Proceedings of the
International Conference on Mechanical Engineering 2007
(ICME2007) 29- 31 December 2007, Dhaka, Bangladesh

ICME07-TH-30

DETERMINATION OF TEMPERATURE AT DIFFERENT LOCATIONS OF THE QUARTZ VIAL CONTAINING 40 GM OF TEO_2 DURING ITS IRRADIATION IN THE DCT AT 3MW OF BAEC TRIGA MK-II RESEARCH REACTOR

M. S. Islam[1], A. Haque[1], I.Kamal[2] and M. Ali Zulquarnain[1]

[1]Reactor Operation and Maintenance Unit
[2]Institute of Nuclear Science and TechnologyBangladesh Atomic Energy Commission, Dhaka-1000, Bangladesh

ABSTRACT

The study is done is to analyze particularly the temperature of the quartz vial wall and also the temperature in and around the sample that contained 40 gm of TeO_2 powder using one dimensional analysis technique. The sample was irradiated with the help of thermal neutron flux 8.71e13 n/cm^2.s at Dry Central Thimble (DCT) of 3MW TRIGA Mark-II Research Reactor. In this study, the temperature at the particular points were calculated at the worst conditions following the 1/7th thumb rule of the total heat transferred by convection mechanism and also 120% of heat generation rates of TeO2 powder and quartz vial for conservative assessment of the Alcan material with assured safety. Finally the temperature at different locations of the quartz vial and necessary recommendations are made in order to safe irradiation of experimental samples at DCT of the reactor core with loading different quantities of TeO2 power at different power levels of the reactor.

Keywords: TeO_2 powder, One-dimensional analysis, DCT, Conservative assessment, Safe irradiation.

1. INTRODUCTION

Irradiation request (IR) from the Radio Isotope Production Division (RIPD) of Institute of Nuclear Science and Technology (INST) has submitted an IR to the Atomic Energy Research Establishment-Research Reactor Operation and Utilization Committee (AERE-RROUC) to irradiate 40 gm of TeO_2 powder in a quartz vial with convex bottom at 3MW in the Dry Central Thimble (DCT). DCT is located in the central point of the reactor core, which is encircled in black color as shown in **Fig.1**. The thermal neutron flux at DCT is taken as 8.71×10^{13} n/cm^2.s at 3MW. The geometry of the quartz vial is quite different from that of the old vials. It is very important to assess the temperature distribution of the quartz vial with 40 gm of TeO_2 powder to ensure safe irradiation. The bottom surface of the old vial is concave upward where as the new vial is concave downward. It is observed that the contact area of the new vial is about 16 times higher than that of old one. The outer radius (1.15 cm) is also higher than that of old one (1.113 cm). Thickness of the new quartz vial is a little bit smaller than that of the old vial according to the data received from RIPD.

One-dimensional steady state axial heat conduction is considered to assess the temperature distribution in and around the TeO_2 powder during its irradiation at 3MW (thermal) power level. Four different material layers namely; (i) TeO_2 powder, (ii) Quartz vial, (iii) Al-Can and (iv) DCT stopper plate are considered in the heat transfer path. The heat generated through nuclear fission reaction in TeO2 powder in the quartz vial is conducted though the quartz vial, through the aluminum can, and through the stopper plate to the coolant (water). The temperature of the water is presumed known to be about 60^{0}C. It is assumed that 1/7th of the total heat is transferred through convection mechanism and the rest of the heat is transferred through conduction mechanism [1]. As Al-Can rests on the aluminum stopper plate and as its thermal conductivity is very high, it is assumed that significant amount of heat is dissipated through the axial (bottom) direction and fraction of the heat is transferred through the radial direction.

.

