Transactions of the 15th International Conference on
Structural Mechanics in Reactor Technology (SMiRT-15)
Seoul, Korea, August 15-20, 1999

# Modelling of Cirus Graphite Reflector with Stored Energy: Comparison of Blind Predictions with High Power Measurements

B. K. Dutta, H. S. Kushwaha, V. Venkat Raj, S. Sankar and S. K. Sharma

*Bhabha Atomic Research Centre, India*

## ABSTRACT

The 40 MW CIRUS research reactor uses graphite as reflector. This reactor is under use for the last thirty years. Over the last few years, the CIRUS reactor has been operated at 20 MW power. There could be an increase in Wigner stored energy due to the absence of concurrent annealing during this period. It was felt necessary to carry out a thermal analysis of this reflector to predict the temperature at higher power levels before any attempt is made to increase the power to rated value. A detailed thermal analysis was done considering the effect of stored energy. This analysis was found to be very useful to provide blind predictions of temperatures. These predictions were used as guidelines to take the reactor to full power safely. The present paper describes the details of the thermal analysis and the comparision of blind predictions with the actually measured temperatures at higher power levels.

## INTRODUCTION

Graphite is under use in many thermal reactors all over the world as moderator or reflector. The intense neutron irradiation of graphite displaces the carbon atoms from their normal lattice sites, thus producing interstitial atoms and vacancies, leading to storage of energy, known as Wigner stored energy. The amount of stored energy depends on the total fluence received by the graphite and the temperature of the graphite during the irradiation. When the irradiated graphite is heated by neutron and gamma radiation during high power operation, the interstitial atoms can recombine with vacancies resulting in release of stored energy.

The 40 MW CIRUS research reactor uses graphite as reflector. This reactor is under use for the last thirty years. Over the last few years, the CIRUS reactor has been operated at 20 MW power. There is likely to be an increase in Wigner stored energy due to the absence of concurrent annealing during this period [1]. It was felt necessary to carry out a thermal analysis of this reflector to predict the temperature at higher power levels, before any attempt is made to increase the power to rated value.

## INITIAL ASSESSMENT OF INPUTS

Geometrical Details of CIRUS Graphite Reflector : The dimensional details of the CIRUS reactor inner graphite reflector are shown in Fig. 1. The inner graphite has twenty seven thermocouples for measuring temperatures at various locations during reactor operation. These thermocouples are installed on three vertical planes at an angular spacing of 120 deg. These three planes are designated as North plane, South-East plane and South-West plane. The nine thermocouples on each of these planes are again attached in three groups at three different elevations. Finally, the three thermocouples at a particular elevation are attached at three different radial locations. The dimensional details of the elevations and radial locations are also shown in Fig.1.

**Spatial Variation of Thermal Conductivity:** The thermal conductivity degradation is an important consideration for the present analysis. Measured data on conductivity were not available for the aged material at the time of carrying out this analysis. This necessitated the use of data available in literature for this purpose. The conductivity degradation with irradiation is expressed as

$$Ko/K(\Phi,T) = 1 + \{Ko/K(\infty,T)\}\ \{1-\exp(-\Phi)\}$$

The value of $Ko/K(\infty,T)$ is taken as 97 at 25°C, 75 at 75°C, 63 at 100°C and 33 at 150°C [1]. In the present analysis, the second term of the above expression is multiplied by a tuning factor to match the steady state experimental temperature profile. Hence for the present analysis the above expression is modified as

$$Ko/K(\Phi,T) = 1 + \Re\ \{Ko/K(\infty,T)\}\ \{1-\exp(-\Phi)\}$$

Where $\Re$ is the tuning factor to match the observed data. The value of Ko for fresh graphite has been taken as 1.88 W/cm/°C.

**Density And Specific Heat:** It is necessary to know the heat capacity of the present aged graphite to compute the transient temperature profile. In the absence of any measured data, the density is taken as 1.6 gm/cc and the specific heat is taken as 0.712 J/gm/°C.

