Journal of the Korean Nuclear Society
Volume 15, Number 3, September, 1983

《Original》

The Measurement of TRIGA Mark-III Core Power Distribution Using Fuel Temperature

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(Received April 17, 1983)

핵연료온도측정에 의한 TRIGA Mark-III 원자로의 노심출력분포유추

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(1983. 4. 17 접수)

Abstract

A method which determines TRIGA Mark-III core power distribution by measuring fuel temperature is developed. The temperature measurement is performed by sweeping the already existing instrumented fuel elements which are loaded as an expedient of safe operation, and the number of fuel positions swept is 16. Experimental results are compared with those from computation using neutron diffusion theory. The maximum and standard deviations are 12 and 5% , respectively. It is confirmed that the estimation of rod power density of measuring fuel temperature is far more convenient than the conventional methods, and that it is proved to be very accurate as well.

요 약

TRIGA Mark-III 원자로에서 핵연료봉의 내부 온도를 측정합으로써 노심의 출력분포를 유추하는 방법을 개발하였다. 핵연료 온도는 원자로의 안전 운전을 위하여 이미 장전되어 있는 계측 연료봉의 위치를 이동시켜 가면서 측정하였고 측정한 연료공의 수는 16개이다. 실험결과를 중성자확산이론에 의거한 노심계산의 결과와 비교한 바 최대편차는 12%, 표준편차는 5%였다. 핵연료 온도를 이용하여 연료봉의 출력밀도를 유추하는 방법은 기존의 다른 방법보다 훨씬 편리하면서 정확성을 유지할 수 있음이 판명되었다.

I. Introduction

The measurement of neutron flux and the subsequent power distribution in a reactor core is usually carried out either by foil activation analysis or by the use of neutron detector such as small ion chamber and/or self-powered neutron detector (SPND). However, the application of the aforementioned techniques for the measurement of neutron flux or power mapping of TRIGA Mark-III reactor core encounters a lot of difficulties. One of the severe problems is how to fix the sensor at an exact position because no instrumentation guide tube is available in the coolant channels which are the only space for sensor installation. The small deviation of sensor position from one place to another is susceptible to inducing erroneous results, and in most cases these drawbacks are impossible to be identified.

After the overall core rearrangement in April 1979, a measurement of the radial neutron flux distribution was performed by gold foil activation method.[1] Even though it required rigorus efforts and careful attention in preparation and installation of foils as well as counting after irradiation, the results turned out to be not so satisfactory. After that, computational approach by multigroup diffusion equation has been attempted on a few occasions.[2],[3] The values calculated for some important parameters such as core effective multiplication factor, fuel rod reactivity worth and others showed reasonable agreement with the operational and experimental data. However, the accuracy of calculated neutron flux and power distribution cannot be confirmed due to the lack of experimental data.

The objective of this paper is to develop a convenient, experimental method which determines TRIGA Mark-III core power distribution with accuracy. The method is to convert fuel temperature into rod power density through proper correlation between them. And an experiment was intended to find out this correlation by measuring fuel temperature versus reactor power at 16 rod positions.

While temperature value of each rod position at a given reactor power differs each other, its variation with respect to reactor power changes reveals somewhat similar tendancy. Such tendency represented by all the rod positions in the core can then be translated into a reference curve by means of proper data processing. Consequently, rodwise core power distribution as a function of reactor power level as well as correlation between fuel temperature and power density can be drawn from the experiment.

However, since overall core sweeping is nearly impossible to achieve, a methodology to extend the partial core sweeping data to be equivalent to the full core data, is required. When the partial core is swept, the measured values represent only the relative values within the measured points. Thus, a constant to determine rodwise power density still remains unkown. In order to determine this unknown, a reference core power distribution is required *a priori*. The result of core calculation previously mentioned is the only one that is available as a reference up to now. Even though the accuracy of the calculated power distribution had not been confirmed, when the correlation coefficient between the measured and calculated values are to fall near unity, both calculated and measured values can be assessed to be accurate.

In data processing two cases—one considering only fuel temperature and the other involving pool water temperature, are compared.

Measuring fuel temperature is far more convenient than the conventional power mapping techniques, and above all it requires no additional experimental instrumentation or devices, because it can be achieved merely by changing the positions of the already existing instrumented fuel elements.

As a result it is concluded that this method is directly applicable to TRIGA Mark-III core power mapping as a convenient tool with high accuracy.

II. Experiment

There are two instrumented fuel rods in

TRIGA Mark-III reactor, which are installed with K-type thermocouples (Alumel-Chromel), and these rods are used for the core maximum and average fuel temperature monitoring during normal operation and also for automatic safe scram if fuel temperature increases over the safety limit at transient.[4] These have also been utilized for measuring core fuel temperature distribution as a part of reactor characteristic experiments.

