CONFIDENTIAL
RESTRICTED DATA
Atomic Energy Act - 1954

MASTER

WANL-TME-545
SEPTEMBER 1963

SWIIC 64-15 63

STATUS OF WANL EXCURSION ANALYSIS PROGRAM

(Title Unclassified)

GROUP - 1
EXCLUDED FROM AUTOMATIC DOWNGRADING
AND DECLASSIFICATION

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Astronuclear Laboratory
Westinghouse Electric Corporation

TME-545

CONFIDENTIAL
RESTRICTED DATA
Atomic Energy Act - 1954

DISCLAIMER

~~CONFIDENTIAL~~
~~RESTRICTED DATA~~
~~Atomic Energy Act - 1954~~

Astronuclear

ANL-TME-545

MASTER

(24)

STATUS OF WANL EXCURSION ANALYSIS PROGRAM

By: D. W. Call

APPROVED:

W. H. Arnold Jr.
W. H. Arnold, Jr.

~~CONFIDENTIAL~~
~~RESTRICTED DATA~~
~~Atomic Energy Act - 1954~~

DISTRIBUTION OF THIS DOCUMENT UNLIMITED

[redacted]

[redacted] DATA

At[redacted]

Astronuclear

WANL-TME-545

TABLE OF CONTENTS

LIST OF FIGURES

C[redacted]

RESTRICTED DATA

Atomic Energy Act - 1954

LIST OF FIGURES

LIST OF TABLES

[redacted]

Astronuclear

WANL-TME-545

I. INTRODUCTION

The recognition of the potential accidents associated with a nuclear rocket engine is of utmost importance to the safety requirements of the NERVA Program. Most such accidents will involve the release of radiation and radioactive fission products resulting from a nuclear excursion due to an abrupt change in core reactivity. Appropriate safeguards in design or procedure are used to alleviate or eliminate the hazards involved with such accidents. Although such safeguards can be extremely reliable, some chain of events can in some cases be postulated which, although remote, could render them ineffective or inadequate. It is, therefore, necessary to assume highly improbable conditions to predict the intensity of accidents so as to adopt extra precautionary measures for safety.

The magnitude of a nuclear excursion is determined by both the amount and rate of reactivity insertion and the shutdown mechanism(s) involved. The complexity of an analytical treatment involves the appropriate description and treatment of these two phenomena for each accident. Whereas, when necessary, a worst case description can be ascribed to the former, the shutdown mechanism is not always amenable to such treatment. Thus, the accuracy of an excursion analysis program is usually dictated by its treatment of the shutdown mechanisms.

At present, the WANL excursion analysis program is based on two computer programs (RTS and RAC) developed by Los Alamos Scientific Laboratory. WANL has made certain modifications and additions to these programs where necessary so as to treat special

[redacted]
~~RESTRICTED DATA~~
Atomic [redacted]

problems of interest. Each program, due to inherent limitations, is applicable only over certain restricted ranges of reactivity. These ranges overlap for the NERVA reactor.

The possible types of accidents can be divided into three classes distinguished by the manner of reactivity insertion.

A. Abnormal Control Rod Motion

This may occur during any phase of reactor operation or result from control system malfunction when the reactor is intended to be shutdown. This type of accident is the most amenable to an analytical treatment since the reactivity insertion is readily defined and the principal mode of shutdown is the doppler and core expansion effects resulting from a temperature rise. In extreme cases, core expansion or loss of fuel due to vaporization may be important. The maximum control drum worth (all twelve drums - critical to full - out position) is 7.7$ of reactivity with a maximum removal rate of 55°/sec.

B. Core Deformation

The reactor core may be compacted by filling in its coolant channel void upon impact with the ground resulting in increased moderation. This could occur either during transport to the launch pad or at the launch pad due to a chemical explosion or booster failure. A chemical explosion may also cause a radial implosion of the core with a similar reactivity effect. Figure 1 shows the reactivity effect of two different modes of compaction. One mode corresponds to a uniform axial compaction of the core over its entire length and is represented by the fairly linear curve in Figure 1. The other mode corresponds to various bottom portions of the core being fully compacted and the upper portion non-compacted. The curves assume an initial shutdown of 3$ whereby full

