NUREG/CR-2198
LA-8917-MS

Fuel Temperatures in an Argonaut Reactor Core Following a Hypothetical Design Basis Accident (DBA)

Prepared by G. E. Cort

Los Alamos National Laboratory

Prepared for
U.S. Nuclear Regulatory Commission

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Manuscript Completed: February 1981
Date Published: June 1981

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Prepared for
Division of Licensing
Office of Nuclear Reactor Regulation
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555
NRC FIN A7122

ABSTRACT

A thermodynamic analysis was prepared to determine if fuel in an Argonaut-type reactor would melt following a hypothetical earthquake which would collapse the superstructure onto the reactor core. The analysis assumed horizontal and/or vertical collapse of the core, wherein the coolant channels were compressed to 25% and 75% of original condition. Reactor core equilibrium conditions were assumed for 100 kW and 500 kW operation.

A two-dimensional thermodynamic analysis indicated no melting of the core at 100 kW equilibrium operation and partial melting of the core at 500 kW operation.

For the condition of vertical and/or horizontal crushing of the core, conduction of heat away from the fuel becomes the dominant heat transfer mechanism.

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WX-4-3692
February 5, 1981

SUMMARY OF COMPUTER MODEL AND SELECTED RESULTS FROM ARGONAUT DESIGN BASIS ACCIDENT EVALUATION

by

G. E. Cort

I. INTRODUCTION

A. Accident Description

The hypothetical Design Basis Accident (DBA) for the ARGONAUT reactor is assumed to be a complete loss of water coolant/moderator while operating at full power (100 kW). The accident is presumed to be caused by an earthquake of sufficient magnitude to potentially cause compaction of the fuel elements. Although the reactor is immediately shut down by the control arms and by the loss of the water moderator, it continues to generate decay heat. Because of the loss of coolant water, the temperatures of the fuel elements and surrounding structure will rise from their normal values at a rate that depends, in part, on the decay heating rate and the mass and specific heat of the fuel. As the temperatures increase, heat will be lost from the fuel elements to the surroundings through the combined mechanisms of conduction, thermal radiation, and natural convection of the air. Depending on many variables, the rate of heat loss will at some point in the transient become exactly in balance with the rate of heat generation from radioactive decay. Core temperatures will then begin to decrease and the extent of core melting, if any, can be determined from the maximum temperatures experienced.

B. Core Compaction from Earthquake

It is difficult to quantify the effects of an earthquake on the reactor structure without extensive analysis and testing. A comparison can be made with the N Reactor, located at Hanford, Washington, which is constructed of stacks of interlocked graphite blocks somewhat like the ARGONAUT. A seismic safety review of that reactor in 1968 concluded that the "graphite stack can safely withstand the 0.25 G maximum earthquake loading". The review also concluded that vertical motion was unlikely to dislodge the stack of graphite blocks and that large deformations in any direction would be resisted by the biological shield.

The acceleration forces that should be applied to the ARGONAUT for seismic analysis will depend on local conditions such as the distance from the nearest fault. Therefore, it cannot be estimated whether 0.25 g's ground acceleration would be conservative or unconservative. However, if we assume an extreme acceleration of 1 g's, the maximum compressive stress in the graphite is still less than one-tenth the compressive strength. Because the blocks are not interlocked, tensile stresses should not occur. There may be some chipping at corners and abrasion from compressive shear, but these small changes in geometry should not adversely affect the heat transfer. Horizontal acceleration can cause the graphite blocks to slide against the metal fuel boxes and, if the impact is severe, crush the box and the fuel elements laterally. The probability and extent of crushing cannot be predicted without dynamic structural analysis. The dynamic analysis of the seismic response of an HTGR core (Ref. 1) that was completed at Los Alamos in 1975 is an example of the type of modeling needed to predict lateral crushing. It is interesting that the maximum impact force between adjacent graphite blocks with a 1 g's horizontal base acceleration was calculated as 0.3 MN (67,000 lb). If this analysis were to hold for the ARGONAUT, lateral crushing seems possible under the severe acceleration.

The core might also be crushed in the vertical direction by falling lead bricks, access plugs, fuel box shielding plugs, or the massive removable concrete shield blocks. These components are interlocked and supported by the reinforced concrete shield. Even though the concrete in the shield may crack and spall, it is difficult to imagine that large displacements could occur that would allow these interlocked components to fall.

In summary, crushing in the lateral direction seems possible under severe accelerations, and crushing in the vertical direction seems less likely. Any crushing that takes place will tend to "squeeze the air out" from between the fuel plates so that heat conduction to the surrounding graphite will be improved relative to the uncrushed state.

The calculations reported herein include cases with the core crushed laterally so that the coolant gap between adjacent fuel plates is reduced to 50 per cent and 25 per cent of its nominal value.

II. METHOD OF ANALYSIS

The analysis was conducted with an existing two-dimensional, finite-element computer program,[2] modified as described below to conform to the problem.

A. Core Geometry

The fuel plates and coolant channels are not modeled individually in the code because of limitations on computer time and memory. Instead, the core is "homogenized" by combining the fuel, structure, and coolant channels, according to their respective volume fractions, into two composite materials. One composite material, occupying the region where fuel is in the core, contains uranium and is the source of decay heat. The other material does not contain uranium and represents the upper and lower unfueled sections of the elements.