From the experience accumulated so far from the repeated experimental and operational fuel temperature data processing, an expectation has sprouted spontaneously such that core power distribution might be extracted from fuel temperature distribution if there should exist a unique correlation between fuel temperature and power density. This correlation might be obatined by analytical or experimental approach. Analytical method was, however, soon abandoned because of several inaccurate parameters such as U-ZrH thermal conductivity, clad-to-coolant heat transfer coefficient in natural convection, uncertainty of thercouple locations in fuel element and so on. On the other hand, we have been driven into the experimental approach with a hope that it could be adopted if power density of fuel be obtainable by other method.

In case that core power distribution shape does not vary with reactor power level and that fuel temperature is determined only by rod power density, the curve of fuel temperature vs. reactor power should have the same shape independent of fuel position. Each curve has dif-

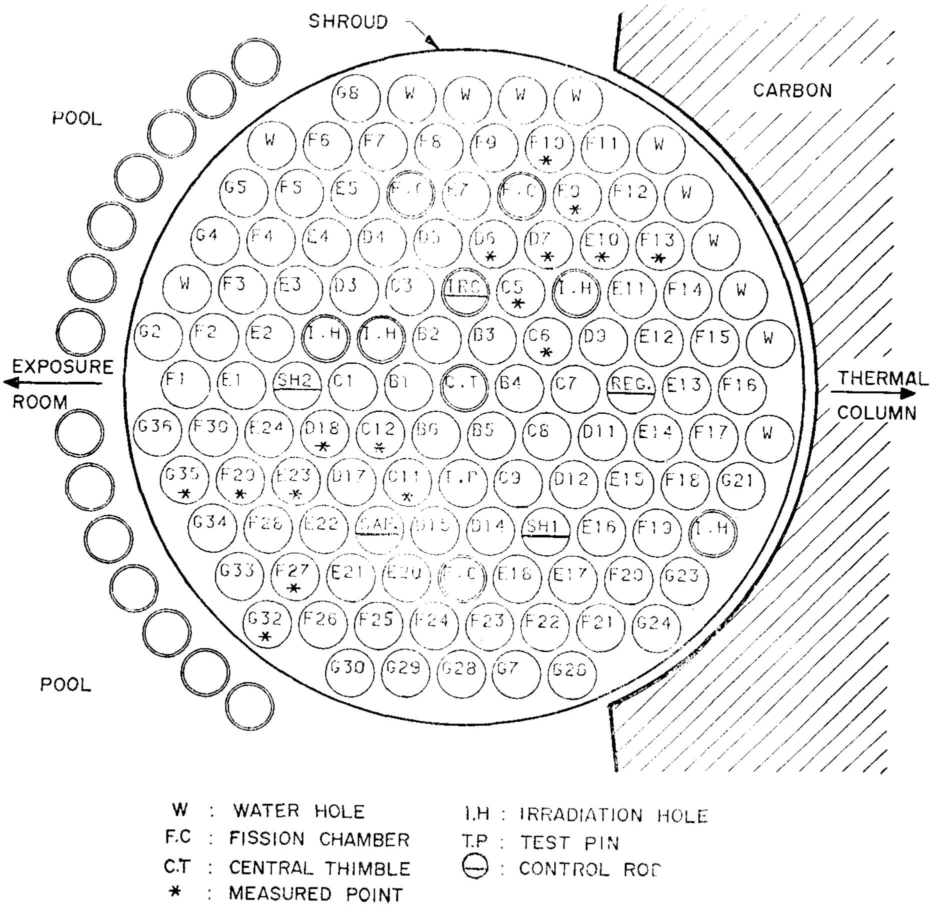

Fig. 1. Current TRIGA Mark-III Core Diagram

ferent magnitude of reactor power value axis, and the inverse of this magnitude represents rod power sharing. Thus if measurement can be made for all positions of the core, overall power distribution and the correlation between fuel temperature vs. rod power density might be extracted.

In real situation, however, core power shape varies slightly with reactor power level, and overall core sweeping is nearly impossible. In this experiment temperature measurement was conducted for 16 fuel positions. The results show that the curves are quite similar each other. This eventually connotes that the variation of core power shape with respect to power level is small. A reference curve representing 16 positions is obtained, and relative power values are produced out of this reference curve. The final unknown parameter is normalization factor which converts relative values associated with 16 rod positions to the core relative ones. The unknown is extracted by proportional relationship of experimental relative power values with computed ones.

