ANL-7471
Addendum 1

ANL-7471
Addendum 1

SPECIFICATIONS AND RESULTS OF A DESIGN-BASIS-ACCIDENT CALCULATION FOR ZPPR

Addendum to ANL-7471, Final Safety Analysis Report on the ZERO POWER PLUTONIUM REACTOR (ZPPR) Facility

MASTER

by

A. L. Hess and F. W. Thalgott

BASE TECHNOLOGY

U of C-AUA-USAEC

ARGONNE NATIONAL LABORATORY, ARGONNE, ILLINOIS

Prepared for the U.S. ATOMIC ENERGY COMMISSION
Division of Reactor Research and Development
under Contract W-31-109-Eng-38

DISCLAIMER

ANL-7471 Addendum 1
LMFBR Safety
(UC-79p)

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60439

SPECIFICATIONS AND RESULTS OF A DESIGN-BASIS-ACCIDENT CALCULATION FOR ZPPR

Addendum to ANL-7471,
Final Safety Analysis Report on the
Zero Power Plutonium Reactor
(ZPPR) Facility

by

A. L. Hess and F. W. Thalgott

Applied Physics Division

September 1974

TABLE OF CONTENTS

	Page
ABSTRACT	7
INTRODUCTION	7
DBA ASSEMBLY CONFIGURATION	9
PROCEDURES OF ANALYSIS	10
RESULTS OF EXCURSION AND VENTING CALCULATIONS	13
ENVIRONMENTAL CONSEQUENCES	15
SUMMARY	16
APPENDIXES	
A. Description of Reactor Calculations	18
B. Derivation of Doppler Feedback Coefficients for a 6000-liter, Two-zone ZPPR Core	21
C. Specifications and Results of the Kinetics/Heat-transfer Calculations for the Design Basis Accident on a 6000-liter Two-zone ZPPR Core	22
REFERENCES	26

LIST OF FIGURES

No.	Title	Page
1.	Calculational Scheme for Analysis of Design Basis Accident: 6000-liter, Voided, Two-zone Core, Fueled with Plutonium of 27% ^{240}Pu	10
2.	Reactivity Worth of Gap in ZPPR for a 6000-liter, Two-zone, Mixed-oxide-fueled Core	12
3.	Power History for Design Basis Accident with 6000-liter, Two-zone ZPPR Core	14
4.	Cell Pressure and Venting Characteristics after Start of Fuel Vaporization in a DBA for a 6000-liter, Two-zone ZPPR Core	15
A.1.	Geometric Details, Quadrant View, of 6000-liter, Two-zone-core Assembly Used for DBA Calculations	18
C.1.	Histories of Reactivity and Fuel Vaporization in a DBA for a 6000-liter, Two-zone Core	24
C.2.	Histories of Fuel and U_3O_8 Temperatures at Core Center in a DBA on a 6000-liter, Two-zone ZPPR Core	25

LIST OF TABLES

No.	Title	Page
I.	Plutonium-isotope Inhalation Doses from a DBA for a 6000-liter, Two-zone ZPPR Core; Strong-inversion and Weak-mixing Meteorological Conditions	16
A.1.	Regional Compositions Used in DBA Analysis: A 6000-liter, Two-zone Core, Fueled with Pu-U-Mo, with a 27% Content of ^{240}Pu in the Plutonium	18
A.2.	Specifications and Results of Diffusion-theory Calculations of k_{eff} for a 6000-liter, Two-zone Core	19
A.3.	Specifications and Results of Transport-theory (DOT) Calculations for Gap Worth and Overload Reactivity for a 6000-liter, Two-zone Core	20
A.4.	Results of First-order Perturbation-theory Calculations, Using Fluxes from RZ Diffusion Calculations, for a 6000-liter, Two-zone, Sodium-voided Core Assembly	20
B.1.	Evaluation of ^{239}Pu and ^{238}U Doppler Effects Measured in Voided Zone of ZPPR-2	21
C.1.	Input Specifications for DBA Kinetics/Heat-transfer Calculations for 6000-liter, Two-zone Core	22
C.2.	Thermal Properties of Materials Used for Oxide-fuel Simulations in DBA Calculations	23
C.3.	Cell-description Parameters Input to DBA Kinetics/Heating Code for 6000-liter, Two-zone Core	23
C.4.	Calculated Cell Overpressures Caused by Heat Released from Oxidation of Vaporized Fuel during a DBA for a 6000-liter, Two-zone Core, Totally Voided of Sodium	24

SPECIFICATIONS AND RESULTS OF A DESIGN-BASIS-ACCIDENT CALCULATION FOR ZPPR

Addendum to ANL-7471,
Final Safety Analysis Report on the
Zero Power Plutonium Reactor
(ZPPR) Facility

by

A. L. Hess and F. W. Thalgott

ABSTRACT

The Zero Power Plutonium Reactor (ZPPR) is a critical facility operated by Argonne National Laboratory in support of the AEC's Liquid Metal Fast Breeder Reactor Development Program. The Final Safety Analysis Report (FSAR) for ZPPR (ANL-7471) reported the results of excursion calculations for hypothetical accidents in simulated metallic-fueled, 1000- and 6000-liter, one-zone cores. Such analyses demonstrated the design capability of the ZPPR containment structure and were designated the Design Basis Accident (DBA). This report documents an analysis carried out for an excursion of more serious consequences for a 6000-liter, two-zone core, simulating an LMFBR fueled with a UO_2-PuO_2 mixture and using a more toxic plutonium isotopic mixture. Postulations and procedures used in the analysis were the same as prescribed for the DBA in the FSAR. Although the new off-site dose calculated is higher by a factor of seven than the dose in the FSAR DBA, it is still a fraction of the AEC-permitted occupational burden. Furthermore, the analysis confirms the capability of the containment structure for a more energetic excursion than in the FSAR DBA, and shows again that operation of the ZPPR poses no unacceptable risk.

INTRODUCTION

This report presents the results of a design-basis-accident (DBA) analysis carried out for the Zero Power Plutonium Reactor for a core more typical of current power reactor designs than that considered in the Final Safety Analysis Report (FSAR) for ZPPR (ANL-7471).[1] From that report (page 17):

> "To further illustrate the capability of the containment structure, the consequence of a hypothetical startup accident has been calculated. This accident is termed the design basis accident (DBA). It is in no way deemed credible."

In the FSAR, hypothetical startup accidents were considered for four different cores:

1. A 1000-liter, uniformly loaded, metal-fueled core with sodium loaded adjacent to the fuel.

2. A 1000-liter, uniformly loaded, metal-fueled core with void replacing sodium adjacent to the fuel.

3. A 6000-liter, uniformly loaded, metal-fueled core with sodium loaded adjacent to the fuel.

4. A 6000-liter, uniformly loaded, metal-fueled core with void replacing sodium adjacent to the fuel.

Of these accident analyses, the fourth was shown to have the most serious consequences, although the consequences were well within acceptable limits and well within the limits defined in the FSAR.

Current designs for power reactors postulate two zones of enrichment of approximately equal volume in the cores with fuel of higher ^{240}Pu and ^{241}Pu content than the basic fuel for ZPPR.

A teletype from Shaw to Dunbar, March 7, 1969, made the following statement:

> "Should the use of fuel of more toxic isotopic content be planned for the facility, or the planned arrangement of fuel be changed so as to increase the potential DBA consequences, a recalculation of minimum acceptable attenuation factor for the ZPPR filtration system will be necessary. ANL has the responsibility for advising AEC of proposed significant changes in the type or use of fuel in the ZPPR."

Although the study of such ZPPR assemblies with fuels of different forms and different enrichments and isotopic content in zones was included in ANL-7471, a DBA-type analysis has been made for such a more typical design. The purpose of this report is to document compliance with the request of the March 7, 1969, teletype.

This addendum shows that the consequences of this hypothetical startup accident, although more severe than those calculated in the SAR, are still within any limits discussed in the SAR.

In particular, as required by the FSAR (see page 18, ANL-7471), this calculation establishes that:

1. The calculated prompt power coefficient is negative.

2. The calculated maximum cell pressure is not in excess of 12.5 psig.

3. The inhalation dose at the NRTS site boundary does not exceed the nonoccupational maximum permissible body burden, or, stated in other words, the minimum acceptable attenuation factor for this analysis is less than that demonstrated for the ZPPR containment filter.