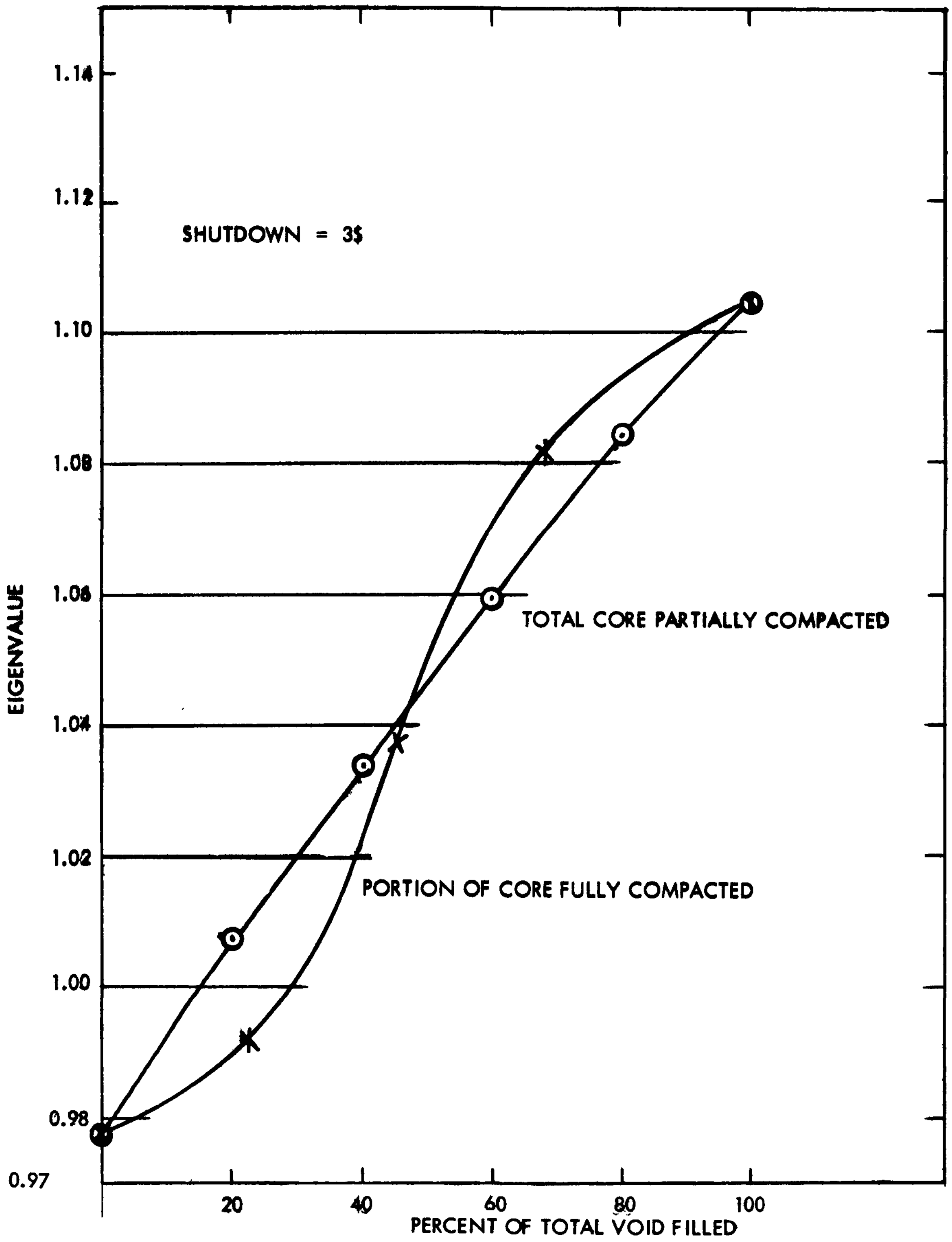

FIGURE 1

EIGENVALUE VS. DEGREE OF COMPACTION
OF COLD NRX-A CORE

compaction results in 10.45% supercriticality. Temperature, vaporization, and core separation would all be important shutdown mechanism.

C. Water Immersion and Hydrogen Propellant Flooding

The latter could occur on the launch pad due to a turbopump failure. Water immersion could result from either a booster failure or a down range abort causing impact with the river or the ocean. Figure 2 shows the worth of water as a function of a uniform water level height in the core. This type of accident is by far the most difficult to analyze due to the gross change in core characteristics involved. Likewise the shutdown mechanisms are exceedingly difficult to describe. For example, fast immersions may develop shock waves which would break-up the core thereby contributing to shutdown. On the other hand, slow immersions may allow time for sufficient heat transfer to the water resulting in steam formation and ultimate water expulsion. Complete water flooding of the unpoisoned core is worth 53% supercriticality.