Fig. 1 shows a diagram of the current TRIGA Mark-III core. All the fuel rods are FLIP(Fuel Lifetime Improvement Program: uranium content 8.5%, U-235 enrichment 70%) fuels except for 6 B-ring rods which are standard TRIGA fuels (Uranium content 8.5%, U-235 enrichment 20%). Compared with the FLIP fuels which have been loaded in early 1979 except for a few rods added in July 1981, standard fuels have more irradiation experience. The current core was rearranged in March 1982. Fuels asterisked in Fig. 1 indicate the measured positions which were chosen for the convenience of fuel handling. Measurement was not attempted for 6 B-ring standard fuels because instrumented fuels are FLIP type.

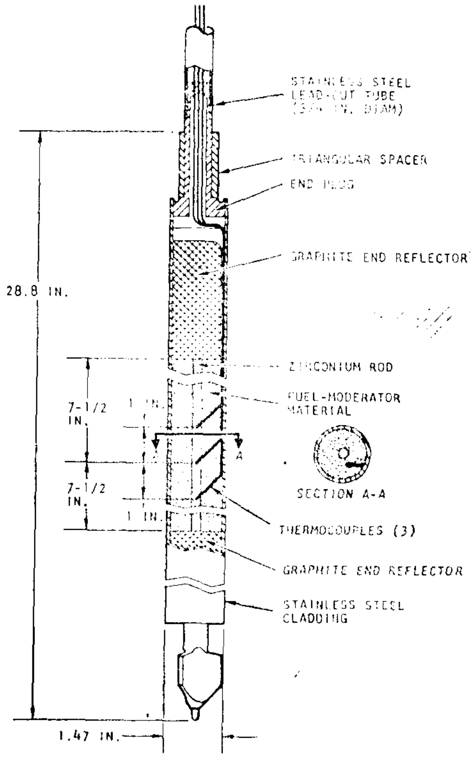

Fig. 2. Instrumented Fuel Element

Fig. 2 depicts the structural view inside the instrumented fuel element. Three K-type thermocouples are installed in the middle part of active fuel of each fuel element with one inch distance apart. Each hot junction is distant about 1/3 fuel radius from the center line, and zirconium rod of 5 mm in diamter is inserted in the hollowed space of fuel. As radial temperature gradient in fuel is large and its distribution is asymmetric in real rod, an eccentric location of hot junction induces considerable variation in temperature with rod rotation. So the measurement of fuel temperature was made at every 30 degree rotation of the instrumented fuel, and then average value representing each 30 degree rotation was calculated being based on many measured records. Fig. 3 is an example of this. Only two thermocouple values out of three are adopted because one thermocouple must always be connected to console fuel temperature meter to comply with the operating procedures, and its temperature reading is not

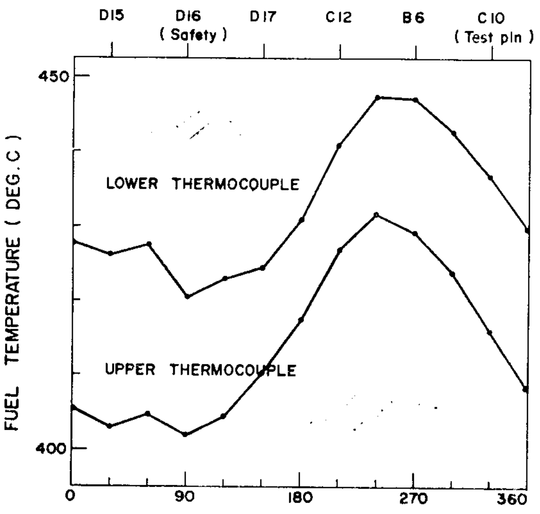

Fig. 3. Fuel Temprature vs. Element Rotation (Fuel Position: C-11, Reactor Power: 1.5MW)

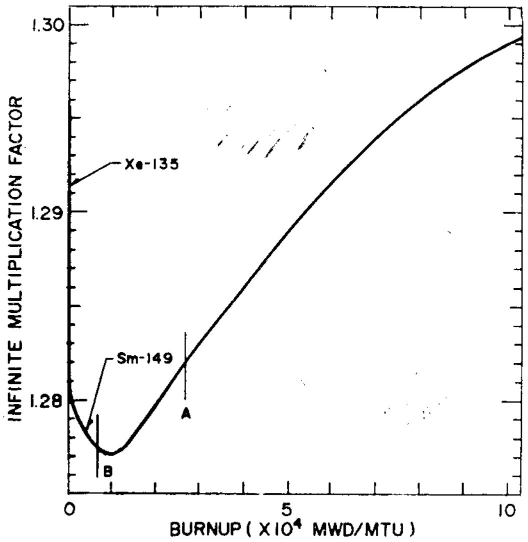

Fig. 4. Infinite Multiplication Factor Variation of FLIP Fuel with Burnup (1.5MW Operation)

so accurate. As the thermocouple in the middle part was connected to console meter during this experiment, the lower and upper part thermocouple readings are presented herein. As pool water temperature, especially, core inlet temperature might influence fuel temperature, pool bulk and inlet temperature values were also measured by the water temperature monitor at the console.