The critical assembly postulated for study is a 6000-liter core of a composition simulating a PuO_2-UO_2-fueled power reactor with an outer-core zone of higher enrichment than the central-core zone. The following assumptions were adopted:

1. The core is entirely fueled with a "dirty" plutonium (higher ^{240}Pu and ^{241}Pu than most of the ZPPR fuel).

2. The entire core is voided of its normal sodium content at the time of the accident.

3. Because of empty cans (replacing sodium) next to the fuel, molten fuel does not flow out of the reactor, and the shutdown occurs through fuel vaporization.

4. The vaporized fuel that eventually escapes the backup containment system is assumed to be the "dirtiest" type available for experiments in ZPPR: the composition used is that for the plutonium perturbation sample No. 48.

Factors 1 and 2 above also contribute to the severity of the accident by giving a pessimistic negative Doppler feedback reactivity.

The appendixes to this report give the specifications and results of all the computer calculations carried out in this analysis.

DBA ASSEMBLY CONFIGURATION

To give an L/D ratio of about 0.5, the height of the 6000-liter DBA core was set at 48 in. Outer radii of 34.84 and 49.28 in., respectively, gave equal volumes to the inner- and outer-core zones. In both the inner- and outer-core zones, the compositions represented a power reactor core of 35 vol % PuO_2-UO_2, 40 vol % sodium, and 16 vol % steel, with the 9 vol % remaining allotted to the inherent void in ZPPR. The fuel enrichment in the outer core was set at 1.5 times the fuel enrichment in the inner core, both enrichments being determined for criticality by diffusion-theory search calculations.

A composition of 35 vol % UO_2, 40 vol % sodium, 16 vol % steel, and 9 vol % void was used in the 16-in.-long axial blankets, and these zones were backed up with axial reflectors of 51 vol % steel, 40 vol % sodium, and 9 vol % void. A 16-in. thickness of a 50 vol % UO_2, 25 vol % sodium, 16 vol % steel composition blanketed the core radially.

More details on the model geometry and the atomic densities used for the various regions in the reactor calculations are given in Appendix A.

PROCEDURES OF ANALYSIS

Figure 1 outlines the processes involved in this DBA analysis. The 27-group cross-section set generated from ENDF/B (Version I) for the analysis

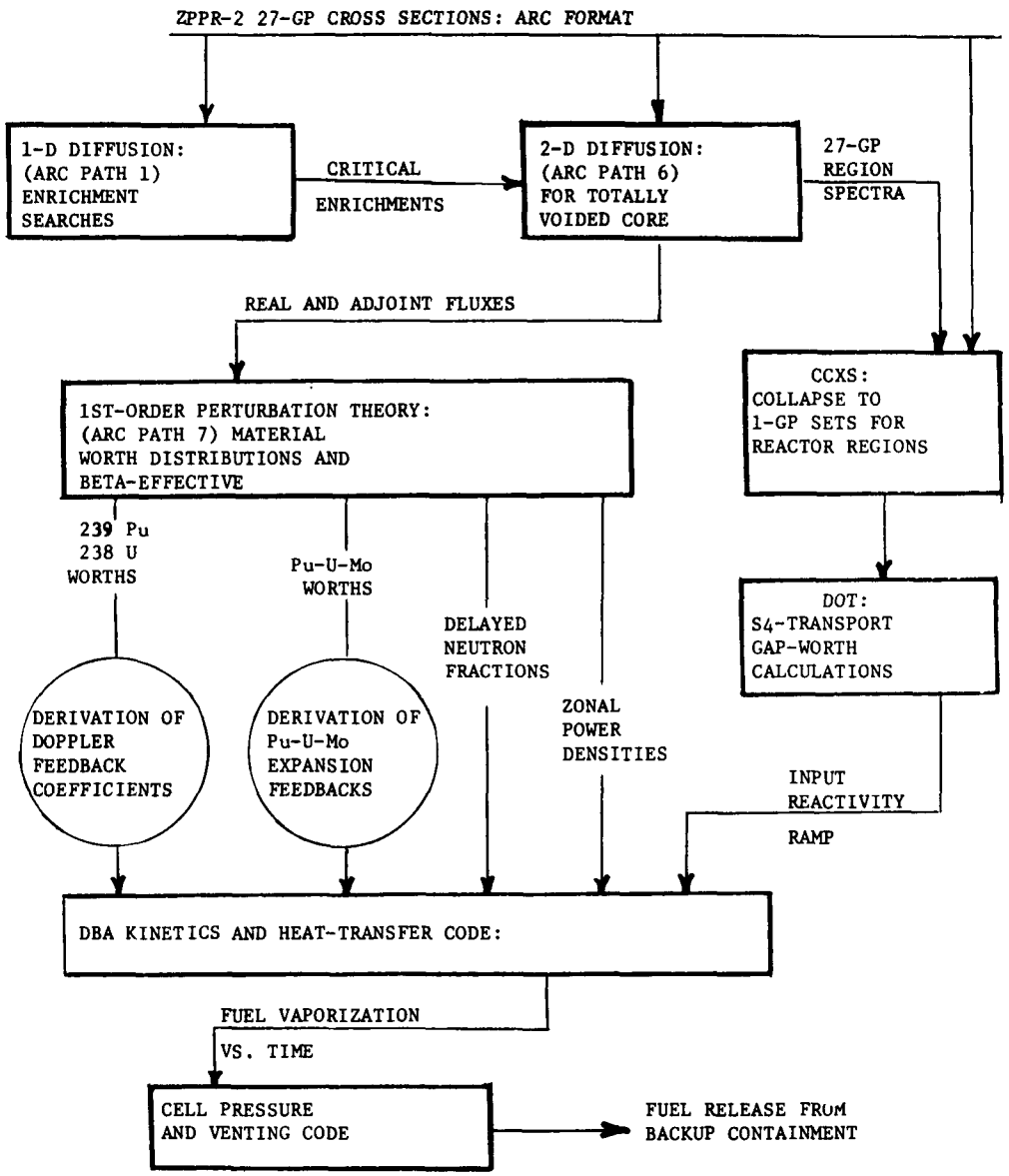

Fig. 1. Calculational Scheme for Analysis of Design Basis Accident: 6000-liter, Voided, Two-zone Core, Fueled with Plutonium of 27% ^{240}Pu. ANL Neg. No. 103-B11507.

of ZPPR Assembly 2 was used for these 6000-liter DBA studies, since the compositions of the two reactor systems are similar.

In the RZ diffusion calculations, the inner core was segmented into six zones (three radial x two axial) and the outer core into four zones (two radial x two axial). The average spectra obtained for these 10 core zones, and also the various blanket zones, were then input to a collapsing code to generate regional macroscopic one-group cross sections for use in RZ transport calculations of the reactivity versus separation of the assembly halves.

Delayed-neutron parameters for the system were derived from perturbation-theory calculations using the real and adjoint fluxes output from the RZ diffusion calculations. The material worths and power distributions for the 10 core zones and various blanket regions were also derived using the fluxes from the RZ diffusion case for the reactor halves together; material worths for nonzero gap configurations were not considered sufficiently different to warrant the expense of specific calculations.

Axial power distributions were used for weighting the axial worth distributions to account for the higher heating rates in the axial positions of higher material worths. The weighted average worths of Pu-U-Mo (fuel-plate composition) in each of the 10 core zones, subtracting the worth at the far axial end of the zone, provided the fuel-expansion worth factors, $\Delta k/k$ per $\Delta \ell/\ell$, according to the zone.

Doppler coefficients were established using calculated weighted zonal worths for ^{239}Pu and ^{238}U in the DBA case and the measured ratios of Doppler reactivity effect to total sample worths for these isotopes determined in the Doppler experiments at the center of the voided zone of ZPPR-2.[2]

The accident code used for this analysis is the combination point-kinetics/heat-transfer code written by Palmer[3] and used in previous DBA studies[1,4] on ZPR systems. In this program, a ramp reactivity insertion is input to represent closure of the ZPR halves. Feedback reactivities are calculated from heated plate regions in a ZPR-type cell for each of several core zones (up to 10). Heat transfer between plates can be accomplished, as well as material melting and boiling.

