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NERVEX, A TWO DIMENSIONAL PROMPT EXCURSION ANALYSIS PROGRAM*
(Title Unclassified)

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ABSTRACT

A mathematical model is described which forms the basis of a computer program (NERVEX) used to calculate energy release and other parameters pertinent to an analysis of a large nuclear excursion. Results are presented for a range of prompt step reactivity additions to the room temperature NERVA core. A hydrodynamic, radially symmetric excursion model is assumed. Simplifying assumptions found necessary were made so as to insure a conservative (over-estimated) calculation of energy release.

INTRODUCTION

In order to perform adequate hazards analyses, it is necessary to predict the thermodynamic behavior associated with a large scale nuclear excursion of the NERVA nuclear rocket engine. In particular, it is necessary to determine the reactivity feedback contributing to shutdown and, hence, the power-time profile and energy release during nuclear excursions resulting from reactivity additions above prompt critical. To this end an analytical model has been developed and programmed for an IBM-7094 computer. Work accomplished under jurisdiction of SNPO - a joint activity of NASA and the AEC.

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The formulation of an excursion analysis model can be considered in two parts. First, one must determine the system reactivity and consequent fission power generation compatible with a certain thermodynamic state, and second, one must evaluate the thermodynamic parameters describing this state. A completely general approach to formulating such a model would at best be extremely difficult and would probably prove prohibitive from the standpoint of computer time required to obtain solutions. The following outlin the simplifying assumptions used in the present approach.

As mentioned above, this model is intended only for excursions resulting from reactivity additions above prompt critical. The model also assumes that the spatial flu distribution is independent of time so that the time dependent neutron diffusion equatio is space-time separable. This limits the model's applicability to "dry" excursions as opposed to those involving water or propellant flooding which would significantly alter flux distribution. Under these conditions, the power generation can be described by a simple prompt neutron kinetics model. Reactivity feedback contributing to shutdown is assumed to have linear dependences on the density and temperature described by predetermi reactivity coefficients. The assumptions described above considerably simplify the neutronics portion of the model and, in fact, render it almost trivial. It is in the thermo dynamic considerations which determine the reactivity feedback response of the system tha the model has its major concern and merit.

The NERVEX formulation is based on a time dependent, two-dimensional fluid flow model wherein the core is assumed to be homogeneous and perfectly elastic with isotropic properties (with the exception of the inclusion of radial shear arising from bending stres in the fuel elements). Cylindrical (R-Z) geometry is used and radial symmetry assumed. Originally, it was intended that the anisotropic properties of the NERVA core, due to the

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inability of the axially aligned fuel elements to sustain radial tension, be included. It was found that such anisotropy resulted in an arbitrariness in pressure assignment when the fuel elements separate and subsequently recombine which could not be readily resolved. The isotropic approximation is necessarily conservative in that the inclusion of radial tension underestimates the core expansion and hence prolongs the excursion. A major simplifying approximation used in formulating the thermodynamic portion of the NERVEX model is the so-called "hydrodynamic" approximation. This assumes that the medium behaves much as a fluid in that the internally generated pressure is roughly hydrostatic. An explicit rather than an implicit (requiring iterations) finite difference approach was used to solve the fluid flow equations based on the Lagrangian form of the equations.

The model considers the conservation of momentum, energy and mass in conjunction with a graphite equation of state to calculate the density and temperature spatial distributions with time. Vapor and liquid production are accounted for by assuming equilibrium conditions dictated by the graphite phase diagram. The excursion is assumed to proceed at such a rate that any vapor formed is contained in the interstitial volume of the fuel.

Of primary importance in correct calculations of the appropriate thermodynamic parameters is the two dimensional (r, z) aspect of the core as opposed to a one-dimensional approach. The a priori assumption that pressure gradients and hence momentum considerations are of primary importance in only one particular direction, say, either the radial or the axial direction cannot be made without first ascertaining this fact from a two-dimensional (r,z) calculation. Without this calculation it appears that the association of properties

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or displacements in one direction corresponding to properties or displacements in some arbitrary preferential direction is not justified. These considerations, coupled with the fact that radial variations in reactivity insertion or core characteristics may be of importance led to the present consideration of the two-dimensional radially symmetric model.

DISCUSSION

Since the problem under consideration is quite involved, certain assumptions and approximations were made to simplify the analysis. These should be discussed prior to the formulation of the pertinent equations in the following section. Exact solutions of three dimensional (or with radial symmetry, two space variable) continuum problems are very lengthy, as noted by Wilkins*, and it is apparent that some simplifications are necessary so that the range of reactivity insertions of interest may be covered within a reasonable amount of computer time.

The major approximation utilized in the NERVEX formulation is the so-called "hydrodynamic" approximation as used in similar problems by Okrent** and Stratton+. This is based upon the assumption that the principle cause of core expansion, the internally generated pressure, may be assumed roughly hydrostatic. This assumption should give

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* M. L. Wilkins, "Calculation of Elastic-Plastic Flow" UCRL-7322, April 19, 1963.

** D. Okrent et.al., "Ax-1, A Computing Program for Coupled Neutronics - Hydrodynamics Calculations on the IBM 704" ANL-5977, May, 1959

\+ W. R. Stratton, et.al., "Analysis of Prompt Excursions in Simple Systems and Idealized Fast Reactors" Peacful Uses of Atomic Energy, Vol. 12, 1958.

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accurate results in the cases of high reactivity insertions where very high pressures are developed and part of the core becomes liquified.

Due to the anisotropy of the NERVA core, in that the fuel rods are aligned axially, radial tension cannot be sustained. During an excursion it is therefore quite possible that radial pressure gradients would result in rod separation and void creation. If the core were unconfined this could be treated by excluding this void creation from the determination of the density which enters into the equation of state. In the case of a confined core, however, these rods will "regroup" at the boundary and it is difficult to determine a pressure upon regrouping. It might be noted that the stresses associated with rod regrouping would be difficult to determine regardless of the mathematical core model assumed. Since the NERVA core is radially confined by reflectors, an unconfined excursion model would overestimate the expansion resulting in premature shutdown. Therefore, to insure conservation results, the core was assumed to be isotropic and hence able to sustain radial tension. It is of interest to note that this assumption becomes significant only during the later stages of an excursion and exerts little influence upon both peak power and total excursion energy. The primary influence is upon the core distortions at the end of the excursion.