**The Heat Transfer Coefficients At The Inner And Outer Surfaces Of The Reflector As A Function Of Coolant Flow:** In view of the empirical nature of heat transfer correlations, a certain uncertainty is associated with the calculated value. An estimation is made to calculate this parameter for full ventilation flow of 18000 scfm using various empirical relations available in the literature. The value varied between 0.003 to 0.006 W/cm$^2$/°C. The same for the inner surface for natural circulation flow is calculated as 0.0005 w/cm$^2$/°C. However, it was felt necessary to tune this number depending upon the observed experimental data as described in the subsequent sections. The coolant (air) temperature at the outer surface is assumed to vary from 30°C to 38°C from top to bottom and the same for the inner surface is taken as 50°C constant in the analysis.

**The Estimation Of Stored Energy And Its Release Spectrum With Temperature:** One of the biggest uncertainties in the inputs for the present analysis is the assessment of stored energy and its spectrum of release with temperature. Such measurements have been done at BARC [3]. Fig. 2 shows the energy release rate as a function of temperature obtained during these measurements. It was found necessary to modify the existing computer code to make use of this form of heat generation data.

**Availability Of Measured Temperature Data:** At the time of carrying out the present analysis, no experimental data were available for direct assessment of individual inputs, such as, thermal conductivity, density, specific heat, nuclear heat generation, heat transfer coefficients, stored energy, etc. In the absence of this, it was decided to take these data from the open literature. However, it was realised that the literature data may not be directly applicable for the present aged reflector material. To fine tune these individual parameters, temperature measurements available from the twenty-seven thermocouples for various steady-state and transient conditions of the reactor and ventilation system were used. The following are the four sets of such important experimental data which were used as benchmark cases in the present analysis.

i) Steady state temperatures at 10 MW reactor power.

ii) Steady state temperatures at 20 MW reactor power.

iii) Transient temperature following reactor trip from 10 MW and emergency bypass fan flow of 4000 scfm.

iv) Transient temperature following reactor trip from 20 MW and simultaneous reduction in ventilation flow between 18000 to 4000 scfm.

Though the temperature data obtained through these experiments are due to the combined effects of individual parameters, they played a crucial role in the present analysis for suitable adjustments of the individual parameters in a systematic manner. This aspect is discussed in detail in the following section.

## MODIFICATIONS OF INPUTS BASED ON EXPERIMENTAL DATA

**Selection Of Code And Required Modification:** It was decided to use the finite element technique for the present thermal analysis problem. An in-house finite element based computer code for thermal analysis 'WELTEM' was developed earlier [4]. This code has been successfully used for the thermal analysis of many reactor structures over the last fifteen years. For the present case, this code required slight modifications to convert the available stored heat energy data provided in the form of dH/dT v/s T (Fig.2) to volumetric heat generation rate. This has been done by computing the temperature T and the gradient dT/dt at every time step during transient calculation at each node. The value of dH/dT is then interpolated from the graph of Fig. 2 and is converted into volumetric heat generation by using the following relationship.

$$Q(\text{cal/cm3-sec}) = dH/dT(\text{cal/gm-}^\circ\text{C}) . \rho(\text{gm/cm3}) . dT/dt(^\circ\text{C/sec})$$

**Modification Of Thermal Conductivity And Heat Transfer Coefficients Based on Radial Variations of Temperature Profile:** First an effort was made to match the middle surface steady state temperature for 10 MW reactor operation. The outer side heat transfer coefficient was adjusted to a value of 0.013 W/cm2-°C for this purpose. After adjusting the outer side heat transfer coefficient, the thermal conductivity was adjusted to match the predicted value of temperature gradient across-the-thickness with the experimental temperature gradient. For this purpose, the tuning factor $\Re$ in the model of thermal conductivity was used. It was found necessary to adjust this factor to a value of 0.15 for this purpose. This revealed that the thermal conductivity degradation is not as significant as was obtained using the above expression from literature.