Each experiment has been carried out once a week in order to minimize interference with reactor users. Instrumented fuel positions were moved on each Monday after weekly check, and temperature measuring experiment was done on the following day after the routine operation in Monday afternoon so as to get rid of perturbation effect from changes in rod positions. The main perturbation might be resulted from differences in burnup and remaining amount of Xe-135 in the exchanged elements. Fig. 4 illustrates FLIP fuel's infinite multiplication factor (k_∞) variation vs. burnup. Infinite multiplication factor slowly increases with burnup as burnable poison (Er-167) burns after Xe-135 and Sm-149 equilibrium. Xe-135 poisoning is the most sensitive and dominant parameter which causes perturbation due to the fuel rod exchange. Though the core was maintained at the constant condition as much as possible during each weekly experiment, the core condition has been monitored by three power monitoring fission chambers, two fixed self-powered neutron detectors and each control rod position in order to detect any changes of core condition.

Each instrumented element cannot indicate the same temperature value even under the same circumstance of power density, owing to the fact that the state of thermocuple installation of each element is not identical and irradiation history of each fuel element is different each other. For instance, one element (A in Fig. 4) has been irradiated since April 1979 and the other (B in Fig. 4) since July 1981. Thus difference in temperature indication between two elements was mutually calibrated at 4 positions. Temperature fluctuation was also observed by the measurement at two positions for 7 times so as to verify reliability of experimental procedures.

III. Results and Discussion

Fuel temperature vs. reator power has been measured at 16 fuel positions, and some results are presented in Figures 5 and 6. The solid lines in the figures represent the least square fitted data with third order of polynomials for the results. If the order of polynomial is 2 the curve cannot follow up temperature variation tendency satisfactorily, while the third or higher order of polynomials are taken the results are nearly the same. As shown in Figures 5 and 6 each fitting curve follows up data variation in satisfactory manner, and each curve shape is shown to be nearly the same. Thermocouples intalled above and below 1 inch from the middle plane are chosen, while the readings of middle thermocouple are not taken because of its reliability. Each reading from upper and lower thermocouples is slightly different, i.e., the lower part temperature is higher than the upper one as shown in Fig. 3, since the power density of lower part is slightly higher than that of the upper part. In this experiment reading of each thermocouple is treated as independent measurement, and two sets of data are produced.

In order to determine the effect of pool water temperature on the fuel temperature, pool temperature was mesured at the inlet and bulk of the pool, and the results of data processing for the two cases, namely, one for the water temperature taken into account and the other not considering it are compared. Fig. 6 is the same with Fig. 5 except for water temperature subtraction from fuel temperature instead of pure fuel temperature as Y-axis. Pool inlet temperature is chosen as representative of pool temperature since the inlet is located beneath the

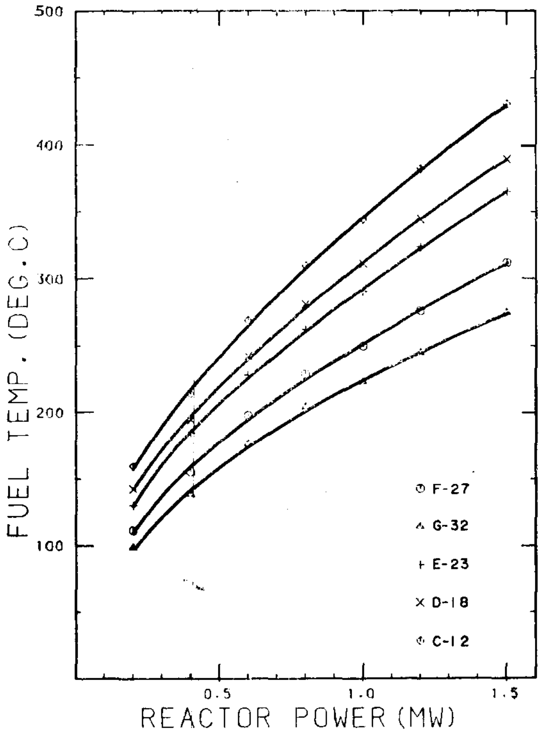

Fig. 5. Fuel Temperature Variation vs. Reactor Power (Measured by Lower Thermocouple of B Element)