In anticipation of ultimately using the NERVEX code for reactor impact excursion analysis, provision for shock waves has been included in the form of the Von Neumann - Richtmyer pseudo - viscous pressure, Q. Although for a full treatment of shock waves a much smaller mesh size would be necessary than that used here, the pseudo-viscous pressure was left in the problem since occasionally it becomes significant to prevent

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a position from starting to "override" another. The formulation of Q is treated in Appendix C. Also, due to the rather strict confinement of the core inlet circumference by a titanium band, provision in the code has been made for transverse shearing stresses but these were found to be negligible in most cases considered.

ANALYSIS

The laws of conservation of momentum, energy, and mass together with an equation of state for the graphite matrix and appropriate boundary conditions form the basis of the problem analysis. The equations are written for a three-dimensional, radially symmetric (two space variables) Lagrangian coordinate system in which R and Z are the radial and axial coordinates respectively of a point initially at position r,z. The coordinates r and z are considered as the independent variables. The symbols are described in the nomenclature and are standard notation.

Momentum Equations

Using the hydrodynamic equations of Richtmyer* and modifying that written for the radial direction to include the shear loading we have:

$$\rho \frac{\partial^2 R}{\partial t^2} = - \frac{\partial (P + Q)}{\partial R} + \frac{E_1 I}{A} \frac{\partial^4 R}{\partial Z^4}$$

$$\rho \frac{\partial^2 Z}{\partial t^2} = - \frac{\partial (P + Q)}{\partial Z}$$

* Richtmyer, R. D., Difference Methods for Initial Value Problems, Interscience Publishers Inc., New York, N. Y.

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In equation (1) the shear loading, $(E_1 I/A)\ \partial^4 R/\partial z^4$, has been obtained by treating the fuel rods elements as beams and applying elementary beam theory. The Q term in (1) and (2) is the Von Neumann-Richtmyer pseudo-viscous pressure stress. For the series of problems considered in this work the shear loading is negligible with respect to the pressure level, P. For integration of equations 1 and 2 we wish to express the spacial derivatives of the pressure with respect to the independent variables so we may write:

$$\rho \frac{\partial^2 R}{\partial t^2} = \frac{\frac{\partial (P+Q)}{\partial z}\frac{\partial Z}{\partial r} - \frac{\partial (P+Q)}{\partial r}\frac{\partial Z}{\partial z}}{\frac{\partial R}{\partial r}\frac{\partial Z}{\partial z} - \frac{\partial R}{\partial z}\frac{\partial Z}{\partial r}} + \frac{E_1 I}{A}\frac{\partial^4 R}{\partial z^4} \qquad (3)$$

$$\rho \frac{\partial^2 Z}{\partial t^2} = \frac{\frac{\partial (P+Q)}{\partial r}\frac{\partial R}{\partial z} - \frac{\partial (P+Q)}{\partial z}\frac{\partial R}{\partial r}}{\frac{\partial R}{\partial r}\frac{\partial Z}{\partial z} - \frac{\partial R}{\partial z}\frac{\partial Z}{\partial r}} \qquad (4)$$

as the final form of the momentum equations.

Conservation of Mass

Consider an elemental volume ring of the reactor core initially located at r_i, z_i and deformed to positions R_i, Z_i as shown in cross section. We note the mass in this element remains constant.

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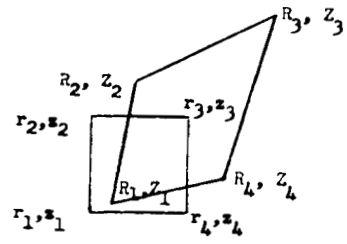

The density may be calculated from

$$\rho = \frac{M_o}{V} \qquad (5)$$

where M_o is the initial mass of the element

$$M_o = \rho_o \pi (r_2^2 - r_1^2)(z_4 - z_1) \qquad (6)$$

and V is the volume of the deformed element which is determined directly by integration.

Energy Equation and Equation of State

Modifying the energy equation of Zemansky* to include the pseudo-viscous pressure we have:

* M. W. Zemansky, Heat and Thermodynamics, McGraw-Hill, New York, 1957

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$$dE = C_v dT + \left[T\,(\partial P/\partial T)_v + Q \right] dV_s/m + h\,dF. \qquad (7)$$

Since $V_s = (1 - \mathcal{F})\, V_{tot} = m\,(1 - \mathcal{F})/\rho$, we may write,

$$dE = C_v dT - (1 - \mathcal{F}) \left[T\,(\partial P/\partial T)_v + Q \right] d\rho/\rho^2 + h\,dF. \qquad (8)$$

This equation has the following different forms depending on the temperature.

a. Sublimation below the triple point ($T < 3960°K$).

Assuming equilibrium compatible with the graphite phase diagram and the perfect gas law for the vapor,

$$P_v = C_1^{(s)}\, e^{-C_2^{(s)}/T} = F^{(s)}\, m R_u T/12.01\, V_{vap}$$

Also, since $V_{vap} = m\,(1 - \mathcal{F})\,(1 - 1/\eta)/\rho$

we have

$$P_v = F^{(s)} \rho\, T/K; \qquad K = 12.01\,(1 - \mathcal{F})\,(1 - 1/\eta)/R_u.$$

Solving for $F^{(s)}$ and differentiating,

$$dF^{(s)} = K P_v \left[(C_2^{(s)}/T - 1)\,\rho\, dT - T d\rho \right] / \rho^2 T^2$$

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Since $E^{(s)} = h^{(s)} F^{(s)} = h^{(s)} K\, P_v/\rho\, T$

$$dF^{(s)} = E^{(s)} \left[(C_2^{(s)}/T - 1)\,\rho\, dT - T d\rho \right] / h^{(s)} \rho\, T$$

substituting into (7) with $F = F^{(s)}$ and $h = h^{(s)}$ and solving for dT, we obtain

$$dT = \frac{dE + \left[(T\,(\partial P/\partial T)_v + Q)\,(1 - \mathcal{F})/\rho + E^{(s)} \right] d\rho/\rho}{C_v + E^{(s)}\,(C_2^{(s)} - 1)/T} \qquad (9)$$

b. Fusion at the triple point while solid remains ($T = 3960°K$). Assuming temperature remains constant during fussion process we have $dT = 0$, $F = F^{(f)}$, and $h = h^{(f)}$ so that equation (7) may be solved for the fraction of material undergoing fusion,

$$dF^{(f)} = \left[dE + (T\,(\partial P/\partial T)_v + Q)\,(1 - \mathcal{F})\, d\rho/\rho^2 \right] / h^{(f)} \qquad (10)$$

c. Liquid vaporization above the triple point ($T > 3960°K$).

