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PROGRESS REPORT

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

For Period
July 1 to September 30, 1964

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For Period
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Prepared by:

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

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DEVELOPMENT AND TESTING OF A TEMPERATURE
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 IN-PILE THERMAL CONDUCTANCE TESTING

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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 will consist 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.

Results of an analog computer study of the out-of-pile test element are presented. They indicate that a single power pulse, at the center of the cylindrical element, will provide enough information in the clad transient response to permit determination of the effective conductivity of the element. The effects of system geometry, system parameters, and pulse characteristics have been studied and the results indicate test feasibility.

Study of the frequency response characteristics of the system has revealed that, by applying a cyclically varying input at a variety of frequencies, both the effective conductivity and the fuel-clad conductance may be determined from measurements of only the clad response. The far-reaching significance of this result justifies continued study of the frequency response approach.

I. SUMMARY

During this quarter extensive studies of the transient response of the out-of-pile test system were made, using analog and digital computation methods. These studies were required to initially define the bounds of the forthcoming experimental work, in that they provided valuable insight into the effects of several important geometrical and thermal parameters. In addition to experimental definition, they provided further confirmation of the feasibility of performing transient testing to determine fuel element characteristics from clad temperature response alone.

In particular, the studies revealed that, for the out-of-pile model, the time-amplitude characteristic of the clad response, i. e., its shape, yields enough information to determine the effective conductivity of the system. The time scale associated with the input pulse and the corresponding clad response is quite convenient from an experimental point of view; pulse lengths on the order of one second, and responses which occur a few seconds later, indicate that sophisticated instrumentation and control may not be needed.

Studies of the frequency response of the clad when the input is a sinusoid of variable frequency show that such a technique may make it possible to separate the contributions of fuel conductivity and fuel-clad conductance from the overall effective conductivity of the element. This approach has such important implications that further study is being made.

Effort during the next reporting period will be aimed at furthering the analytical understanding of both the out-of-pile system and the in-pile system, and at performing out-of-pile experiments.

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.

In the last quarter the analytical procedures were established, and an analog computer program prepared. Use of the analog during this quarter has provided valuable insights into the behavior of the thermal system. It has, in addition, led to the use of digital computation. The result of the computer work has been confirmation of the feasibility of the out-of-pile test. Potentially significant information regarding the thermal characteristics of the system may be gained through the use of frequency response testing; further computer work is needed to determine the utility of this technique.

III. BACKGROUND

Development of the analytical treatment of the out-of-pile test system was presented in the previous quarterly report. * The test element consists of a cylindrical stack of UO_2 pellets, contained within a water cooled clad. Electrical power applied to an axial heater will result in heat flow which is primarily radial, giving rise to a temperature gradient from heater to clad. This gradient depends upon the thermal conductivity of the UO_2 and on the fuel-clad conductance. By measuring the heater temperature, and the clad temperature, k_{eff} (effective conductivity) may be obtained for the system. Clad temperature may be easily measured with thermocouples, while the heater temperature may be measured optically or calculated from its electrical resistance.

The conventional method of obtaining data in this type of test is to allow the system to reach equilibrium after each change in power level, then to read the clad temperature and the heater temperature. If, on the other hand, after reaching equilibrium at a specific power level, the heater power is caused to increase or decrease by a small increment, the results of this input perturbation appear at the clad only after a time delay. It is the time variation of the clad temperature, resulting from input variations, which yields the transient response information of interest in the program. From the clad transient response alone, the effective conductivity of the system can be determined.

* Burd, C. E., J. R. Parrette, R. I. Brockett, and W. P. Chernock, CEND-3336-218 (July 1964), "Development and Testing of a Temperature Transient Method for Performing In-Pile Thermal Conductance Testing - Progress Report."

IV. PULSE STUDY

One of the important functions of the analytical effort in the early stages of the program is to provide assistance in the design of experiments. As soon as the mathematical model had been established, and initial parameters chosen, a series of analog computer runs were made. These runs, listed in Table I, explored the effects on temperature responses in the system caused by varying several of the system parameters. In this way the required sensitivity and speed of instrumentation could be determined, the effect of dimensional changes could be evaluated, and the ability to effectively measure the several thermal parameters could be estimated.

A desire for simplicity in experimental apparatus led to the initial proposal that the power input transient could be either a step, where the power is increased a small amount and held at that new amount; or a pulse, where the step increase is shortly followed by an equal step decrease, thus finally holding at the original power level. Almost all of the analog runs were made with a pulse input, as this form of input yielded the more useful data.

