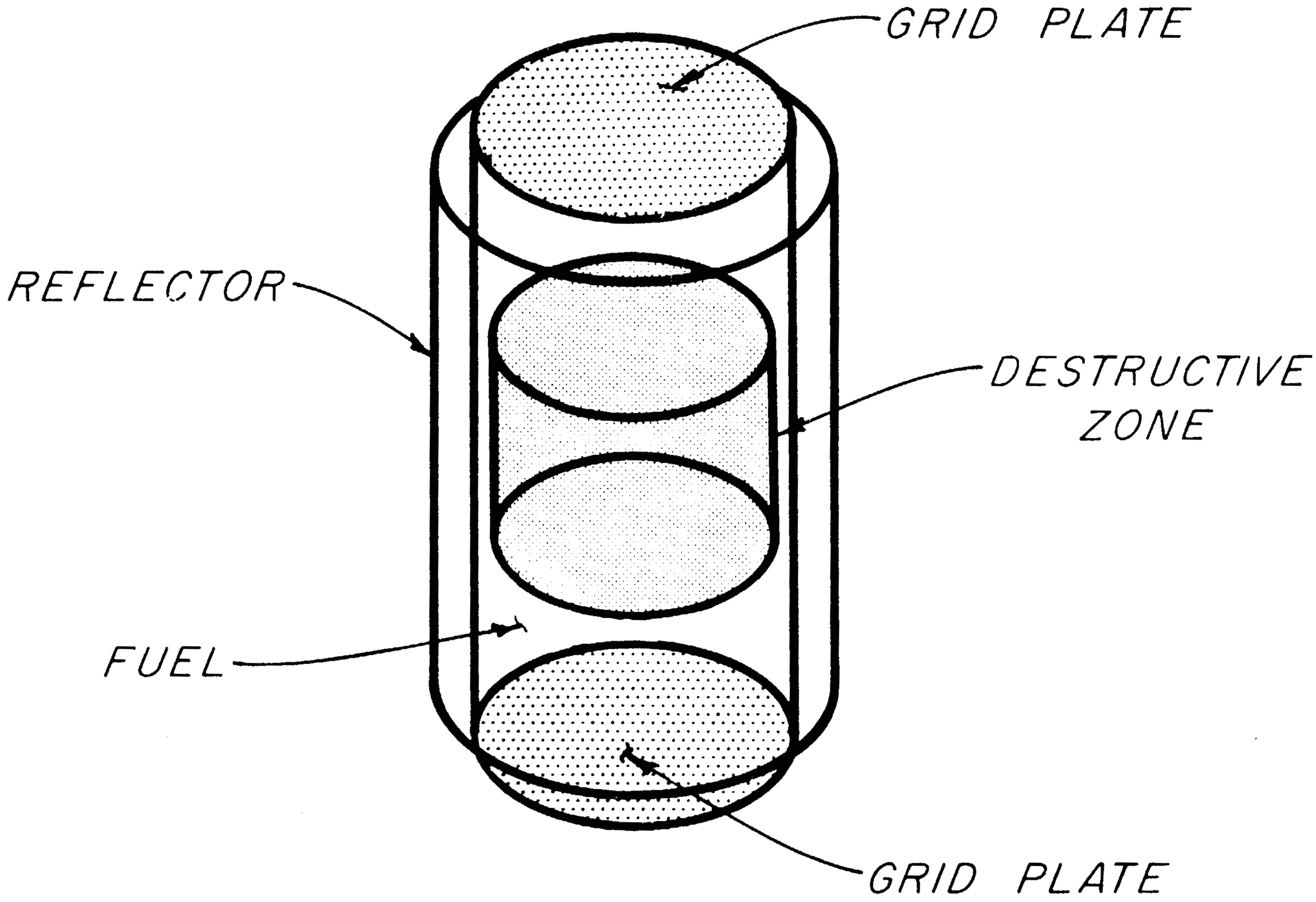
<u>List of Figures</u>

CORE DIAGRAM



1186402

SIMPLIFIED CORE SCHEMATIC



1186403

032-2729

SPACE-INDEPENDENT KINETICS:

$$\dot{\phi} = \frac{\beta}{\ell}\left[(R(t)-1)\,\phi + \sum_{i=1}^{6} f_i\, X_i\right] + S_0 \qquad (1)$$

$$X_i = \lambda_i\,(\phi - X_i),\quad i = 1, 2, \ldots, 6 \qquad (2)$$

$$X_i = \frac{\ell\lambda_i}{\beta f_i}\, c_i \qquad (3)$$

032-2732

PARTITION OF REACTIVITY EFFECTS:

$$R(t) = R_o + R_{in}(t) + R_{fb}(\bar{T}(t)) + R_d(D_a(t), D_r(t)) \quad (4)$$

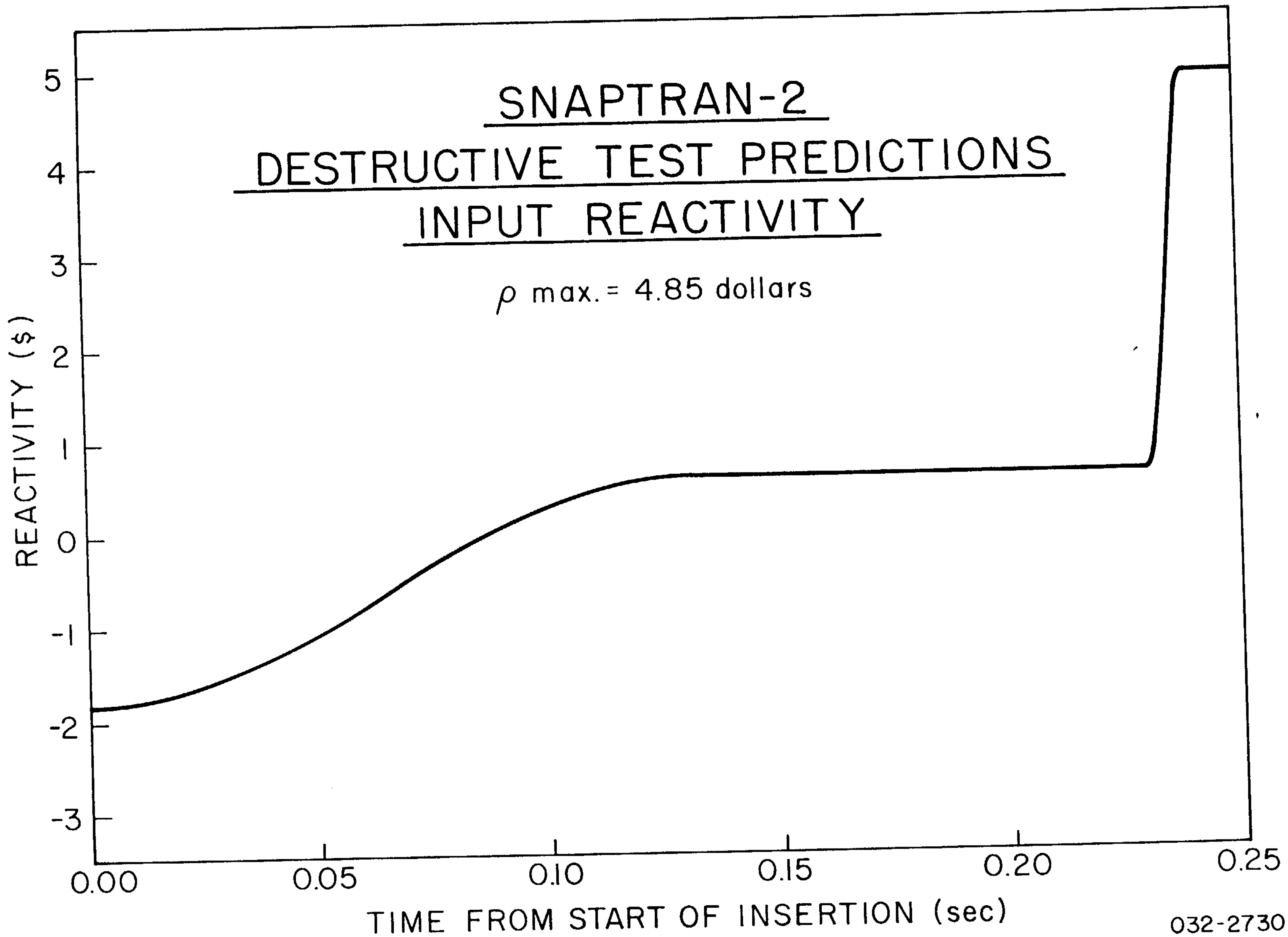
$$R_{fb}(\bar{T}) = \begin{cases} -C_T(\bar{T} - T_O), & \bar{T} < T_m \\ -C_T(T_m - T_O), & \bar{T} > T_m \end{cases} \quad (5)$$