In this case,

$$P_v = C_1^{(e)}\, e^{-C_2^{(e)}/T} = (F^{(s)} + F^{(e)})\,\rho\, T/K$$

and the derivation is the same as in the case of sublimation but with $h = h^{(e)}$ and $F = F^{(e)}$ yielding,

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$$= \frac{dE + \left[(T\,(\partial P/\partial T)_v + Q)\,(1 - \nu)/\rho + E^{(e)} + E^{(s)}(h^{(e)}/h^{(s)}) \right] d\rho/\rho}{C_v + (E^{(e)} + E^{(s)}(h^{(e)}/h^{(s)}))\,(C_2^{(e)}/T - 1)/T} \qquad (11)$$

The graphite equation of state is taken as

$$\frac{dV}{V} = -\frac{d\rho}{\rho} = \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_{P_m,\tau} dT + \frac{1}{V}\left(\frac{\partial V}{\partial P_m}\right)_{T,\tau} dP_m + \frac{1}{V}\left(\frac{\partial V}{\partial \tau}\right)_{P_m,T} d\tau \qquad (12)$$

where the partial derivatives are to be taken under hydrostatic conditions. This gives,

$$\frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_{P_m,\tau} = 2\alpha_a + \alpha_1 \equiv \alpha_T, \quad \frac{1}{V}\left(\frac{\partial V}{\partial P_m}\right)_{T,\tau} = -(1 - 2\nu)\frac{1}{E_1} + \frac{2}{E_a} \equiv \beta$$

and from geometry considerations, with $\gamma \equiv \tau/G$, we have,

$$\frac{1}{V}\left(\frac{\partial V}{\partial \gamma}\right)_{P_m,T} = -\tan\gamma + \frac{\cos\gamma\,(2\sin\gamma - 3\,\Delta r/\Delta z)}{\sin^2\gamma - 3\sin\gamma\,(\Delta r/\Delta z) + (i+1)(\Delta r/\Delta z)^2} \equiv F(\gamma)$$

where i is the radial mesh in question. Substituting into (12) and solving for dP_m, we obtain,

$$dP_m = \left[d\rho/\rho + \alpha_T\, dT + F(\gamma)\, d\gamma \right]/\beta \qquad (13)$$

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Neutron Kinetics

Power generation in NERVEX is calculated by a simple prompt neutron kinetics routine. This assumes the power to be exponential with time of the form

$$p = p_o e^{\alpha t} \qquad \text{where } \alpha = \Delta K_p/\ell$$

and

$$\Delta K = \Delta K_{in} - \Delta K_T - \Delta K_\rho$$

The input reactivity can be represented by up to a sixth degree polynomial with time. The negative reactivity feedback is obtained by using temperature and density reactivity coefficients (input) in conjunction with the spacial and flux weighted changes in these parameters.

$$\frac{1}{K}\frac{dK_T}{dt} = \left(\frac{dK}{dT}\right)_T \frac{\int_v \frac{dT}{dt}\varphi^2\, dV}{\int_v \varphi^2\, dV},$$

$$\frac{1}{K}\frac{dK}{dt} = \left(\frac{dK}{dT}\right)_\rho \frac{\int_v \frac{1}{\alpha}\left(\frac{1}{\rho}\frac{d\rho}{dt}\right)\varphi^2\, dV}{\int_v \varphi^2\, dV}$$

A cosine flux shape is assumed axially and either a flat or Bessel dependence can be used radially.

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For the flat dependence,

$$\varphi(r,z) = 1.5708 \cos \frac{\pi (z - L/2)}{L}, \quad \int_V \varphi^2 dV = 1.2337$$

For the Bessel dependence,

$$\varphi(r,z) = 3.6364\, J_o \left(\frac{j_o r}{R_m} \right) \cos \frac{\pi (z - L/2)}{L}, \quad \int_V \varphi^2 d V = 1.781$$

Both distributions are normalized so that $\int_V \varphi(r,z)\, dV = 1.$

RESULTS AND CONCLUSIONS

It has been estimated by Call that the largest excursion of the dry NRX-A reactor would result from total core compaction (voids completely filled) upon ground impact. This would involve about a 10% ΔK addition almost instantaneously. Figures 1 and 3 indicate that in such a case about 40,000 MWATT-SEC of energy would be released. Actually, total compaction is an unrealistic assumption and ground impact would result in some partial degree of compaction.

In any case the following conclusions are indicated for a cold dry NERVA excursion. Up to about a 3% prompt ΔK step essentially all the energy generated is utilized in raising the core temperature. At 3% the center of the core just reaches the triple point. Vapor is formed in the core center due to sublimation but very little energy is involved in doing so. From 3 to 4% an increasingly large area of the core sublimates, whereas the core center has begun to fuse forming liquid. At 4% the maximum

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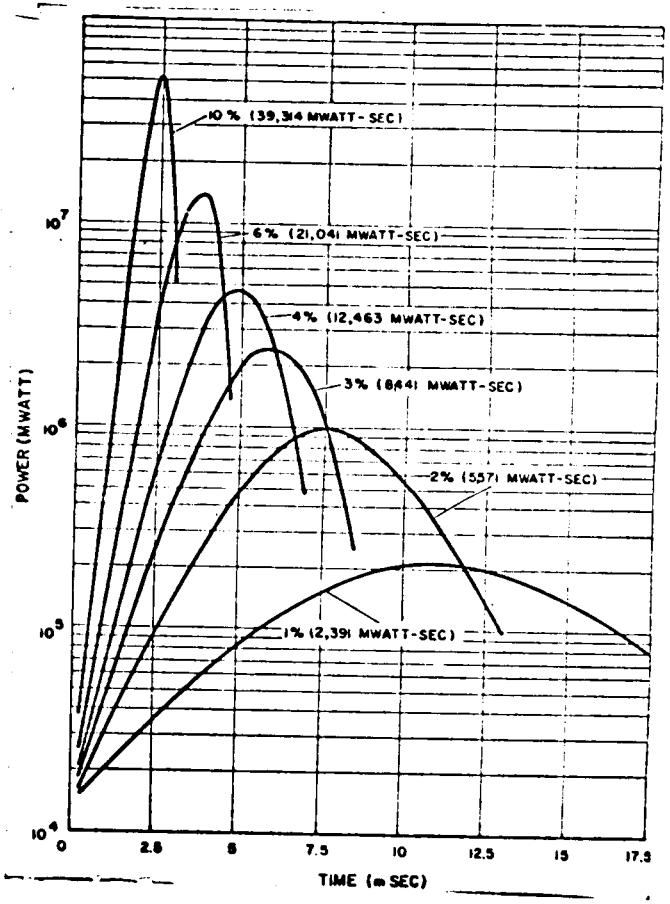