A. General Case

Figure 1, Run #20, is a typical plot of the output of the analog computer. In this case the temperature response to a pulse input is shown at nine points in the fuel and three points in the clad (the three clad temperatures are so close as to be inseparable). At locations successively outward in the fuel from the center toward the clad, as shown by the intermediate curves, it takes a correspondingly longer time for the temperature to reach its peak value after the pulse. The shape of the curve becomes more "rounded" at each successive

TABLE I

(All values are relative to the nominal case)

Run No.	Input Function Power to Fuel Inside Diameter	Relative UO ₂ Conductivity	Relative Fuel-to-Clad Conductance	Relative Clad to H ₂ O Conductance	Relative Fuel Diameter	Mode of Input Power *
1	Unit Step	1	1	1	1	Fuel
2	Unit Step	0.5	1	1	1	Fuel
3	Unit Step	1	1	0.5	1	Fuel
4	10 Sec Unit Pulse	1	1	1	1	Fuel
5	10 Sec Unit Pulse	0.5	1	1	1	Fuel
6	10 Sec Unit Pulse	1	1	0.5	1	Fuel
7	Square Waves	1	1	1	1	Fuel
8	Square Waves	0.5	1	1	1	Fuel
9	Square Waves	1	1	0.5	1	Fuel
10	10 Sec Unit Pulse	1	1	1	1	Fuel
11	10 Sec Unit Pulse	1	1	2	1	Fuel
12	10 Sec Unit Pulse	1	1	0.5	1	Fuel
13**	10 Sec Unit Pulse	1	1	0.5	1	Fuel
14**	10 Sec Unit Pulse	1	1	2	1	Fuel
15	10 Sec Unit Pulse	Variable	1	1	1	Fuel
16	10 Sec Unit Pulse	0.9 (Variable)	1	1	1	Fuel
17	Unit Step	Variable	1	1	1	Fuel
18	1 Sec Unit Pulse	1.5, 1, 0.6	1	1	1	Fuel
19	1 Sec Unit Pulse	1.5	1	1	1	Fuel
20	1 Sec Unit Pulse	1	1	1	1	Fuel
21	1 Sec Unit Pulse	0.6	1	1	1	Fuel

TABLE I (Continued)

(All values are relative to the nominal case)

Run No.	Input Function Power to Fuel Inside Diameter	Relative UO ₂ Conductivity	Relative Fuel-to-Clad Conductance	Relative Clad to H ₂ O Conductance	Relative Fuel Diameter	Mode of Input Power*
22	1 Sec Unit Pulse	1	0.5	1	1	Fuel
23	1 Sec Unit Pulse	0.96	2	1	1	Fuel
24	1 Sec Unit Pulse	0.96, 1, 1.08	2, 1, 0.5	1	1	Fuel
25	1 Sec Unit Pulse	1	2, 1, 0.5	1	1	Fuel
26	4 Sec Unit Pulse	1.5	1	1	2	Fuel
27	4 Sec Unit Pulse	1	1	1	2	Fuel
28	4 Sec Unit Pulse	0.8	1	1	2	Fuel
29	4 Sec Unit Pulse	1.5, 1, 0.5	1	1	2	Fuel
30	4 Sec Unit Pulse	1	2, 1, 0.5	1	2	Fuel
31	4 Sec Unit Pulse	1.5, 1, 0.8	2	1	2	Fuel
32	4 Sec Unit Pulse	1	0.5	1	2	Fuel
33	4 Sec Unit Pulse	1	2	1	2	Fuel
34***	1 Sec Unit Pulse	1	1	1	1	Fuel
35	Unit Step	1	1	1	1	Non-linear
36	1 Sec Unit Pulse	1	1	1	1	Non-linear
37	1 Sec Unit Pulse	1	1	1	1	Linear
38	1 Sec Unit Pulse	1	2	1	1	Linear
39	1 Sec Unit Pulse	1	2	1	1	Linear and non-linear

* Runs #1 through #34 were made with simulated power input to fuel ID. Runs #35 through #39 were made with simulated power input to tungsten heater.

** These runs were to compare the shapes of the fuel OD temperature and the clad ID temperature responses.

*** Check Run.

TEMPERATURE RESPONSE AT VARIOUS RADIAL POSITIONS, WITH PULSE INPUT
Fig. 1

location. These characteristics of the response, the shape and the time dependence, are the significant characteristics which enable determination of the nature of the medium through which the thermal transient has passed. It is important to recognize that the magnitude of the response is not needed.