$$R_d = -C_a D_a - C_r D_r \quad (6)$$

$R_{in}(t)$ As Shown In Next Slide

032-2733

1186405


SNAPTRAN-2
DESTRUCTIVE TEST PREDICTIONS
INPUT REACTIVITY
ρ max. = 4.85 dollars
REACTIVITY ($)
5
4
3
2
1
0
-1
-2
-3
0.00
0.05
0.10
0.15
0.20
0.25
TIME FROM START OF INSERTION (sec)
032-2730

1186406

GENERAL FUEL TEMPERATURE EQUATIONS

$$\frac{dT}{dt} = \frac{f}{A+BT} \phi(t) \; ; \; T(0) = T_0 \qquad (7)$$

WHERE T IS ONE OF $\bar{T}$, $\hat{T}$, T_z, AND T_b WITH THE APPROPRIATE VALUE OF f ($\bar{f}$, $\hat{f}$, f_z, f_b).

THE HEAT CAPACITY IS OF THE FORM

$A + BT \equiv$ FUEL DENSITY X SPECIFIC HEAT

$(\text{watt} - \text{sec}/{}^{\circ}\text{F} - \text{in}^3)$

032-2734

GAS RELEASE AND REACTOR DISASSEMBLY

$$W(t) = \begin{cases} 0 & T < T_1 \\ W_0 e^{a(T_z - T_2)} & T > T_1, T_z < T_2 \\ W_0 & T_z > T_2 \end{cases} \quad (8)$$

$$V(t) = \pi h_0 (r_0 + D_r)^2 + 2\pi r_0^2 D_a - V_f \quad (9)$$

$$P(t) = K W(t) \left[T_g(t) + 460\ °F \right] / V(t) \quad (10)$$

$$\frac{d^2 D_a}{dt^2} = K_a P(t) \ ; \ \frac{d^2 D_r}{dt^2} = K_r P(t) \quad (11)$$

032-2731

1186408

GAS TEMPERATURE EQUATION:

ENERGY BALANCE: $dU + PdV = dU'$ (12)