FIGURE 1

POWER-TIME PROFILES FOR VARIOUS PROMPT ΔK STEPS

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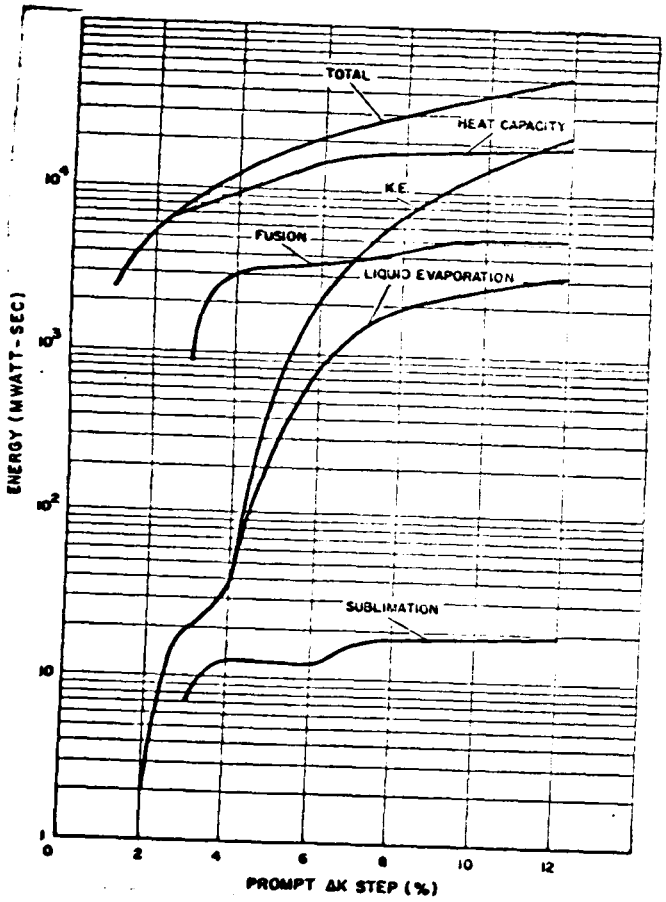

FIGURE 2

ENERGY PARTITIONING VERSUS PROMPT ΔK STEP

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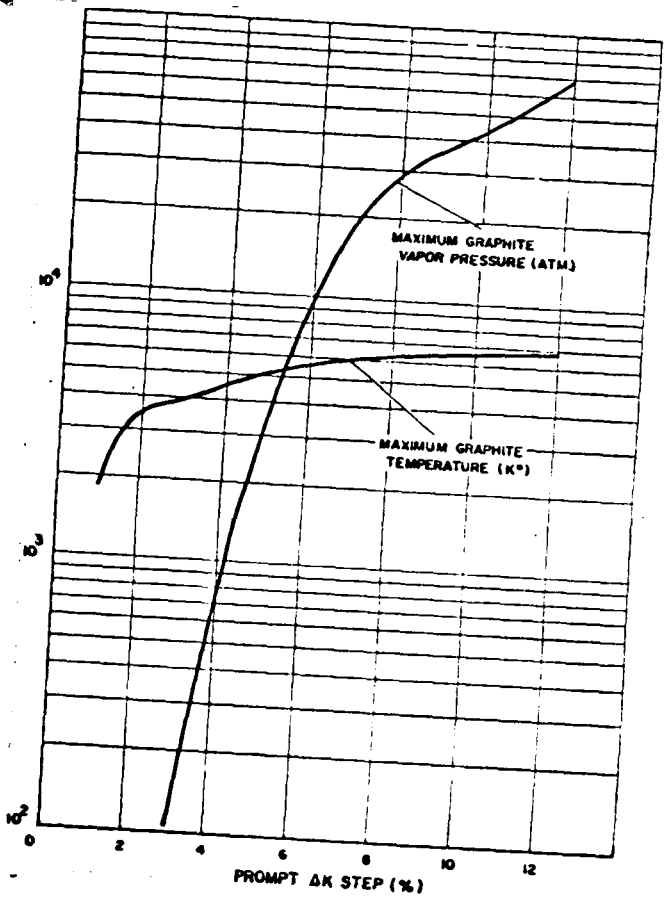

FIGURE 3

MAXIMUM GRAPHITE TEMPERATURE AND VAPOR PRESSURE VERSUS PROMPT ΔK STEP

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graphite temperature is 4500°K and the maximum vapor pressure is 780 atm. From 4 to 6% the amount of sublimation and fusion remains roughly the same whereas the kinetic energy and the amount of liquid evaporation increase rapidly. At 6% the maximum graphite temperature is 5600°K and the maximum vapor pressure has increased to 10,000 atm. From 6 to 9% the remainder of the core has sublimated and subsequently fused with no solid remaining. An increasing amount of liquid evaporates forcing the maximum vapor pressure up to 36,000 atm. The kinetic energy continues to increase rapidly and the temperature levels off at a maximum of about 6400°K. Above 9% all processes level off except the kinetic energy which finally surpasses the heat capacity as the dominant energy reservoir at about 11% and liquid evaporation which increases the maximum graphite vapor pressure to 67,000 atm at 12% Δ K. These results are depicted graphically in Figures 1 through 3.

Shutdown is realized through the temperatures and density changes resulting from the energy generated during the excursion. Density is the major factor, contributing about 72% of the shutdown reactivity for the 1% Δ K step and increasing to about 94% for the 12% step where the kinetic energy becomes large.