The cell model used for this analysis contained four regions: a plate of Pu-U-Mo, two plates of U_3O_8, and a broad region representing the structure and the voided sodium cans. The combined width of the two U_3O_8 plates represented the U_3O_8 content per Pu-U-Mo plate in the six inner-core zones. In the four outer-core zones, the U_3O_8 content per Pu-U-Mo plate was represented using only one of the U_3O_8 plates (zero feedbacks from the other plate). The relative power densities assigned to the 10 core zones, and within the cell to the four different regions, were adjusted to provide the proper relative heating of the Pu-U-Mo plates in all zones. For simplicity, the average $^{238}U/^{239}Pu$ fission ratio in the outer core was assumed the same as in the inner core.

To achieve the worst-case calculation in which sodium had been replaced by void adjacent to the fuel plates, an adiabatic excursion was achieved by specifying essentially zero (10^{-10}) heat-conductance coefficients for the boundaries between the regions of the cell. As previously stated, molten fuel is not allowed to flow from the core (to give a negative feedback), but is assumed to occupy the adjacent empty-can space. Thus, the excursion shutdown must result from fuel vaporization, and the calculated Pu-U-Mo worths in the zones provided the reactivity loss per kilogram evaporated.

Thermal-property specifications are required in the DBA code for each material involved for up to 10 different temperature ranges. For Pu-U-Mo, the values used were taken from Tables III and VII of Ref. 1. For U_3O_8, the parameters were adopted from Table 5.2-1 of the FSAR for the VTRZ.[4]

The coefficients of expansion for Pu-U-Mo in five temperature ranges up to the melting point (1230°K), multiplied by the zone expansion-worth factors ($\Delta k/k$ per $\Delta \ell/\ell$), provided the fuel-expansion reactivity-feedback coefficients for the code. The temperature changes and worths of the U_3O_8 plates in all the zones were assigned no feedback coefficient for expansion. Doppler feedback coefficients were specified for the Pu-U-Mo and both the U_3O_8 regions in the inner-core zones, and for the Pu-U-Mo and one U_3O_8 region in the outer-core zones.

The basic postulation in these DBA excursions is an overloading of the reactor sufficient to achieve prompt criticality during closure of the halves. Two-dimensional transport-theory calculations of k_{eff} for the system at various stages of halves separation provided the reactivity insertion rate due to table motion. Figure 2 shows the relative reactivity as a function of gap width.

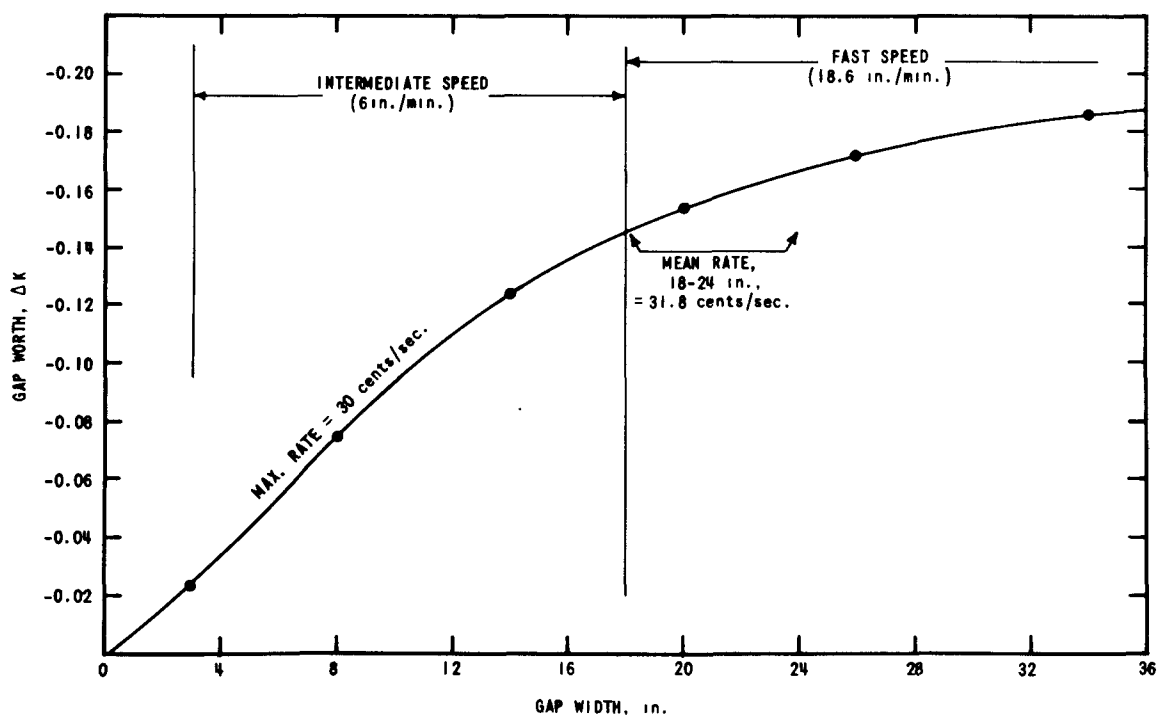

Fig. 2. Reactivity Worth of Gap in ZPPR for a 6000-liter, Two-zone, Mixed-oxide-fueled Core. ANL Neg. No. 103-B11509.

The maximum slope of the curve, 1.045 %k/in., occurs at about 6 in. in the intermediate-speed range. However, for a sufficient overloading (giving at least 15% $\Delta k/k$ excess), the closure rate on the high speed would produce a greater ramp. For the DBA analysis, which involves fuel boiling for 20 sec, the average ramp in the last 6 in. on the high speed was adopted. From 18 to 24 in., the mean slope is 0.355 %k/in., giving a 0.11 %k/sec ramp, or 31.8 cents/sec, for a beta-effective of 0.00346.

Appendix A includes the specifications and results of the diffusion and transport calculations cited above and also lists the regional worths of fuel, ^{239}Pu, and ^{238}U obtained from the perturbation calculations. Additional transport calculations and material-worth calculations reported in Appendix A indicate that to obtain criticality beyond 18 in. of gap requires loading the entire inner core with outer-core composition.

Appendix B contains a discussion of the derivation of Doppler reactivity feedbacks as used in this DBA analysis.

RESULTS OF EXCURSION AND VENTING CALCULATIONS

Figure 3 shows the variation with time of the reactor power and integrated power as calculated by the DBA kinetics code for the 6000-liter, two-zone core. The peak power attained, just before fuel boiling, is preceded by rapid growth during the period of fuel melting (when expansion feedbacks are cut off, and Doppler feedbacks are temporarily zero, for various zones in succession). Figure 4 contains a plot of the total fuel vaporized as a function of time after the start of boiling, indicating an initial vaporization rate of about 80 kg/sec. After 20 sec of boiling, at which time the excursion is considered terminated, a total of 305.9 kg has been vaporized.

The output from the kinetics code, which gives the fuel-vaporization chronology, serves as the input for the final computation of the DBA analysis, which is the cell-pressure and containment-venting calculation; this computation uses a computer program, written by C. Beck, and is a combination of the cell-pressurization code described in Appendix A of Ref. 1 and the venting routine in Appendix B of that report. The cell overpressure versus time, as determined by the calculation, is shown in Fig. 4: the peak pressure, 12.08 psig, occurs 1.3 sec after the start of boiling. The residual overpressure of 1.2 psig at the end of boiling would drop to zero in a few seconds more.

Figure 4 also shows the fuel venting versus time from the backup containment structure (assuming no filtration) during the 20 sec of boiling. At the end of the period, the total fuel vented is 18.92 kg of Pu-U-Mo. Assuming an attenuation of 5×10^4 for the gravel-sand filter and tophat filters combined, the release to the atmosphere becomes 0.3784 g of Pu-U-Mo. With the mixture content of 34.14 wt % plutonium, the plutonium release is then 129.2 mg.

Appendix C contains listings of all the input parameters for the DBA kinetics code and the cell-pressure code and other details of these calculations.