$$dU = C_V N \cdot dT_g + C_V T_g \cdot dN \quad (13)$$

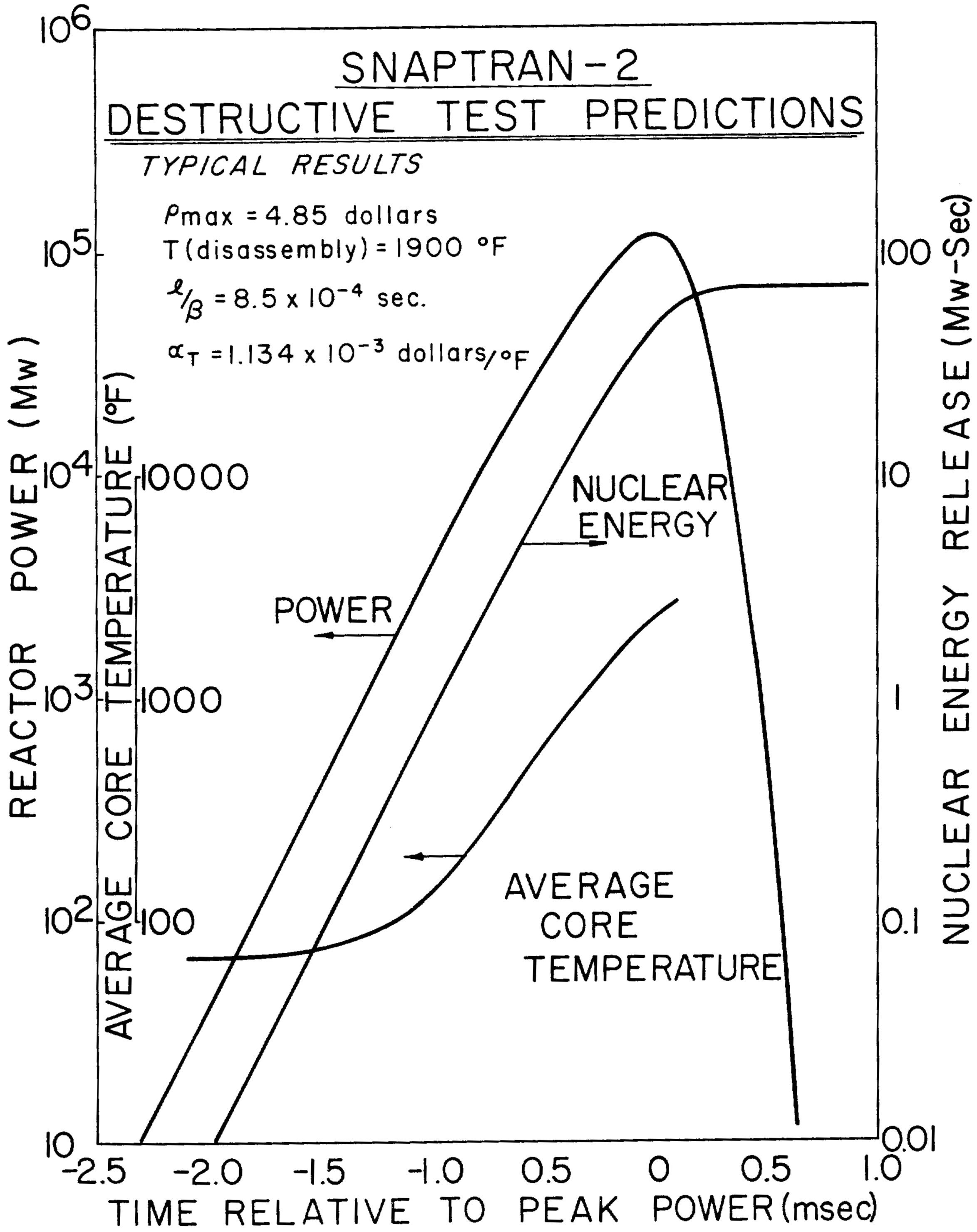
$$dU' = C_V T_Z \cdot dN \quad (14)$$

$$\frac{dT_g}{dt} = \frac{T_Z - T_g}{W} \frac{dW}{dt} - (\gamma - 1) \frac{T_g + 460°F}{V} \frac{dV}{dt} \quad (15)$$