B. The Effect of Fuel Diameter

One of the basic variables in the test element design is the UO_2 diameter. In order to show the effects of diameter variation on the transient measurements, an analog run was made simulating the behavior of a test element with double the nominal diameter. Referring again to Figure 1, this double diameter Run #27 can be compared to nominal Run #24. The curves are essentially the same, except that the time base is different for the two cases. This modification of time base is the major effect of diameter changes. Since no difficulty is expected from the time scale associated with the nominal diameter, there is no analytical reason to change the fuel diameter from that proposed for the nominal case. The final selection will be determined for experimental and fabrication convenience.

C. The Effect of Temperature-Dependent UO_2 Conductivity

The conductivity of UO_2 is known to vary considerably with temperature. There is no real theoretical difficulty in incorporating this fact into the analog simulation; however, certain practical problems arise. The use of a conductivity which is not fixed would require that the parameters of the analog be recomputed for each power level to be studied. For the purposes of exploring the response characteristics of the system, such refinement did not appear to be justified. To confirm that the simplification would not obscure the significant

results, analog runs were made to compare a case using temperature-dependent conductivity with one using fixed conductivity. The temperature response at the clad was essentially the same for the two cases. This result justified holding the fuel conductivity constant for the remaining runs of the parameter survey.

D. The Effect of Fuel Conductivity, Fuel-Clad Conductance, and Effective Conductivity

The major objective of the program is to determine the effective conductivity of a fuel element from measurements of the temperature response at the clad. The effective conductivity is a measure of the overall effectiveness of the heat transfer system and thus includes the effects of the fuel-clad interface ("gap" conductance). It may be possible to measure the temperature of the outside surface of the fuel as well as that of the clad and determine the fuel-clad conductance. On the other hand, it is probable that transient response testing will enable us to determine the separate contributions by the fuel conductivity and by the fuel-clad conductance from temperature response measurements on the clad only. If this proves to be true, then considerable experimental simplification can be made. Fuel-clad interface conductance, in addition to effective conductivity, could be measured without the need to penetrate the clad with temperature instrumentation. The significance of this for in-pile testing is manifest.

With this concept in mind, the effects of fuel conductivity and fuel-clad conductance on the response at the clad were studied in detail. Figure 2, Run #18, shows the effects of fuel conductivity changes. The curves show a large separation (in time dependence and shape) indicating that changes in conductivity could be correlated with the response. This correlation is not

unique, however. The fuel-clad conductance is also important in determining the response at the clad. Figure 2, Run #25, shows the effects of changes in this variable. Changes might occur during the test because of differential expansion of the fuel and clad. Since Run #25 indicates a substantial effect on the clad response, one could easily misinterpret changed clad response to be the result of a change in the fuel conductivity, whereas it could really be caused by fuel-clad conductance changes.

Figure 3 shows quite dramatically how changes in fuel conductivity and fuel-clad conductance can compensate to control the clad response. For this run, the effective conductivity of the test element system was maintained constant, by increasing the fuel conductivity when the fuel-clad conductance was decreased (or the reverse). Note that the shape of the curves for all three cases is essentially constant when the input is a simple pulse. It is apparent that when the shape of the curve does not change, one cannot separate the contributions of the two thermal parameters to the overall effective conductivity.

E. Conclusions

Inspection of a curve of the temperature response at a single point, on the surface of the clad, would enable one to determine the effective conductivity of the system. The method is quite independent, within broad limits, of the magnitude of the input pulse or of the resulting clad response. Only the time function and temperature change at the clad need be measured.

The prime objective of this portion of the program can be met with pulse testing; it permits determination of effective conductivity from clad response alone.

*RUN No. 18 - VARIABLE FUEL CONDUCTIVITY,
CONSTANT FUEL-CLAD CONDUCTANCE*

*RUN No. 25 - VARIABLE FUEL-CLAD CONDUCTANCE,
CONSTANT FUEL CONDUCTIVITY*

**TEMPERATURE RESPONSE AT CLAD WITH ONE SECOND
PULSE INPUT**

Fig. 2

RUN No. 24

	<u>RELATIVE</u>	
	<u>FUEL-CLAD CONDUCTANCE</u>	<u>FUEL CONDUCTIVITY</u>
No. 1	0.5	1.08
No. 2	1.0	1.00
No. 3	2.0	0.96

TEMPERATURE RESPONSE AT CLAD WITH ONE SECOND PULSE
INPUT. FUEL-CLAD CONDUCTANCE VARIED, FUEL CONDUCTIVITY
ADJUSTED TO ACHIEVE CONSTANT OVERALL EFFECTIVE
CONDUCTIVITY

