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CEND-3336-237

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ATOMIC ENERGY COMMISSION
RESEARCH AND DEVELOPMENT PROGRAM

EUR/AEC Report. 1371

PROGRESS REPORT

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

For Period
January 1 to March 31, 1965

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Issued April 1965

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UC-25, Metals, Ceramics
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TID-4500, 39th Edition

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Prepared by:

C. E. Burdg

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

Issued April 1965

Unclassified
Classification

Approved by:

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PREFACE

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. Burdick

ABSTRACT

The concept now being investigated is one whereby measurement of 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 consists first of out-of-pile demonstrations of feasibility, followed by in-pile confirmation of the method. Concurrent mathematical analyses of the thermal model will provide the bases for data interpretation, as well as guides for the design of the experimental portions of the program.

Completion of the computer studies of both the out-of-pile case and the in-pile case has led to the conclusion that the clad response to cyclically varying input may yield both effective conductivity and fuel-clad conductance values. With the aid of these analyses of the thermal models, out-of-pile experimental tests have been designed to permit verification of the predicted performance. These tests will include introduction of sinusoidal variations of power input in the frequency range from 0.1 to 1 radians per second, testing of both UO_2 and ZrO_2 pellets, and testing of elements with various pellet-clad assembly clearances.

I. SUMMARY

During this quarter the detailed planning of the experimental program has been completed, with special attention being paid to the results of the computer studies previously performed. Design of the experiments has included consideration of the materials to be tested, the feasible and meaningful assembly clearances, the form of inputs and the manner in which output information is obtained.

Fabrication of test materials is now in process, and the test apparatus power supply modifications have been designed. Completion of the experimental work will permit an assessment of the validity of the mathematical analyses, and thus provide an insight into the potential value of the proposed in-pile test program.

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 the previous quarter a digital computer survey of the frequency response characteristics of the in-pile analytical model was completed. The effects of changing UO_2 conductivity and the pellet-clad conductance were investigated for a test model with typical fuel element geometry. The results of this survey indicated that the method could be of value for the in-pile case. As in the out-of-pile case, investigated earlier, the frequency response method of testing was found to hold promise of yielding both system effective conductivity values and pellet-clad interface conductance values. With these results an out-of-pile testing program was planned and was aimed at devising test methods and choosing materials and configurations which would provide meaningful data.

During this current contract period, the detailed test parameters were chosen, and a test procedure was established. The use of ZrO_2 was selected as a comparison material, since in many respects, it should behave in a similar fashion to UO_2 ; however its thermal conductivity is approximately half the conductivity of UO_2 . Mechanical design of the power supply modifications has been completed; the low frequencies required for the testing will be generated by a synchronous motor and changeable gear train driving a cam and adjustable autotransformer. Fabrication of the several configurations of ZrO_2 and UO_2 pellets is in process.

III. TEST PROGRAM MATERIALS

Transient response of the fuel element system is largely determined by thermal diffusivity of the material contained within the element.⁽¹⁾ Thermal diffusivity can be expressed as $D = K/\rho C$, where K is the thermal conductivity, ρ is the density of the material, and C is the heat capacity per unit mass. Variation in any of these three parameters will affect the diffusivity, and thus affect the transient response in turn. For instance, an increase in K alone will result in a "faster" response; similarly, an increase in C will result in a "slower" response.

The product ρC can be termed the volumetric heat capacity, expressed in the units calories/deg. K/cm³. It is directly proportional to the density of the material and is a maximum when the material has its theoretical crystallographic density; the presence of porosity, as is found in most ceramic materials, serves merely to reduce the volumetric heat capacity proportionately. The contents of the pores is usually a gas and as such has negligible heat capacity compared to a similar volume of the matrix material. At the same time, mixtures of materials, or solid solutions of materials, will have heat capacities approximately proportional to the weight proportions and heat capacities of the individual components, provided that phase transformation or other anomalies are not observed over the temperature range of interest.