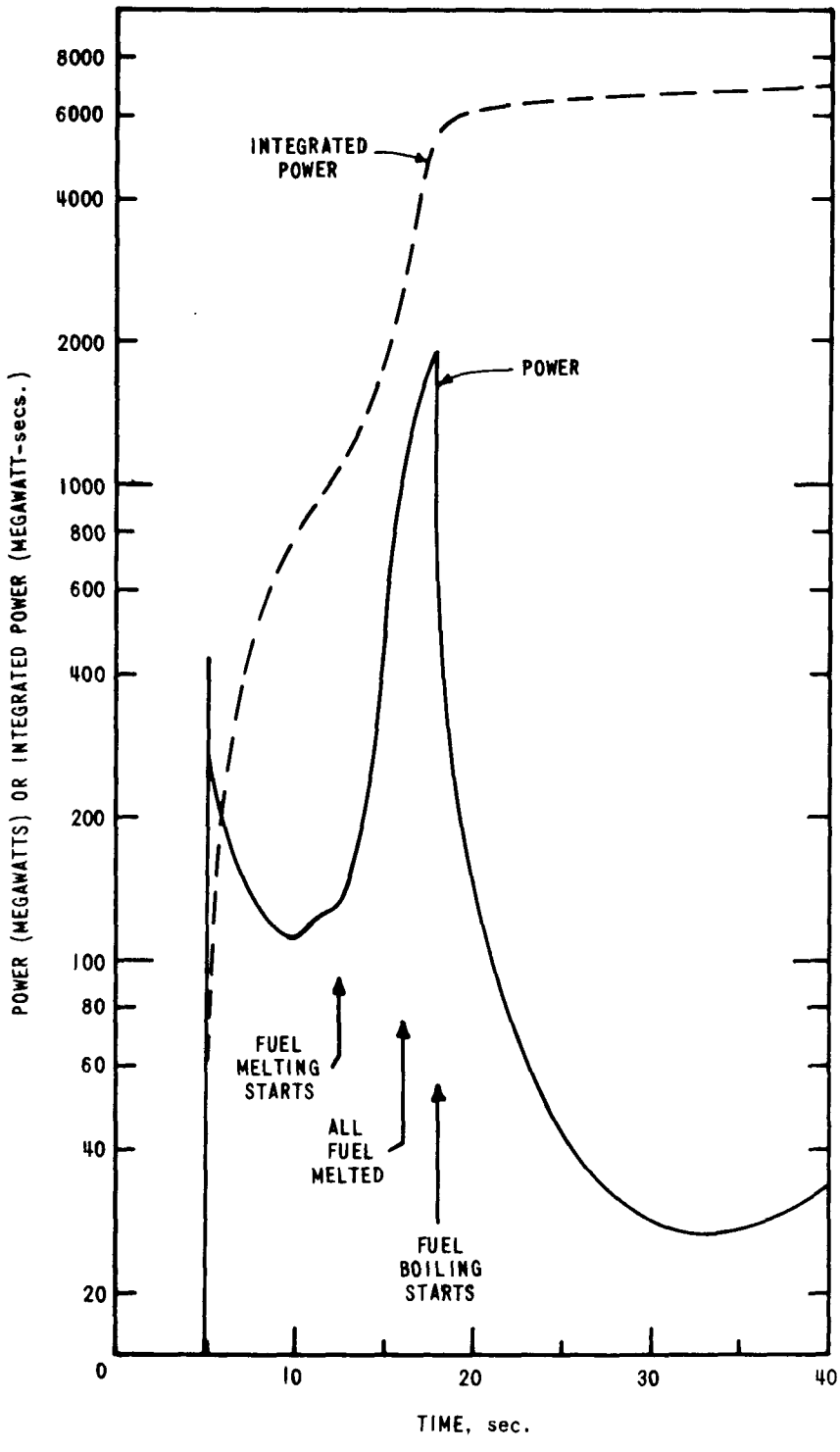

Fig. 3. Power History for Design Basis Accident with 6000-liter, Two-zone ZPPR Core. ANL Neg. No. 103-B11510.

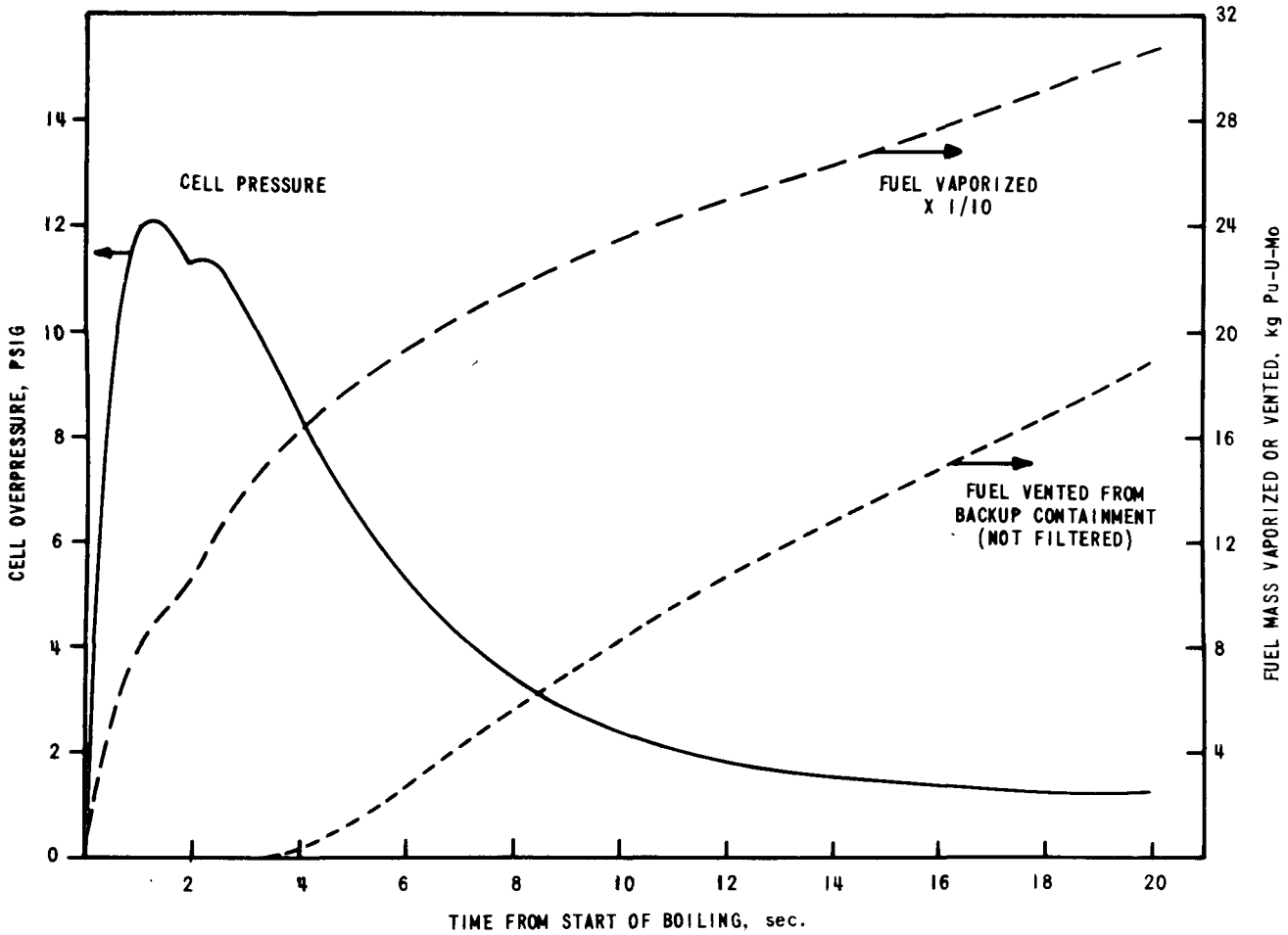

Fig. 4. Cell Pressure and Venting Characteristics after Start of Fuel Vaporization in a DBA for a 6000-liter, Two-zone ZPPR Core. ANL Neg. No. 103-B11512.

ENVIRONMENTAL CONSEQUENCES

To provide an extreme case, which would present the most pessimistic conditions during an accident in ZPPR, the composition of the fuel released from the backup containment was assumed to be that of the "dirtiest" plutonium on hand at the facility for in-core experiments. The mixture used was 40.5% ^{239}Pu, 46.4% ^{240}Pu, and 13.1% ^{241}Pu, and these values were derived from the composition of a plutonium perturbation sample (No. 48) after combining the ^{238}Pu and ^{241}Am with ^{241}Pu, and the ^{242}Pu with ^{240}Pu. Thus, the release from the tophat becomes 52.3 mg ^{239}Pu, 59.9 mg ^{240}Pu, and 16.9 mg ^{241}Pu.

The downwind plutonium concentrations from this DBA release were evaluated as prescribed for the original DBA in the FSAR, assuming a strong inversion and using a wind velocity of 1 m/sec. Using the same breathing rate and retention factors as before, the plutonium doses listed in Table I were obtained.