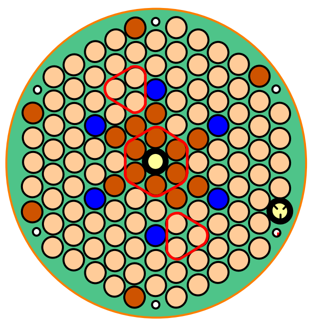

Fig 1: Reactor core configuration with DCT location at the centre of the core

Heat generation in TeO_2 powder is mainly due to interaction of neutron (n) and gamma (γ) radiation. The value of heat generation rate for TeO_2 powder during irradiation in the DCT is taken from reference [1]. For conservatism, total heat generation rate is taken to be 120 % higher than their actual values [Safety Factor (SF) =1.2]. Geometry factor was taken as 80% to simulate the real situation

2. METHOD OF CALCULATION OF TEMPERATURES

In order to calculate temperature at different locations, geometrical configuration is given in Figs .2 -3. Figures 2 and 3 show section views of the target material containment with DCT in the radial and axial directions, respectively. The thermo-physical properties of each material along with their figures are provided for convenience**.** Figure 4 shows the approximate contact area that plays an important role in transferring heat in the axial direction. Heat transfer mainly depends in the axial direction on surface contact area of the quartz vial on the Al-Can. Figures 5 and **6** show thermal resistances considered along the heat transfer path for two different approaches. In method-1, total heat transfer rate is considered. And In method-2, surface heat flux is considered. Both the methods show similar results. Centerline temperature of the TeO2 powder is determined using one-dimensional heat conduction equation with heat generation.

(1) <u>Physical Dimensions</u>

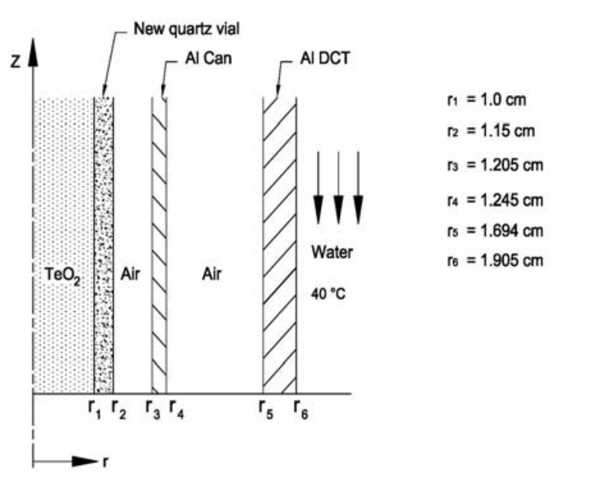

Fig 2: Section view (radial) of the target material containment with DCT

r_1 = inner radius of quartz vial, r_1 = 1.000 cm
r_2 = outer radius of quartz vial, r_2 = 1.150 cm
r_3 = inner radius of aluminum Can, r_3 = 1.205 cm
r_4 : outer radius of aluminum Can, r_4 = 1.245 cm
r_5 : inner radius of aluminum DCT, r_5 = 1.694 cm
r_6 : outer radius of aluminum DCT, r_6 = 1.905 cm
t_1 : thickness of quartz vial, t_1 = 0.15 cm
t_2 : thickness of aluminum Can, t_2 = 0.04 cm
t_3 : thickness of the stopper plate of aluminum DCT, t_3: 3.81 cm
t_4 : thickness of air film between quartz vial and Al Can, t_4 = 0.1 cm
L : Length of quartz vial, L : 6.3 cm