The heat transfer model of the core includes the graphite blocks and considers the concrete (and air if natural convection is modeled) as the ultimate heatsinks. The two-dimensional model extends vertically from the top to the bottom of the fuel boxes. In the horizontal direction perpendicular to the fuel plates, the model extends from the core midplane (halfway between the rows of fuel boxes) to the graphite/concrete interface. In the other horizontal direction parallel to the surface of the fuel plates and also parallel to the row of fuel boxes, no heat transfer takes place in the model. This is equivalent to an assumption that the row of three fuel boxes in a line is extended to infinity at both ends. This is a conservative, but reasonable, assumption when applied to the middle fuel box of the three because it is "guarded" on both sides by another box. Actual temperatures in the middle box are thus expected to be somewhat cooler than those presented here, and temperatures in the two end boxes will be much cooler because of the neglected heat conduction in the third dimension.

The homogenized core and graphite reflector were subdivided into a series of rectangular finite elements as depicted in Fig. 1, with a plane

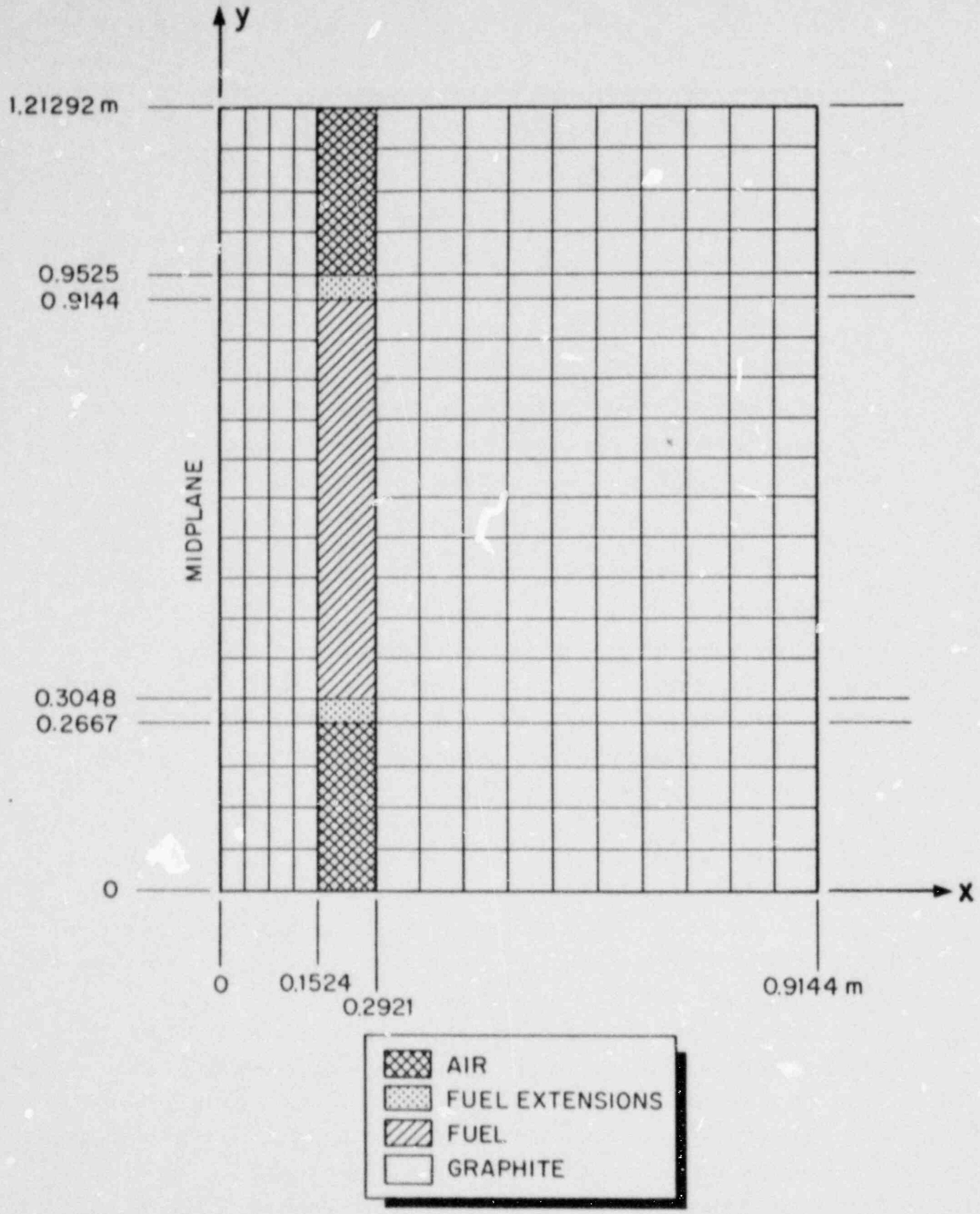

Fig. 1. Finite element mesh.

of symmetry along the vertical midplane. Heat transfer from graphite moderator blocks to the concrete shield occurs by thermal radiation and natural convection. Air flows by natural convection through the coolant passages and is treated in the homogenized model as described below.