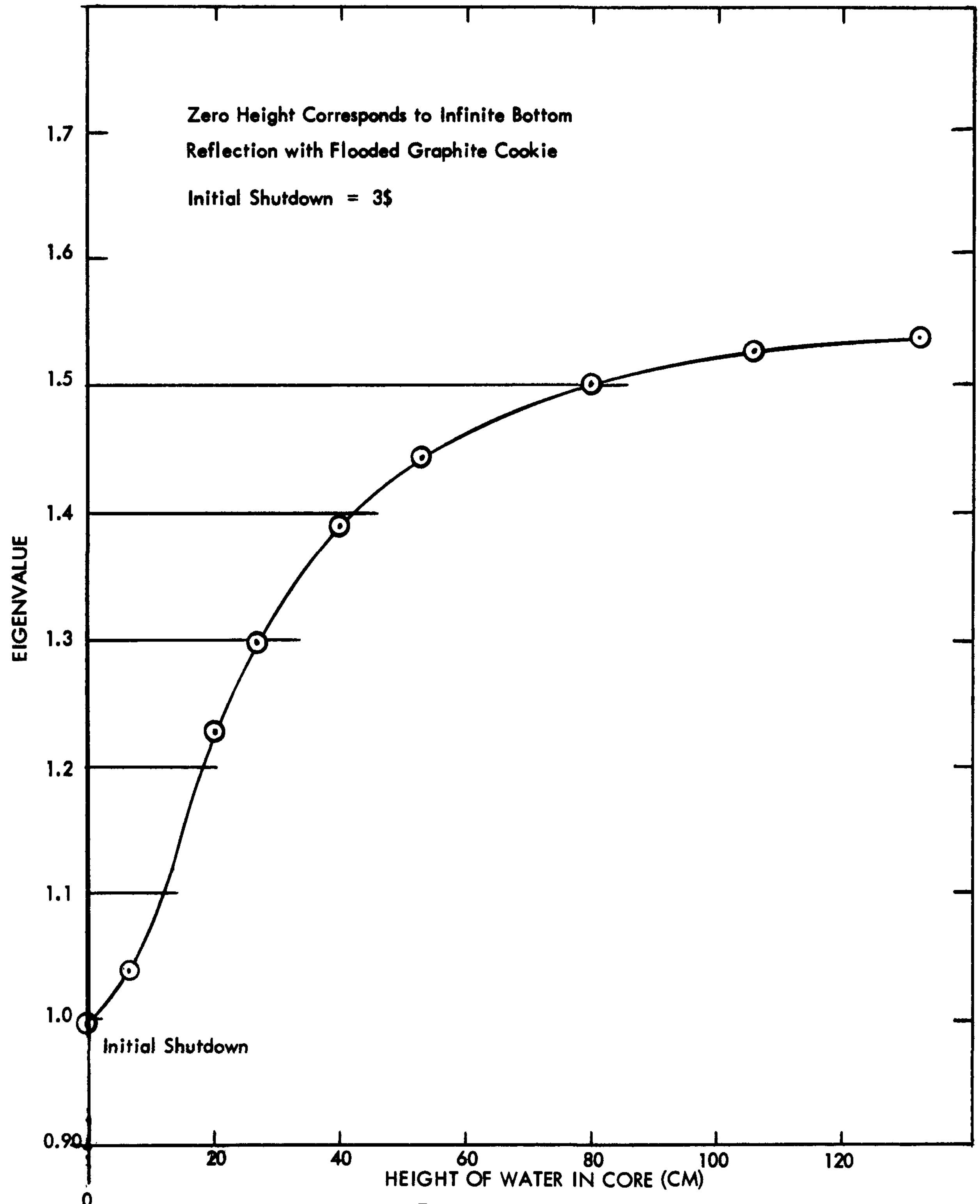

FIGURE 2

EIGENVALUE VS. WATER HEIGHT IN COLD NRX-A CORE

II. RAC - REACTOR ACCIDENT CALCULATIONS[1]

RAC is a one dimensional description of the thermodynamic and hydrodynamic behavior of a uranium-graphite core during a nuclear excursion. Such a description enables the program to incorporate the shutdown effects of vaporization and core break-up which usually occur during "large" accidents, i.e., reactivity insertions above prompt critical. The program neglects the effect of delayed neutrons and is, therefore, not applicable in the reactivity range near or below prompt critical. Table 1 illustrates some of the results obtained using RAC for various prompt step reactivity insertions. These results are based on the kinetic parameters accompanying the table and include the boundary effect of the tie-rod springs with a spring constant of 50 lbs. per inch. A cosine flux distribution is assumed throughout. The information shown is also calculated on a section by section basis of the core along with other parameters such as internal pressures, temperatures,and velocities.

RAC assumes the core is homogeneous and is divided equally into an arbitrary number of squat cylinders. An arbitrary axial flux distribution is specified in the input which determines the relative fission energy generated in each section. This distribution is invariant throughout the problem. A reactivity insertion rate can be represented by a sixth-order polynomial in time. Provision is made to examine an excursion started at an elevated power level by specifying an arbitrary initial axial temperature distribution as input. The program cyclically generates fission energy in each section using the prompt approximation to the neutron kinetics. Internal pressures result in each section due to temperature increase and vapor formation determined by the heat capacities, the graphite

TABLE 1

ENERGY RELEASES AND PEAK POWERS FOR SEVERAL REACTIVITY STEP INPUTS

-RAC-

Prompt ΔK_p Step ($\Delta K_p = K-1-\beta$)	Total Energy (MW-Sec)	Energy Into Temp. (MW-Sec)	Energy Into Vapor (MW-Sec)	Energy Into Liquid (MW-Sec)	Peak Power (MW)
0.01	3005	3005	0	0	2.665×10^5
0.015	4924	4924	0	0	6.546×10^5
0.02	6925	6907	18	0	1.241×10^6
0.03	9728	8276	119	1333	3.081×10^6
0.05	16,833	10,365	2625	3843	1.036×10^7
0.07	23,866	11,522	7800	4544	2.526×10^7

-RTS-

ΔK Step ($\Delta K = K-1$)	Total Energy (MW-Sec)	Peak Power (MW)
0.006	1380	80
0.01	1475	1.42×10^4
0.013	2090	7.56×10^4
0.016	2800	1.88×10^5
0.02	3490	4.20×10^5

(continued):

Kinetic Parameter	Description	NRX-A Value
β	Effective delayed neutron fraction	0.0078
ℓ^*	Prompt neutron lifetime	2.5×10^{-5} sec.
$\Delta K/\Delta T^{\dagger}$	Temperature reactivity coefficient	-1.1×10^{-5} $^{o}C^{-1}$

$\dagger$ Doppler contribution is 0.26×10^{-5} $^{o}C^{-1}$.

equation of state, and an assumed equilibrium compatible with the graphite phase diagrams. Negative pressures are allowed to simulate tensions which can ultimately rupture the core if they exceed a limit which depends on temperature. Each section does thermodynamic work on its neighboring sections thereby relieving its internal pressure. Reactivity is decreased via density and temperature coefficients of reactivity in conjunction with the weighted sums of the density and temperature changes in each section. The weighting factor is the square of the neutron flux, i.e., the flux times its adjoint. The density and temperature reactivity effects are solved independently to account for non-equilibrium conditions existing during core break-up. At present, the reactivity effect of radial expansion is treated through a modified density reactivity coefficient which assumes an axial expansion is accompanied by an equivalent radial expansion in each region. RAC is the primary analytical tool for examining core compaction and water immersion accidents.

III. RTS - REACTOR TRANSIENT SOLUTION [2]

RTS solves the one group, space independent, neutron kinetics equations using a six-group delayed neutron model. The reactivity insertion rate and an energy coefficient of reactivity can be represented by sixth-order polynomials in time and energy, respectively. The energy coefficient is based on an effective core temperature which is a spacially weighted average temperature determined by an assumed neutron flux distribution. The weighting factor accounts for spacial importance of neutrons in the core and is equal to the flux times its adjunct. The program permits removal of reactivity by such means as control drum insertion initiated when a specified scram power level is reached.

Table 1 illustrates some of the results obtained using RTS in conjunction with the kinetic parameters shown for various step reactivity insertions. These results are compatible with the RAC results for reactivities of about 1 to 2% above prompt critical. RTS is inadequate for larger reactivities due to its neglect of vapor formation as a shutdown mechanism.

The core response to a series of ramp and step reactivity insertions under a variety of operating conditions were analyzed for the Pre-Assembly Critical using RTS. In most cases, it was assumed that the automatic scram system was operative and that a power level scram was initiated at 2 kilowatts. In such cases an instrument delay time of 0.1 seconds was assumed between the scram signal and the initial control drum motion. For those cases where the automatic scram system is inoperative, various human response delay times are assumed. The power profiles and energy release curves corresponding to these cases are shown in figures 3-8. Figures 9 and 10 correspond to step reactivity insertions