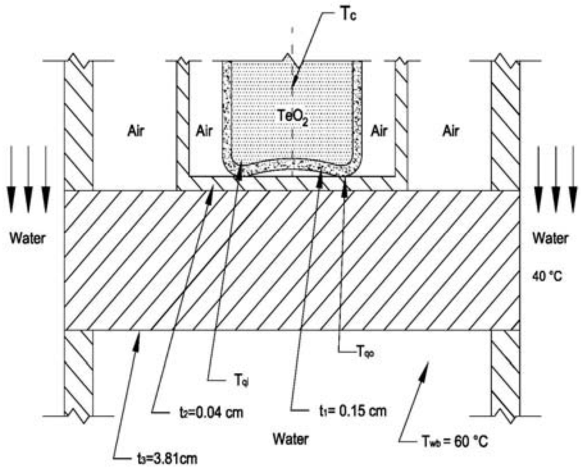

Fig 3: Section view (axial) of the target material containment with DCT

Fig 4: Bottom contact area of quartz vial

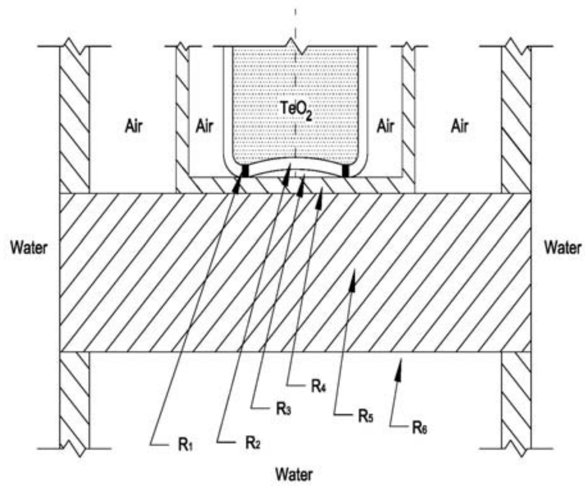

Fig 5 (a): Thermal resistances encountered during heat transfer from TeO_2 powder in the axial direction

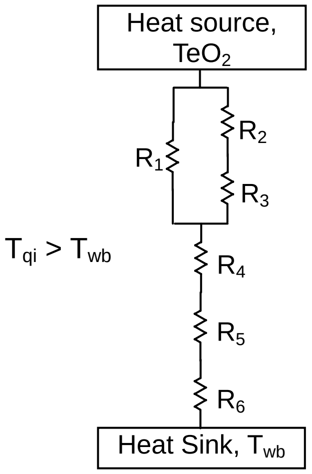

Fig 5(b): Circuit diagram of the thermal resistances along the heat transfer path

Thermal Properties

(i) TeO_2 powder

ρ_{Te} : density [2], $\rho_{Te} = 4.5$ g/cm^3

h_{grTe} : heat generation rate (n+γ) @ 5.56×10^{13} n/cm^2.s, $h_{grTe} = 1.664$ W/g

K_{Te} : thermal conductivity , $K_{te} = 0.03$ W/cm ^{0}C

m_{Te} : mass of TeO_2 in gram, $m_{Te} = 40$ g

(ii) Quartz vial

h_{grqu} : heat generation rate (n+γ) @ 5.56×10^{13} n/cm^2.s , $h_{grqu} = 0.008$ W/g

K_{qu} : thermal conductivity , $K_{qu} = 0.05$ W/cm ^{0}C

ρ_{qu} : density, $\rho_{qu} = 2.654$ g/cm^3

(iii) Aluminum (Al 6061-T6)

K_{al} : thermal conductivity, $K_{al} = 2.3$ W/cm ^{0}C

(iv) Air

K_{air} : thermal conductivity , $K_{air} = 0.00032$ W/cm ^{0}C

$P_{cf} = \frac{8.71\times10^{13}}{5.56\times10^{13}}$ [TRF Flux = 8.71 x 10^{13} n/cm^{2}s @ 3MW thermal Power.

$\therefore P_{cf} = 1.567$

$Q_{Te} = m_{Te} \times h_{grTe} \times P_{cf} \times G_f$ (1)

$= 40 \times 1.664 \times 1.567 \times 0.8$ [$G_f = 0.8$]

$= 83.44$ W

$Q_{qu} = m_{qu} \times h_{grqu} \times P_{cf} \times G_f$ (2)

$= [\{\pi(r_2^2 - r_1^2) \times L + 2 \times \pi r_2^2 \times t_1\} \times \rho_{qu}] \times h_{grqu} \times P_{cf} \times G_f$