B. In-core Natural Convection

The problem of heat transfer by natural (or "free") convection between heated vertical plates has been investigated in many recent analytical, numerical, and experimental studies (Refs. 3 and 4, for example). These studies are based on uniform wall heat fluxes or uniform wall temperatures and do not consider the internal heat generation, heat storage, and conduction within the plate and surrounding structure. These references do provide useful limiting cases that were used as checks on the model's validity.

The basic assumption in the model is that the air flow and the resulting heat transfer within the core are governed by a balance between buoyancy forces and the viscous drag, plus acceleration momentum change within a typical "average" channel. The core pressure drop is calculated with the following expression.

$$\Delta P = L(\rho_\infty - \bar{\rho}) = (\bar{\rho}\bar{V})^2 \; 1/g \left[(1/\rho_2 - 1/\rho_1) + \frac{2\,fL}{D_H \bar{\rho}} \right],$$

where

ΔP = pressure drop across the core,

L = length of core,

ρ = air density (1, 2, and ∞ signify channel inlet, channel exit, and in the volume surrounding the core, respectively; a bar signifies the average value along the channel length),

g = gravitational constant,

f = fanning friction factor based on the average Reynolds number in the channel, and

D_H = channel hydraulic diameter.

An expression for the average air velocity is obtained assuming that the air density at the channel inlet (ρ_1) is equal to the air density in the volume outside the core (ρ_∞), the gas is ideal, and pressure differences are small. The resultant expression is

$$\bar{v} = \left[\frac{gL(1 - \frac{T_\infty}{\bar{T}})}{(T_2/T_\infty - 1) + \frac{fL}{D_H}(\frac{T_2}{T_\infty} + 1)} \right]^{1/2},$$

where

T = gas temperature, with the same significance for subscripts and bar as before.

The velocity was calculated at each time step with the friction factor calculated in the previous time step. The flow velocity increases with time, and the friction factor decreases with increasing velocity. Therefore, the calculative results are conservative because higher than actual friction factors were used. The air velocity and heat removal are based on the average temperature of the core and, as a result, the convective cooling is less than expected in the hottest regions, which is an additional conservatism.

In the core model, the actual gas velocity is converted to an equivalent velocity for the homogenized core to achieve the same energy transport, or

$$V_e = V(\rho\epsilon C)/(\rho C)_e,$$

where

ρ, ϵ, C, = average density, volume fraction, and specific heat capacity for the air;

V_e, $(\rho C)_e$ = equivalent velocity, density, and specific heat capacity for the homogenized core, and V_e was set to zero for the cases where no air flow through the core was assumed.

C. Properties

The thermophysical properties for the homogenized core are determined from appropriate weighting functions, based on the volume occupied by the air, aluminum, and uranium. For example, the equivalent density and specific heat capacity for the homogenized core are

$$\rho_e = \epsilon_1 \rho_1 + \epsilon_2 \rho_2 + \epsilon_3 \rho_3, \text{ and}$$

$$c_e = \epsilon_1 c_1 + \epsilon_2 c_2 + \epsilon_3 c_3,$$

where subscripts 1, 2, and 3 represent aluminum, air, and uranium. For the uncrushed core, the volume fractions, ϵ, are 0.336, 0.662, and 0.002, respectively.

The effective thermal conductivity of the homogenized core is based on the assumption that the dispersed phase (air) can be represented by lumped parallel or series resistances.[5] For example, in the direction parallel to the fuel plates (that is, the vertical direction), the effective thermal conductivity is

$$\lambda_e = \lambda_1 \epsilon_1 + \lambda_2 \epsilon_2,$$

where λ is the thermal conductivity.

In the horizontal direction perpendicular to the fuel plates (the X-direction in Fig. 1), where the plates and void spaces are in series, it is

$$\lambda_e = \lambda_1 \epsilon_1 / (\epsilon_2 \lambda_1 + \epsilon_1 \lambda_2).$$

The heat transfer by conduction through the air in the void spaces is augmented by thermal radiation from one fuel plate to the next. This effect is accounted for in the model by adding the molecular conductivity for air in the gap to the effective conductance for thermal radiation, which is

$$4 \sigma \bar{T}^3 / (\frac{2}{e} - 1) ,$$

where

σ = Stefan-Boltzman constant,

T = average temperature of the fuel plates on either side of the gap, and

e = total hemispherical emittance for thermal radiation for the fuel plates.

D. Boundary Conditions

The outer surfaces of the graphite moderator blocks are cooled simultaneously by thermal radiation to the concrete shield and the natural circulation of air in the gap betweeen the shield and moderator. The normal total emittance[6] on the graphite is taken as 0.72.

The heat transfer coefficient on the top and side surfaces or the moderator caused by natural circulation is found from the following Nusselt number correlation.[7]

$$Nu = cRa^m,$$

where

Nu = Nusselt number,

Ra = Rayleigh number, and

c,m = constants based on the value of Ra and on the orientation of the surface.

E. Decay Heating

The total power in the core at time t from radioactive decay of the fission products is calculated by the Untermeyer-Weills formula for an equilibrium inventory of fission products over the range 1 to 10^6 s (278 h). The heating rates caused by radioactive decay throughout the active core are distributed radially and axially, according to the operating fission density. In the radial direction, "fuel-shuffling" makes prediction of a "typical" distribution of heating rates difficult, so a radial peaking factor of 1.0 is used. This could easily be modified if a particular core loading were to be studied. In the axial direction, the heating distribution is a modified cosine shape, typical of pool-type reactors.[8] The axial peak-to-average heating rate is 1.494 and is reached at 0.4 m below the top of the fueled portion of the core.