Fig. 3

V. FREQUENCY RESPONSE STUDY

The discussion so far has been limited to the results of an analog computer study, with a single power pulse input to the system. While it is a satisfactory method of obtaining the overall, or effective, conductivity of the fuel element system, it does not have the potential of readily separating the effects of fuel-clad conductance variations from the effects of fuel conductivity changes. The possibility of achieving additional information with little added effort was justification for further study of the system. As will be seen, the preliminary results of this second study are of far-reaching significance.

A. Background

The previous quarterly report presented the results of preliminary analog studies based on a cyclic, or repetitive, input. This approach has been given considerable further study. It is not a departure from the general concept of the transient technique; rather, it is another way of obtaining information by the use of transients. The idea of studying the frequency response of a "black box" system in order to determine the parameters of that black box is well established. The analogy to the present problem is direct.

Earlier it was stated that the shape of the clad response curve, that is, its change of temperature with respect to time, is dependent on the nature of the medium through which the thermal transient had passed. In particular, Figure 2, Run #18, shows that the time for the clad temperature change to reach a peak value after the pulse input is quite sensitive to changes in the fuel conductivity. If the input power pulse were to be repeated at regular intervals, the clad temperature would vary in a cyclic fashion at the same fre-

quency. However, there would be a distinct and measurable time lag between the peaks of the power input pulse and the peaks of the clad response. Further, it was noted in Figure 1 that the shape of the clad response was very "rounded" compared to the shape of the temperature response at the center of the fuel, next to the heater. If the power input pulses were repeated at higher and higher frequencies, the response at the clad would eventually be smoothed out and show no variations. Here, then, is the essence of frequency response testing: measurement of the phase shift or time lag, and the magnitude of the response, at one point in the system when various frequencies of driving force are impressed as input at another point in the system.

A further discussion of frequency response testing and computer application appears in Appendix I.

B. Results

Using a digital computer program (developed by Combustion Engineering, Inc.) the frequency response of the test element system was studied in detail. It was found that, with sinusoidal inputs, the time lag of the clad response was a significant indicator of the thermal properties of the element. Figure 4 shows the time lag as a function of the effective conductivity of the element, at two different frequencies. The frequencies were 6.28 seconds per cycle, and 62.8 seconds per cycle. In this Figure, the effective conductivity is varied by changing the fuel conductivity (circles) or by changing the fuel-clad conductance (triangles).

It is very important to note in Figure 4 that the time lag variation with frequency is not the same for the two methods of changing the effective

CLAD TEMPERATURE LAG FOR SINUSOIDAL INPUT

Fig. 4

conductivity. It is this difference which offers the potential of discrimination using the clad temperature response alone. In theory, by simply measuring the clad time lag at only two frequencies, the effective conductivity and the fuel-clad conductance could both be determined. In practice it will probably be desirable to measure the frequency response over a range of frequencies.

C. Conclusions

In summary, the use of cyclic inputs to the system offers a significant increase in the amount of information which can be gained, with very little added difficulty. The use of a single power pulse input would enable determination of the effective conductivity of the fuel element from the clad response, and thus meet the prime objective of the program. On the other hand, use of easily generated cyclic inputs, at several frequencies, appears to permit the determination of both the effective conductivity and the fuel-clad conductance.

VI. EXPERIMENTAL IMPLICATIONS

In the preceding, the results of analytical studies of the out-of-pile test are reported. They indicate, to the experimentalist, that the prime objectives of this phase of the program can be readily met. Further, there is the exciting potential of achieving significant further information with only a slight modification of the proposed test method. Several of the more important conclusions can now be summarized:

A. The system time scale, using the originally proposed geometry, is a convenient one. Input pulses may be on the order of one second long, readily achieved and controlled. Or, if sinusoidal inputs are used, the frequencies of interest appear to lie in the range between 6 seconds per cycle and 100 seconds per cycle; again, readily achieved. Response at the clad has two general characteristics: a delay from the input, and, in the case of the pulse input, a change in shape. Again, the times involved range from a few seconds to a few tens of seconds. The net result of this time scale is that instrumentation need not be particularly complicated; as an example, output recorders might very well be ordinary pen recorders. At the same time the time scale is short enough that tests can be performed within a reasonable time.