$= [\{\pi(1.15^2 - 1^2) \times 6.3 + 2 \times \pi \times 1.15^2 \times 0.15\} \times 2.654] \times 0.008 \times 1.567 \times 0.8$

$= 0.203$ W

$Q_T = (Q_{Te} + Q_{qu}) \times SF$ (3)

$= [(83.44 + 0.203) \times 1.2]$ W [SF = 1.2]

$= 100.37$ W

Since 1/7th of the total heat is transferred through convection mechanism and the rest of the heat is transferred through conduction mechanism, the total heat conduction stands;

$Q_{cond} = Q_T \times Q_{cf}$ (4)

$= 100.37 \times 0.857$ [$Q_{cf} = 6/7 = 0.857$]

$= 86.02$ W

3) Contact areas in the Heat Transfer Path

Contact area of new quartz vial with Al Can, $A_1 = \pi \times (0.85^2 - 0.75^2) = 0.503\ \text{cm}^2$

Area of trapped air under new quartz vial, $A_2 = \pi \times 0.75^2 = 1.767\ \text{cm}^2$

Contact area of Al Can with aluminum DCT, $A_3 = \pi r_4^2 = \pi \times 1.245^2 = 4.87\ \text{cm}^2$

Area under stopper plate of aluminum DCT, $A_4 = \pi r_5^2 = \pi \times 1.694^2 = 9.015\ \text{cm}^2$

(4) Thermal Resistances

$$R_1 = \frac{t_1}{K_{qu}A_1} = \frac{0.15}{0.05\times0.503} = 5.964\ {}^0\text{C/W}$$

$$R_2 = \frac{t_1}{K_{qu}A_2} = \frac{0.15}{0.05\times1.767} = 1.698\ {}^0\text{C/W}$$

$$R_3 = \frac{t_4}{K_{air}A_2} = \frac{0.1}{0.00032\times1.767} = 176.85\ {}^0\text{C/W}$$

$$R_4 = \frac{t_2}{K_{al}A_3} = \frac{0.04}{2.3\times4.87} = 0.0036\ {}^0\text{C/W}$$

$$R_5 = \frac{t_3}{K_{al}A_3} = \frac{3.81}{2.3\times4.87} = 0.34\ {}^0\text{C/W}$$

$$R_6 = \frac{1}{h_w A_4} = \frac{1}{4.5\times9.015} = 0.0247\ {}^0\text{C/W}$$

2.1 Temperature at Inside and Outside of the Quartz Vial (Method–1)

$$R_{eq(1)} = \frac{R_1\times(R_2+R_3)}{R_1+R_2+R_3}$$

$$\Rightarrow R_{eq(1)} = \frac{5.964\times(1.698+176.85)}{5.964+1.698+176.85}\ {}^0\text{C/W}$$

$$\therefore\ R_{eq(1)} = 5.7712\ {}^0\text{C/W}$$

$$R_{eq} = R_{eq(1)} + R_4 + R_5 + R_6$$

$$\Rightarrow R_{eq} = 5.7712 + 0.0036 + 0.34 + 0.0247\ {}^0\text{C/W}$$

$$\therefore\ R_{eq} = 6.1395\ {}^0\text{C/W}$$

$$Q_{cond} = \frac{T_{qi} - T_{wb}}{R_{eq}} \quad (5)$$

$$\Rightarrow T_{qi} = Q_{cond}\times R_{eq} + T_{wb} \quad (6)$$

$= [86.02 \times 6.1395 + 60]\ ^0$C

$= [528.12 + 60]\ ^0$C

$\therefore T_{qi} = 588.12\ ^0$C

Again,

$$Q_{cond} = \frac{T_{qi} - T_{qo}}{R_{eq(1)}}$$

$$\Rightarrow T_{qo} = T_{qi} - Q_{cond} \times R_{eq(1)} \quad (7)$$

$$= [588.12 - 86.02 \times 5.7712]\ ^0C$$

$$\therefore T_{qo} = 91.68\ ^0C$$

2.2 Determination of Centerline Temperature of Teo$_2$ Powder

One dimensional radial heat conduction equation with heat generation is;

