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PROGRESS REPORT

MASTER

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

For Period
October 1 to December 31, 1964

Issued February 1965

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TID-4500, 37th Edition

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Prepared by:

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TRANSIENT METHOD FOR PERFORMING
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DEVELOPMENT AND TESTING OF A TEMPERATURE
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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 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.

A digital computer study of the expected transient characteristics of the proposed in-pile element has been made. The predicted behavior is somewhat similar to that predicted for the out-of-pile element, in that the clad response to cyclically varying input may yield both effective conductivity and fuel-clad conductance values. An important difference is that the in-pile element is expected to be less sensitive to changes in the thermal parameters, a direct result of distributed power generation as opposed to axial line heating. With the aid of these analyses of the thermal models, out-of-pile experiments are being designed to permit verification of the predicted performance.

I. SUMMARY

During this quarter further study of the transient response of the test system has been made, with particular emphasis on determining the predicted response of the in-pile test element. These studies were performed using the CEND developed digital computer program GUPPY. Results obtained during the prior reporting period indicated that use of frequency response methods of transient testing might reveal detailed information regarding the separate contributions of pellet conductivity and pellet-clad conductance to the overall effective element conductivity, from cladding response alone.

The results of this quarter's study show that the frequency response method may have value in determining the detailed thermal properties information in-pile. However, it has been calculated that the sensitivity of the method to changes in thermal properties is less in-pile than out-of-pile, because of the difference in the manner of heat input in the two cases. It is calculated that, for the in-pile case, input frequencies of as high as 1 radian per second yield no significant information; lower frequencies, in the range of 0.1 radian per second, become of interest. Further, it has been calculated that the change in cladding time lag, for comparable changes in effective conductivity, are significantly less for the in-pile case, at comparable frequencies. The net result is that experimental measurements in-pile may well require lower frequencies than out-of-pile, and the instrumentation system must be capable of detecting small changes in the cladding time lag.

Effort during the next reporting period will be aimed at providing a correlation between experimental results and computed responses. This comparison will permit determination of the validity of the analytical models, and thus provide a basis for assessment of the potential for success for the in-pile tests.

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 concentrated effort was placed upon an analysis of the out-of-pile model using both analog and digital computer methods. It was concluded that a convenient time scale could be utilized and that complicated instrumentation would not be required, since the frequencies of interest appeared to lie in the range of 6 seconds per cycle to 100 seconds per cycle. Use of inputs in this frequency range resulted in calculated clad time lags ranging from seconds to tens of seconds. Analyses of the cladding frequency response showed that use of several different input frequencies might permit separation of the contributions of fuel conductivity and fuel-clad conductance to the overall effective conductivity of the element. Therefore, it was concluded that frequency response testing, of the out-of-pile model, showed considerable promise as a means of determining thermal property information. It was further concluded that fabrication and experimental convenience, rather than analytical necessity, would dictate selection of out-of-pile test geometries.

Before proceeding with out-of-pile tests to verify the computed results, it became desirable to investigate the in-pile analytical model. This would permit introduction of experimental variables which would permit some evaluation of the sensitivity of the method when applied to the in-pile case. On this basis, the initiation of the out-of-pile experimentation was delayed until a computer study of the in-pile model was completed.

During this reporting period a digital computer survey of the frequency response characteristics of the in-pile analytical model has been 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 indicate that the method could be of value for the in-pile case. However, correlations between the computed results and experimental data, at least for the out-of-pile case, must be established before a firm assessment of the feasibility of the method for in-pile measurements can be made. All of the effort during the next reporting period will be applied to such an experimental program.

III. ANALYTICAL INVESTIGATIONS

Frequency response techniques for this program have been described previously ⁽¹⁾ and consist of a measurement of the phase shift (time lag) and the magnitude of response at one point in the system when inputs of various frequencies are imposed at other parts of the system. It was concluded that the use of cyclic inputs at several frequencies might permit the determination of both the effective conductivity and the fuel-clad conductance. These results warranted further exploration of the approach, with particular emphasis on the in-pile model.