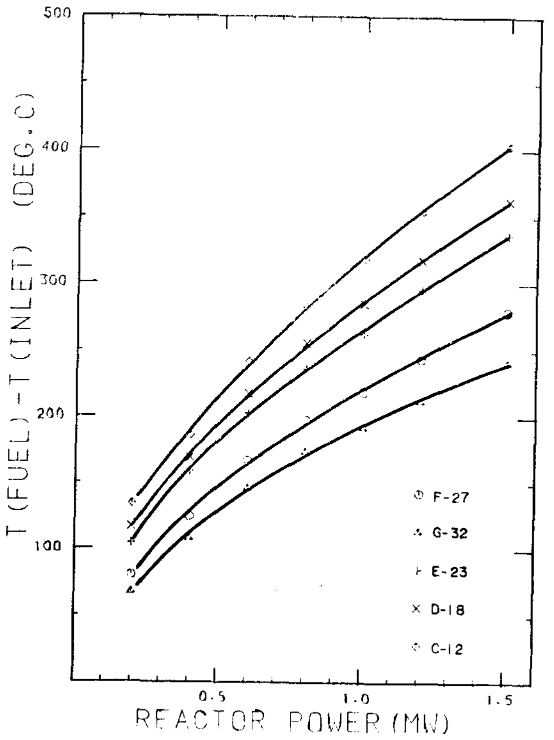

Fig. 6. Variation of Fuel Temperature-Inlet Temperature vs. Reactor Power (Measured by Lower Thermocouple of B Element)

core and eventually it might represent the core inlet temperature more closely.

As two instrumented elements were used for their temperature indications were mutually calibrated. The result is shown in Figs. 7 and 8 that the Element A with higher burnup indicates somewhat lower temperature than the Element B which has undergone less irradiation. Quantitative analysis of this phenomenon is considered to be nearly impossible. The difference may be attributed to numerous factors such as irradiation effect on materials, aging of welded junction and like. Heat resistance of fuel element might vary with burnup, owing to the fact that fuel pellet conductivity, gap conuctance and clad-to-coolant heat transfer coefficient vary with pellet swelling, fission gas release oxidation, etc. Thermocouple's EMF characteistic variation with burnup and inherent unceraint from hot junction also contribute to cause difference between temperature indications of the two instrumented elements. K-type thermocouple has stable EMF characteristics even though it has been irradiated in the reactor for a long time at temperature environment up to 600°C. However, unpredictable short-term change in EMF characteristics happened to occur in the range of $250 \sim 550$°C due to its phase change. From the comparison of two Figures 7 and 8, it is found that the result of T_f reveals more dispersion than that of $T_f - T_{in}$. T_f and $T_f - T_{in}$ have been measured 7 times at F-27 and E-9 respectively, with variant inlet coolant temperature. However, the standard deviation of T_f is nearly the same as that $T_f - T_{in}$, i.e., both values fall within 2°C. In data processing, temperature values measured with Element A are converted as if they were from Element B by the correlation obtained as in Figs. 7 and 8.

Among 16 measured positions C-11 being the highest in temperature is chosen as the reference. If the power rate of C-11 is assumed to be unity independent of reactor power level, relative power rate values of other positions depending on reactor power level are derived from the fitting curve of C-11. For each position, the values of reactor power axis are multiplied by the average of the above relative power rate.

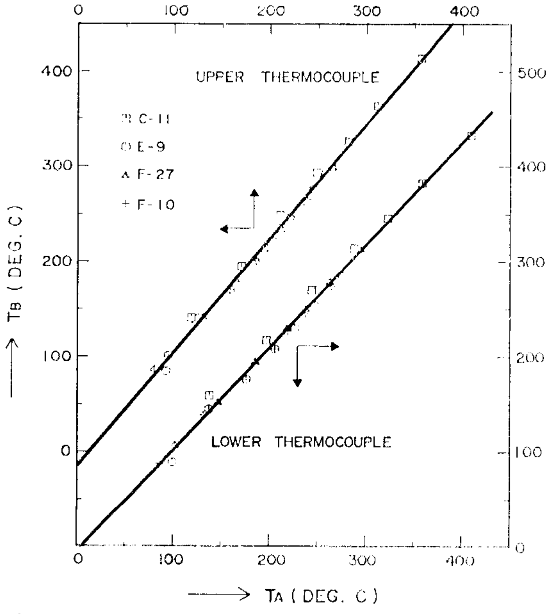

Fig. 7. Mutual Calibration between Two Instrumented Elements by T(fuel).