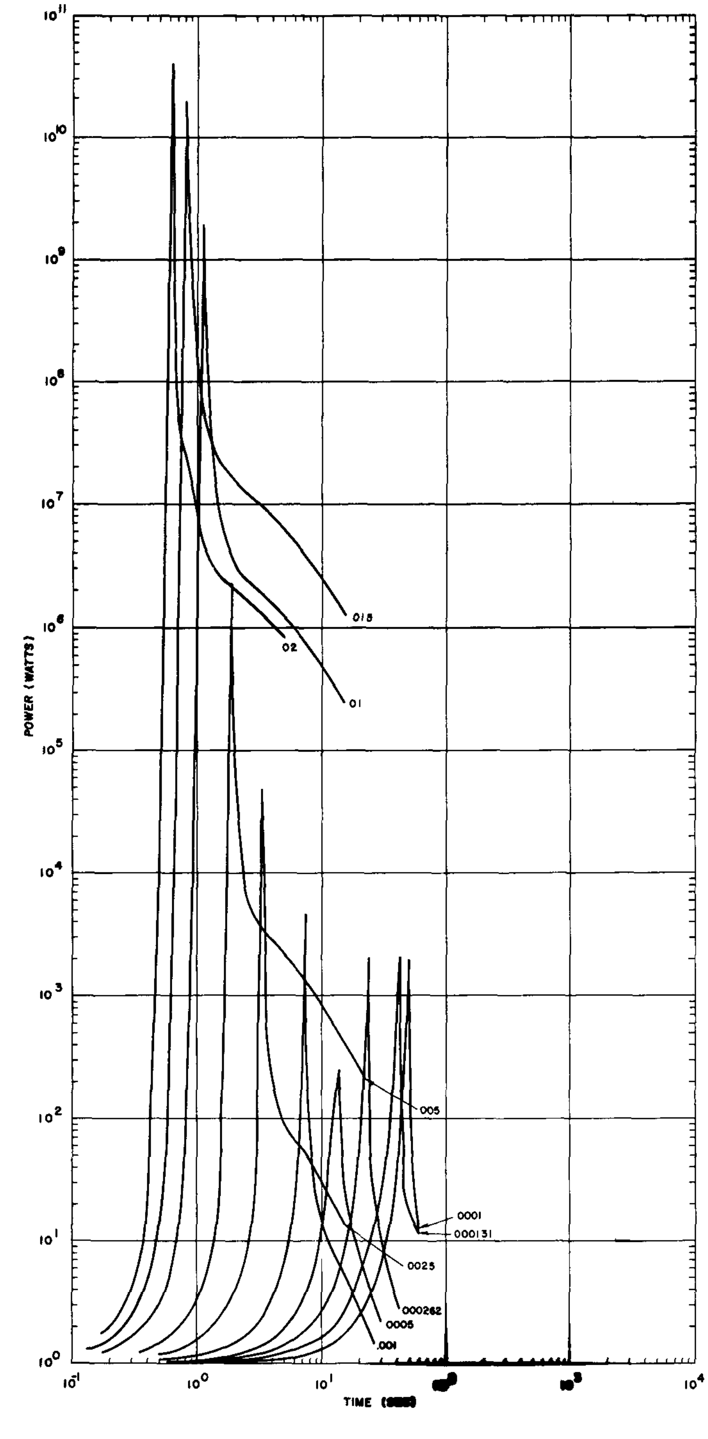

FIGURE 3

POWER PROFILES FOR RAMP REACTIVITY INSERTIONS (ΔK/SEC)

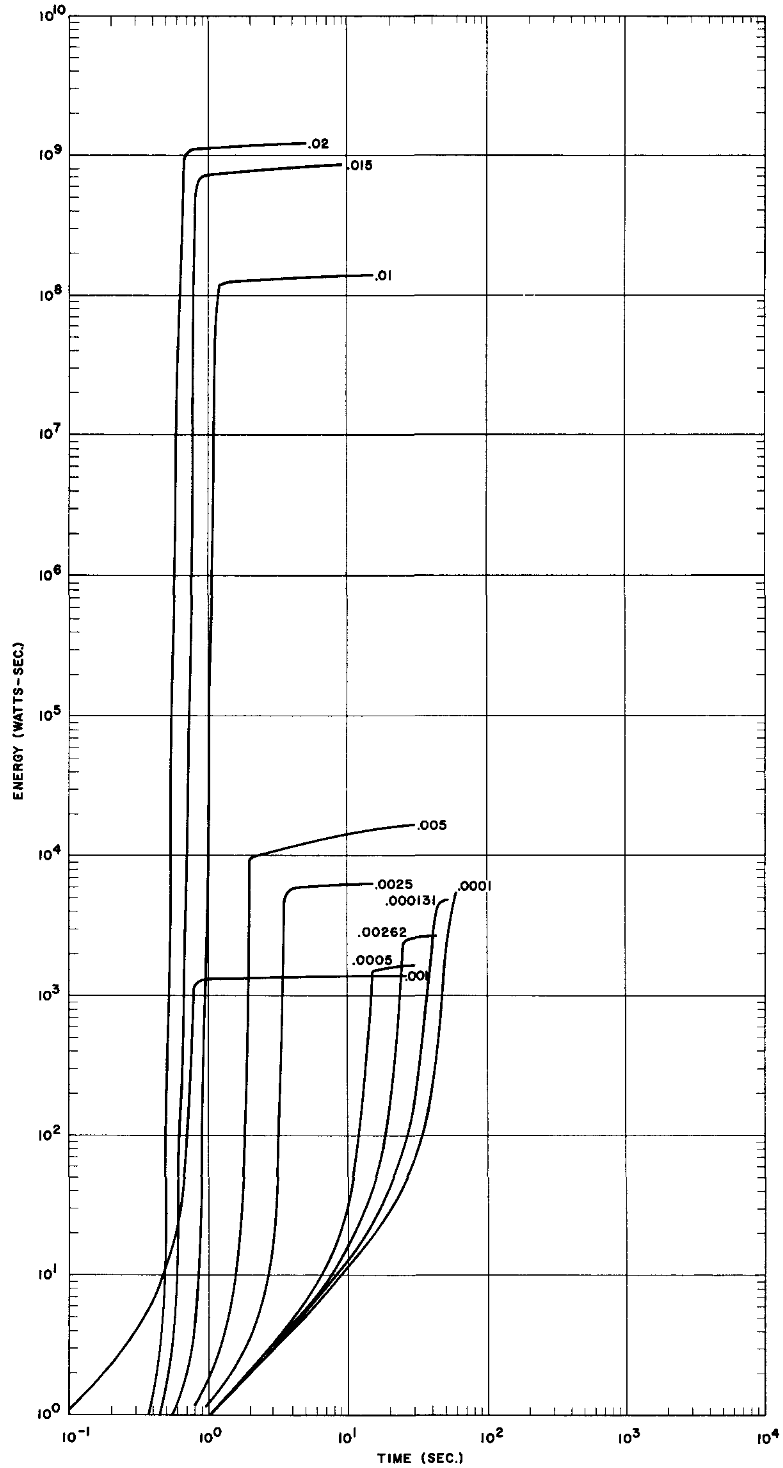

FIGURE 4

ENERGY RELEASE FOR RAMP REACTIVITY INSERTIONS (ΔK/SEC)