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{dT}{dr}\right) + \frac{\ddot{q}}{K_{Te}} = 0 \quad (8)$$

$$\Rightarrow \frac{d}{dr}\left(r\frac{dT}{dr}\right) + \frac{\ddot{q}r}{K_{Te}} = 0$$

$$\Rightarrow \frac{d}{dr}\left(r\frac{dT}{dr}\right) = -\frac{\ddot{q}r}{K_{Te}}$$

$$\Rightarrow r\frac{dT}{dr} = -\frac{\ddot{q}r^2}{2K_{Te}} + C_1 \quad (9)$$

$$\Rightarrow \frac{dT}{dr} = -\frac{\ddot{q}r}{2K_{Te}} + \frac{C_1}{r}$$

$$\Rightarrow T(r) = -\frac{\ddot{q}r^2}{4K_{Te}} + C_1 \ln r + C_2 \quad (10)$$

Applying boundary conditions;

at $r = 0$; $\frac{dT}{dr} = 0$; from equation (5), $C_1=0$

at $r = r_1; T(r) = T_{qi}$; from equation (6),

$$T_{qi} = -\frac{\ddot{q}r_1^2}{4K_{Te}} + C_2$$

$$\Rightarrow C_2 = T_{qi} + \frac{\ddot{q}r_1^2}{4K_{Te}}$$

$\therefore$ From equation (6)

$$T(r) = -\frac{\ddot{q}r^2}{4K_{Te}} + \frac{\ddot{q}r_1^2}{4K_{Te}} + T_{qi}$$

The general heat conduction equation becomes;

$$\Rightarrow T(r) = \frac{\ddot{q}r_1^2}{4K_{Te}}\left[1 - \left(\frac{r}{r_1}\right)^2\right] + T_{qi} \quad (11)$$

At r = 0 in the general heat conduction equation, the centerline temperature of TeO_2 powder is

$$T_c = \frac{\ddot{q}r_1^2}{4K_{Te}} + T_{qi} \quad (12)$$

$$\left[\text{Here,} \quad \ddot{q} = (h_{grTe} \times pcf \times \rho) \times SF \times G_f \quad W/cm^3\right]$$

$$\Rightarrow T_c = \frac{1.664 \times 1.567 \times 4.5 \times 1.2 \times 0.8 \times 1^2}{4 \times 0.03} + 588.12$$

$$\Rightarrow T_c = (93.87 + 588.12)\ ^0C$$

$$\Rightarrow T_c = 682\ ^0C$$

Table 1: Temperatures at different locations with varying conduction heat transfer rate in the axial direction [* Equation number]

Q_{cond} = 85.83 W	Heat Transfer through axial direction				
	100%	90%	80%	70%	60%
T_c (^0C) [12]*	682	629.18	576.37	523.55	470.74
T_{qi} (^0C) [5]*	588.12	535.31	482.5	429.68	376.87
T_{qo} (^0C) [7]*	91.68	88.51	85.35	82.18	79

2.3 Temperature at Inside and Outside of the Quartz Vial (Method–2)

Volumetric Heat Generation:

$$\dddot{q}_{Te} = h_{grTe} \times P_{cf} \times \rho_{Te} \times SF \times G_f \times Q_{cf} = 1.664 \times 1.567 \times 4.5 \times 1.2 \times 0.8 \times 0.857 = 9.65\ W/cm^3$$

$$\left[\dddot{q}_{qu} = h_{grqu} \times P_{cf} \times \rho_{qu} \times SF \times G_f \times Q_{cf} = 0.008 \times 1.567 \times 2.654 \times 1.2 \times 0.8 \times 0.857 = 0.027\ W/cm^3\right]$$