Because the model of the core combines the fuel plates, structure, and coolant channels in one homogeneous material, the heating cannot be isolated in the "meat" of the fuel plates. This means that the local transverse temperature difference between the center of a fuel plate and the center of the adjacent coolant channel is not calculated. For the average volumetric heating rate at 1 min after shutdown, the fuel plate could be a maximum of 12 K hotter than calculated by the model. This temperature difference will decrease over time because of the decrease in decay power. When maximum core temperatures are reached (>3 h), the maximum temperature difference is less than 4 K.

F. Transient and Initial Conditions

The reactor is assumed to be at a uniform temperature of 311 K initially at 100-kW (or 500-kW) power. It is assumed that continuous operation at full power has been of sufficient duration to reach an equilibrium inventory of fission products, such that the Untermeyer-Weills formula is valid. At time zero, the water is completely drained from the fuel elements and plenums in less than 1 s. The reactor shuts down immediately and the transient calculation begins with the dry core condition; zero velocity air is in the spaces between the fuel plates. Any delay in draining the core and any evaporation of water remaining in the core (either collected in crevices or clinging to the fuel by surface tension) will provide additional heatsinks and further reduce temperatures from those calculated.

The transient time step was nominally 10 s initially, increasing gradually during the calculation to a maximum of 1800 s at the end. The time steps were shortened for several cases to insure that numerical errors were not being introduced by taking too long a time step. Previous calculations for the heat-up transient of nonpower reactors have verified that the finite element mesh size in the model depicted in Fig. 1 is adequate.

III. RESULTS

Ten different cases have been run on the computer model, six at 100 kW and four at 500 kW. For the 500-kW cases, the fueled volume was increased by a factor of 13/12. Five cases were run with natural convection air flow between the fuel plates and five with stagnant air in the space between the plates. Four cases were run with the core in the uncrushed condition and six with the core crushed. The maximum calculated fuel temperatures for the 10 cases are summarized in Table I.

TABLE I

CALCULATED PEAK TEMPERATURE IN ARGONAUT
FUEL FOLLOWING LOSS-OF-COOLANT

	Steady Power Before Transient			
	100 kW		500 kW	
	Uncrushed	Crushed	Uncrushed	Crushed[a]
Natural convection air flow	396	478[a] ~410[b]	629	880
No air flow	631	527[a] 460[b]	1260[c] (40-60% > 900 K)	997[c] (20-35% > 900 K)

---

[a] Coolant gap between fuel plates reduced to one-half the nominal value (void fraction ≃ 75% of nominal).

[b] Coolant gap reduced to 25 per cent of nominal (void fraction ≃ 50% of nominal).

[c] Fuel would melt before reaching these temperatures. The percentage melted is estimated for the two center fuel boxes only. The four end boxes should have substantially less (if any) melting.

The first thing to note in the table is that blocking the natural convection air flow causes an increase in the temperature, as expected. But fuel melting (which occurs at temperatures above 900 K) does not occur for the 100 kW case. For the 500-kW reactor, blocking the air flow is sufficient to cause melting in the central part of the fuel plates of the middle two boxes. The extent of melting can be estimated from the volume of the fuel that exceeds 900 K, but the estimate is an upper limit because the latent heat of fusion is neglected in the model (this could be changed). For the uncrushed 500-kW reactor, about half the fuel in the middle two boxes could melt, and for the crushed core, about a third exceeds 900 K.

It is interesting, but expected, that crushing the core causes an increase in temperatures when air flow is present (because the flow area is restricted), but a decrease in temperature when air flow is not present (because conduction heat transfer is improved). For the case with air flow at 100 kW, we observe a maximum in the peak temperature at approximately 50 per cent crushing. This is because of the competition in the two mechanisms, one tending to restrict convection heat transfer and the other tending to improve conduction heat transfer.

Figure 2 shows typical isotherms in the model, for a 500-kW reactor with air flow. One feature to be noted is that temperatures are somewhat higher near the top of the fuel elements because of the vertical upward air flow. Also, because of the relatively good heat transfer in the graphite, its temperature does not exceed 340 K. The steep temperature gradients, where the isotherms are piled on top of one another, are at the lateral edges of the fuel boxes. This is where the poor thermal conductivity (because of the gaps between fuel plates) combines with high heat flux to maximize the thermal gradients. Finally, the temperatures in the core appear to be fairly symmetrical about the vertical plane, a consequence of the good heat transfer in the graphite that was noted previously.

The significance of these observations is that the boundary conditions on the outside of the model (that is, the heat transfer between the graphite blocks and the concrete shield) are not important in determining the maximum fuel temperature. These boundary conditions will be important later in the transient to control the long-term cool-down and equilibration of the reactor temperatures. However, in the relatively early (<10 h) part of the heat up, the large heat capacity of the graphite and the relatively poor thermal conductivity laterally in the fuel elements are more important.

