AUG 14 1964

CEND-3336-218

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ATOMIC ENERGY COMMISSION
RESEARCH AND DEVELOPMENT PROGRAM

EUR/AEC Report. 1154

PROGRESS REPORT

DEVELOPMENT AND TESTING OF A TEMPERATURE
TRANSIENT METHOD FOR PERFORMING
IN-PILE THERMAL CONDUCTANCE TESTING

Period Ending
June 30, 1964

Facsimile Price \$ 2.60
Microfilm Price \$ 1.07

Available from the
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Joint U. S. -Euratom
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TID-4500, 29th Edition

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Prepared by:

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Contract AT(30-1)-3336
U. S. Atomic Energy Commission

Issued July 1964

Unclassified
Classification

Wm. H. Simon 7/20/64
Authorized Classifier Date

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INTRODUCTION

The United States and the European Atomic Energy Community (EURATOM) on May 29 and June 18, 1958, signed an agreement which provides a basis for cooperation in programs for the advancement of the peaceful applications of atomic energy. This agreement, in part, provides for the establishment of a Joint U.S. -Euratom research and development program which is aimed at reactors to be constructed in Europe under the Joint Program.

The work described in this report represents the Joint U.S. -Euratom effort which is in keeping with the spirit of cooperation in contributing to the common good by the sharing of scientific and technical information and minimizing the duplication of effort by the limited pool of technical talent available in Western Europe and the United States.

DEVELOPMENT AND TESTING OF A TEMPERATURE
TRANSIENT METHOD FOR PERFORMING
IN-PILE THERMAL CONDUCTANCE TESTING

By

C. E. Burdg, J. R. Parrette, R. I. Brockett, and W. P. Chernock

ABSTRACT

The concept now being investigated is one whereby the transient temperature response at the surface of an operating fuel element, following a reactor power change, will yield thermal conductance values. This two-phase investigation will consist first of out-of-pile demonstrations of feasibility, followed by in-pile confirmation of the method. Concurrent mathematical analysis of the thermal model will provide the basis for data interpretation, as well as guides for the design of the experimental portions of the program.

Initial analytical models of both the out-of-pile and the in-pile cases are presented, and the methods of converting the continuous differential equations into usable finite difference equations are described. These have been used in preparing an analog computer simulation of the out-of-pile thermal model; the first runs made on the analog indicate good agreement with previously observed physical phenomena.

I. SUMMARY

During this quarter the prime emphasis has been on development of the analytical portion of the program. With improved definition of the basic thermal problem, the construction of the mathematical model becomes less formidable, and derivation of usable equations has been accomplished for both the out-of-pile case and the in-pile case. While these are necessarily of a tentative nature, they provide a basis for investigation of the various parameters affecting the transient response of the system.

In particular, a set of differential equations defining the response of the out-of-pile system has been written. These, in turn, have been modified by a transformation of variables so that the analog computer simulation of both the in-pile and the out-of-pile systems will have essentially the same form, and will provide solutions of certain functions. Finally, these transformed differential equations have been converted to finite difference equations to match the lumped parameter spatial nature of the analog computer.

Preliminary analog runs are being made to evaluate the effect of varying several parameters in the physical system, so that the experimental systems can be designed to yield usable information. The next quarter's work will be aimed at further refining the experimental requirements, through the use of both analog and digital computer studies.

II. INTRODUCTION

The objective of this program is to develop a method of determining the thermal conductance of UO_2 fuel elements while operating in a reactor. Transient response of element surface temperature, following a power change, is the parameter to be utilized.

The present program contains two phases: Out-of-pile and in-pile investigations. The out-of-pile phase is intended to prove the feasibility of the method to be employed in-pile. It is also intended to demonstrate that reliable values for fuel element conductances can be obtained through transient testing techniques. Upon completion of this first phase, a review of the results will be made and concurrence of the Commission obtained prior to initiation of the second phase of the program. This second, or in-pile, phase will utilize the correlations and experience gained during the first phase of the program. The methods and analytical techniques should prove particularly useful.