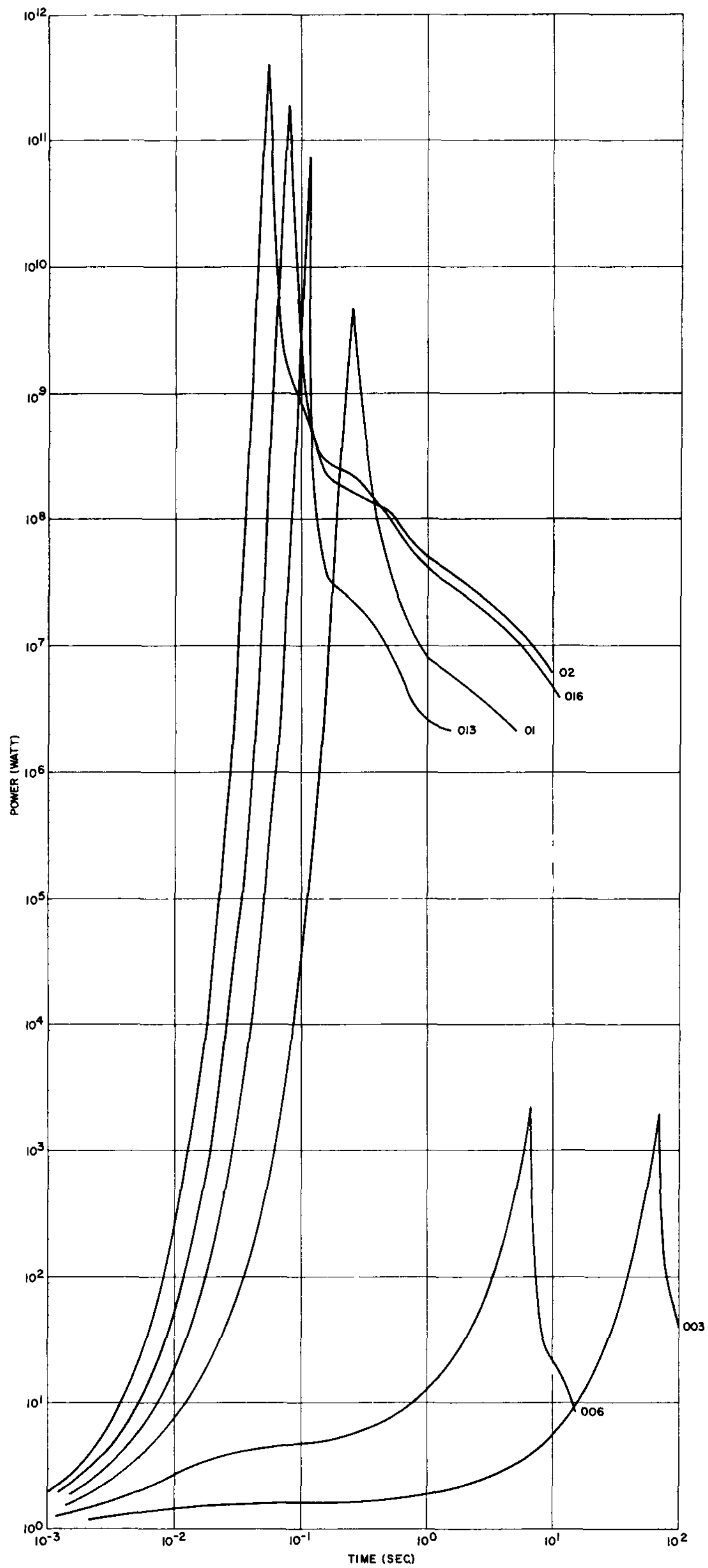

FIGURE 5

POWER PROFILES FOR STEP REACTIVITY INSERTIONS (ΔK)