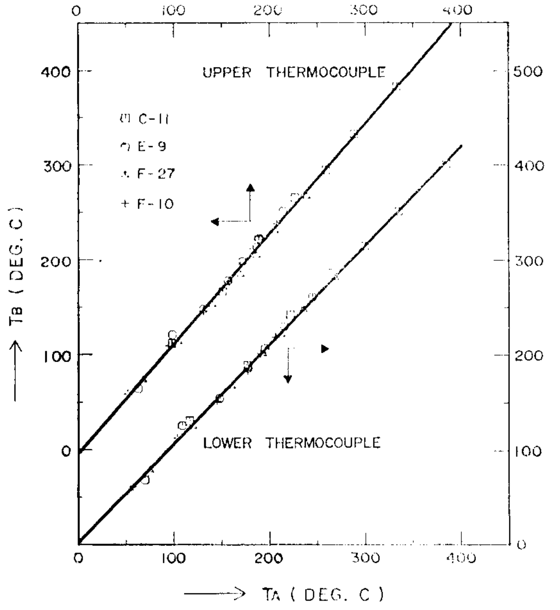

Fig. 8. Mutual Calibration between Two Instrumented Elements by T(fuel)−T(inlet).

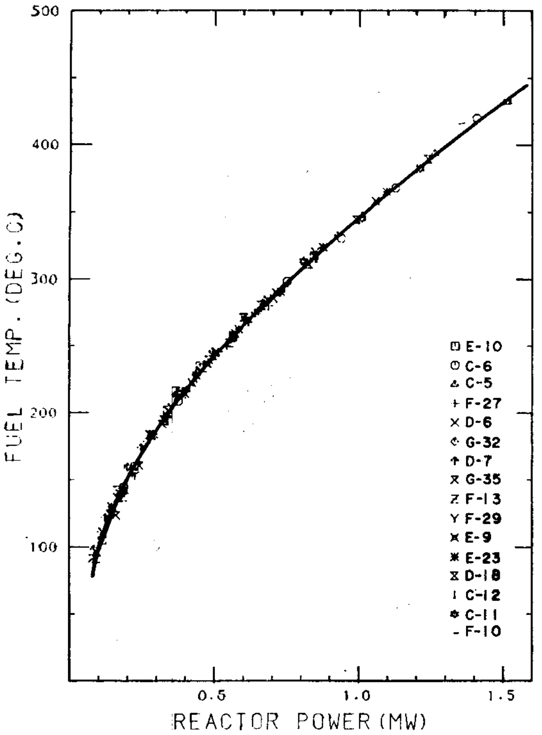

Fig. 9. **Fuel Temp. vs. Reactor Power When All Data Are Moved to Fitting Curve of C-11** (Lower Thermocouple).

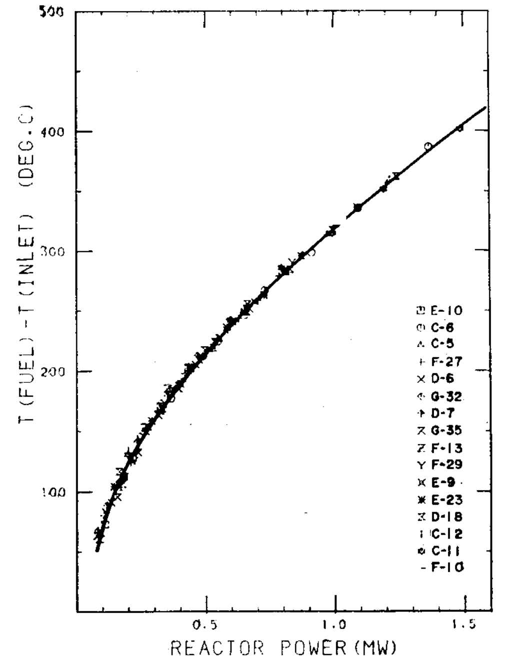

Fig. 10. **Fuel Temp.-Inlet Temp. vs. Reactor Power When All Data Are Moved to Fitting Curve of C-11** (Lower Thermocouple).

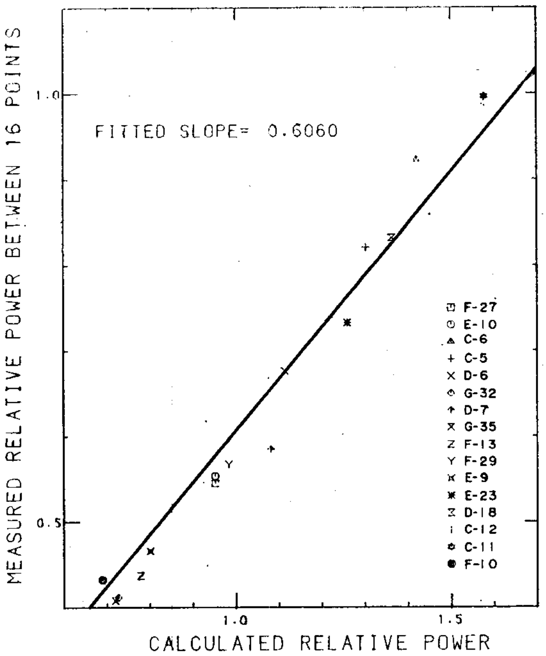

Fig. 11. **Comparison of Relative Power Values between Measured and Calculated** (Measured Data Are from Fuel Temperature).