TABLE I. Plutonium-isotope Inhalation Doses from a DBA for a 6000-liter, Two-zone ZPPR Core; Strong-inversion and Weak-mixing Meteorological Conditions[a] (breathing rate = 3.47×10^{-4} m^3/sec; retention factor = 0.2)

Location	Total Plutonium		^{239}Pu		^{240}Pu		^{241}Pu	
	μg	μCi	μg	μCi	μg	μCi	μg	μCi
ZPPR Support Wing,[b] 55 m	3.4×10^{-2}	5.0×10^{-1}	1.4×10^{-2}	8.5×10^{-4}	1.6×10^{-2}	3.5×10^{-3}	4.5×10^{-3}	5.1×10^{-1}
Laboratory and Service Building,[b] 150 m	3.2×10^{-2}	4.8×10^{-1}	1.3×10^{-2}	8.0×10^{-4}	1.5×10^{-2}	3.3×10^{-3}	4.2×10^{-3}	4.8×10^{-1}
EBR-II Reactor,[b] 300 m	2.8×10^{-2}	4.2×10^{-1}	1.1×10^{-2}	7.0×10^{-4}	1.3×10^{-2}	2.8×10^{-3}	3.7×10^{-3}	4.2×10^{-1}
Nearest Site Boundary,[b] 4700 m	1.9×10^{-3}	2.7×10^{-2}	7.5×10^{-4}	4.6×10^{-5}	8.5×10^{-4}	1.9×10^{-4}	2.4×10^{-4}	2.7×10^{-2}
Maximum Permissible Total Body Burdens, Occupational (bone as critical organ)	5.10×10^{-2}	7.6×10^{-1}	6.5×10^{-1}	4.0×10^{-2}	1.8×10^{-1}	4.0×10^{-2}	8.0×10^{-3}	9.0×10^{-1}
Emergency Maximum Permissible Body Burden (bone as critical organ)	5.10×10^{-3}	7.6×10^{-2}	6.5×10^{-2}	4.0×10^{-3}	1.8×10^{-2}	4.0×10^{-3}	8.0×10^{-4}	9.0×10^{-2}

[a]Wind velocity = 1 m/sec.
[b]Using a containment attenuation of 5×10^4 by gravel-sand roof and the backup containment structure.

After 20 sec of fuel boiling in the excursion, the integrated power was 6890 MW-sec, representing 2.07×10^{20} fissions, and 24.8% of the initial air remained in the cell (compared with 1.18×10^{20} fissions and 28.8% of the air remaining in the FSAR DBA). Compared with 11.5% of the cell air in the FSAR DBA venting from the backup containment, 8916 ft^3 or 15.4% of the cell air vents to the atmosphere in the present analysis.

Assuming all the gaseous fission products are mixed into the cell air before pressurization, the fission products vented in the revised DBA are a factor of $2.07/1.18 \times 15.4/11.5 = 2.35$ times the quantity vented in the DBA of the FSAR. The revised iodine-inhalation doses would also be 2.35 times the values in Table XVIII of the FSAR.[1]

SUMMARY

1. The analysis for a DBA for ZPPR was carried out using a 6000-liter, two-zone-core design of a composition simulating 35 vol % PuO_2-UO_2, 40 vol % sodium, 16 vol % steel, and 9 vol % void.

2. A high-^{240}Pu mixture of plutonium was assumed, and at the time of the accident, the core was totally voided of sodium.

3. With an input reactivity of 31.8 cents/sec and an isothermal Doppler coefficient of -25×10^{-6} $\Delta k/°C$, the peak power reached was 1900 MW and the fuel started boiling at 80 kg/sec.

4. The maximum cell overpressure attained is 12.08 psig, and a total of 306 kg of Pu-U-Mo is vaporized in 20 sec of boiling.

5. The release from the backup containment amounts to 378 mg of Pu-U-Mo (129 mg plutonium) and the gaseous fission products from 3.2×10^{19} fissions ($2.07 \times 10^{20} \times 0.154$).

6. The plutonium released from the backup containment is assumed to be the "dirtiest" available.

7. A strong inversion with a wind velocity of 1 m/sec is assumed in determining downwind concentrations.

8. The off-site (4700 m) plutonium dose attains a value of 1.9×10^{-3} μg or 2.7×10^{-2} μCi, about 37% of the AEC's Emergency Maximum Permissible Body Burden for the high-^{240}Pu isotopic mixture. The dose for this two-zone, 6000-liter DBA is thus seven times the dose for the DBA in the FSAR.

9. Beta/gamma and iodine doses in this revised case are 2.35 times the values in the FSAR.

APPENDIX A

Description of Reactor Calculations

The geometry and compositions used for the diffusion-theory calculations are presented in Fig. A.1 and Table A.1. Table A.2 gives the mesh structures and other specifications for the diffusion calculations, along with the calculated k values.

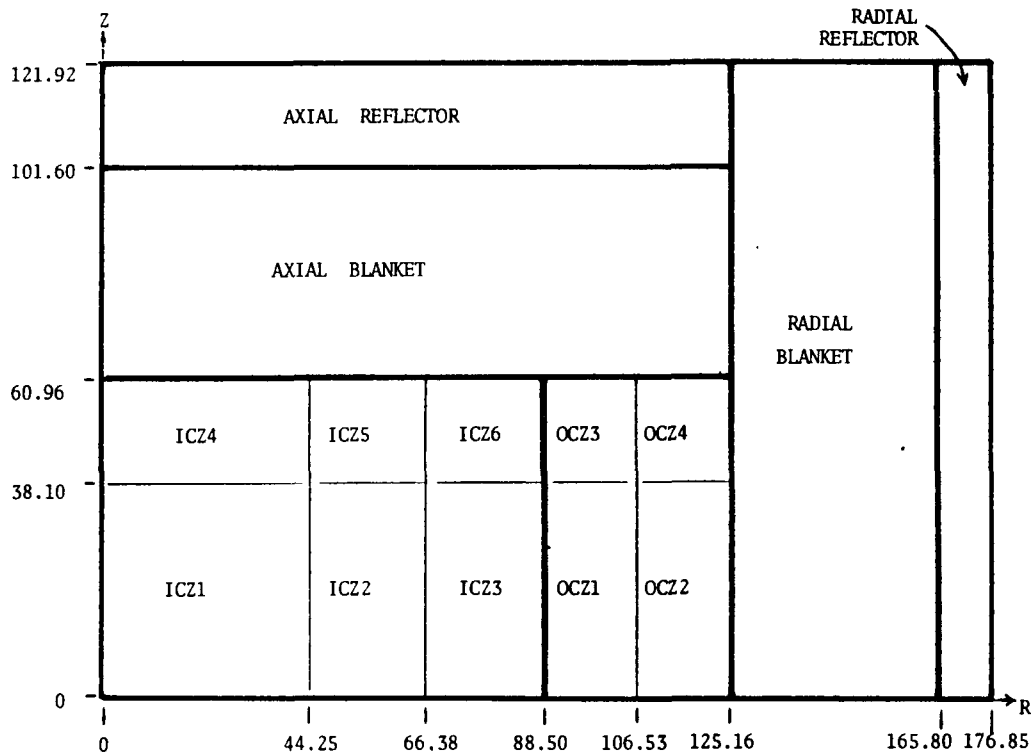

Fig. A.1. Geometric Details, Quadrant View, of 6000-liter, Two-zone-core Assembly Used for DBA Calculations. ANL Neg. No. 103-B11508.

TABLE A.1. Regional Compositions Used in DBA Analysis: A 6000-liter, Two-zone Core, Fueled with Pu-U-Mo, with a 27% Content of ^{240}Pu in the Plutonium

	Average Region Composition, 10^{22} atoms/cm^3					
Material	Inner Core	Outer Core	Radial Blanket	Axial Blanket	Radial Reflector	Axial Reflector
^{239}Pu	0.06970	0.10530	-	-	-	-
^{240}Pu	0.02825	0.04268	-	-	-	-
^{241}Pu	0.00485	0.00734	-	-	-	-
^{238}U	0.70714[a]	0.65471[b]	1.15747	0.80970	-	-
^{235}U	0.00143[c]	0.00133[c]	0.00234	0.00166	-	-
O	1.62272	1.62272	2.31840	1.62272	-	-
Na	-	-	0.56980	0.91169	-	0.91169
Fe	0.95380	0.95380	0.95380	0.95380	5.22210	3.23660
Cr	0.27060	0.27060	0.27060	0.27060	1.44320	0.89450
Ni	0.11870	0.11870	0.11870	0.11870	0.65070	0.40330
Mn	0.02480	0.02480	0.02480	0.02480	0.13890	0.08610
Mo	0.01833	0.02769	-	-	-	-

[a]27.10% in fuel plates, 72.90% in U_3O_8 plates.
[b]44.23% in fuel plates, 55.77% in U_3O_8 plates.
[c]Total content in fuel and U_3O_8 plates.