The thermal conductivity of heterogenous mixtures, even a simple mixture of solid matrix plus dispersed porosity as is found in typical sintered materials, does not yield readily to mathematical analysis.

Further, experimental evidence does not completely support those hypotheses which have been developed by several investigators in an attempt to explain the effects of porosity. At the same time, for materials which have a density approaching the theoretical crystallographic density (those which have a small pore volume with respect to the matrix) the thermal conductivity is nearly proportional to the density of the material.

This relationship can be expected to hold approximately true for densities which are at least 80% of theoretical and where the heat flow process is by lattice conduction. For most materials of interest, and over most of the temperature range of interest, these conditions are met adequately.

At first glance it would appear that a range of thermal conductivity values could be achieved by simply testing UO_2 of various densities, and that the resulting transient responses would then be indicative of the trends to be expected for a material whose thermal conductivity changes for one reason or another. However, if only the density of the UO_2 is changed, the volumetric heat capacity changes at the same rate as the thermal conductivity. The net result is that the thermal diffusivity remains approximately constant and no significant change in the transient response is expected. Therefore, a second material is required which has a thermal diffusivity quite different from that of UO_2 .

In selecting a second material, consideration was given to several ceramics. To have value, the selected ceramic should be capable of operation at high temperature; be similar to UO_2 in crystallographic structure; have comparable microstructure; be free of phase changes in the temperature range of interest; be an electrical insulator; and, as discussed above, have a thermal diffusivity significantly different from that for UO_2 .

Zirconia stabilized with 20 m/o CaO fulfills these requirements. In addition, the material is readily available and easily fabricated to the precise ceramic shapes required.

Some comparative values are given below:

	<u>UO₂</u>	<u>ZrO₂*</u>
Crystal Structure	FCC (CaF ₂)	FCC (CaF ₂)
Lattice Parameter a/o	5.468 Å	5.142 Å
Melting Point	2790°C	2500°C
Phase Changes**	None	None

* 20 m/o CaO Stabilized ZrO₂

** Room Temperature to Melting

The volumetric heat capacity of 20 m/o CaO stabilized ZrO₂ is not known over the temperature range of interest, from 500°C to 2000°C. However, if the heat capacity of ZrO₂ is used (considering that the CaO content is only 10 weight percent of the stabilized mixture) an approximation can be obtained from Kelley's data ⁽²⁾ and extrapolated to 2000°C.

The product ρC , using a density of 5.32 gm/cc, is then:

$$.719 + .0778 \times 10^{-3}T - .145 \times 10^5 T^{-2} \text{ Cal/Deg K/cm}^3$$

The same product for UO₂ is:

$$.779 + .0658 \times 10^{-3}T - .161 \times 10^5 T^{-2} \text{ Cal/Deg K/cm}^3$$

Over the temperature range from 500°C to 2000°C, these values differ by less than 5%. Inasmuch as the thermal conductivity of ZrO₂ is no more than half that of UO₂, the diffusivity of the ZrO₂ "fuel" will be about half that of the UO₂ "fuel". This is a difference great enough to demonstrate the validity of the mathematical analysis and yet not so great as to require revision of the basic assumptions used to derive the analysis.

IV. TEST PROGRAM ASSEMBLY CLEARANCES

Mathematical analysis of the thermal model, conducted during the earlier phases of this program ^(3,4), demonstrated quite clearly that the transient response of the outside of the cladding depended significantly on the thermal resistance of the interface between the "fuel" pellet and the inside diameter of the cladding. Many factors affect the thermal resistance of this interface. The one most easily varied, and probably the most important single factor, is the contact pressure. Although the contact pressure is not readily measureable, it can certainly be changed from a low value to a high value by simply changing the cold assembly clearance between the pellet and the cladding. During the experimental program, assembly clearances will be chosen ranging from a slight interference fit to a loose fit, within the nominal 1.27 cm outside diameter tubing.