During this quarter the effort consisted of establishing the analytical procedures and further defining the basic problem. An analog computer program has been written, and preliminary results obtained. Design of the out-of-pile experiments is, in part, contingent on the analytical results with particular regard to the geometry of the elements and the required instrumentation. This computer work is, therefore, the first phase of the iterative process between analysis and experiment, leading to the development of a realistic mathematical model of the thermal behavior of the system.

III. BACKGROUND

A need exists for a simple, accurate, and reliable method of measuring in-pile thermal conductance of UO_2 fuel elements. Reliable thermal conductance values have been difficult to obtain and such information has been expensive and generally limited to measurements well below the temperatures of current interest. In instances where higher temperature data are being sought, interpretation is based upon the identification of melting from post-irradiation photomicrographs. In another method, direct temperature measurements are made by means of thermocouples in the fuel element. A third method depends upon a correlation of post-irradiation microstructure with temperature.

These methods have limitations which impede their usefulness. Post-irradiation correlations of temperature and microstructure represents the best approach of all of the previous test methods. This latter method relies heavily on the ability of the investigator to associate a specific microstructural characteristic with a definitive temperature. The result is, at best, a technique for approximating thermal conductance values. The bases for the microstructure-temperature relationships were obtained under isothermal conditions, and it is not clear that these relationships will be completely valid under the high thermal gradient conditions encountered in an operating fuel element.

After a review of work performed to date on the in-pile measurement of thermal conductance in UO_2 fuel elements, it is evident that a need exists for an improved method for non-destructive determination of in-pile conductance of UO_2 fuel elements. If a method could be evolved which is also simple,

rapid and inexpensive, a great step forward will have been made through a more realistic understanding of the behavior of UO_2 under irradiation.

This program is aimed at developing and testing such a method. The approach will employ the observation that the time required for a thermal pulse to travel through a material is directly dependent upon the thermal conductivity of that material. In addition, the rate of approach to steady state conditions, at a finite distance from the source of a thermal pulse, is dependent upon the thermal conductivity of the material. Therefore, simple measurements of temperature as a function of time at a finite distance from the source of a thermal pulse will provide data from which thermal conductance values can be obtained. During the latter stages of earlier CEND work on out-of-pile determinations of thermal conductance of UO_2 fuels, conducted as part of the United States Atomic Energy Commission Fuel Cycle Development Program, recordings of clad temperature versus time were made when the center temperature was increased in steps. These data were analyzed, using the above principles, and good correlations were obtained with the actual measured thermal resistance for these elements.

Figure 1 is a reproduction of one of these recordings of clad temperature versus time, at a certain center temperature. On the Figure are shown two parameters, the transport lag and the time constant. Transport lag, T_1 , is that time from the start of the power step until the first evidence of temperature increase appears at the clad; or, more precisely, where the tangent to the response curve intercepts the time axis. The time constant is the time required for the clad temperature to rise to 63%, or $1/e$, of its final value,

CLAD TEMPERATURE VS. TIME

with the time measured from the tangent intercept. Analysis of many of these recordings, each at a different center temperature, yielded Figures 2 and 3. The two parameters are plotted versus center temperature of the test element, with the measured steady state thermal resistance added for comparison.

TIME. CONSTANT VS. TEMPERATURE
Figure 2

TRANSPORT LAG vs. TEMPERATURE
Figure 3

IV. ANALYSIS

A. Introduction

The function of the analytical portion of this program is to provide a basis for the correlation between the thermal properties of out-of-pile UO_2 test elements and certain transient temperature measurements, and to provide an analytical model suitable for extension of these results to in-pile tests. The value of the model is in its being truly representative of a physical system, so there is necessarily an iteration process between the mathematical analysis and the "hardware" experimentation. The primary effort in this quarter has been in the provision of an operating analog simulation, and in initiation of parametric studies to aid in the design of the out-of-pile experiments.

An analog simulation of the test element temperature behavior was initially chosen instead of a digital approach because the analog method is more flexible, gives output directly in a form suitable for comparison with experimental temperature traces, and is continuous in time, so that no problems as to solution stability or the choice of time interval arise.