TABLE A.2. Specifications and Results of Diffusion-theory Calculations of k_{eff} for a 6000-liter, Two-zone Core

I. One-dimensional (finite-cylinder) Concentration Search

A. Specifications

Basic Core Composition:	35 vol % PuO_2-UO_2 (Pu = 27% ^{240}Pu) 40 vol % Na, 16 vol % steel, 9 vol % void outer/inner enrichment ratio = 1.5
Radial Blanket Compositions:	As in Table A.1.
Axial Reflector Savings: (based on ZPPR-2 data)	Inner core 22.52 cm Outer core and blanket 21.23 cm
Radial Boundaries·	As illustrated in Fig. A.1.
Mesh Intervals:	Inner core· 36 Outer core· 24 Radial blanket 18 Reflector 4
Cross Sections·	27-group, ZPPR-2 homogeneous MC^2. (based on ENDF/B, Version I)
Search Parameter.	Relative fraction of Pu-U-Mo, keeping constant total content of plutonium and uranium isotopes--also keeping OC/IC enrichment ratio of 1.5.

B. Results

With homogeneous cross sections, convergence on k = unity for enrichment of 9.579% (content of ^{239}Pu + ^{241}Pu + ^{235}U, relative to total U + Pu) in inner core.

Variation of reactivity with enrichment = 6.19% k per 1.0% enrichment of the total core.

Correcting for heterogeneity (1.3% k, estimated on basis of ZPPR-2 calculations) and voiding (0.05% k) indicating a critical enrichment for the 2-D calculations of 9.36% in inner core, 14.04% in outer core.

II. Two-dimensional RZ Calculations for Real and Adjoint Fluxes

A. Specifications

Compositions. As listed in Table A.1, basic core compositions in Part A above, with IC enrichment of 9.36%, OC enrichment of 14.05%.

Geometry: As shown in Fig. A.1.

Mesh Intervals: (See Fig. A.1 for boundaries.)

Radial		Axial	
Boundaries, cm	No. of Intervals	Boundaries, cm	No. of Intervals
0.0 to 44.250	4	0.0 to 38.100	6
44.250 to 66.375	4	38.100 to 60.960	5
66.375 to 88.500	4	60.960 to 76.200	3
88.500 to 106.830	4	76.200 to 101.600	3
106.830 to 125.160	4	101.600 to 121.920	2
125.160 to 145.480	4		
145.480 to 165.800	4		
165.800 to 176.850	2		

Cross Sections: 27-group, generated for voided-core zones of ZPPR-2, including resonance-shielding and spatial effects of heterogeneity.

B. Results, k_{eff} calculated

Real: 0.99895 ± 0.00005, adjoint: 0.99891 ± 0.00005.

Table A.3 gives the details on the DOT calculations (S4-transport) that provided the reactivity variation with separation of the reactor halves. The two last calculations listed in part B, of the table were to determine the excess reactivity that would result from replacing the entire inner-core composition with outer-core composition.

TABLE A 3 Specifications and Results of Transport-theory (DOT) Calculations for Gap Worth and Overload Reactivity for a 6000-liter Two-zone Core

A Specifications

Cross sections	One-group sets for each region defined in Fig A 1, collapsed using region spectra from RZ diffusion calculations
Geometry	As defined in quadrant view in Fig A 1 except for addition of air-filled region at lower horizontal boundary with height equal to half of gap width
Mesh intervals	As used in RZ diffusion calculations (Table A 2) for core and blanket regions Additional intervals used for gap as specified below
Quadrature	S_4

B Results

Problem	Gap in	Gap Mesh Intervals (from Z = 0 0 to 1/2 x gap)	Core-zone Loadings	Calculated k_{eff} (±0 00005)	% Δk/k (from gap = 0 0 in)
1	0 0	0	Normal	1 03015	0 000
2	3 0	2	Normal	1 00607	2 338
3	8 0	6	Normal	0 95388	-7 404
4	14 0	11	Normal	0 90294	-12 349
5	20 0	6	Normal	0 87214	-15 338
6	26 0	8	Normal	0 85350	-17 148
4	34 0	11	Normal	0 83925	-18 521
8	0 0	0	Overload[a]	1 21577	0 000
9	14 0	11	Overload[a]	1 06676	12 256

[a]Outer-core composition loaded into entire inner core (one-group macroscopic cross sections for OCZ1 used in the six inner-core zones) Overload reactivity (for 0 0-in gap) = 18 02% Δk/k

Table A.4 lists the results of the perturbation-theory calculations (ARC path 7) to obtain the worths per kilogram of Pu-U-Mo, ^{239}Pu in Pu-U-Mo, ^{238}U in Pu-U-Mo, and ^{238}U in U_3O_8 for each of the 10 core regions. These material worths were required to derive the temperature feedback coefficients for the kinetics code. Additional worth calculation provided the worth of restoring sodium to the voided core, by zones, and of replacing inner-core with outer-core composition in each of the six inner-core zones.

TABLE A 4 Results of First-order Perturbation-theory Calculations Using Fluxes from RZ Diffusion Calculations for 6000-liter Two-zone Sodium-voided Core Assembly (27% ^{240}Pu in Pu-U-Mo)

Region	Volume liters	Power Fraction	Average Material Worths 10^{-5} Δk/k per kg: Fuel (Pu-U-Mo)	^{239}Pu in Pu-U-Mo	^{238}U in Pu-U-Mo	^{238}U in U_3O_8	Sodium	Worth of Replacing Inner-core Composition with Outer-core Composition % Δk/k
Inner Core								
ICZ1	469	0 0842	9 233	39 54	-2 216	-2 328	-1 694	3 147
ICZ2	586	0 1045	9 109	38 96	-2 173	-2 283	-1 704	3 878
ICZ3	820	0 1438	8 717	37 08	-2 032	-2 137	-1 684	5 170
ICZ4	281	0 0332	4 226	17 50	-0 762	-0 825	+0 216	0 829
ICZ5	352	0 0411	4 154	17 14	-0 740	-0 802	+0 210	0 102
ICZ6	492	0 0562	3 937	16 16	-0 671	-0 730	+0 229	0 134
Outer Core								
OCZ1	857	0 1933	7 256	30 31	-1 545	-1 619	-0 988	-
OCZ2	1018	0 1689	4 200	16 77	-0 577	-0 631	+0 702	-
OCZ3	514	0 0748	3 220	12 96	-0 478	-0 519	+0 460	-
OCZ4	611	0 0650	1 839	7 10	-0 149	-0 175	+0 755	-
Radial Blanket	4529	0 0215	-	-	-	-0 020	-	-
Axial Blanket	875	0 0135	-	-	-	-0 166	-	-

APPENDIX B

Derivation of Doppler Feedback Coefficients for a 6000-liter, Two-zone ZPPR Core

Temperature-dependent cross sections were not available in the 27-group library for ZPPR Assembly 2. Doppler effects for the two-zone-core DBA calculations were therefore derived on the basis of the Doppler experiments carried out in a sodium-voided central zone of the inner core of ZPPR-2.[2] The assumption made was that in the 6000-liter, sodium-voided-core DBA, the ratio of Doppler effect to total worth of a material would be the same as the corresponding experimental ratio in ZPPR-2. The ZPPR-2 experimental data were fitted to a 1/T-law relationship ($d\rho/dT = c/T$) as shown in Table B.1; consistent c could only be obtained for ^{239}Pu by assuming a large coefficient of thermal expansion ($40 \times 10^{-6}°C^{-1}$). Expansion effects were estimated on the basis of calculated axial worth distributions for ZPPR-2.

For ^{239}Pu, a slightly positive Doppler effect was obtained, and the normal worth-to-c ratio was found to be 936. For the DBA calculations, a factor of w/c = 1000 was adopted to reflect the probably harder spectrum in a totally voided core.

For ^{238}U, a worth-to-c ratio of 21 was found in ZPPR-2. For conservatism, the average ratio selected for the ^{238}U in the Pu-U-Mo and U_3O_8 plates in the revised DBA was 25.