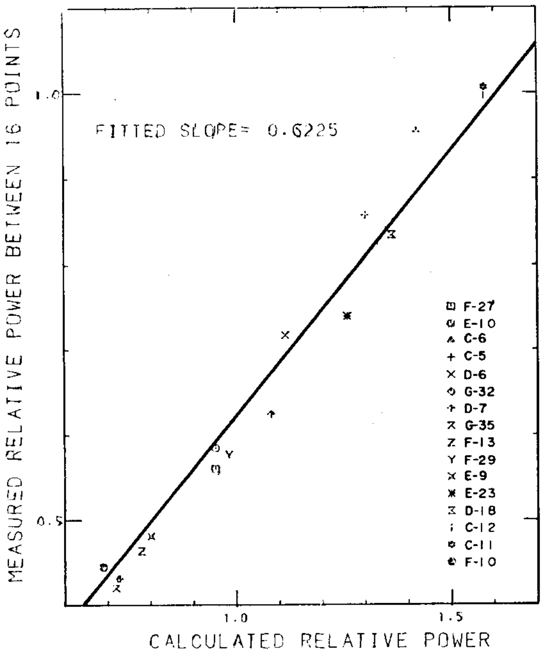

Fig. 12. **Comparison of Relative Power Values between Measured and Calculated** (Measured Data Are from Fuel Temp.-Inlet Temp.)

That is, all data of fuel temperature vs. reactor power as shown in Figs. 3 and 4, are converted to fuel temperature vs. the value (reactor power × average relative power of each position). Then, all the converted data fall near the fitting curve of C-11 as illustrated in Figs. 9 and 10. The above data are refitted by the third order polynomial, and the curves are drawn in solid line in Figs. 9 and 10. Close order of data points in Figs. 9 and 10 indicates strong relationship between fuel temperature and power density as well as stability of power distribution shape against reactor power variation.

Eventually, relative power values between 16 measured positions are obtained for each reactor power level from the fitting curves. Relative power values from the upper and lower thermocouples show nearly the same, and for convenience sake their average values are taken herein. These values do not represent relative power of overall core but relative values between 16 positions. These are compared with the computed ones to be converted to core relative power values and the results are depicted in Figs. 11 and 12. If both values measured and calculated are ideally correct, they have an exact proportional relationship, and all the points in each figure lie on a straight line passing through the origin of the coordinate. Each real distribution has, however, some dispersion and the proportional constant should be obtained by fitting technique. The results of fiitting are