The out-of-pile model uses electrical heat input at the inner boundary of a stack of cylindrical fuel pellets contained within a cladding tube. In the in-pile model, the heat input is distributed over the pellet volume and a different dependency of the cladding response on thermal properties is to be expected. The analytical model for use in the in-pile case has been described previously ⁽²⁾. A transformation and subsequent finite difference process was required to provide a suitable form for the solution of the original partial differential equation. It was found that the preferred in-pile representation is a radius squared transformation only for the UO_2 , and a log radius transformation for the cladding. Using this representation, the frequency response of the in-pile model has been established over a range of UO_2 conductivities and pellet-clad conductances, using the CEND digital program GUPPY.

In Figure 1, the time lag at the cladding has been plotted as a function of effective conductivity for the in-pile model. Effective conductivity is defined in the Appendix for both analytical models. The cladding time lag is the time between the peak in the sinusoidal power input variations and the corresponding temperature peak at the outer boundary of the cladding.

CLAD TEMPERATURE LAG FOR SINUSOIDAL INPUT
 — In-Pile Model —

Fig. 1

Relationships between cladding time lag and effective conductivity are shown for two frequencies (1.0 and 0.1 radian/second). These relationships, (designated by circles) represent the frequency response for various effective conductivities which were obtained by varying the pellet conductivity while maintaining constant pellet-cladding conductance. Data points designated by triangles are for cases in which the pellet-clad conductance was varied and are given for frequencies of 0.1 and 1.0 radian/second (62.8 and 6.28 seconds/cycle). Data previously (1) generated for the out-of-pile case are shown in Figure 2. A comparison of the in-pile and out-of-pile cases (Figures 1 and 2) leads to the following conclusions:

- A. At frequencies of 1 radian/second and greater, the in-pile cladding time lag is not a good indicator of test element thermal properties.
- B. Use of the frequency response technique to investigate thermal properties may require a lower range of frequencies in-pile than out-of-pile.
- C. The frequency response technique shows promise, in-pile and out-of-pile, of discriminating between those changes in effective conductivity due to changes in UO_2 conductivity and those due to changes in pellet-cladding conductance.

CLAD TEMPERATURE LAG FOR SINUSOIDAL INPUT
 — Out-of-Pile Model — Fig. 2

IV. EXPERIMENTAL IMPLICATIONS

The analytical study has demonstrated that, for the out-of-pile case, there is a change in the cladding time lag of about 4 seconds at a frequency of 0.1 radian/second, for a change in the effective conductivity of about 2:1. On the other hand, for the in-pile model there is a change of cladding time lag of about 1.8 seconds for a 2:1 change in the effective conductivity. Thus, instrumentation capable of a higher degree of time resolution than had been expected ⁽¹⁾ may be required for in-pile measurements. It is apparent that the instrumentation system must be capable of determining small differences in the time lag between input power variations and output clad temperature variations if small changes in effective conductivity are to be measured. During the out-of-pile testing the significant factors controlling instrumentation limits will be considered and an attempt will be made to predict the capabilities of in-pile instrumentation systems.

A further implication of the in-pile analysis is the indication that the in-pile system will be more sensitive to changes in pellet-clad conductance than the out-of-pile system. Analyses of irradiation data for UO_2 fuel elements indicate a preponderance of conditions which should provide major changes in pellet-clad conductance during fuel element lifetime. Thus, the method should be capable of providing good engineering conductance data for operating fuel elements.

V. OUT-OF-PILE TEST PROGRAM

The out-of-pile test program is aimed at providing a correlation between the experimental results and computed predictions of results. This comparison is vital to the assessment of the potential for success for the in-pile tests. Determinations of the correlations, out-of-pile, will permit a more accurate evaluation of the validity of the computed data for the in-pile model. An iterative process may be required.