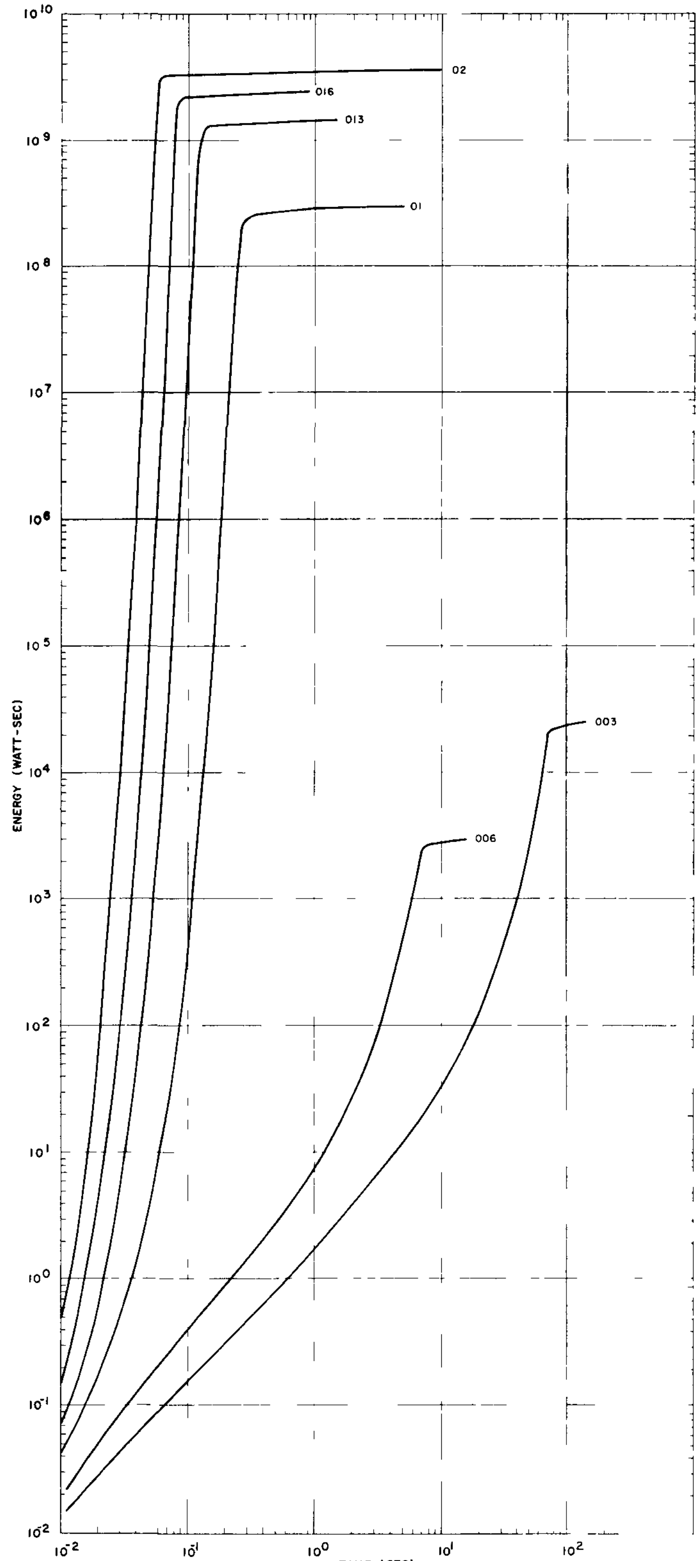

FIGURE 6

ENERGY RELEASE FOR STEP REACTIVITY INSERTIONS (ΔK)

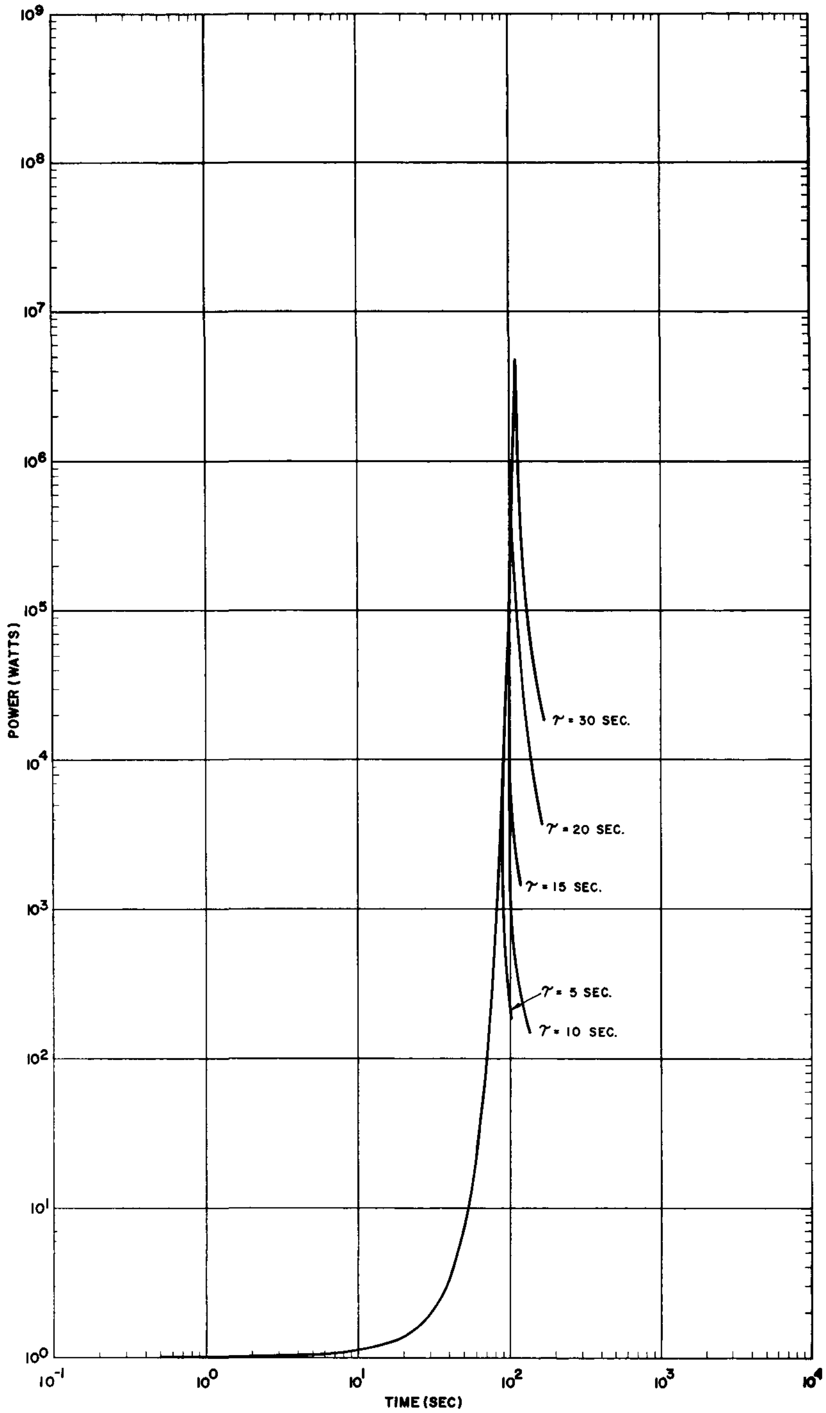

FIGURE 7

POWER PROFILES FOLLOWING ROTATION OF SINGLE DRUM FROM 30° BANK POSITION (τ = DELAY TIME FOR SCRAM)