**Modification of Nuclear Heat Generation Based on Axial Variation of Temperature Profile:** Nuclear heat generation in the reflector was provided as input to the present analysis. However, it was found necessary to modify the axial variation of nuclear heat generation to match the measured temperature data. For this purpose, the total steady state heat generation was split into two components. The first is an uniformly distributed component for the entire length of the graphite reflector and the second is a cosine distribution of heat flux over the moderator height. The sum of these two components is same as the calculated value. Their relative magnitudes were so adjusted to have good matching with the steady state temperatures measured for all the thermocouple locations. It was found necessary to distribute about 70% of the total steady state heat uniformly. To have a better comparison of transient measured data, the cosinely distributed heat was assumed to decay as per theoretical calculation. However, the uniformly distributed heat was assumed to decay much slowly.

Verification of Adjusted Inputs: All the above adjustments of various inputs were done for the steady state and transient measured temperature at 10 MW reactor power. These adjustments were then verified by comparing the computed steady state and transient temperatures with the measured values at 20 MW reactor power.

## BLIND PREDICTIONS OF TEMPERATURES AT HIGHER POWER LEVELS

Based on the assessments made, it was decided to increase the reactor power to full capacity. For this purpose, the thermal model developed above was used for blind prediction of temperatures at various power levels. The model predictions showed the temperatures to be within acceptable values. The required safety clearances were obtained to increase the reactor power based on these blind predictions. It was also decided to have a comparison of the measured data with the computed data at various intermediate reactor power levels. Further power increase was attempted only after ensuring close agreement between predicted and measured temperature values.

## COMPARISON OF BLIND PREDICTIONS WITH THE MEASURED DATA

Figure 3 shows the measured temperatures of three thermocouples at the inner most surface of middle elevation during this high power operation. The computed temperatures were compared with the circumferentially averaged experimental values as the axisymmetric model was used in the present analysis. Table 1 shows the comparison of computed data with the measured data at various power levels. This comparison is also shown in Fig.4 in graphical form.

## CONCLUSIONS

1. The power of CIRUS reactor could be raised without any abnormal behaviour of inner graphite temperature. From this it is concluded that the no damage has been caused in terms of significant stored energy during low power (20 MW) operation of many years.
2. The circumferential average of measured temperatures match well with the predicted values for all the reactor power levels.
3. The adjusted values of thermal conductivity, heat transfer coefficient and heat load have a realistic basis.
4. No release of stored energy was envisaged during the present high power reactor operation.
5. Almost a linear variation of temperature with the reactor power in Fig. 4 led to the conclusion that there is insignificant release of stored energy. Similar conclusion

may be drawn from Fig. 5 also. This figure shows that the graphite temperature rise per MW of reactor power almost remained constant throughout the power history.

6. The steady state temperatures were recorded at 20 MW of reactor power both before and after the present high power operation. These temperatures were found to match well as shown in Fig. 3,. This leads to the conclusion that the thermal conductivity of the graphite remained unaffected during the high power operation. It may be noted here that any release in stored energy should lead to an improvement in the conductivity of the graphite.

## REFERENCES

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3. 'Wigner Energy Release Studies on Irradiated Graphite Reflector of CIRUS', Technical Report No. RMD/PIES-KU/97/813 (1997).
4. 'Computer Program WELTEM (Analysis of Two Dimensional Heat Transfer Problems by Finite Element Technique) Theory & User's Manual', B.K.Dutta, H.S.Kushwaha, A.Kakodkar, BARC/I-671 (1981).

| S.No. | Thermal Power (MWt) | Measured Temperatures | | | | Predicted Temp. | |
|---|---|---|---|---|---|---|---|
| | | Middle North | Middle S-E | Middle S-E | Average | Average | Peak |
| 1. | 18.611 | 78.0 | 75.8 | 80.4 | 78.1 | ---- | ---- |
| 2. | 25.341 | 95 | 92 | 98 | 95 | 95 | 98 |
| 3. | 29.951 | 103.5 | 100 | 107 | 103.5 | 104 | 107 |
| 4. | 35.292 | 117.2 | 112.4 | 121.3 | 116.9 | 115 | 118 |
| 5. | 36.531 | 118.6 | 113.6 | 121.6 | 117.6 | ----- | ------ |