Heat Transfer Rate:

$$Q_T = V_{Te} \times \dddot{q}_{Te} + V_{qu} \times \dddot{q}_{qu} \quad (14)$$

$$\Rightarrow \frac{Q_T}{\pi \times r_2^2} = \frac{\Delta V_{Te} \times \dddot{q}_{Te} + \Delta V_{qu} \times \dddot{q}_{qu}}{\pi \times r_2^2}$$

$$\Rightarrow \ddot{q} = \frac{\Delta V_{Te} \times \dddot{q}_{Te} + \Delta V_{qu} \times \dddot{q}_{qu}}{\pi \times r_2^2}$$

$$\Rightarrow \ddot{q} = \frac{\frac{m_{Te}}{\rho_{Te}} \times \dddot{q}_{Te} + [\pi(r_2^2 - r_1^2) \times L + 2 \times \pi r_2^2 t_1] \times \dddot{q}_{qu}}{\pi \times r_2^2}$$

$$\Rightarrow \ddot{q} = \frac{\frac{40}{4.5} \times 9.65 + [\pi(1.15^2 - 1^2) \times 6.3 + 2\pi \times 1.15^2 \times 0.15] \times 0.027}{\pi \times 1.15^2}$$

$$\Rightarrow \ddot{q} = \frac{87.78 + 0.21}{4.155}$$

$$\therefore \ddot{q} = 21.18\ W/cm^2$$

2.3.1 Thermal Resistances for Method-2

$$R_1' = \frac{t_1}{K_{qu} \times CF} = \frac{0.15}{0.05 \times 0.16} = 18.75\ cm^2\ ^0C/W$$

$$R_4' = \frac{t_2}{K_{al}} = \frac{0.04}{2.3} = 0.0174\ cm^2\ ^0C/W$$

$$R'_5 = \frac{t_3}{K_{al}} = \frac{3.81}{2.3} = 1.66 \ \ cm^2 \ {}^0C/W$$

$$R'_6 = \frac{1}{h_w} = \frac{1}{4.5} = 0.222 \ \ cm^2 \ {}^0C/W$$

$$R'_{eq} = R'_1 + R'_4 + R'_5 + R'_6$$
$$\Rightarrow R'_{eq} = 18.75 + 0.0174 + 1.66 + 0.222$$
$$\therefore \ \ R'_{eq} = 20.65 \ \ cm^2 \ {}^0C/W$$

Again,

$$\ddot{q} = \frac{T'_{qi} - T_{wb}}{R'_{eq}} \qquad (15)$$

$$\Rightarrow T'_{qi} = \ddot{q} \times R'_{eq} + T_{wb}$$
$$\Rightarrow T'_{qi} = 21.18 \times 20.65 + 60$$
$$\therefore \ \ T'_{qi} = 497.37 \ \ {}^0C$$

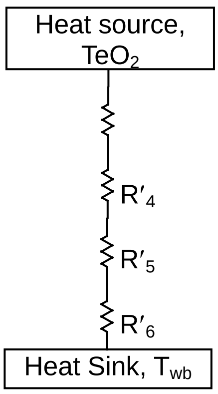

Fig 6: Circuit diagram of the thermal resistances along the heat transfer path

3. CONCLUDING REMARKS

Based on the calculation results, it is found that temperature of the inner surface of the quartz vial (T'_{qi}) is found at 497.37 ^{0}C using method-2. This temperature agrees well with the temperature calculated by method-1, which is about 80 % heat generated (Ref.:Table 1) in the TeO_2 powder transferred by conduction mechanism through the axial (bottom) direction. There is a small temperature difference (T_{qi} & T'_{qi} ; $\cong 15$ ^{0}C) of the inner surface of the quartz vial between the two methods, which can be accepted within a small range of uncertainty. The outer surface temperature of the quartz vial (T_{qo}) is found to be 85.35^{0}C. The estimation of surface temperatures is calculated for a quartz vial containing 40 gm of TeO_2 powder during its irradiation in the DCT at 3MW thermal power level. From these calculative results, it can be seen that there is a very high temperature gradient between the inner and outer surface of the quartz vial. Such a high temperature gradient may not be a problem for causing excessive thermal stress in the quartz vial.