The time-dependence of the peak temperatures is shown in Fig. 3 for three cases where the air flow was blocked. All 10 cases show the same general behavior with a steep increase early in the transient. Then, as the heat generation falls off with the power decay curve and the heat transfer improves as thermal gradients are developed, the curves bend over

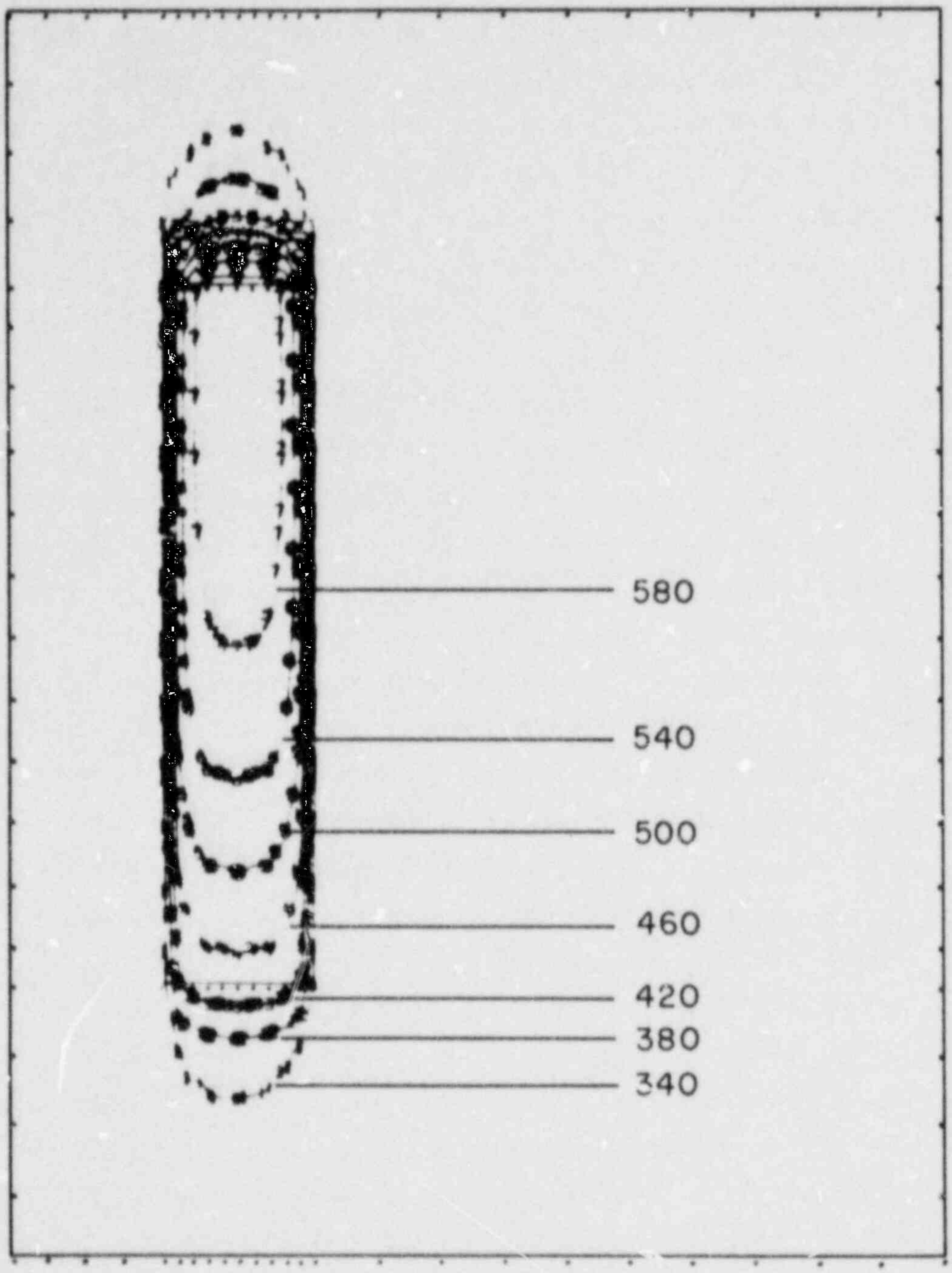

Fig. 2. Isotherms in 500 kW reactor at 3670 s, uncrushed, with natural convection.