The precision of the analog is limited by the precision of its components. As is discussed below, the analog is so arranged that its precision is at least an order of magnitude better than that expected in the experimental measurements.

It is clear that in the out-of-pile and in-pile tests, two considerably different physical situations must be met. In this quarter the analytical approach and the resulting analog simulation were initiated for the out-of-pile case. The modifications expected to be required for the in-pile case are also discussed briefly.

B. System Equations

The geometrical basis for the analytical model is shown in Figure 4. It is assumed that the test section is of sufficient length and homogeneity so that all heat flow is radial. For this initial simulation, it is also assumed that all heat transfer is by conduction except at the boundaries and interfaces, where an effective conductance is assumed.

In addition to these general assumptions the following specific assumptions are made in each region:

1. In the heater, electrical resistivity is a known function of the heater temperature, and the thermal conductivity of the heater is high enough so the heater temperature is essentially constant with radius.

2. In the UO_2 , the thermal properties may vary with radius, but in any transient the temperature variations are so small that the thermal properties may be considered constant in time. The thermal conductivity may be anisotropic; that is, the conductivities may differ along the three axes, r , z , and Θ .*

3. The thermal properties are constant in the clad.

For these assumptions, the following set of differential equations can be written describing the analytical model:

The temperature in the heater is given by

$$M_H C_H \frac{\partial T_H}{\partial t} = P(V, T_H) - h_1 [T_H - T_{\text{UO}_2}(r_1)],$$

where $P(V, T_H)$ is the power per unit length in the heater as a function of applied voltage and heater temperature.

* Symbols are defined in the Appendix.

h =INTERFACE THERMAL RESISTANCE

OUT-OF-PILE ANALYTICAL MODEL
Figure 4

In the UO_2

$$\rho_C \frac{\partial T}{\partial t} = K \left[\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} \right] + \frac{\partial K}{\partial r} \cdot \frac{\partial T}{\partial r} ,$$

where the second term on the right appears because of the radial variation of conductivity. If the conductivity is anisotropic, "K" is its radial component.

In the clad,

$$\frac{\rho_C}{K} \frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} .$$

The gap between the UO_2 and the clad is represented by an effective conductance h_2 , and another conductance h_3 represents the thermal resistance at the outside of the clad. These give as boundary conditions,

$$K_{\text{UO}_2} \frac{\partial T_{\text{UO}_2}}{\partial r} \Big|_{r_2} = -h_2 \left[T_{\text{UO}_2}(r_2) - T_C(r_2) \right] = K_C \frac{\partial T_C}{\partial r} \Big|_{r_2}$$

and

$$+K_C \frac{\partial T_C}{\partial r} \Big|_{r_3} + h_3 \left[T_C(r_3) - T_W \right] = 0.$$

The equations for the in-pile analysis would be similar depending, of course, upon the details of the test geometry. A generation term (which could be radially varying) must be added to the UO_2 equation.

C. Analog Simulation

The analog computer is a device which, through the use of both active and passive components, is used to solve differential equations. By judicious choice of component values, the electrical behavior can be made to be analogous to the thermal behavior of a system; that is, both the electrical system and the thermal system can be represented by the same kinds of differential equations, with electrical quantities such as voltage and current being directly representative of such thermal quantities as heat flow and temperature. However, the analog computer is a lumped parameter system composed of a finite number of discrete components, whereas the thermal system is a distributed parameter system with an almost infinite number of components, even to the individual atoms in the UO_2 crystal lattice. Fortunately, the thermal system can be adequately represented if a sufficient number of analog components are used to represent the temperature behavior, so that the interval between discrete sampling points or nodes is small enough. It is for this reason that the continuous differential equation is modified into a finite difference equation for the analog simulation.

Two methods have been used to enhance analog precision; first, a rather large number of radial nodes (for example, 9 in the UO_2) have been chosen. Second, the space interval between nodes has been chosen to optimize the steady state analog solution, which in the small perturbation approach should also optimize the transient solution. This has involved transforming the radial variable so that in the new space variable the steady state temperature profile is a straight line. Then the analog approximation for the space

derivative, the difference between temperatures at two successive nodes divided by the node interval, is exact. For the out-of-pile representation, the appropriate transformation is $X = \ln(r)$, whereas for the in-pile representation, the transformation is $\xi = r^2$.