**Table-1 A Table Showing Thermal Power, Steady State Measured Temperature and Predicted Temperature**

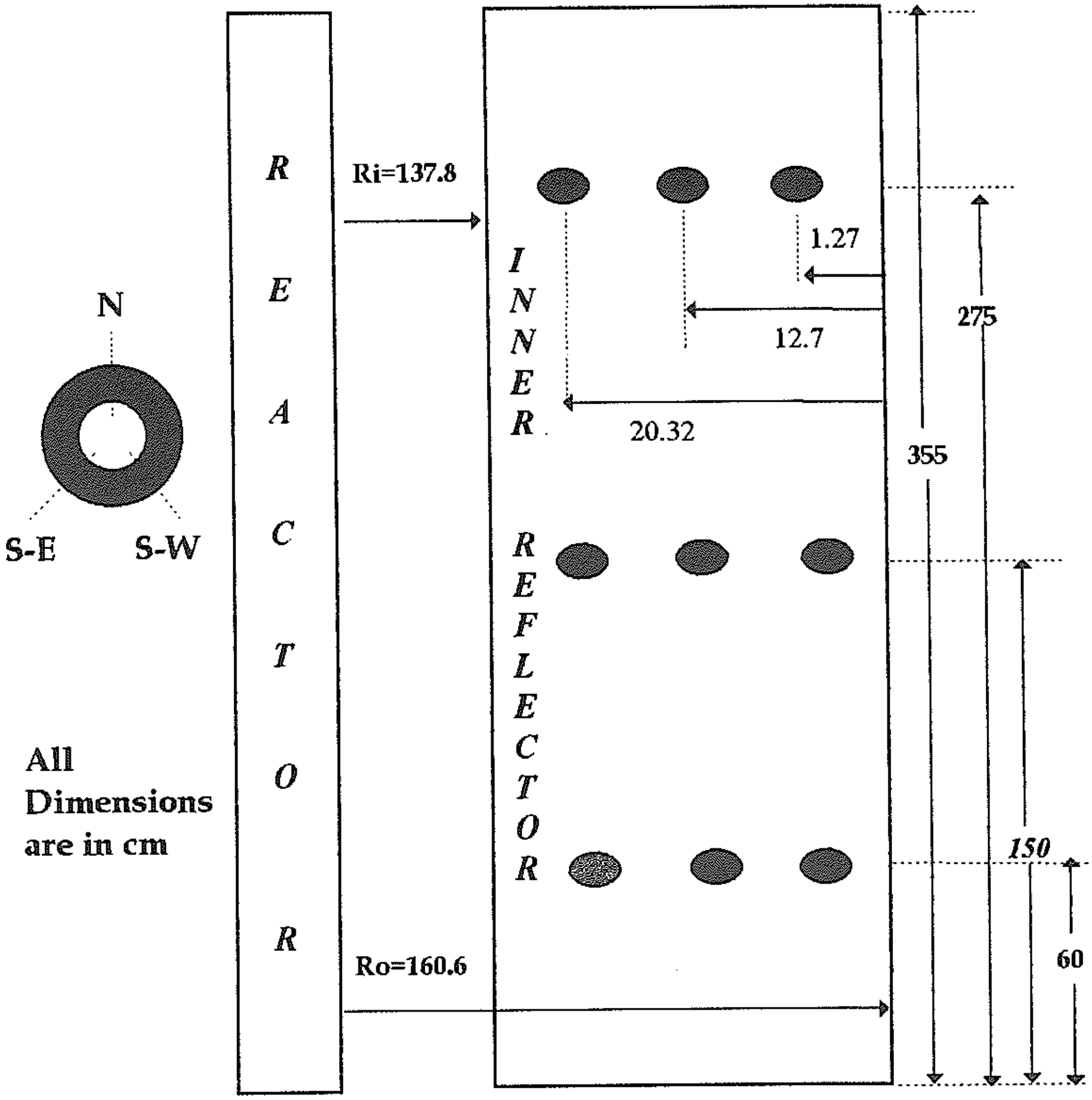

Fig. 1 Dimensional Details & Locations of Thermocouples in CIRUS Graphite Reflector