The calculated worths of ^{239}Pu and ^{238}U listed in Table A.4 for the 10 core subzones of the 6000-liter DBA model first were divided by 1000 and 25 (for ^{239}Pu and ^{238}U, respectively) to obtain the Doppler factors c ($\Delta k/kg$). Multiplying by the zone masses of these isotopes and dividing by 300°C then gave the Doppler feedback coefficients ($\Delta k/°C$) required by zone for the Pu-U-Mo and two U_3O_8 plates in the kinetics-code cell.

TABLE B.1. Evaluation of ^{239}Pu and ^{238}U Doppler Effects Measured in Voided Zone of ZPPR-2

Temperature Range, °K	Measured Effect, Ih/kg	Expansion Correction, Ih/kg	Doppler Effect, Ih/kg	Doppler Factor c,[a] Ih/kg
		A. ^{239}Pu		
445-700	-0.044	-0.0973	+0.053	0.1177
445-830	-0.076	-0.1469	+0.071	0.1137
445-920	-0.109	-0.1813	+0.072	0.0995
Average c = 0.1103 Ih/kg. Worth ^{239}Pu in Sample = 103.2 Ih/kg. Worth/c = 936 (for 1/T law and an expansion coefficient of 40×10^{-6}).				
		B. ^{238}U		
300-500	-0.144	+0.002	-0.146	-0.286
300-800	-0.306	+0.004	-0.310	-0.316
300-1100	-0.406	+0.006	-0.412	-0.317
Average c = -0.306 Ih/kg. Worth ^{238}U in Sample = -6.44 Ih/kg. Worth/c = 21.0.				

[a]For relationship $d\rho/dT = c/T$, or $(\rho_2-\rho_1)/c = \ell n(T_2/T_1)$.

APPENDIX C

Specifications and Results of the Kinetics/Heat-transfer Calculations for the Design Basis Accident on a 6000-liter, Two-zone ZPPR Core

Table C.1 gives the kinetics parameters used in the excursion calculation and describes the cell model adopted. Table C.2 lists the material properties according to temperature range used for Pu-U-Mo and U_3O_8. Table C.3 lists the core-zone parameters for the calculations, including the Doppler feedback coefficients and worth factors for fuel expansion.

TABLE C.1. Input Specifications for DBA Kinetics/Heat-transfer Calculations for 6000-liter, Two-zone Core

A. Kinetics-code Parameters

1. Ramp rate = 0.0011 $\Delta k/k$ per sec.
2. Initial conditions: Power = 2W k_{excess} = -0.002
   Source = 61200 Precursors = 0
3. Excursion terminated after 20 sec of fuel boiling.
4. Time step = 0.5 msec, lifetime = 4.085×10^{-7} sec
5. Delayed-neutron parameters

Group:	1	2	3	4	5	6
Beta-effective, 10^{-5}	8.27	71.52	63.58	125.97	57.97	19.00
Lambda, sec^{-1}	0.013	0.0314	0.136	0.340	1.320	3.500

6. Thermal parameters

   Average core heat input = 3.9815×10^{-8} cal/cm^3-W-sec.
   Temperature feedbacks initiated after integrated power of 0.1 MW-sec.
   Temperature feedbacks calculated every 2.5 MW-sec.

B. Description of Model Cell

Structure + Void	Pu | U | Mo	U_3O_8 Plate A	U_3O_8 Plate B

0 5.311 5.870 7.315 8.591

Cell Region	Feedback Region No.	Material	Thickness, cm	No. of Nodes	Δx per Node	Power-density Ratio[a]
1	-	Structure & void	5.311	3	1.7703	0.0000
2	2	Pu-U-Mo	0.5588	5	0.11176	13.5160
3	1	U_3O_8	1.4451	3	0.4817	0.3814
4	3	U_3O_8	1.2759	3	0.4253	0.3814

[a]Ratio of average power density in plate to average power density in cell.

TABLE C.2. Thermal Properties of Materials Used for Oxide-fuel Simulations in DBA Calculations

Range	Upper Temp, °K	Heat Capacity, cal/g-°C	Thermal Conductivity	Latent Heat, cal/g	Coefficient of Expansion, 10^{-6} deg^{-1}
		Pu-U-Mo Fuel Alloy (density = 18.4 g/cc)			
1	500	0.030	0.064	-	15.4
2	650	0.035	0.074	-	28.5
3	818	0.037	0.082	-	28.6
4	900	0.039	0.092	-	52.0
5	1230	0.040	0.110	-	24 7
6	1230	1.0×10^{10}	0.130	20	-
7	1900	0.044	0.160	-	-
8	2800	0.046	0.240	-	-
9	3700	0.048	0.300	-	-
10	3700	1.0×10^{10}	0.300	450	-
		U_3O_8 (density = 7.60 g/cc)			
1	400	0.070	0.0014	-	
2	500	0.077	0.0012	-	
3	750	0.082	0.0010	-	
4	1150	0.088	0.0012	-	
5	1550	0.094	0.0014	-	
6	1950	0.100	0 0016	-	
7	1950	1.0×10^{10}	0.0020	67	
8	3000	0.100	0.0020	-	
9	4200	0.100	0.0020	-	
10	4200	1.0×10^{10}	0.0020	1000	

TABLE C.3. Cell-description Parameters Input to DBA Kinetics/Heating Code for 6000-liter, Two-zone Core

Core Subzone[a]	"Cell" Power Density[b]		Total Mass	Doppler Feedback Coefficients at 300°K, 10^{-6} Δk/k-°C			Pu-U-Mo Expansion Feedback
	Core-average Power Density	Fuel Mass, kg Pu-U-Mo	U_3O_8, kg	Pu-U-Mo	U_3O_8 Plate A	U_3O_8 Plate B	Factor,[c] (Δk/k)/(Δℓ/ℓ)
ICZ1	1.07802	561.0	1128.3[d]	-0.878	-1.656	-1.390	-0.04012
ICZ2	1.07557	701.3	1410.3[d]	-1.075	-1 930	-1.704	-0.04915
ICZ3	1.05201	981.8	1974.4[d]	-1.403	-2.529	-2.233	-0.06426
ICZ4	0.70879	336.8	676.9[d]	-0.171	-0.335	-0.296	-0.00740
ICZ5	0.70176	420.8	846.2[d]	-0.207	-0.407	-0.359	-0.00887
ICZ6	0.68465	589.1	1184.7[d]	-0.260	-0.519	-0.458	-0.01072
OCZ1	0.94387	1549.8	1461.4	-1.658	-	-2.670	-0.08859
OCZ2	0.69451	1840.7	1735.6	-0.659	-	-1.237	-0.06290
OCZ3	0.60878	929.9	876.8	-0.283	-	-0.513	-0.01502
OCZ4	0.77547	1104.4	1041.5	-0.078	-	-0.206	-0.01128

[a] As shown in Fig. A.1.

[b] For region accompanying a fuel column: Accounts for higher density and power fraction for Pu-U-Mo in outer core.

[c] Multiplied by expansion coefficients in Table C.2 gives expansion feedbacks (Δk/k-°C) according to temperature range.

[d] For two plates per cell (split 53.11 and 46.89% into plates A and B, respectively) in inner core.

Table C.4 presents the history of the fuel evaporation given by the kinetics code and the corresponding history of cell overpressurization given by the pressure/venting code. A graph of the fuel vaporized versus time is shown in Fig. C.1, along with a plot of the excess reactivity in the reactor from the start of the kinetics calculation until 20 sec after fuel boiling starts. Figure C.2 shows the histories of the Pu-U-Mo and U_3O_8 temperatures in the central-core zone.

TABLE C.4. Calculated Cell Overpressures Caused by Heat Released from Oxidation of Vaporized Fuel during a DBA for a 6000-liter, Two-zone Core, Totally Voided of Sodium (32-cent/sec reactivity insertion rate)

Time after Vaporization, sec	Total Fuel Vaporized, kg Pu-U-Mo	Cell Overpressure, psig	Time after Vaporization, sec	Total Fuel Vaporized, kg Pu-U-Mo	Cell Overpressure, psig
0	0.0	0.00	6	194.7	5.26
0.2	26.8	5.37	7	206.8	4.20
0.4	44.9	8.50	8	217.3	3.42
0.6	58.0	10.30	9	226.6	2.85
0.8	68.5	11.34	10	235.1	2.42
1.0	77.4	11.87	11	243.0	2.10
1.3	88.5	12.08	12	250.4	1.86
1.6	97.8	11.85	13	257.4	1.68
2.0	108.5	11.21	14	264.3	1.55
2.5	126.0	11.19	16	277.7	1.37
3	140.2	10.48	18	291.4	1.28
4	162.8	8.50	20	305.9	1.23
5	180.4	6.68			

Note: After 20 sec of fuel vaporization, 24.8% of initial cell air remains in cell.