Several areas in the approach to formulating NERVEX involved approximations which result in an over-estimation (conservative) of the energy release. The more important of these areas are:

a. The use of a homogeneous, isotropic model. Such a model allows radial tension to be sustained which actually is absent due to the axial alignment of the fuel elements.

b. The inner reflector is treated as a rigid wall boundary which disallows radial expansion greater than about 5/8".

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c. The top support plate is treated as a rigid wall boundary which disallows axial expansions greater than 1" of the top of the core. Further axial expansion can only be realized in the downward direction which is impeded by the relatively large spring constant associated with the stretching of the tie rods. No provision is incorporated for tie rod breakage due to their extreme ductility.

d. Thermal equilibrium is assumed between the fuel beads and the graphite matrix. For excursions involving short periods there will probably be a significant temperature gradient across the pyrocoating of the beads which would enhance early vapor formation and hence early shutdown.

Due to the use of the prompt kinetics approximation NERVEX is applicable only for ΔK additions sufficiently above prompt critical (K = 1.0078) that the energy contribution during the delayed neutron controlling portion of the excursion is negligible. Furthermore, NERVEX is applicable only to dry excursions since the spacial neutron flux distribution is assumed fixed. Thus, an analysis of the important class of problems involving water immersion or hydrogen flooding is at present not possible.

Los Alamos' KIWI-TNT excursion experiment is well within the limits of applicability of NERVEX and provides a rather unique opportunity to check the credence of the program. The excursion was accomplished by adding reactivity via rapid rotation of the control drums from 0° to 180° in about 65 msec. Preliminary results show a total drum worth of about $8.85 nearly all of which was inserted prior to the attainment of a significant core temperature increase. In lieu of the foregoing and an estimated initia shutdown reactivity of -$0.65, the excursion can be considered as equivalent to about a $7.00 prompt reactivity step. Measurements indicated a prompt neutron lifetime of 35.6 sec as compared to 25 sec used in generating the results associated with the NERVA reactor presented elsewhere in this report. Also, the gap width between the outer

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core periphery and the graphite barrel is about 0.95 cm for the KIWI-TNT experiment as compared to 0.635 cm incorporated in the NERVA (NRX-A2) design. Table I shows the results of a NERVEX run based on the above information. A comparison with KIWI-TNT results analyzed by LASL,* shows the NERVEX results to be about a factor of two greater in total fission release and peak fission rate although the pulse widths are about the same. These results are to be expected due to the conservative assumptions incorporated in the NERVEX formulation.

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* LASL will present a paper at the Reactor Nucleonics session of the AIAA Propulsion Joint Specialist Conference entitled Analysis of the KIWI-TNT Experiment.

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TABLE I

NERVEX PREDICTIONS FOR THE KIWI-TNT EXPERIMENT

($7 PROMPT REACTIVITY STEP, 35.6 μ SEC LIFETIME)

Total Energy Release	5.71×10^{20} fissions
Kinetic Energy	940 Mwatt - sec
Maximum Temperature	5365°K
Maximum Vapor Pressure	6000 Atm
Peak Power	2.23×10^{23} fissions/sec
Mass Sublimated	0.2 Kgm
Mass Fused	900 Kgm
Mass Vaporized	6.9 Kgm

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NOMENCLATURE

A	Fuel Element Cross-Sectional Area (cm^2)
C_v	Specific Heat (ergs/gm°K)
C_1, C_2	Empirical Constants of the Phase Equilibrium Diagram (Listed in Appendix A)
E	Internal Energy Generated per Gram of Core (ergs/gm)
E_a	Modulus of Elasticity Across the Grain (dynes/cm^2)
E_l	Modulus of Elasticity Along the Grain (dyne/cm^2)
F	Mass Fraction of Material Which has Changed Phase to Original Mass
G	Modulus of Rigidity (dynes/cm^2)
h	Heat of Change of Phase Reaction (ergs/gm)
I	Fuel Element Bending Moment of Inertia (cm^4)
K	Eigenvalue
ΔK_p	Reactivity Above Prompt Critical
ΔK_{ext}	Reactivity Added
ΔK_T	Temperature Feedback Reactivity
ΔK_ρ	Density Feedback Reactivity
$(dK/dT)_T$	Temperature Reactivity Coefficient Including Change of Thermal Base and Doppler (°K^{-1})
$(dK/dT)_\rho$	Density Reactivity Coefficient Due to Change in Neutron Mean Free Path Upon Expansion (°K^{-1})

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NOMENCLATURE (Cont'd)

L	Core Length (cm)
ℓ	Prompt Neutron Lifetime (sec)
m	Section Mass (gm)
P	Total Hydrostatic Pressure (dynes/cm^2)
P_m	Mechanical Pressure (dynes/cm^2)
P_v	Vapor Pressure (dynes/cm^2)
Q	Pseudo Viscous Pressure (dynes/cm^2)
R	Dependent Radial Coordinate (cm)
r	Radial Lagrangian Coordinate (cm)
R_m	Core Radius (cm)
R_u	Universal Gas Constant (ergs/mole °K)
T	Temperature (°K)
t	Time (sec)
$\mathcal{F}$	Coolant Channel Void Fraction
V_{tot}	Total Volume (cc)
V_{vap}	Intersticial Volume Available to Vapor (cc)
V_s	Volume Exclusive of Coolant Channel Voids (cc)
Z	Dependent Axial Coordinate (cm)
z	Axial Lagrangian Coordinate (cm)

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NOMENCLATURE (Cont'd)

α	Prompt Neutron Inverse Period (sec^{-1})
α_l	Coefficient of Linear Expansion Along the Grain ($°K^{-1}$)
α_a	Coefficient of Linear Expansion Across the Grain ($°K^{-1}$)
β	$(1/E_l + w/E_a)$
γ	Shearing Strain
η	Ratio of Theroetical to Actual Core Density
ν	Poisson's Ratio
τ	Shearing Stress ($dynes/cm^2$)
$\phi(r,z)$	Neutron Flux Distribution (cm^{-2})

Superscripts:

f	Fusion Process
s	Sublimation Process
e	Evaporation process

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APPENDIX A

The mechanical and thermodynamic properties of the graphite core which are used in the NERVEX code are summarized in this appendix. In Figures 1A to 6A these properties are given as functions of temperature with the dashed lines corresponding to data from the WANL Material Manual except for Figure 1A which is from Blackman*.