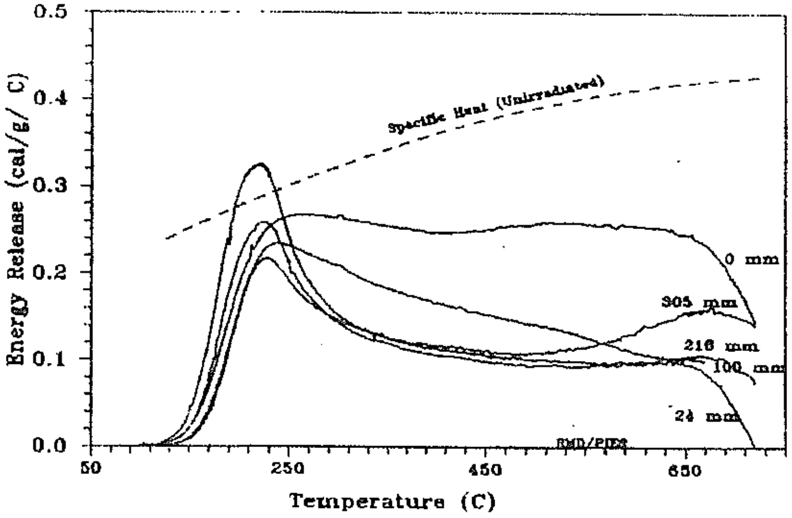

Fig. 2 Variation of Wigner Energy Release Rate withTemperature for Samples taken from different Radial Locations of CIRUS Reflector [3]

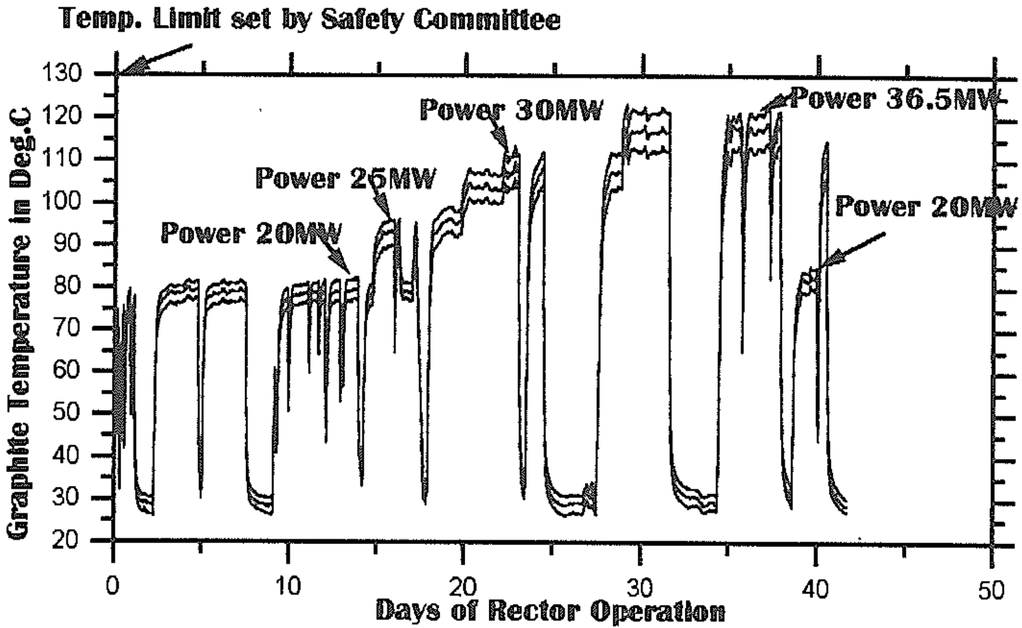

Fig.3 Temperatures Recorded by Three Thermocouples Circumferentially Placed at Middle Elevation Near Inner Surface