B. The originally proposed geometry, particularly the diameter of the fuel, yields adequate analytical results. While it may prove desirable to test several diameters near that of the nominal case, the only significant result should be an acceptable modification of the time scale. Therefore, fabrication and experimental convenience, rather than analytical necessity, will dictate the choice of fuel diameter.

C. Simple pulse testing will yield the information needed to determine the effective conductivity of the fuel element system. This would satisfy the prime objective of the program.

D. Frequency response testing may yield the information needed to determine both the effective conductivity and the fuel-clad conductance, from only clad response measurements.

VII. FUTURE WORK

A large amount of analog and digital computer data has been generated, during the course of parameter studies. Evaluation of this information in the light of the overall program objectives, and the needs of experimental design, is continuing. Frequency response studies, having the potential of readily providing extremely useful data, are continuing.

Thermal test work is expected to start in the coming quarter. As confirmation of the present analytical results is needed, significant parameters of the test element and of the power input transients will be varied. Concurrent analytical work will aid in interpretation of the experimental results, and will provide guidance. The ultimate objective of this program is to develop a technique suitable for measurement of thermal properties in-pile. Therefore an analytical examination of the in-pile case using the frequency response approach will be made.

Finally, the results of the analytical work will be combined with the practical conclusions derived from out-of-pile experimentation to estimate the chances of success for the in-pile program.

APPENDIX I

In the analog simulation the computer provides the solution to a set of differential equations when a given wave shape is impressed on the computer input. A Fourier analysis of the input and of the output response would yield two series of sinusoidal waves. A comparison of the two series would indicate that the system between input and output had modified the amplitude and phase of each component in the input to give the output series. This amplitude and phase information could then be used to obtain information about the nature of the system between input and output.

Although simple step or pulse functions contain all the information necessary to obtain amplitude and phase information, for each frequency, the mathematical task of obtaining frequency response from these functions is difficult. Further, the experimental task is rendered difficult by the fact that important high frequency components of the response, as well as those in the input function, are so reduced in amplitude that they may be obscured by noise. The term "noise" refers to random disturbances of the signal, without regard to the source of these disturbances.

A more direct method of obtaining the frequency response for a system is to apply a sinusoidal input of varying frequency but constant amplitude to the system. The output amplitude and phase, relative to the input, is measured. This is highly advantageous because the repeated (cyclically varying) signal permits taking several successive observations; thus the measurement "statistics" improve in the presence of noise and finite sensor sensitivity and

and resolution. Further, the ability to use constant amplitude inputs improves measurement of the important high frequency components in the response.

On the analog computer the determination of frequency response data for sinusoidal inputs is laborious and time-consuming. The general problem is solved more efficiently by the use of a digital computer. Using a digital computer program developed by Combustion Engineering, Inc., a complete frequency response for one set of system parameters can be calculated and plotted in less than a minute.

The digital program receives as input a specification of the system parameters, such as fuel conductivity, fuel-clad conductance, fuel diameter, and location of the point at which the temperature response is desired. The computer then calculates frequency response data for as many as 200 different frequencies. The response at each frequency is printed out as in Figure 5. This is a tabulation of the frequency, real component, imaginary component, magnitude ratio, phase angle, and Db gain. These values are computed, and printed, for ten frequencies in each frequency decade between 10^{-3} and 10^2 radians/second. The computer then plots the Db gain and the phase angle over the entire frequency range, as shown in Figure 6. By inserting a new input, such as a change in fuel conductivity, a new frequency response plot will be calculated and plotted. In this manner a wide range of system parameters can be explored with a reasonable amount of effort.

Conventionally, the phase shift of a sinusoidal signal is expressed in terms of an angle, calling one complete cycle 2π radians. The measurement can be made, and the phase shift expressed, in terms of the time lag between corresponding peaks in the input and output sinusoids. This form of the phase shift expression is used in Figure 4.