Figure 1A Specific Heat of Graphite as Function of Temperature

Figure 2A Coefficient of Thermal Expansion as Function of Temperature

Figure 3A Phase Equilibrium Curve for Graphite, Triple Point at 100 Atms.

Figure 4A $\beta = (1/E_l + 2/E_a)$ as Function of Temperature

Figure 5A Compression Strength of Graphite as Function of Temperature

Figure 6A Tensile Strength of Graphite as Function of Temperature

Other important properties are:

Poisson's Ratio----------0.15

Heat of Sublimation----------5.995×10^{11} ergs/gm

Heat of Fusion----------3.8338×10^{10} ergs/gm

Heat of Vaporization----------5.612×10^{11} ergs/gm

Equilibrium constants:

$C_1^{(s)}$----------1.1958×10^{29} $dynes/cm^2$

$C_2^{(s)}$----------1.9214×10^5 °K

$C_1^{(e)}$----------$6.0[illegible]7 \times 10^{14}$ $dynes/cm^2$

$C_2^{(e)}$----------6.1819×10^4 °K

*L. C. F. Blackman, "Properties of Graphite" Research, London (1960) 12, 442.

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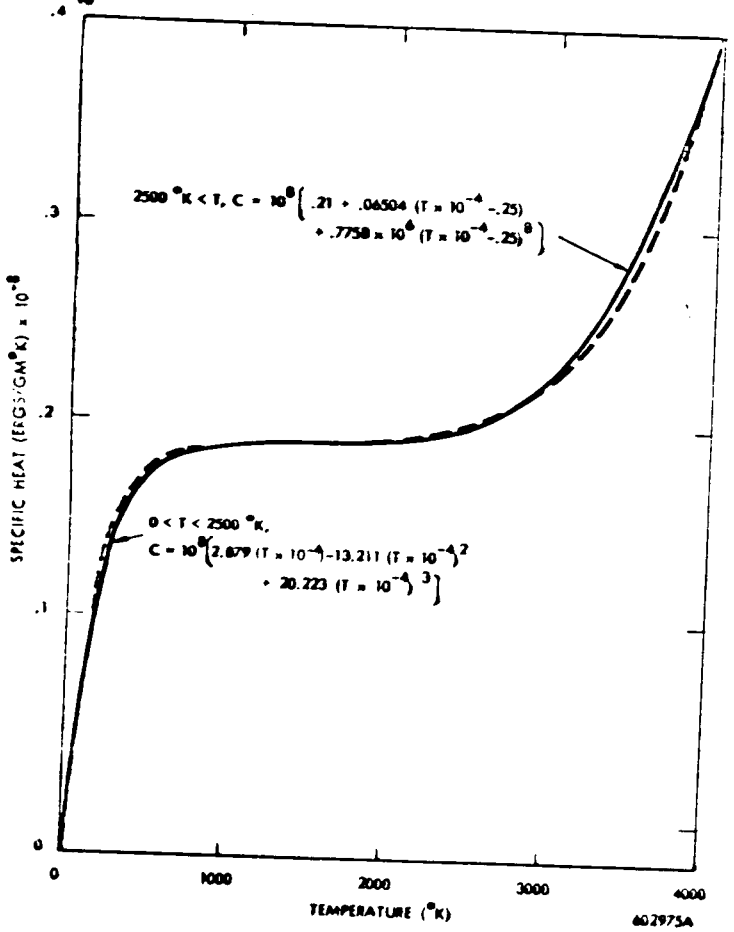

FIGURE 1A

SPECIFIC HEAT OF GRAPHITE AS FUNCTION OF TEMPERATURES

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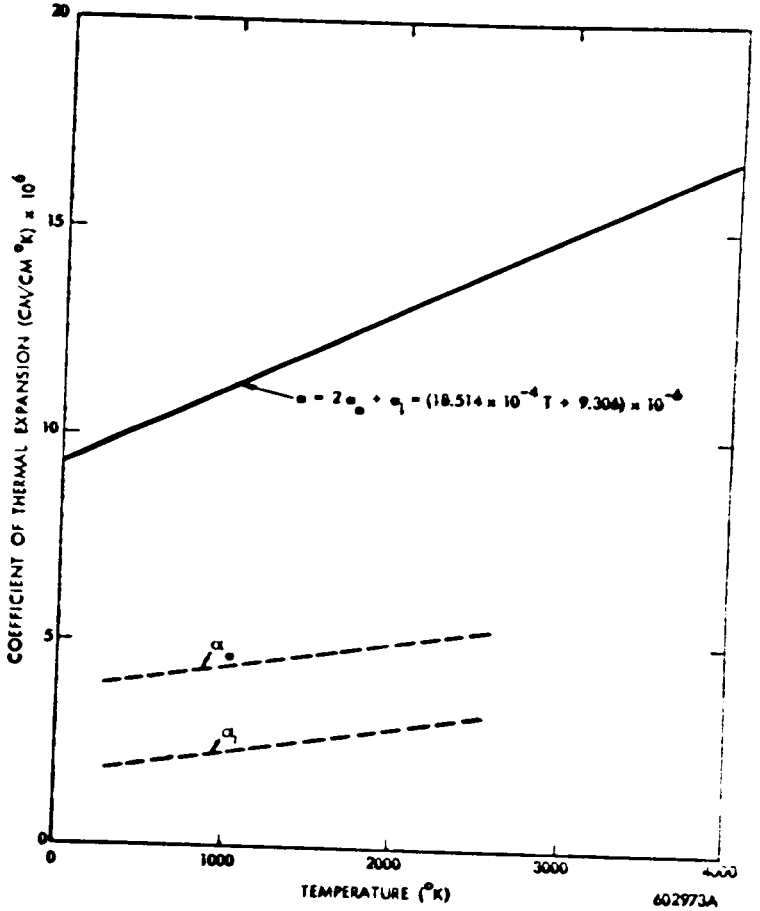