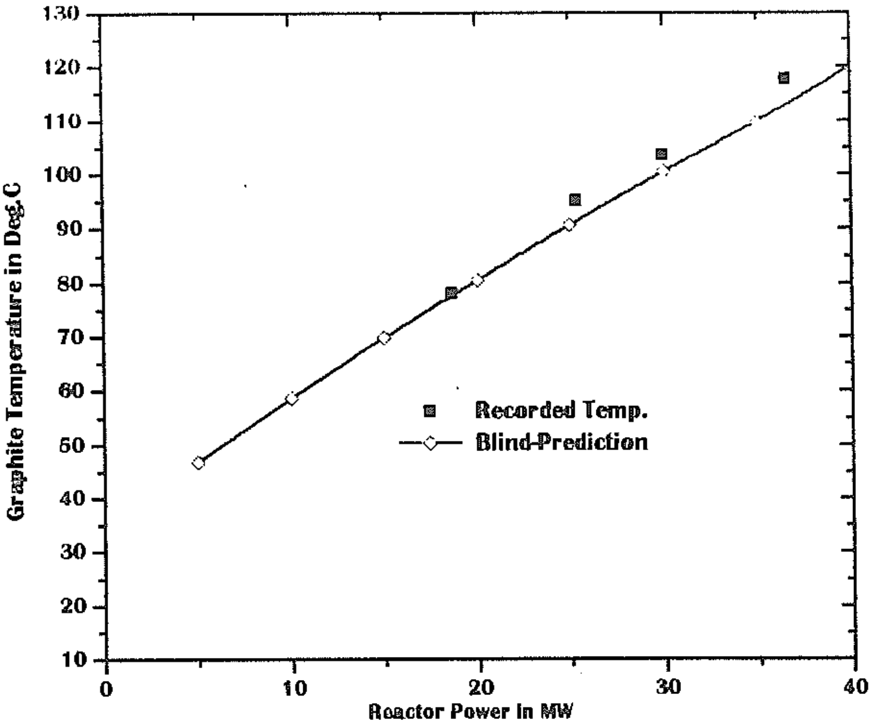

Fig. 4 Comparision of Observed Temperature with Blind Prediction at Various Reactor Power

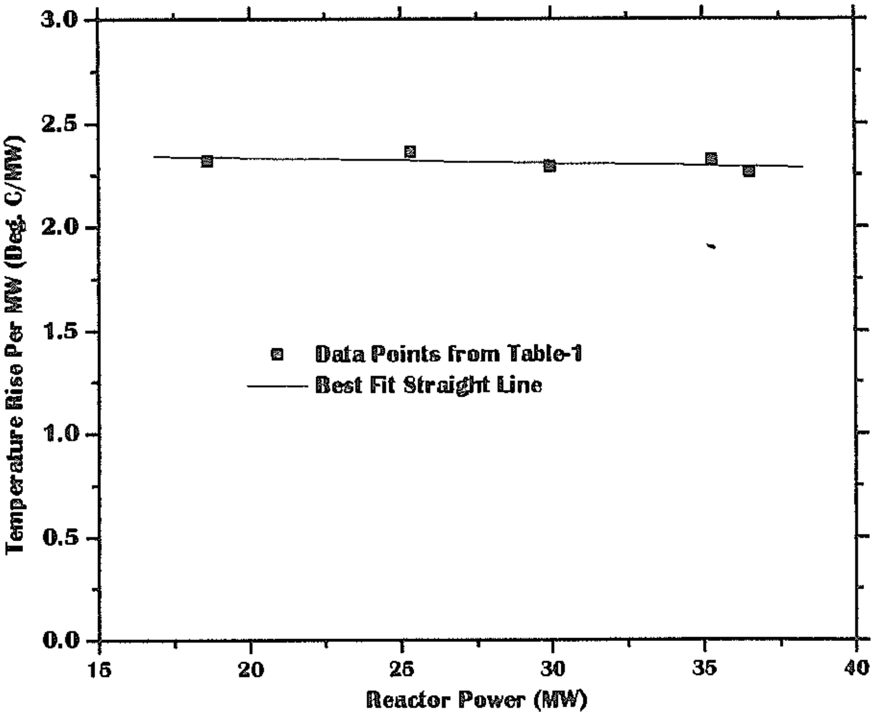

Fig. 5 variation of Temperature Rise Per NW with Reactor Power