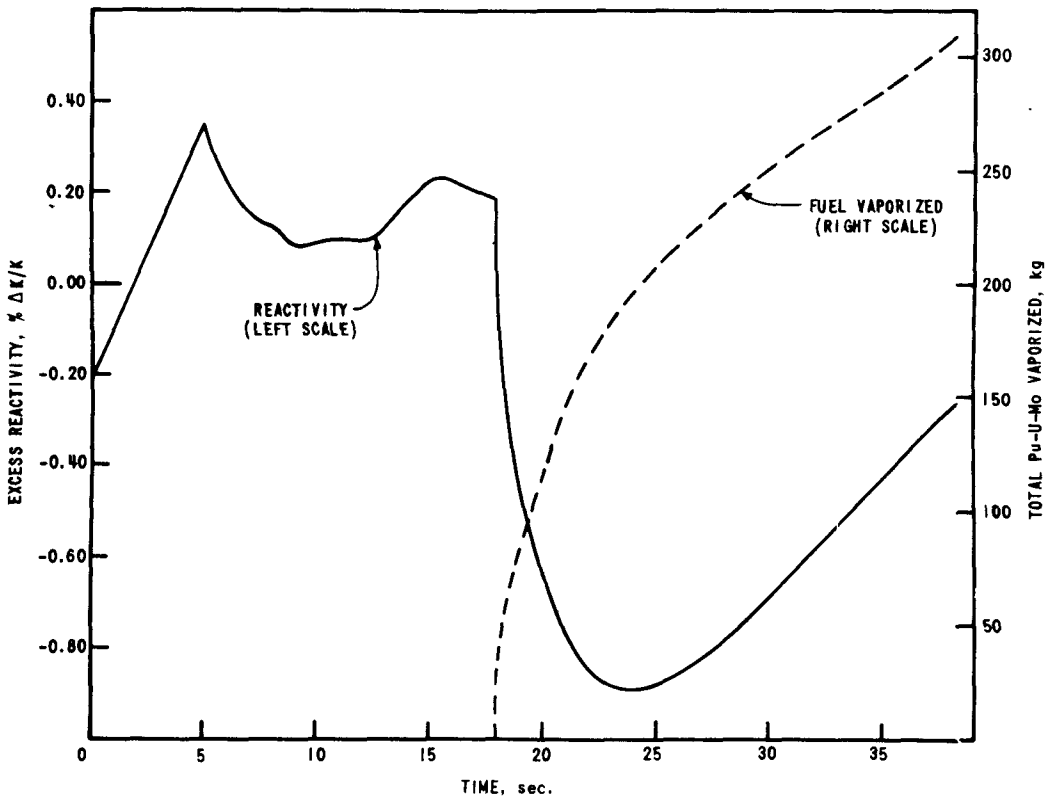

Fig. C.1. Histories of Reactivity and Fuel Vaporization in a DBA for a 6000-liter, Two-zone Core. ANL Neg. No. 103-B11513.

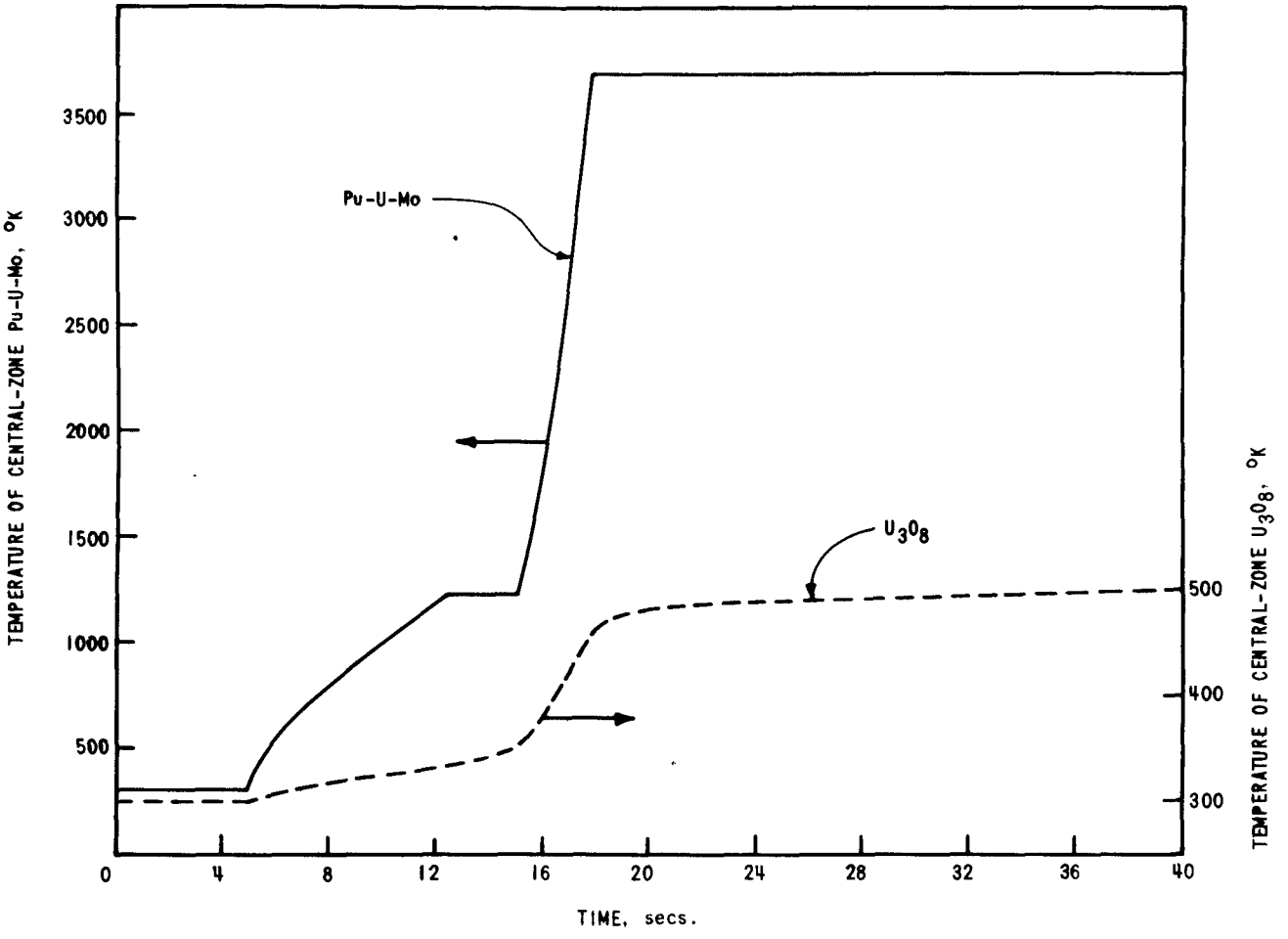

Fig. C.2. Histories of Fuel and U3O8 Temperatures at Core Center in a DBA on a 6000-liter, Two-zone ZPPR Core. ANL Neg. No. 103-B11511.

REFERENCES

1. H. Lawroski, R. G. Palmer, F. W. Thalgott, R. N. Curran, and R. G. Matlock, *Final Safety Analysis Report on the Zero Power Plutonium Reactor (ZPPR) Facility*, ANL-7471 (June 1972).

2. R. E. Kaiser, J. M. Gasidlo and W. G. Davey, "Reactivity Doppler Measurements in ZPPR Assembly 2," *Applied Physics Division Annual Report: July 1, 1970, to June 30, 1971*, ANL-7910, pp. 265-270 (Jan 1972).

3. R. G. Palmer, ANL, *Input Description for ZPR Kinetics and Cell-Heat-Transfer Code*, private communication.

4. R. A. Lewis, K. D. Dance, J. F. Meyer, and E. M. Bohn, *Variable Temperature Rodded Zone Project: Final Safety Analysis Report*, ANL-7638 (Jan 1972; published March 1974).