It is also found from the calculation that the centerline temperature of the TeO_2 powder (T_c) is 576.37 ^{0}C, which is below the sintering temperature of the TeO_2 powder. The above-mentioned temperatures are found based on the conservative values of heat generation rate, contact areas and geometry factor.

4. RECOMMENDATIONS

The problem is a complicated one. One-dimensional equations are used for simplicity. 2 or 3-dimensional analysis (numerical) may be used for better results. However, as a first approximation, one-dimensional heat transfer analysis is very much useful to assess the temperature. Commercial temperature indicators (color code)/thermocouples can be inserted at inner and outer surfaces of the quartz vial to verify the calculated results with the experimental one.

5. REFERENCES

1. H. Kim, Calculation of Heat & Heat Transfer During Reactor Irradiation, Dec 1-12, 2003, IAEA-TCR-02079.
2 Wagner, “Assessment of the temperature distribution in irradiated tellurium dioxide samples”, Germany, July 12, 2002.
3 Md. Shafiqul Islam, “Assessment of Temperature Distribution in Irradiated Tellurium Dioxide Sample in the DCT of a BAEC 3 MW TRIGA Mark-II Nuclear Research Reactor”, Reactor Operation and Maintenance Unit (ROMU), AERE, Savar.
4 M. S. Islam, A. Haque, M. A. Salam and M. A. Zulquarnain, "Heat Transfer Analysis During Irradiation of TeO_2 Sample in a Target Vial at DCT Tube of BAEC 3MW TRIGA Mark-II Research Reactor", International Seminar on Nuclear Safety, Tokaimura, Japan, Nov 8-19, 2004.
5 M. A. Zulquarnain and A. Haque, “Report on Evaluation of Safety of In-core Irradiation of TeO_2 Targets for Increasing the Production of I-131”, May 11, 2005, ROMU, AERE, Savar.
6 M. Necati Ozisik, Heat Transfer, A Basic Approach, McGRAW-Hill International Publications, International Edition, 1985.

6. NOMENCLATURE

A : Heat transfer area (m^2)
C : Constant parameter
CF : Contact factor
G_f : Geometry correction factor
h_{gr} : Heat generation rate (W/g)
h_W :Convective heat transfer coefficient of water under the stopper plate of aluminum DCT, W/cm^2.^{0}C
K : Thermal conductivity (W/m K)
M : Mass of TeO_2 powder
P_{cf} : Correction factor for power
Q_{cf} : Heat conduction factor
Q_{Te} : Heat from TeO_2 powder, W
Q_{qu} : Heat from quartz vial, W
Q_T : Total heat generated (Q_{Te}+Q_{qu}), W
Q_{cond} : Total heat transferred through conduction mechanism, W

$\ddot{q}_{Te}$ $= Volumetric\ heat\ generation\ of\ TeO_2\ powder,\ W/cm^3$

$\ddot{q}_{qu}$ $= Volumetric\ heat\ generation\ of\ quartz\ vial,\ W/cm^3$

$\ddot{q}$ $= Heat\ flux\ in\ axial\ direction,\ W/cm^2$

r : Local radius

R : Thermal resistances (Method-1), $^0C/W$

R' : Thermal resistances (Method-2), $cm^2.^0C/W$

$R_{eq(1)}$: Equivalent resistance of R_1, R_2 and R_3 (Method-1), $^0C/W$

R_{eq} : Equivalent resistance (Method-1), $^0C/W$

R'_{eq} : Equivalent resistance (Method-2), $cm^2.^0C/W$

SF : Safety factor

T_{wb} : Water temperature under the stopper plate of aluminum DCT, ^0C

T_{qi} : Inner temp. of the quartz vial (Method-1), ^0C

T'_{qi} : Inner temp. of the quartz vial (Method-2), ^0C

T_{qo} : Outer temperature of the quartz vial, ^0C

T_c : Center temperature of the TeO_2 powder, ^0C

ρ : Density (kg/m^3)