In the UO_2 , the equation becomes

$$r^2 \rho C \frac{\partial T}{\partial t} = K \frac{\partial^2 T}{\partial X^2} + \frac{\partial K}{\partial X} \frac{\partial T}{\partial X}$$

In finite difference form for a general node n,

$$\begin{aligned} r_n^2 \rho_n C_n \frac{dT_n}{dt} = & K_n \left[\frac{T_{n+1} - 2T_n + T_{n-1}}{\Delta X^2} \right] \\ & + \left[\frac{(K_{n+1} - K_{n-1})(T_{n+1} - T_{n-1})}{4 \Delta X^2} \right] \end{aligned}$$

The finite difference scheme in X is shown on Figure 5 with the location of the same points in r .

For the in-pile representation, a different form can be expected for the steady-state solution and the transformation is $\xi = r^2$, giving in the UO_2 ,

$$\frac{\rho C}{4} \frac{\partial T}{\partial t} = K \xi \frac{\partial^2 T}{\partial \xi^2} + K \frac{\partial T}{\partial \xi} + \xi \frac{\partial K}{\partial \xi} \frac{\partial T}{\partial \xi} + q'''$$

In finite difference form for a general point, n, this becomes

$$\begin{aligned} \frac{\rho_n C_n}{4} \frac{dT_n}{dt} = & K_n \xi_n \left[\frac{T_{n+1} - 2T_n + T_{n-1}}{\Delta \xi^2} \right] \\ & + K_n \left[\frac{T_{n+1} - T_{n-1}}{2 \Delta \xi} \right] + \xi_n \left[\frac{(K_{n+1} - K_{n-1})(T_{n+1} - T_{n-1})}{4 \Delta \xi^2} \right] \\ & + q'''_n \end{aligned}$$

This finite difference scheme in ξ and the corresponding locations in r are shown on Figure 6 for a possible in-pile arrangement.

TRANSFORMATION AND FINITE DIFFERENCE SCHEME-OUT-OF-PILE
Figure 5

V. RESULTS

The first study in which this analog representation has been employed is an examination of the time-temperature traces for various changes of input power. Figure 7 shows the clad temperature response to a step change of input power. This has the shape of an exponential except that there is a delay at the start of the curve. This delay is the result of the time required for the heat to pass through the UO_2 from the center axial heater to the clad. The similarity between Figure 7, derived from fundamental analysis and the mathematical analog, and Figure 1 which was recorded earlier on an experimental test element, stimulates confidence in this first round of iteration between computer and experiment.

Figure 8 again shows the clad temperature response, but in this case the power input is a step increase, followed in ten seconds by a step decrease to the original level. That is, this curve shows the response to a pulse of power ten seconds in duration. This curve has a sharp leading edge compared to the trailing edge, which is to be expected since the leading edge is only the initial portion of the total exponential, but the trailing edge is the entire exponential decay. Figure 9 shows the clad temperature response when the pulse is repeated at different rates. As the pulse rate is increased, the clad temperature becomes nearly sinusoidal and decreases in amplitude. Only the average temperature change is visible at the highest frequency.

Studies of this type will permit determining the form of power input transients best suited to obtaining optimum results, and are feasible only through the convenient analog computer simulation.

Figure 7

Figure 8

COMPUTED 10 SECOND PULSE RESPONSE

COMPUTED SQUARE WAVE RESPONSE
Figure 9

VI. FUTURE WORK

The first computer studies are now in progress to determine the effects on the transient response of the clad temperature resulting from changes in a variety of parameters; in particular, the thermal conductivity of the UO_2 and the magnitude of the interface thermal resistances. Preliminary results of investigation of the effects of power input transient shape suggest that a cyclic variation of power, at various frequencies, may yield valuable results. A digital computer run will be made, using an existing computer code, to determine the frequency response characteristics of the system. It was decided that in this case the digital computer would provide results more economically than the analog computer.