A summary of the planned out-of-pile experimental program is presented below:

- A. Modify existing power supply system to enable introduction of small transients, especially sinusoids, superimposed on a base level of power input.
- B. Prepare test elements, composed of "fuel" pellets contained within clad, with various thermal parameters so that the validity of the computed results may be checked. As an example, the initial two elements may contain UO_2 pellets and ZrO_2 pellets, so that a wide difference in the pellet conductivity may be realized.
- C. Perform frequency response tests under a variety of conditions, varying the frequency of the input power variations, the base level of the input power, and perhaps the amplitude of the input power variations.
- D. Compare the temperature response at the cladding outside surface with the predicted response based on analytical considerations.
- E. Adjust the analytical model as necessary, to reduce differences between predicted response and actual response.

F. Repeat tests with experimental elements, adjusting thermal parameters to explore the effects of variations in pellet-clad assembly clearances, inner diameter, and outer diameter.

APPENDIX

The analytical models used for frequency response studies are shown in Figures 3a and b. For both models, effective conductivity is defined as:

$$K_{\text{eff}} = \frac{A q'}{(T_o - T_{\text{cO.D.}})}$$

where K_{eff} = effective conductivity, W/cm°C

T_o = maximum UO₂ temperature, °C

$T_{\text{cO.D.}}$ = clad O.D. temperature, °C

q' = the linear heat generation rate in the test element, W/cm.

A = a dimensionless constant depending on the model.

The definition of the constant A is based on treating everything between the point of maximum UO₂ temperature and the clad O.D. as a homogeneous material having constant thermal properties (and in the in-pile model having a uniform internal heat generation rate).

In steady-state, for an annular cylinder of uniform properties, the temperature difference from I.D. to O.D. is given by:

$$(T_o - T_{\text{cO.D.}}) = \frac{q' \ln(r_3/r_1)}{2\pi K}$$

where K is the constant conductivity. So if $(T_o - T_{\text{cO.D.}})$ is computed for the out-of-pile model, K_{eff} is found to be

$$K_{\text{eff}} = \frac{q' \ln(r_3/r_1)}{(T_o - T_{\text{cO.D.}}) 2\pi},$$

and

$$A = \frac{\ln(r_3/r_1)}{2\pi}$$

For uniform generation at a rate q''' per unit volume in a solid cylinder, the steady-state temperature solution is

$$T_o - T_{\text{cO.D.}} = \frac{q''' r_3^2}{4 K} \quad \text{and}$$

$$q' = q''' \pi r_3^2$$

(a) Out-of-Pile

STANDARD CASE		
$r_1 = 0.095 \text{ cm}$	$k_{\text{UO}_2} = 0.044 \text{ W/cm } ^\circ\text{C}$	
$r_2 = 0.584 \text{ cm}$	$k_{\text{clad}} = 0.173 \text{ W/cm } ^\circ\text{C}$	
$r_3 = 0.635 \text{ cm}$	$h_2 = 0.568 \text{ W/cm } ^\circ\text{C}$	
	$h_3 = 0.764 \text{ W/cm } ^\circ\text{C}$	

(b) In - Pile

Thus, for the in-pile model K_{eff} is given by

$$K_{eff} = \frac{q''' r_3^2}{4(T_o - T_{cO.D.})} = \frac{q'}{4\pi(T_o - T_{cO.D.})} \quad \text{and}$$

$$A = \frac{1}{4\pi}$$

For the same values of q' , external diameter, clad thickness, and pellet-to-clad conductance, the temperature drop in the clad and at the pellet-clad interface are identical for the in-pile and out-of-pile models. On the other hand, the temperature drop across the pellet, even for the same assumed value of UO_2 conductivity, is not necessarily equal in the two models. This inequality depends, of course, upon the inside radius of the UO_2 pellet in the out-of-pile model.

For the standard geometry and thermal parameters assumed in the frequency response studies, the temperature drop across the pellet is a less important part of the total temperature difference in-pile than out-of-pile. Thus, using the definitions of effective conductivity given above, the effective conductivity is seen to be less sensitive to changes in UO_2 properties in-pile than out-of-pile. This explains why the range of effective conductivity in the in-pile frequency response study is less than that in the out-of-pile study.

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