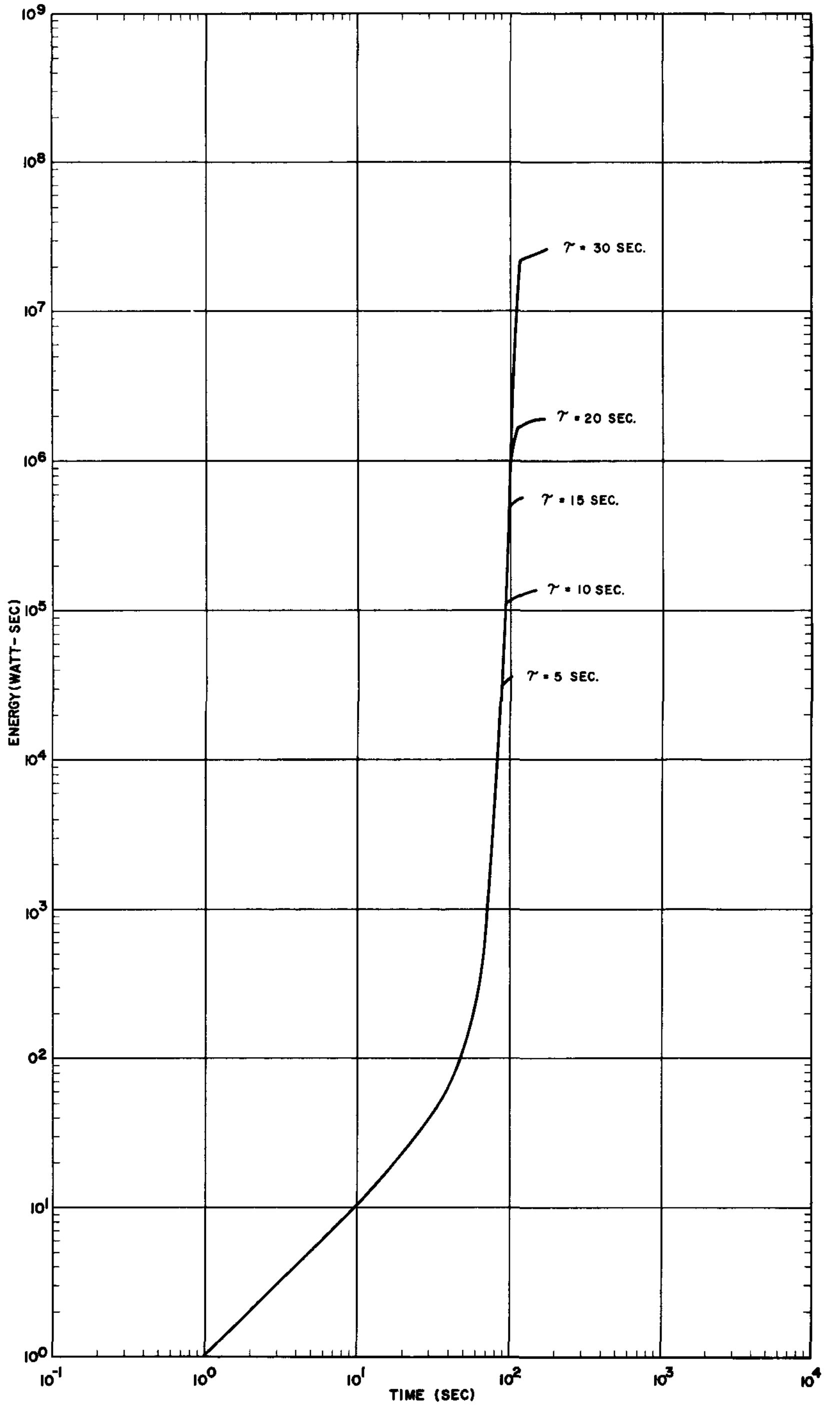

FIGURE 8

ENERGY RELEASE FOLLOWING ROTATION OF SINGLE DRUM FROM 30° BANK POSITION (τ = DELAY TIME FOR SCRAM)