FIGURE 2A

COEFFICIENT OF THERMAL EXPANSION AS FUNCTION OF TEMPERATURE

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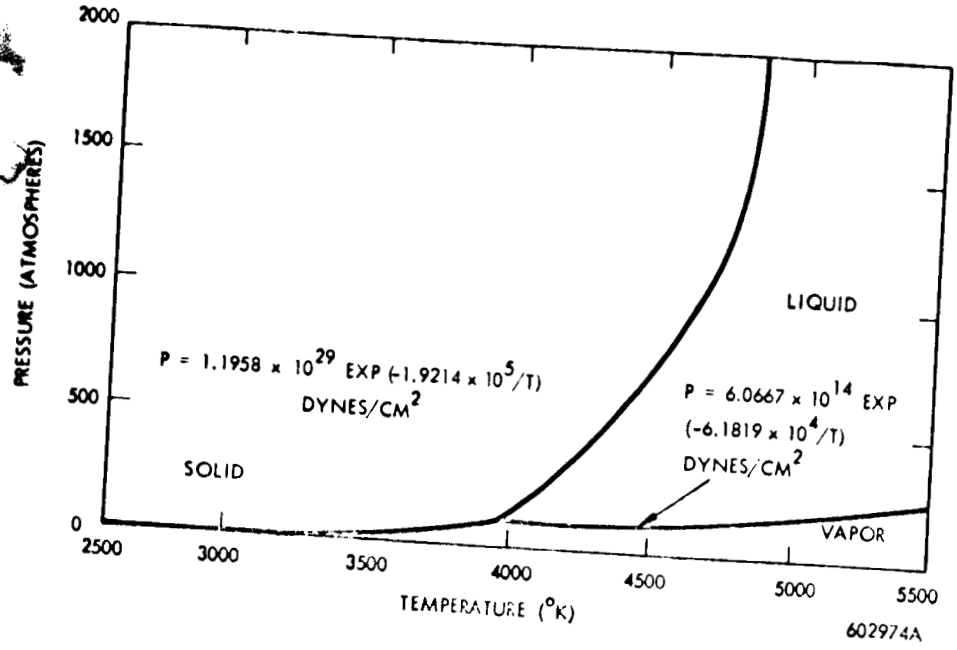

FIGURE 3A

PHASE EQUILIBRIUM CURVE FOR GRAPHITE, TRIPLE POINT AT 100 ATMS, 3960°K

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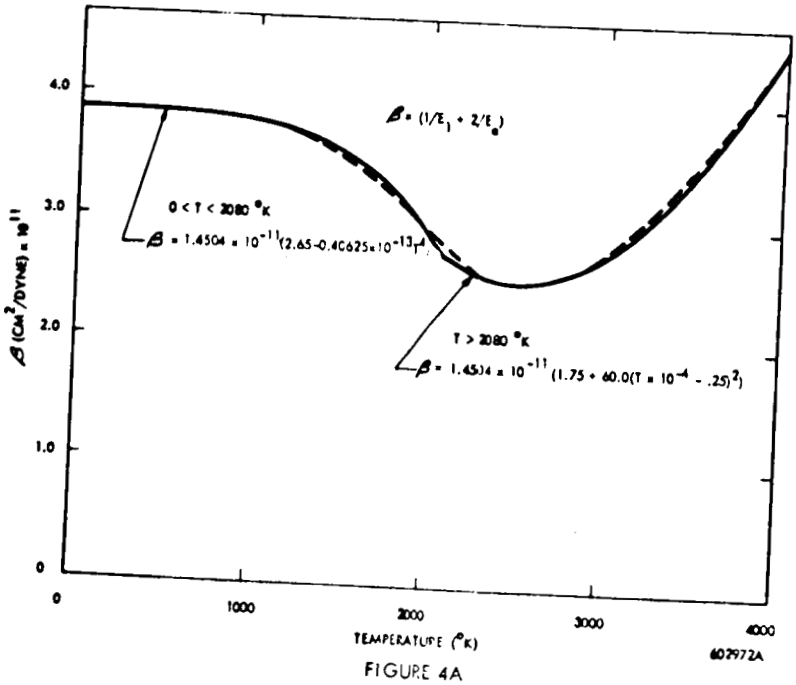

FIGURE 4A

β AS FUNCTION OF TEMPERATURE

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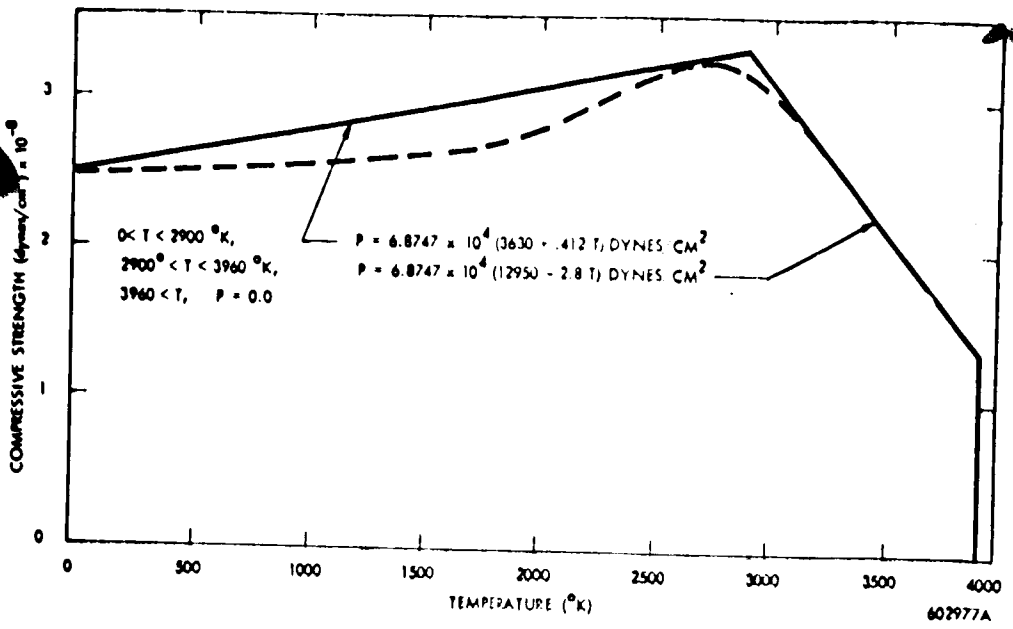