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W = OMEGA	REAL	IMAGINARY	MAGNITUDE	ANGLE	DB GAIN
0.	0.	0.	0.	0.	0.
1.259E-03	4.668E 01	-5.406E-01	4.668E 01	-0.66	33.38
1.585E-03	4.667E 01	-6.806E-01	4.668E 01	-0.84	33.38
1.995E-03	4.667E 01	-8.567E-01	4.668E 01	-1.05	33.38
2.512E-03	4.666E 01	-1.078E 00	4.668E 01	-1.32	33.38
3.162E-03	4.665E 01	-1.357E 00	4.667E 01	-1.67	33.38
3.981E-03	4.663E 01	-1.708E 00	4.667E 01	-2.10	33.38
5.012E-03	4.661E 01	-2.150E 00	4.665E 01	-2.64	33.38
6.310E-03	4.656E 01	-2.705E 00	4.664E 01	-3.32	33.37
7.944E-03	4.649E 01	-3.401E 00	4.661E 01	-4.18	33.37
1.000E-02	4.638E 01	-4.274E 00	4.657E 01	-5.27	33.36
1.259E-02	4.620E 01	-5.366E 00	4.651E 01	-6.62	33.35
1.585E-02	4.592E 01	-6.725E 00	4.641E 01	-8.33	33.33
1.995E-02	4.548E 01	-8.407E 00	4.625E 01	-10.47	33.30
2.512E-02	4.480E 01	-1.047E 01	4.601E 01	-13.15	33.26
3.162E-02	4.375E 01	-1.295E 01	4.563E 01	-16.49	33.18
3.981E-02	4.215E 01	-1.587E 01	4.504E 01	-20.64	33.07
5.012E-02	3.978E 01	-1.917E 01	4.416E 01	-25.74	32.90
6.310E-02	3.636E 01	-2.267E 01	4.285E 01	-31.94	32.64
7.944E-02	3.168E 01	-2.600E 01	4.098E 01	-39.38	32.25
1.000E-01	2.567E 01	-2.862E 01	3.844E 01	-48.11	31.70
1.259E-01	1.859E 01	-2.988E 01	3.519E 01	-58.11	30.93
1.585E-01	1.108E 01	-2.929E 01	3.132E 01	-69.28	29.92
1.995E-01	3.989E 00	-2.673E 01	2.702E 01	-81.51	28.64
2.512E-01	-1.868E 00	-2.253E 01	2.261E 01	-94.74	27.09
3.162E-01	-5.980E 00	-1.734E 01	1.834E 01	-109.03	25.27
3.981E-01	-8.184E 00	-1.188E 01	1.442E 01	-124.57	23.18
5.012E-01	-8.605E 00	-6.810E 00	1.097E 01	-141.64	20.81
6.310E-01	-7.581E 00	-2.679E 00	8.040E 00	-160.54	18.11
7.944E-01	-5.636E 00	1.498E-01	5.638E 00	-181.52	15.02
1.000E 00	-3.411E 00	1.574E 00	3.756E 00	-204.78	11.50
1.259E 00	-1.503E 00	1.819E 00	2.359E 00	-230.44	7.46
1.585E 00	-2.735E-01	1.358E 00	1.385E 00	-258.61	2.83
1.995E 00	2.496E-01	7.110E-01	7.535E-01	70.66	-2.46
2.512E 00	2.986E-01	2.283E-01	3.759E-01	37.41	-8.50
3.162E 00	1.701E-01	5.300E-03	1.702E-01	1.78	-15.38
3.981E 00	5.609E-02	-4.064E-02	6.926E-02	-35.92	-23.19
5.012E 00	6.373E-03	-2.430E-02	2.512E-02	-75.31	-32.00
6.310E 00	-3.516E-03	-7.263E-03	8.069E-03	-115.83	-41.86
7.944E 00	-2.102E-03	-8.976E-04	2.286E-03	-156.88	-52.82
1.000E 01	-5.438E-04	1.746E-04	5.712E-04	-197.80	-64.86
1.259E 01	-6.699E-05	1.071E-04	1.263E-04	-237.98	-77.97
1.585E 01	3.006E-06	2.469E-05	2.487E-05	83.06	-92.09
1.995E 01	3.072E-06	3.142E-06	4.395E-06	45.65	-107.14
2.512E 01	6.918E-07	1.217E-07	7.024E-07	9.98	-123.07
3.162E 01	9.362E-08	-4.141E-08	1.024E-07	-23.86	-139.80
3.981E 01	7.686E-09	-1.134E-08	1.370E-08	-55.87	-157.27
5.012E 01	1.154E-10	-1.690E-09	1.694E-09	-86.10	-175.42
6.310E 01	-8.113E-11	-1.771E-10	1.948E-10	-114.62	-194.21
7.944E 01	-1.637E-11	-1.300E-11	2.090E-11	-141.55	-213.60
1.000E 02	-2.049E-12	-4.725E-13	2.103E-12	-167.01	-233.55

CLAD TEMPERATURE FREQUENCY RESPONSE

Fig. 5

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CLAD TEMPERATURE FREQUENCY RESPONSE
Fig. 6

Fig. 6

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