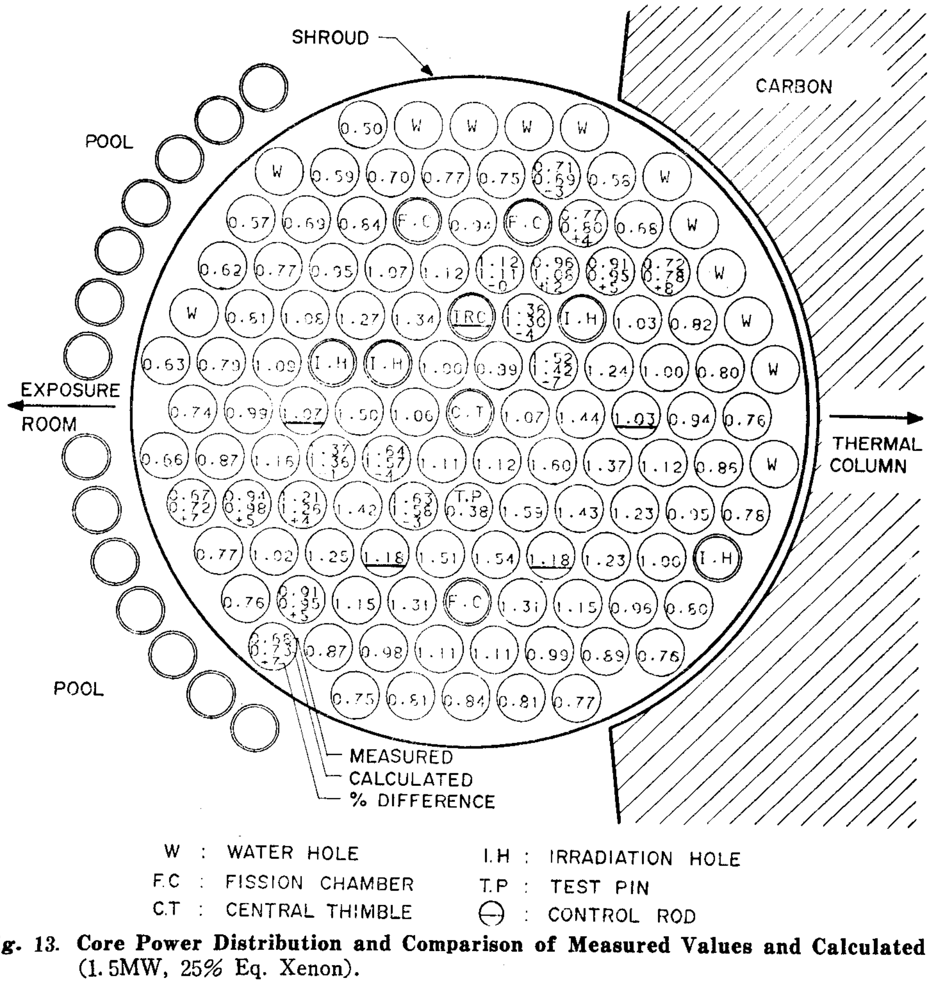

Fig. 13. Core Power Distribution and Comparison of Measured Values and Calculated Ones (1.5MW, 25% Eq. Xenon).

depicted as solid lines and as fitted slope in figures. The correlation coefficient of each figure is 0.9989 for T_f and is 0.9986 for $T_f - T_{in}$, respectively. As is indicated by the correlation coefficients and also shown in figures, the result from T_f has stronger correlation than that from $T_f - T_{in}$, which is out of our prediction.

Core calculation is performed by two dimensional diffusion equation for 7 neutron energy groups with a mesh point allocated at each rod position. Mesh distance which is identical with pitch (=4.3535cm), is not sufficiently short enough to ensure accuracy of difference equation especially for those regions where flux variation is sharp. This mesh condition accelerates the tendency that diffusion theory estimates broader flux distribution than the real one. This phenomenon is also found in Figs. 11 and 12. While the calculated values are lower than the measured ones for hot rods, the formers are higher than latters for less powered rods.

Even though the relative power values derived from $T_f - T_{in}$ result in larger differences than those from T_f when compared with calculated ones, it is reasonable to take account of water temperature, and it shows more stable mutual correlation between two instrumented elements as shown in Figs. 7 and 8.

Relative power values between 16 positions are normalized so as to be core relative power values by the fitted slope, and the result is shown in Fig. 13. The maximum and standard deviations of calculated values from the measured ones are 12 and 5% each.

As the final data processing, each thermocouple temperature indication curve vs. rod average linear power density is derived and they are drawn in Fig. 14. By these curves further measurement of rod power density can be achieved simply by measuring fuel and water temperatures.

A thorough analysis of coolant flow effect on fuel temperature still remains as further task. It practically requires a considerable effort to measure the flow velocity and coolant inlet temperature in the channel.

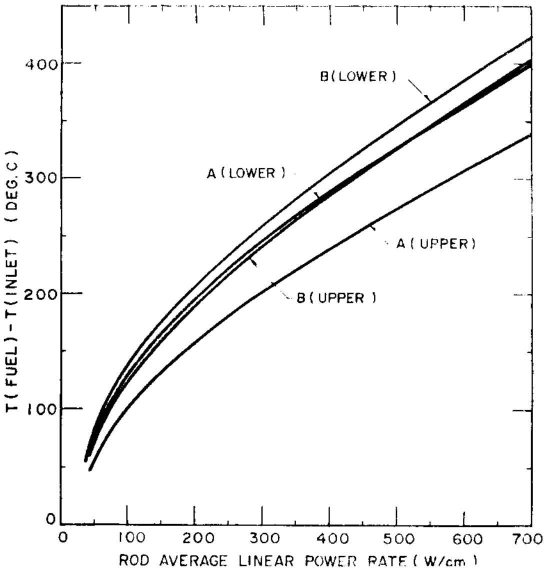

Fig. 14. Temperature Indication of Each Thermocouple with Rod Average Linear Power Rate.

Acknowledgements

The authors are very grateful to the members of the reactor operation group, KAERI, for their sincere assistance during experiment. The authors also wish to express their sincere thanks to Dr. H.J. Kim, KAERI, for his advice in data processing.

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