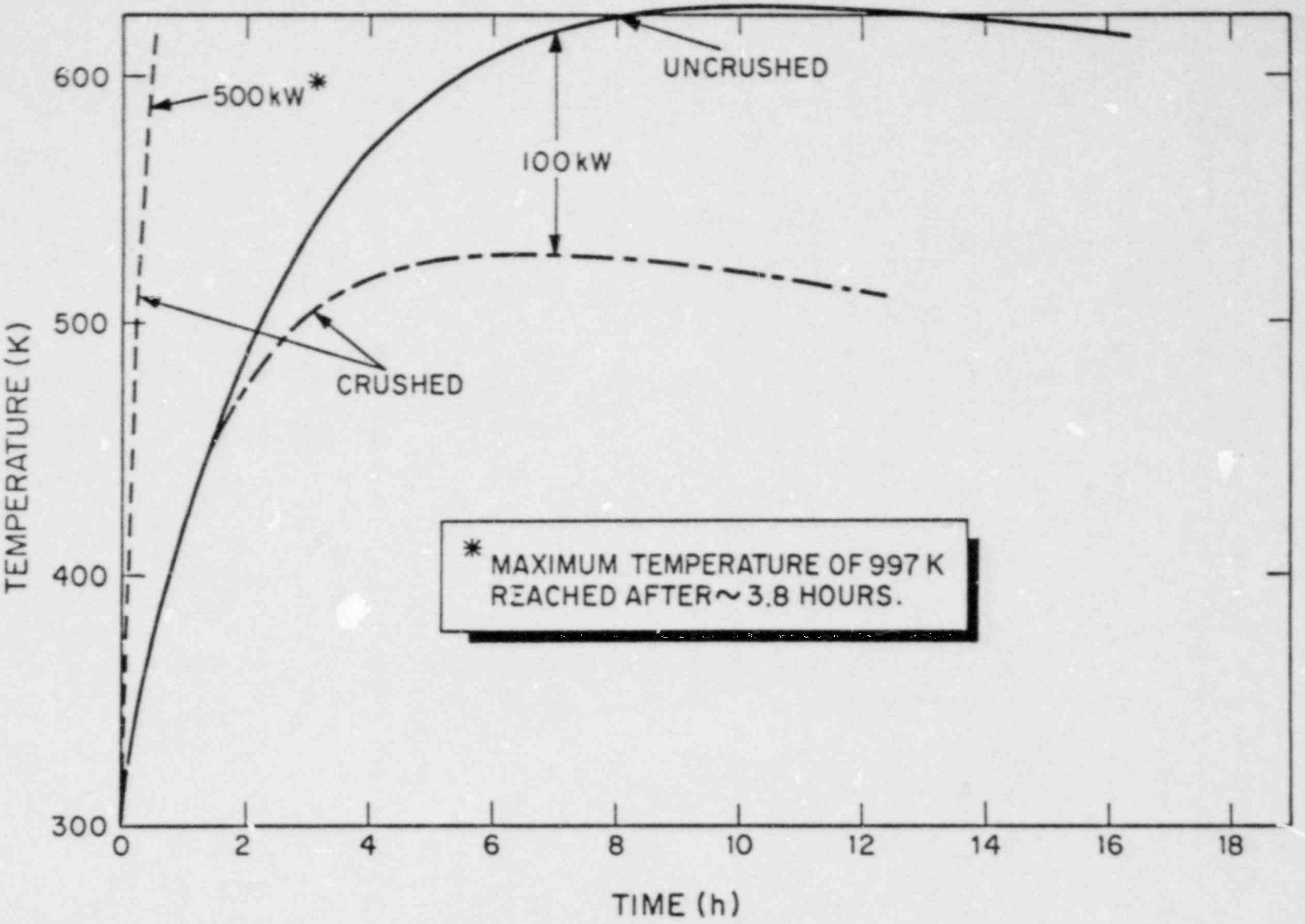

Fig. 3. Maximum temperature versus time with no convection air flow.

and go through a maximum. The initial slope of the temperature-time curve is about five times greater for the 500 kW case, as expected. There is no difference in the initial slopes for the crushed versus the uncrushed case at 100-kW.

Figure 4 is a plot of the heat balance in the model as a function of time. The power decay curve, at the top, is balanced by the sum of the rate of energy storage in the fuel, plus the rate of energy storage in the graphite, plus the rate energy is conducted through the graphite into the concrete, plus the rate that energy is carried out of the system by the natural convection air flow. Initially, almost all of the power generated is stored in the fuel and later (after about 1.4 h) the rate becomes negative as the core temperatures go through the maximum. The heat removal by natural convection starts at zero and increases steadily until after the fuel temperatures have turned around. At this point, >1.5 h, the natural convection accounts for most of the heat removal. The heat stored in the graphite and the heat conducted into the concrete shield are both fairly small and constant quantities.

IV. SUMMARY

The model of the DBA accident for the ARGONAUT reactor is believed to be conservative in the modeling assumptions that were made. It is reasonable to conclude that fuel melting is precluded for the 100-kW reactor under the DBA scenario. For the 500-kW reactor, some fuel melting may take place under the extreme condition of complete blockage of air flow through the fuel elements. It is quite possible that refinement of some of the conservative assumptions, such as a three-dimensional rather than two-dimensional model and including the latent heat of fusion, would show that melting would not occur at 500 kW.