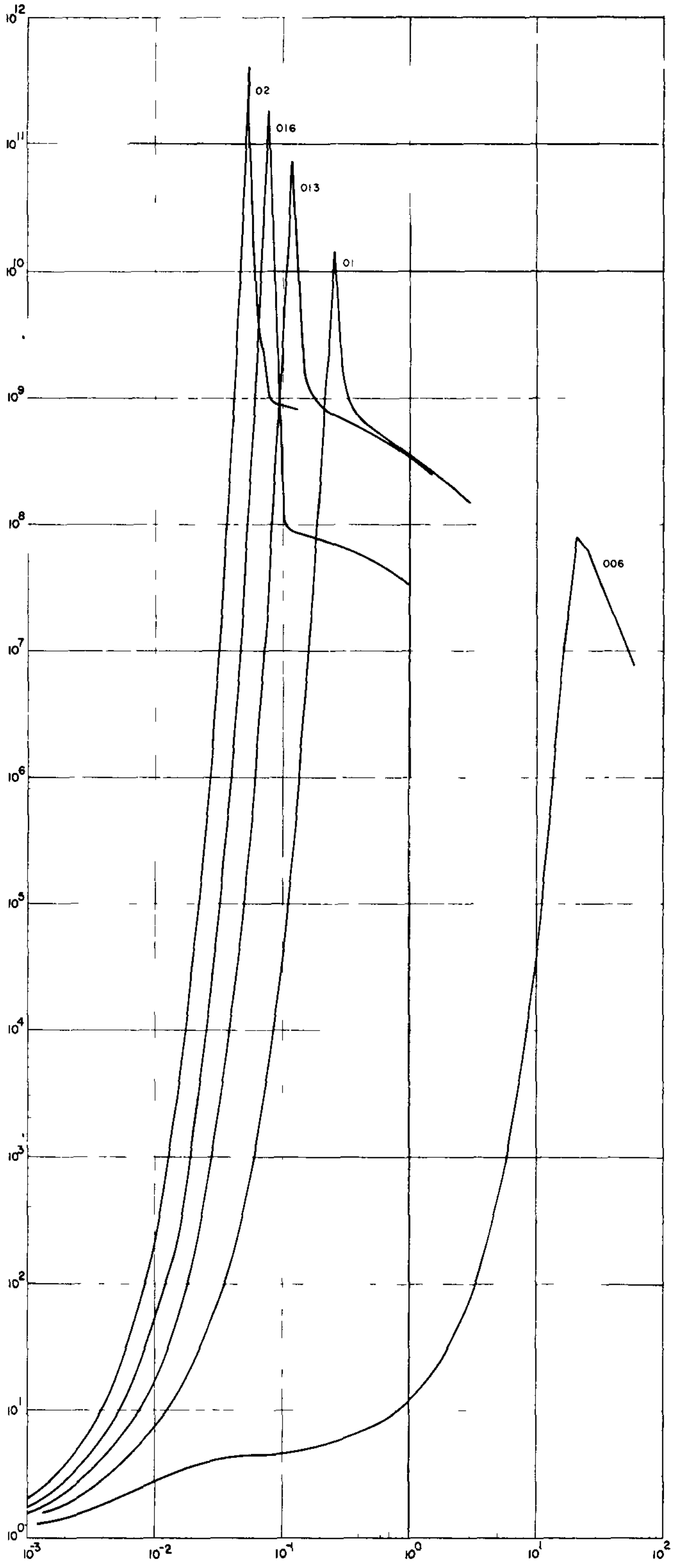

FIGURE 9

POWER PROFILES FOR STEP REACTIVITY INSERTIONS (ΔK)
WITHOUT DRUM SCRAM

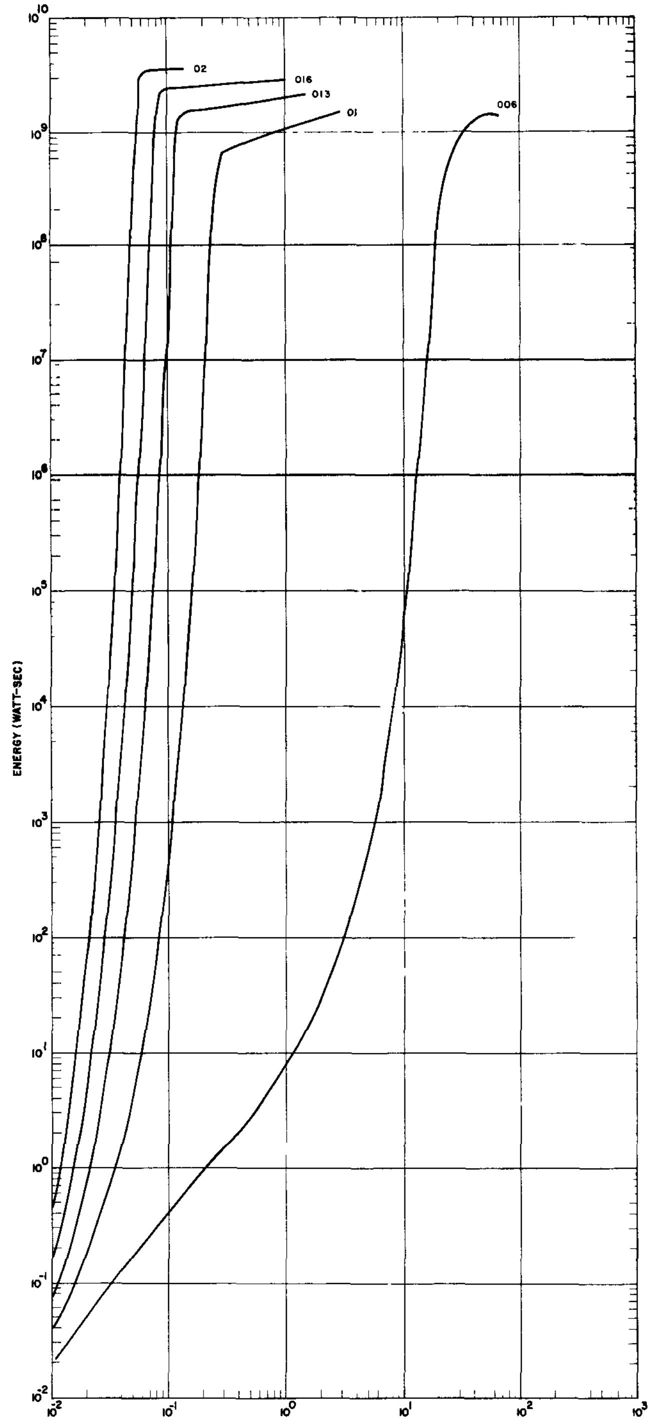

FIGURE 10

ENERGY RELEASE FOR STEP REACTIVITY INSERTIONS (ΔK)
WITHOUT DRUM SCRAM

without scram.

IV. LIMITATIONS

The RTS computer program is considered adequate over the range of problems for which its use is intended. Minor, if any, limitations are anticipated in the use of this program. Conversely, RAC has some obvious limitations arising primarily out of its relatively simple treatment of exceedingly complex hydrodynamic and thermodynamic phenomena. A few of the more important limitations which would have priority in determining any future modifications are as follows:

1. The time independent neutron spacial flux distribution restricts an adequate representation of accidents involving water immersion. The water has a moderating effect which grossly alters the neutron population locally.
2. There is no provision for the escape of graphite vapor through the coolant channels. Such an escape could drastically reduce internal pressures which would otherwise contribute to shutdown through expansion.
3. Since RAC is a one-dimensional treatment, radial pressure gradients, and therefore radial motion, must be assumed to be directly derivable from the axial pressure gradients.

4. The pyrolytic fuel pellet coating has fairly good insulation properties which may result in severe hot spots and earlier vapor or liquid formation than RAC predicts.

5. Since RAC assumes a homogeneous rigid core material, a loss of rigidity due to core break-up is unaccountable.

V. REFERENCES

1. LAMS-2920, RAC, A Computer Program for Reactor Accident Calculations, August 20, 1963.

2. Nuclear Science and Engineering, General Solution of the Reactor Kinetic Equations, 8, 670-690 (1960).