WHERE $\gamma = 1 + R/C_V = C_P / C_V$

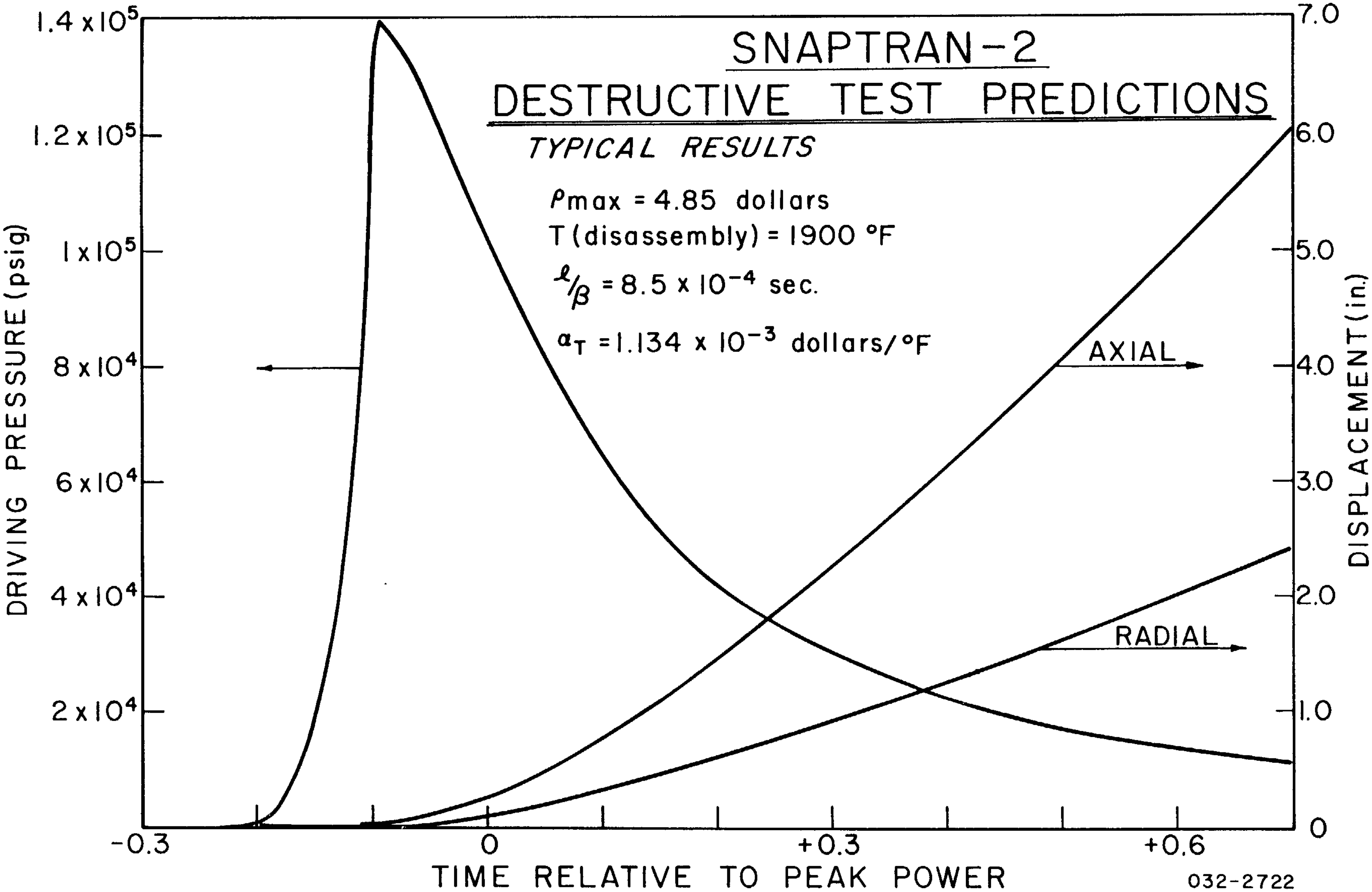
032-2728

1186409



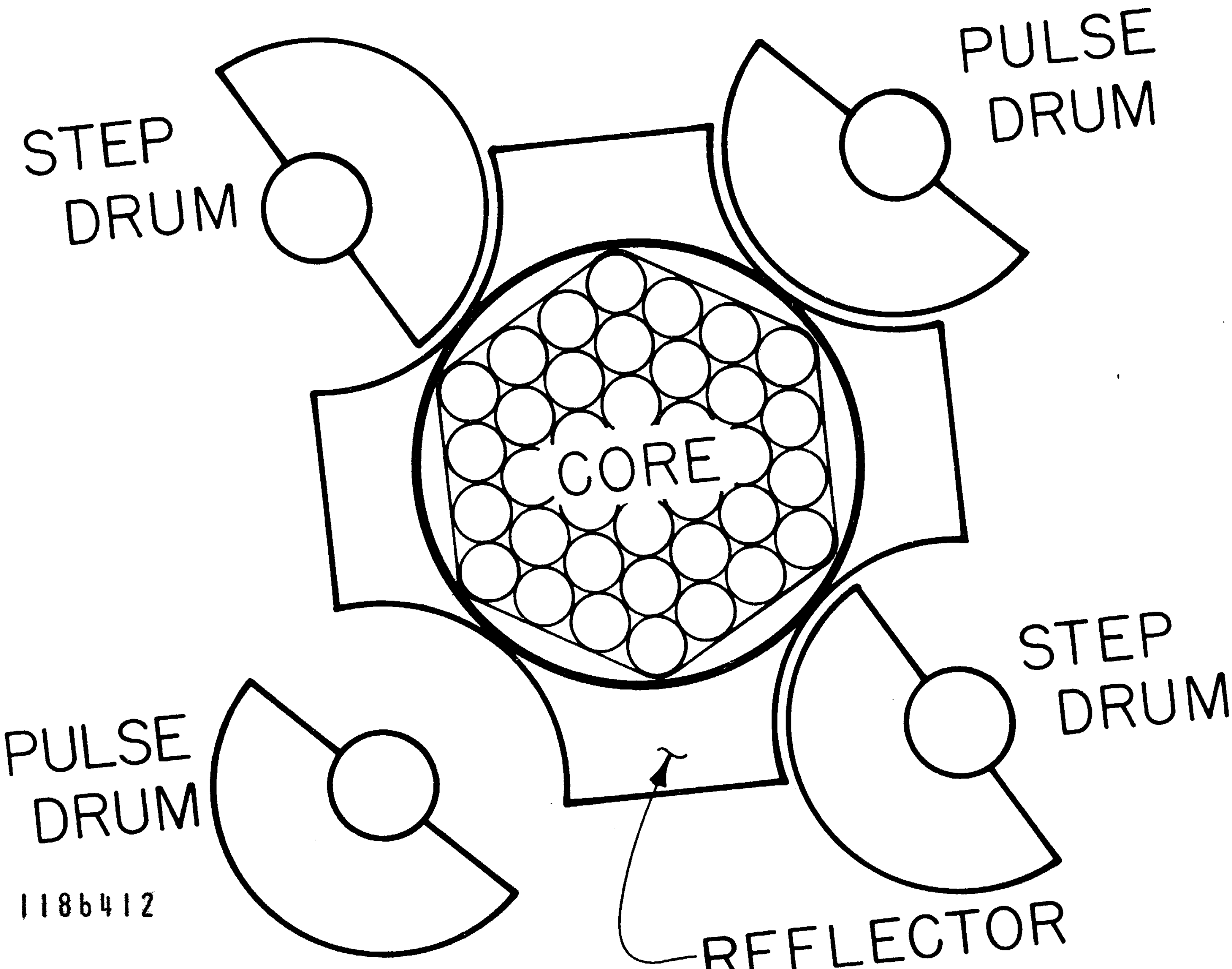
032-2723

1186410


SNAPTRAN-2
DESTRUCTIVE TEST PREDICTIONS
TYPICAL RESULTS
ρmax = 4.85 dollars
T (disassembly) = 1900 °F
ℓ/β = 8.5 x 10^-4 sec.
αT = 1.134 x 10^-3 dollars/°F
AXIAL
RADIAL
DRIVING PRESSURE (psig)
1.4 x 10^5
1.2 x 10^5
1 x 10^5
8 x 10^4
6 x 10^4
4 x 10^4
2 x 10^4
DISPLACEMENT (in.)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
-0.3
0
+0.3
+0.6
TIME RELATIVE TO PEAK POWER
032-2722

1186411

CORE DIAGRAM



1186412