In the case of the interference fit, the pellets will be ground to a diameter approximately 0.0025 cm greater than the inside diameter of the clad tubing. Past experience with similar systems ⁽⁵⁾ has shown that if the pellet diameters are held to about ± 0.0005 cm for a given loading, the tubing will be in intimate contact with the pellet surfaces at all places. During assembly, the tubing is "sized" by pressing the first pellet in; all succeeding pellets then merely strain the tubing within its elastic range.

In the second case, a low contact pressure fit between the pellets and the cladding will be assured by removing approximately 0.018 cm from the diameter of the pellets prior to loading in the clad tubing.

Finally an intermediate case will be studied in which the pellets are ground undersize approximately 0.005 cm on the diameter.

V. TEST PROGRAM INPUT

Power to an axial heater will be used to control the test element power to a desired "base level"; superimposed on this level will be sinusoidal variations of adjustable amplitude and frequency. Variation of the base level of power, in separate runs made on a given element, will result in changes of the centerline temperature. These changes, in turn, will cause at least two major changes in the thermal parameters of the element. First, the thermal expansion of the "fuel" will result in a slight increase in the contact pressure at the fuel-cladding interface in the interference fit element, a large increase in the contact pressure in the intermediate fit element, and no significant change in the contact pressure in the loose fit element. These changes in contact pressure will be reflected as changes in the contact thermal resistance.

Second, an increase in the centerline temperature in UO_2 elements will cause a slight decrease in the effective conductivity of the test element, because of the decreasing conductivity of UO_2 with increasing temperature in the region from room temperature to about 1400°C . At the higher temperatures, UO_2 exhibits an increasing thermal conductivity with temperature, (6) thus the test element would not be expected to show a decreasing effective thermal conductivity with increasing temperature. Thermal conductivity of ZrO_2 does not change appreciably with temperature in the range from room temperature to 1400°C (7), but does show an increase at the higher temperatures.

Previous analyses have shown (4) that, for a linear system, frequency response testing may yield significant information regarding both the system conductance and the pellet-cladding interface resistance. In this out-of-pile test a range of frequencies from 0.1 radian/second to 1 radian/second should prove adequate to demonstrate the validity of the method.

During testing, the element will be first powered to a selected base level input; a low amplitude sinusoidal variation will then be superimposed on this input. The sinusoid will continue at a selected frequency until enough cycles have been accumulated to provide statistically sound data. When enough different frequencies have been run, the base level of power will be changed to a new value and the frequency again varied.

Perturbations of the power input will be achieved by varying the voltage to the heater element in a cyclic manner. Because the heater power does not necessarily vary sinusoidally with voltage, the power will be monitored separately and the wave shape of the voltage variation adjusted until the power variation is a close approximation to a sinusoid.

To determine if there are significant non-linearities in the system, selected values of base level and frequency will be run at a higher amplitude of the superimposed sinusoid and the results compared with those for a low level of perturbation.

VI. TEST PROGRAM OUTPUT

The most important information obtained from the experimental runs will be the phase shift of the cladding temperature variations with respect to the power input variations, as a function of frequency. In order to obtain this, it will be necessary to record both the power input variations and the cladding temperature variations simultaneously.

Cladding temperature will be measured by the use of fine wire thermocouples spotwelded directly to the outside diameter of the element. Several thermocouples will be applied, and these will be monitored and recorded in turn. It is expected that the transient response will be slightly different at each cladding location; the use of several thermocouples permits determination of the magnitude of the point-to-point variations in response.

VII. FUTURE WORK

It is expected that during the next quarter the test equipment modifications will be completed, and about six test elements run. These will be three UO_2 elements, and three ZrO_2 elements, each "fuel" with three different assembly clearances. The information gained from these tests should be sufficient to gain an evaluation of the basic soundness of the methods, and determine the course to be followed if further out-of-pile work is needed.

Based in part on the results of these expected out-of-pile tests, a review will be prepared for the Contracting Officer in which the overall approach will be presented and the probable in-pile success potential will be assessed.

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