FIGURE 5A

COMPRESSION STRENGTH OF GRAPHITE AS FUNCTION OF TEMPERATURE

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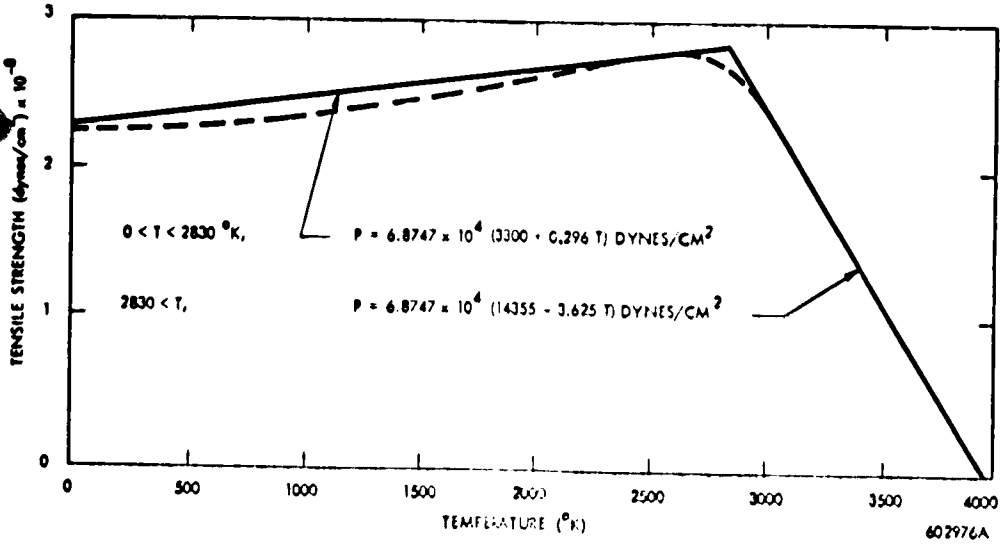

FIGURE 6A

TENSILE STRENGTH OF GRAPHITE AS FUNCTION OF TEMPERATURE

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APPENDIX B

Core Description

The core which has been analyzed in this work was assumed to have a length of 132.0 cm and a radius of 45.2 cm. The ratio of the theoretical density of graphite to that of the fuel rods is 1.1415 and the coolant channels provide an initial void volume of 25% of the total volume.

The core has been assumed to have an initial bundling pressure of 1 atmosphere. At the top (inlet end) of the core the spring constant (in terms of pressure) is taken as 1.07×10^6 dynes/cm^3 with a maximum motion restraint of 2.54 cm imposed by the top support plate. The spring constant impeding downward motion due to tie-rod stretching is 3.74×10^7 dynes/cm^3. The radial bundling springs have a spring constant of 4.072×10^5 dynes/cm^3 are bottom against the graphite barrel after 0.635 cm outer displacement.

The initial core temperature has been taken to be 273°K and a negligible initial power of 10^{11} ergs/gm-sec. The density and temperature coefficients of reactivity are -8.90×10^{-6} ($\Delta k/k$)/°K and -3.56×10^{-6} ($\Delta k/k$)/°K respectively with a prompt neutron lifetime of 2.50×10^{-5} sec.

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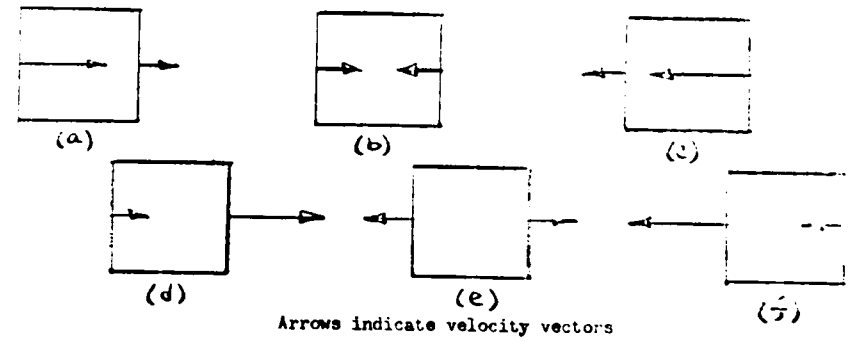
APPENDIX C

It is possible that shock waves may arise during the reactor excursion and they must either be accounted for or a satisfactory reason for their neglect be stipulated. Of course in impact problems they must be included.

The pseudo-viscous pressure of Von Neuman and Richtmyer is available for one dimensional shocks and with modifications may be extended into two dimensions. This pseudo-viscous stress introduces a pressure which is proportional to the square of the spacial velocity derivative and satisfies the Rankine-Hugoniot shock relations across the three or four mesh points over which it distributes the shock front.

The method of determining whether or not a shock front (a pseudo-viscous pressure term) exists is simply to examine the relative velocities at various points of a mesh. In Figures a, b and c below Q is non zero while in Figures d, e and f it is zero.



Arrows indicate velocity vectors

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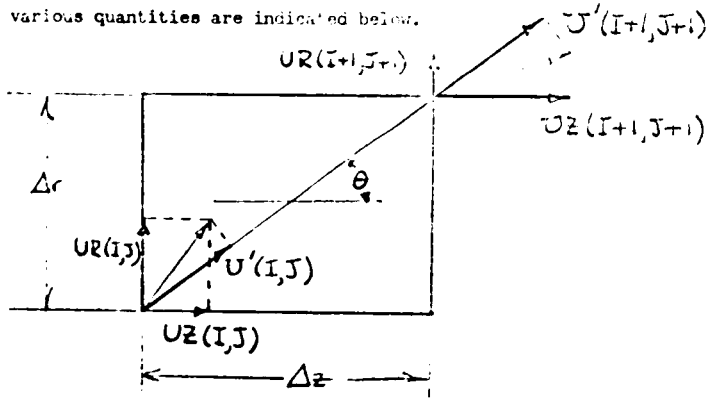
In NERVEX a test is made to determine the maximum value of Q with regard to four directions through the element volume. Q is calculated from

$$Q_i = a^2 \left(\Delta z \cos\theta + \frac{r}{R}\Delta r \sin\theta\right)^2 \rho \left(\frac{\partial \frac{u}{s}}{\partial s}\right)^2 \qquad \text{(C1)}$$

where the various quantities are indicated below.



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In the diagram the U' values are those used in equation C1 for the tests on relative velocities to determine if Q is nonzero and to evaluate it if not. UR and UZ are the radial and axial velocities respectively.

The constant, a, is a factor which determines the number of mesh points over which a shock wave will be spread and is taken to be 2.0 in the present evaluation of NERVEX.

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