The work in the coming quarter will be limited to these computer studies. They are expected to be useful in designing the thermal experiments described below, in that a variety of conditions and geometries can be explored without committing hardware. In this manner the optimum test conditions and sensitivities can be established so that the objectives of the program can be met.

Although experimental thermal test work is not planned for the next quarter, it is useful at this time to consider the form that the experimental test elements might take. As indicated previously, the optimization of the experiment is being studied via the computer route, so the following must be considered as a preliminary scheme. In particular, the form of the power input transient is expected to have a major influence on the out-of-pile experiment.

The out-of-pile test specimen is expected to be a cylinder of UO_2 pellets,

about one-half inch diameter and 8 inches long, with an axial electrical heater and with the outer clad cooled. Electrical power applied to the heater will result in heat flow which is primarily radial, giving rise to a temperature gradient from heater to clad that depends upon the thermal conductivity of the UO_2 and the gap resistances; axial heat flow is negligible. By measuring heater temperature and clad temperature, K_{eff} (effective conductance) may be obtained for the system. Additional measurements at various radial depths will permit determination of the shape of the temperature profile, and thus establish local conductivity.

Clad temperature, of course, is easily and reliably measured with thermocouples. Heater temperature may be determined by its electrical resistivity or by optical pyrometry. Temperature at the several radial positions within the UO_2 can be obtained by optical pyrometry. Power input may be measured electrically and confirmed by calorimetry.

The conventional method of obtaining data in this type of test is to allow the material to reach equilibrium after each change of power level, then to read the various temperatures of interest. If, on the other hand, after reaching equilibrium at a specific power input the power input is caused to increase (or decrease) by a small increment, it will take a definite time for equilibrium to be re-established. The most striking effect takes place at the clad, where the temperature remains essentially constant for a few seconds, then rises (or falls) exponentially to a new value. The shape of the curve is a function of thermal conductance of the sample, and is within broad limits, independent of the size of the power input increment. Therefore, by simply measuring time functions, K_{eff} can be deduced for the system. Further, only the clad

temperature versus time is needed.

In-pile, the general test method will be similar to that used in out-of-pile testing with the exception that the heterogeneous heating element will have been replaced by nearly homogeneous heat generation throughout the fuel. The analytical model will properly represent the new mode of heat generation and different temperature distribution. The sample will be brought to an equilibrium, then the power input will be changed by a small increment. The resulting transient variation of fuel and clad temperature will yield the parameters for correlation.

In-pile, the sample configuration will be conventional. A cylindrical fuel rod, clad in stainless steel, will be placed in a capsule filled with a heat transfer material (such as sodium). Instrumentation would consist of thermocouples at the fuel cladding and at the outer periphery of the sodium. The temperature drop across the sodium within the capsule would provide data necessary to calculate total heat flow for each data point.

Two methods are under consideration for obtaining the power control within the fuel sample. The first consists of surrounding the capsule with a series of neutron absorbing shields, which could be removed incrementally by simple remote actuation. When placed in a constant reactor flux, they would permit introduction of the needed transient power steps within the fuel. The second method involves use of a reactor capable of rapid flux variations, such as BRR and possibly GETR. Power levels and transient steps would then be controlled by variation of the whole reactor level in discrete steps.

APPENDIX

Nomenclature

Symbol

C	- heat capacity
h	- surface conductance
k	- thermal conductivity
M	- mass per unit length
$P(V, T_H)$	- heater power per unit length
T	- temperature
t	- time
q'''	- volumetric heat generation rate
r, z, Θ	- cylindrical coordinates
V	- applied voltage
$X, \Delta X$	- the transform variable $X = \ln(r)$, an interval in that variable
ρ	- density
$\xi, \Delta \xi$	- the transform variable $\xi = r^2$, an interval in that variable

Subscripts

C	- clad	W	- water
H	- heater	$1, 2, 3$	- positions given on
UO_2	- UO_2		Figure 4

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