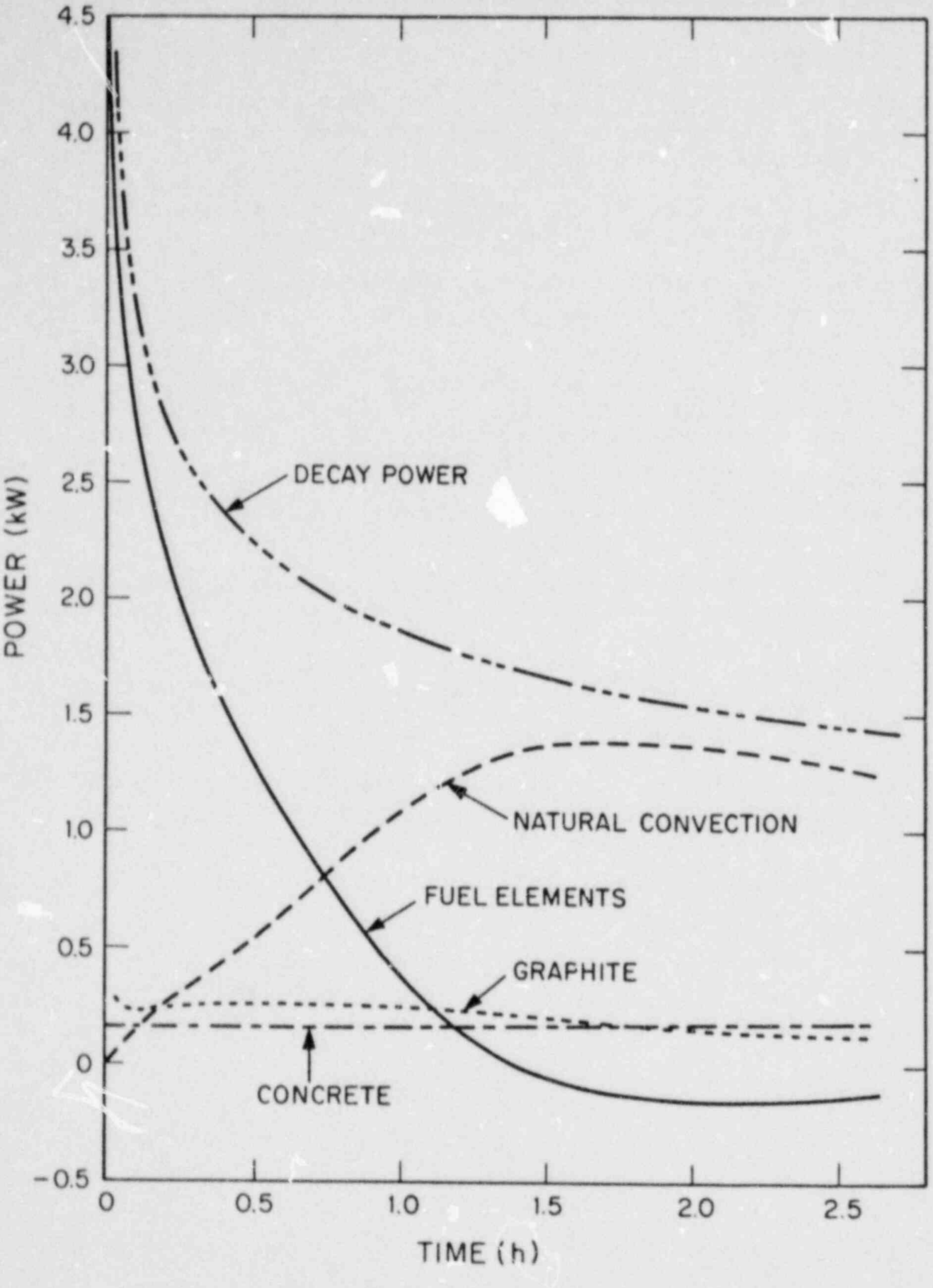

Fig. 4. Heat balance versus time for 100 kW reactor, uncrushed, with air flow.

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APPENDIX A

University of California
LOS ALAMOS SCIENTIFIC LABORATORY
Post Office Box 1663 Los Alamos, New Mexico 87545

In reply refer to: WX-4-3895
Mail stop: 985

April 20, 1981

Dr. Hal Bernard
DL/SSPB
Mail Stop P228
Office of Nuclear Reactor Regulation
Nuclear Regulatory Commission
Washington, DC 20555

Dear Dr. Bernard:

Confirming our telephone conversation of April 17, 1981, the following are my thoughts on the hypothetical Design Basis Accident for the ARGONAUT reactor. Lateral crushing of the core was chosen for the heat transfer analysis reported in the reference because it seemed to be more probable than crushing in the vertical direction. However, the consequences of crushing in the vertical direction (without air flow, in particular) are expected to be substantially the same as the consequences of crushing in the lateral direction. That is, crushing the fuel elements will squeeze the air out from between the fuel plates and improve the conduction heat transfer laterally (and vertically in the case of vertical crushing). Consequently, the results presented in the reference for the case of lateral crushing of the core are expected to apply equally to the case of vertical crushing. It may be supposed that blockage of the natural convection air flow would be more likely in the case of vertical crushing than if (partial) lateral crushing were to occur. This is of no great consequence because the "worst case" is still blockage of the air flow with no crushing.

Finally, one could imagine various asymmetric configurations of the crushed fuel plates within the box that might be conjectured to cause locally higher temperatures than those caused by lateral crushing (or more to the point, by no crushing). For example, the fuel plates could buckle outward toward the sides of the box, leaving a single central plate isolated by two large air gaps on each side. Aside from the geometric incompatibility of this configuration, it does not result in higher temperatures for the central plate. The heat transfer vertically from the central plate is probably improved, and that in the lateral direction is certainly improved by the following:

1. Conduction heat transfer is governed only by the total thicknesses of metal and air, and this can only change for the better (more metal and less air).

2. Radiation heat transfer will be short-circuited by localized contacts between the deformed fuel plates.
3. A localized natural convection cell may be set up in the larger gaps beside the plate to enhance the conduction and radiation.

If we can be of any further service to you, do not hesitate to call.

Sincerely,

G. Edward Cort

GEC:mrm

CY: L. W. Hantel, WX-DO, MS 945 (R661)
F. P. Schilling, WX-4, MS 985
J. J. Koelling, WX-8, MS 928
R. A. Haarman, ADEP, MS 671
CRMO (2), MS 150

REFERENCE:

Letter WX-4-3692, dated February 11, 1981, from G. E. Cort to Dr. Millard Wohl, with attachment.

APPENDIX B

University of California
LOS ALAMOS SCIENTIFIC LABORATORY
Post Office Box 1663 Los Alamos, New Mexico 87545

In reply refer to: WX-4-3692
Mail stop: 985

February 11, 1981

Dr. Millard Wohl, P608
Office of Nuclear Reactor Regulation
Nuclear Regulatory Commission
Washington, DC 20555

Dear Millard:

As you requested, enclosed is a brief report on the analysis that was done to predict the temperatures in an ARGONAUT reactor following a hypothetical Design Basis Accident (DBA). The conclusion of the study is that fuel in the 100-kW reactor could not melt under conditions of the DBA, even if all natural circulation of air between the fuel plates were blocked. Crushing the core, in the case of no air flow, tends to improve the heat conduction from the fuel into the surrounding graphite.

For the 500-kW ARGONAUT, portions of the core may melt if the air flow is completely blocked. As you know, the release of fission products from the aluminum-uranium alloy plates can occur only after the fuel has melted. For the "worst case" of the 500-kW reactor without air flow in the uncrushed condition, it is estimated that 40-60 per cent of the fuel in the center two fuel boxes would melt. Because the model includes the conservative assumption that heat transfer takes place in only two dimensions, the actual temperatures of the fuel in the four end boxes will be significantly cooler than calculated. In fact, there is a strong possibility that a calculation based on a three-dimensional model would show that no fuel melts in the four end boxes.

The model also assumes that the fuel remains in place after it has melted. This conservative assumption may be unrealistic because the molten fuel is expected to drip into cooler portions of the core or entirely out of the core into the lower plenum. Some relatively minor changes to the existing model could be made to determine effects of the redistribution of molten fuel under certain limiting conditions. The effect will probably be a reduction in the total volume that is ultimately melted.

The enclosed description gives details of the calculative model and some selected computer-generated results. Also enclosed are the copies of assembly drawings that you provided to develop the model.

This report completes the work that was planned for the ARGONAUT DBA evaluation. It has been a pleasure working with you and I hope that we can be of service again sometime.

Very truly yours,

Ed Cort

G. E. Cort

GEC:11/mrm

Enclosures: As cited

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F. P. Schilling, WX-4, MS 985
J. J. Koelling, WX-8, MS 928
R. Haarman, ADEP, MS 671
CRMO (2), MS 150

NRC FORM 335
(7 77)

U.S. NUCLEAR REGULATORY COMMISSION
BIBLIOGRAPHIC DATA SHEET

1. REPORT NUMBER *(Assigned by DDC)*
NUREG/CR-2198

4. TITLE AND SUBTITLE *(Add Volume No., if appropriate)*
FUEL TEMPERATURES IN AN ARGONAUT REACTOR CORE FOLLOWING A HYPOTHETICAL DESIGN BASIS ACCIDENT (DBA)

2. *(Leave blank)*

3. RECIPIENT'S ACCESSION NO.

7. AUTHOR(S)
G. E. Cort

5. DATE REPORT COMPLETED
MONTH February | YEAR 1981

9. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS *(Include Zip Code)*
Los Alamos National Laboratory
Los Alamos, NM 87545

DATE REPORT ISSUED
MONTH June | YEAR 1981

6. *(Leave blank)*

8. *(Leave blank)*

12. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS *(Include Zip Code)*
Division of Licensing
Office of Nuclear Reactor Regulation
U.S. Nuclear Regulatory Commission
Washington, DC 20555

10. PROJECT/TASK/WORK UNIT NO.

11. CONTRACT NO.
FIN A-7122

13. TYPE OF REPORT

PERIOD COVERED *(Inclusive dates)*
DECEMBER 1980 - FEBRUARY 1981

15. SUPPLEMENTARY NOTES

14. *(Leave blank)*

16. ABSTRACT *(200 words or less)*

An thermodynamic analysis was prepared to determine if fuel in an ARGONAUT-type reactor would melt following a hypothetical earthquake which would collapse the superstructure onto the reactor core. The analysis assumed horizontal and/or vertical collapse of the core, wherein the coolant channels were compressed to 25% and 75% of original condition. Reactor core equilibrium conditions were assumed for a 100 kW and 500 kW operation.

A two-dimensional thermodynamic analysis indicated no melting of the core at 100 kW equilibrium operation and partial melting of the core at 500 kW operation.

For the condition of vertical and/or horizontal crushing of the core, conduction of heat away from the fuel becomes the dominant heat transfer mechanism.

17. KEY WORDS AND DOCUMENT ANALYSIS

17a DESCRIPTORS

Argonaut Reactor Fuel, Argonaut Fuel Melt, Earthquake Damage to Fuel, Fuel Temp Analysis, Argonaut Core Accident

17b. IDENTIFIERS/OPEN-ENDED TERMS

18. AVAILABILITY STATEMENT
UNLIMITED

19. SECURITY CLASS *(This report)*
UNCLASSIFIED

20. SECURITY CLASS *(This page)*
UNCLASSIFIED

21. NO. OF PAGES

22. PRICE
$

☆ U.S. GOVERNMENT PRINTING OFFICE: 1981 — 341-742 1161